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***Urban Ventilation, Improving the Wind Environment in  
High Density Cities by Understanding the Urban Morphology***

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The North American Conference on Sustainability, Energy & the Environment 2014  
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**Abstract**

There is clear evidence that Heat island has changed cities microclimate from their original and it has led to increased overheating risk, longer summer periods and higher energy consumption for cooling. Understanding of the relation between urban morphology and favorable wind conditions could provide a key to avoid such serious episodes and to improve the cities' air quality as one the most important parameters affecting the urban life experience. Yet optimizing permeability of urban fabric to ensure adequate natural ventilation in urban areas is an unresolved issue faced by planners and architects.

In this paper a method has been introduced to analyze microclimate in urban compact patterns. Through this method are examined nine pilot samples, taken from different compact cities around the world. The results of the analysis are patterns' wind flow direction, speed and temperature that are compared among selected patterns. These kind of comparisons and analysis could be helpful not only for monitoring the existing microclimate condition for necessary interventions, but also to evaluating natural ventilation and wind comfort in further urban projects.

It is also proposed a user-friendly method to map the urban microclimate. The proposal is initiated from the fact that existing simulation software are time consuming and complex process of model preparation, simulation and results interpretation. The method is mainly made of three steps: 1) patterns recognition, 2) recognition of the main street canyons, 3) integration of patterns microclimate database with the GIS tables of data to provide wind maps.

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## **Introduction**

Urban ventilation is in a close relation with today's most concerning issues of cities environmental management. Study of the airflow in and around buildings on one hand demonstrates the role of urban ventilation in mitigation of cost and energy consumption through both conservation and production of energy. On the other hand, it shows the influence it could have on both outdoor and indoor comfort as well as the air quality.

The question is how we can analyze or measure the effect of invisible force of the wind on the urban tissue and by understanding it how we can improve the air condition in that context.

The mission of the research was to introduce an intermediate level technique for wind analyzes to fill the gap between regional wind maps and wind simulations at district and building scale.

This technique is based on the analysis of air fluxes in compact cities build-up patterns. It proposes a way to investigate the permanent effect of build environment on the cities microclimate. A morphological kind of approach has been employed to emphasizing the effect of different urban forms and patterns on cities' ventilation and wind comfort.

Examination of the wind flow field in the actual urban context and mapping them, allows us to not only evaluate the existing urban tissue, but also, to predict the city's microclimate changes implied by the urban densification process and new urban projects. Appliance of this tool lets us examine the effect of built environment on the parameters such as wind speed, air temperature and flow direction.

What makes this technique sought-after in comparison with the existing simulation software, at the urban level, are advantages such as fast computability, user friendly, and modifiability of the maps over the time along with ever-changing cities and comparability of results obtained from several urban project.

Microclimate condition of urban patterns three-dimensional models are simulated using the Computational fluid dynamic method. A method in which Computers are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces. In each simulation it is involved a comprehensive set of environmental indicators describing the climate of the site, characteristic of the wind inflow and sun light.

MATLAB software is the other tool used in this research in order to figure out the morphological properties of each pattern by analyzing their 2.5 Dimensional models. The result from MATLAB were useful to understand better the simulation results as well.

The outcomes of this technique could be summarized in patterns wind and air quality maps. Wind maps could be used to map the existing/potential/necessary ventilation paths and fields, essential in mitigating the heat island effect and pollution dispersion.

Air quality maps are the other outcomes that illustrate the urban wind comfort as an invisible but distinguishing parameter of livability.

### **Where the idea came from?**

In the last decades, a compact city dilemma is questioning the relation between the densification and transformation of the existing urban tissue and its sustainability. By following the actual densification policies, made to obtain more sustainable cities, there would be the risk of affecting the urban environment through changing its microclimate. Cities heating up by the famous heat island effect and consequently increase in energy consumption during the summer time are only some of issues which makes us concern. Of course, these effects are more evident in cities with already compact tissue.

With the rapid development of urbanization, the economy and number of vehicles, the urban climate has worsened in recent years, causing serious urban problems. One of the most dramatic changes is the warming effect that cities have on local air temperatures. According to some studies, the heat-retaining properties of the building blocks of urban development can make cities up to 10 degrees Celsius warmer than the surrounding area. The average temperature in cities is going up more than twice as fast as the temperatures on the rest of the planet.

Thus, in this research it is tried to understand how the physical transformation of the cities could affect its microclimate and how this knowledge could be utilized to improve our cities environmental quality.

### **For whom and how?**

Urban forms have always fascinated urban planners, urban designers and architects, as a tool to improve the sustainability and performance of urban areas. Wind maps could be useful to City and environment managers by helping them evaluating the effect of urban developments and new proposals on urban ventilation.

Wind maps could be used to map the existing/potential/necessary urban ventilation paths and areas, essential in mitigating the heat island effect and pollution dispersion. Air quality map is the other outcome of which an invisible but distinguishing parameter of livability; wind comfort and so on.

### **The state of the art**

In the book called *the compact city, a sustainable urban form?*<sup>1</sup> It is addressed some of the questions raised about the conception of the compact city from social, economical and environmental point of view. According to this book, it is not clear if the compact city is the best or only way forward to obtain more sustainable cities. It is argued, "While there may be strategic benefits, the impacts of the compact cities are likely to be felt local". They tried to examine the complex relation between high density living and mixed up environment and a high quality of life. A great degree of uncertainty in theory and in particular issues surrounding the compact city debate exist. It is argued, "Complexity and uncertainty mean that a precautionary principle should be applied in relation to the development of more compact form." In this paper, it is tried to examine the morphological changes of urban form from an urban

ventilation point of view. To see how different forms of morphological realization could have negative or positive effect on urban microclimate.

Urban heat island effect is one of the major problems faced in the process of urban microclimate changes. In a work called *a simple method for designation of urban ventilation corridors and its application to urban heat island analysis*<sup>2</sup> it is confirmed that ventilation is a key parameter in mitigating heat island formation. They tried to map the urban wind ventilation, using the concept of “building frontal area index”, in the study area of Kowloon peninsula of Hong Kong as an example of a dense, sub-tropical urban environment where ventilation is critical for human health. Using the map of frontal area index, the main ventilation pathways across the urban area are located using least cost path analysis in a raster GIS. Comparison of the pathways with a map of the urban heat island suggests that ventilation is a key parameter in mitigating heat island formation in the study area.

Heat island effect could highly effect the energy consumption trend in urban areas. The consumption patterns of cities are severely stressing the global ecosystem. The world’s total energy consumption in 2006 was equivalent to a constant-use rate of 16 terawatts (1 terawatt, or TW, equals 1 trillion watts)<sup>3</sup>. Of that, an average rate of 6.7 TW was consumed in 86 metropolitan areas in the Northern Hemisphere.

This fact shows the importance of knowing what happens to electricity usage as the outdoor temperature rises. in a research done by *Opowers*<sup>4</sup> it has been examined an anonymized energy usage data across 18,000 homes from 3 different cities in the western part of US, which has faced blistering temperatures during July 2012 (the hottest July on record by that time). Analysis shows that increased air-conditioning during the hottest days of summer 2012 caused residential electricity demand, where More than 60% of US households now have central air conditioning, to shoot through the roof. As the result the average electricity usage of homes on a 103°-high summer day was registered up to 40% higher than during a typical summer day.

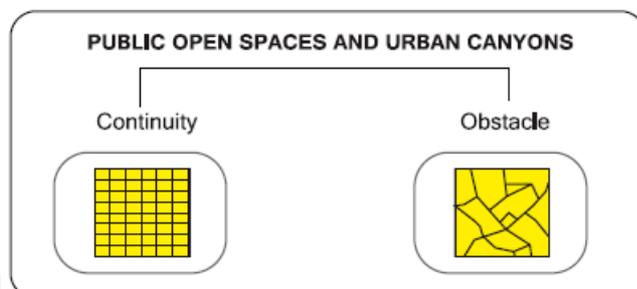
## **Methodology**

Here it is introduced steps taken in the process of wind map-making, through a morphological approach.

1. Analyze of the compact cities tissues in order to find the prevailing patterns of the compact city. Framework: based on urban landscape model, patterns of different compact cities were selected from all around the world. A work based on the studies and recognition of urban forms extracted from the book called *Cities and Forms: On Sustainable Urbanism*. This method was employed in selection of the compact cities<sup>5</sup>.
2. Compact cities prevailing patterns categorization, by identifying the possible wind flow areas. This concept takes in to consideration three main urban Items, in order to distinguish patterns from each other, 1- Buildings (built-up area), 2- Paths (streets and possible urban canyons) and 3- Open areas.

Paths:

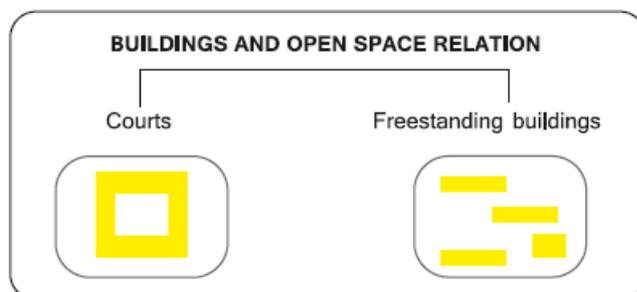
According to the knowledge of fluid dynamics, streets network could be formed in a manner to ease up the air fluxes and even amplify them which I have called them *continuity network*, or they could form barriers against the wind flow, in this case they are called *obstacle network*.



Scheme 1. Network public open spaces and urban canyons regarding to the wind flow  
Source: Author

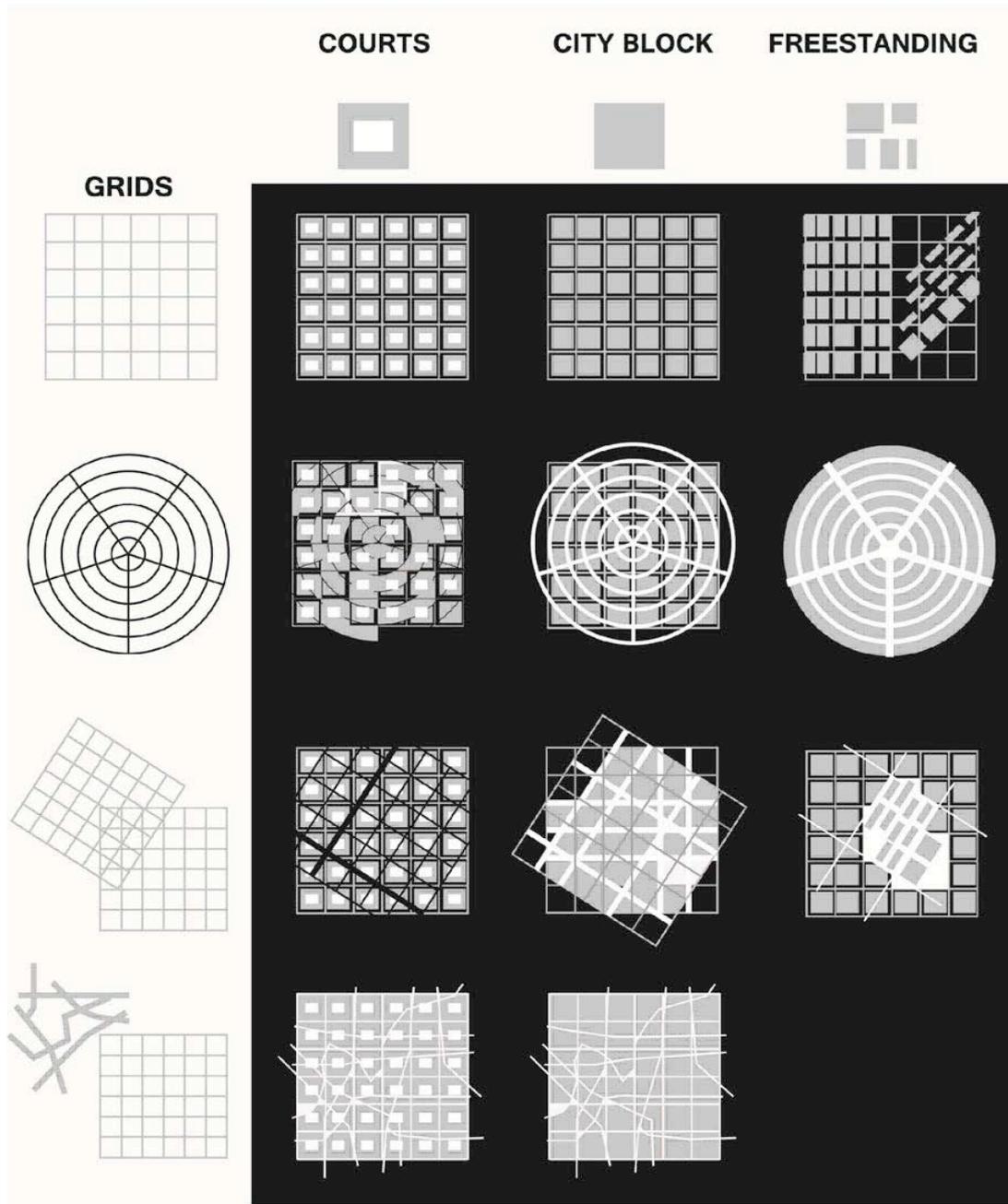
Open areas:

This type of urban space could be analyzed at two different scales; first, the Urban level such as parks and piazzas, and second the District level such as micro open spaces around and within buildings. Mapping the Parks and piazzas as they are simply distinguishable by the streets and built environment. What is of interest we can find at district level, where the relation between buildings and open spaces are translated in to; open spaces surrounding the buildings, here called *freestanding buildings* and buildings surrounding the open space, here called *Courts*.



Scheme 2. Relation between buildings and open spaces regarding to the wind flow  
Source: Author

The assumption here is that the wind flows in the courtyards are that slow in relation with the other open areas and their effect on the overall urban ventilation is so minimal that in mapping the urban wind flow areas we can even disregard them. Here is to say this assumption has been approved after the wind simulation of different compact patterns in this research.



Scheme 3. Taxonomy of patterns, defined by topology based on the patterns recognition concept  
Source: Author

By adopting this methodology, patterns are divided in to preliminary groups with the possible same or close air fluxes according to the similarity of their morphologies as followed: *orthogonal grid, irregular grids, hybrids, linear orders and city enclaves.*



Scheme 4. Selected samples  
Source: Author

This framework was implemented for eleven pilot-studies, even though, in a specific city analysis regarding to the scale of the city, it is possible to arrive to other kind of morphological groups. A series of samples with densities ranging between low, medium and high have been selected for each category.

After selecting the samples, the next step is to analyze and measure their morphological properties such as built and un-built area, density and roughness that in

this research has been done by the mean of algorithms created in the MATLAB software<sup>6</sup>.

In a parallel work, the wind flow of each sample is simulated by the ENVI-met software, using the computational fluid dynamics method, at hottest period of the year regarding to the local climate of the chosen sample. The main outcomes are the maps representing the microclimate condition such as flow speed, temperature and direction at different elevations from the ground.

### **Interpretation of outcomes**

The outcome has been study in numerical and qualitative way for each sample and the results are crossed-comparison.

Numerical analysis includes:

- The change in airflow velocity and temperature between the inflow and the average wind flow on site at 3 different elevation (First cut: 3m – Second cut: 9m-15m – Third cut: on the model's top);
- The velocity and temperature variation between three cuts;
- Comparative vision between samples total floor area, built area footprint, built area intensity (volumetric and surface area), mean roughness;
- histogram relation between wind speed % at first cut regarding the prevailing wind and samples' density;
- Histogram relation between air temperature changes at first cut regarding the prevailing wind and samples' density.

What emerges is that in general increase in built-up intensity does not affect the urban ventilation and air quality in a direct and linear way. Nevertheless, individual analysis on each sample confirms that it highly depends on the amount and form of the possible wind flow areas (continuity and obstacle form of the un-built areas). The so-called network of un-built area could be in favor or against the wind flow, independently from the incoming wind direction. Consequently, it could increase/decrease the quality of temperature exchange process between buildings and flow around them. The better this network is formed in favor of wind flow, such as orthogonal or linear order patterns with specific morphological factors, slower would be the formation of heat island and faster would be the urban ventilation process.

In specific in order to have a better performance, a pattern should have factors as following:

- at the same density, the continuity street network performance is much better than obstacle street network
- high built area porosity: even with high-density patterns such as the New York City pattern, with skyscrapers, due to the high porosity of the pattern registers a good performance.
- good street canyons morphologies: width-height ratio > 1, length-height ratio > 1, length-width ratio > 1
- good grains porosity: the court yard buildings have better temperature exchange than massive building blocks, whether it highly depends on the % of the court yard surface to the total building footprint or better to say it depends

on the court's form (width-length and width-height ratio). In cases where its form is closer to rectangular and the width-height ratio is  $< 2$ , the court performance is major.

- good street canyons and buildings mass relation: average building width/length to average canyon width is  $= < 2$ .

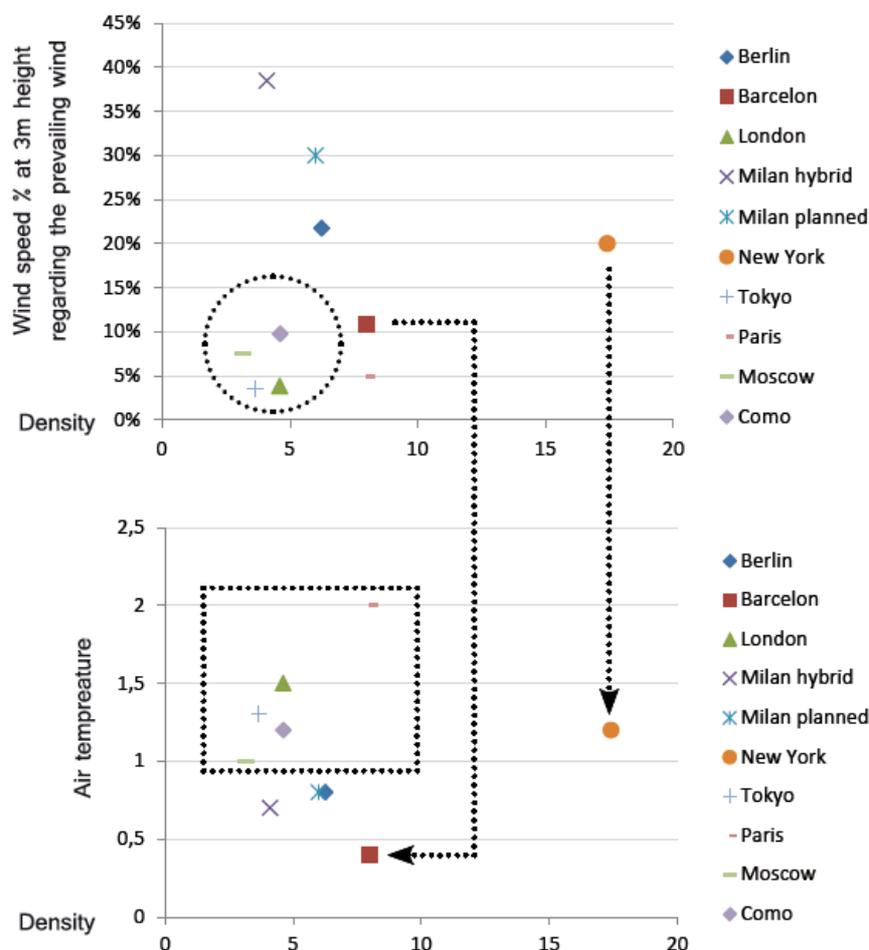


Chart 1. Comparative vision,

On the top) relation between samples density and wind speed (percentage of the wind velocity at first cut regarding the prevailing wind speed).

On the bottom) relation between samples density and wind temperature (difference from air temperature at first cut and prevailing wind temperature)

### Concern and future work

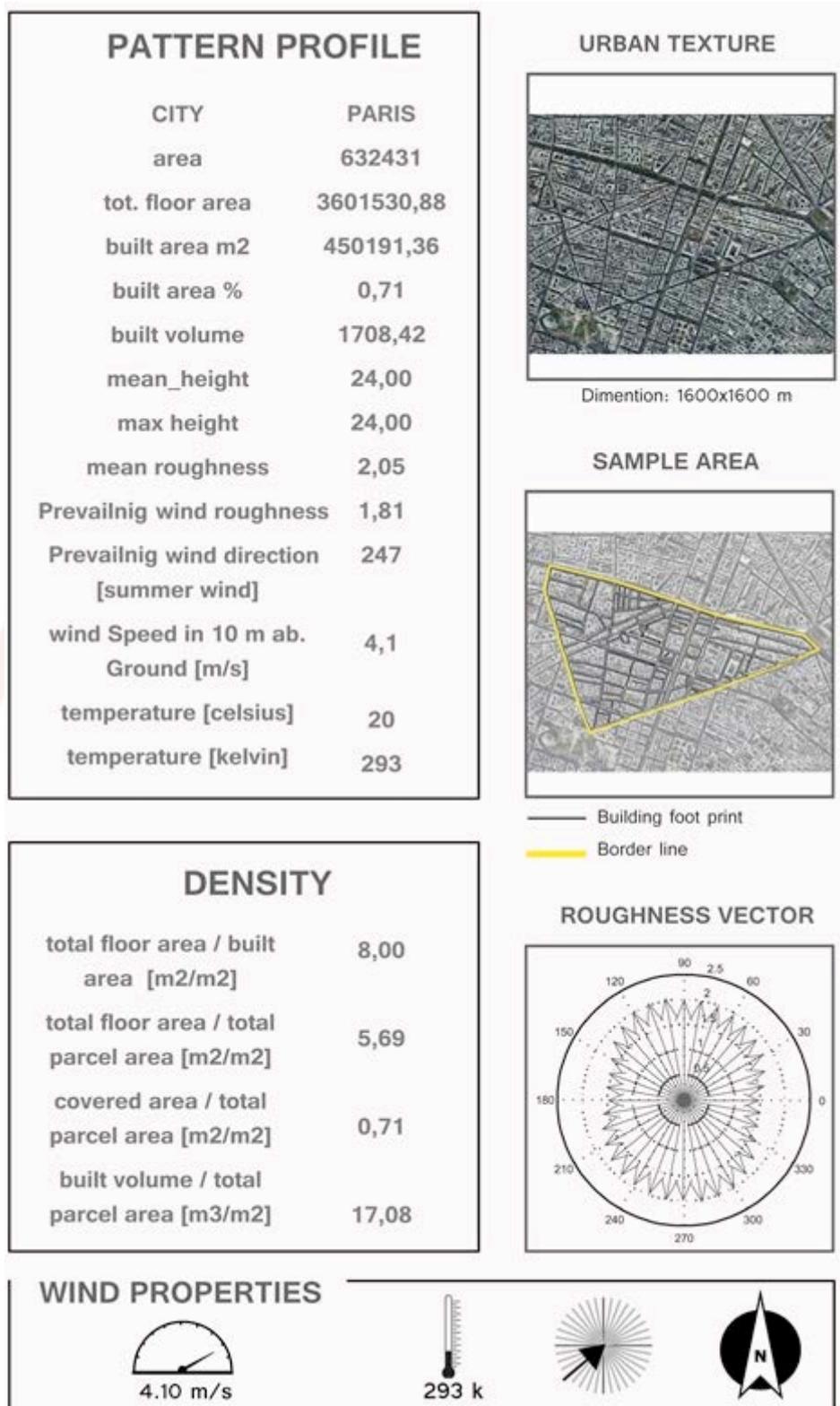
What is suggested as future work is integration of the patterns wind profile with GIS data, in order to provide cities Wind Map. Results obtained from MATLAB an ENVI-met could be stored as database for GIS. In GIS, each category of pattern would be related to a specific layer through an automated recognition process of urban objects <sup>7</sup>. In this way, it is possible to map the wind velocity map, air temperature map and urban ventilation/ wind flow quality map. These maps could help recognizing the necessary interventions or evaluating the future urban projects.

These data are modifiable regarding to the seasonal and climate condition of the city under study. Potential users can use the proposed set of patterns to create wind maps, add new patterns to it in order to compare different design solutions, or add new groups based on their necessity. These possible modifications make it highly flexible to use in different case studies as well.

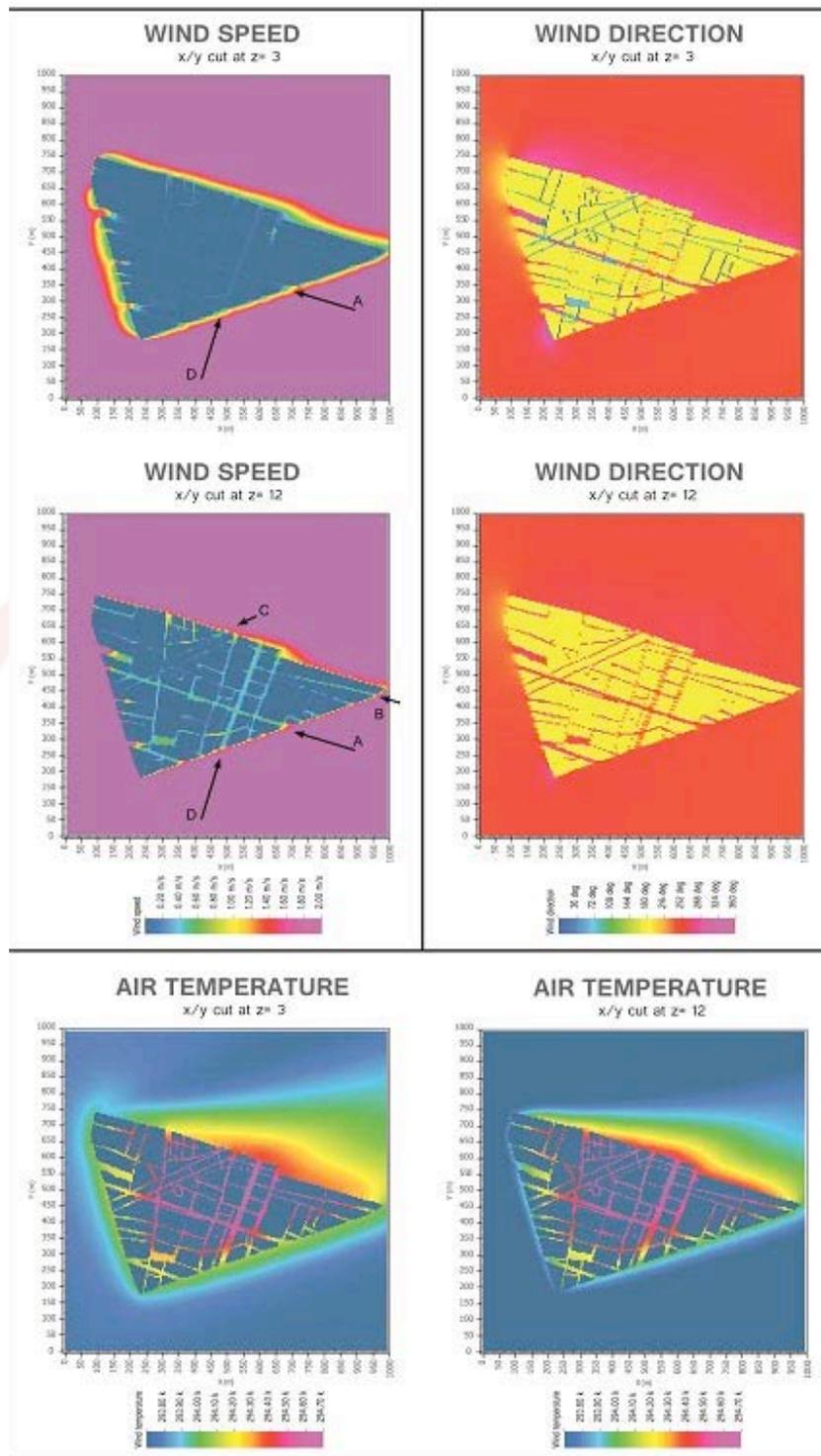


## References and further reading

1. M. Jenks, E. Burton, K. Williams, Compact City Series: The Compact City: A Sustainable Urban Form? , 2005;
2. Man Sing Wong, Pui Hang To, Jingzhi Wang, Janet E. Nichol, A simple method for designation of urban ventilation corridors and its application to urban heat island analysis, Building and Environment, Volume 45, Issue 8, August 2010, Pages 1880–1889
3. Guang J. Zhang, M. Cai, A. Hu. Energy consumption and the unexplained winter warming over northern Asia and North America. Nature Climate Change, 2013; DOI
4. Opower's is a big-data and energy blog, "Outlier," which leverages energy usage data across 50 million US households. They works with 80 utility companies to empower millions of customers to understand their energy usage in U.S.<http://blog.opower.com>
5. S. Salat, F. Labbé, C. Nowacki, "Cities and Forms: On Sustainable Urbanism", CSTB Urban Morphology Laboratory, 2011, 2705681116, 9782705681111
6. E. Morello, C. Ratti, 2007, "Raster Cities: image processing techniques for environmental urban analysis", in K. Thwaites, S. Porta, O. Romice, M. Greaves (editors), Urban Sustainability through Environmental Design: approaches to time, people and place responsive urban spaces, Spon Press, London, UK, pp. 119-122
7. A. Peeter , Y. Etzion , "automated recognition of urban objects and their morphological attributes using GIS," ISPRS Archives Vol. XXXVIII, Part 4-8-2-W9, 2010



Scheme 5. Example of Irregular grid pattern profile, Paris - France



Scheme 6. Example of Irregular grid, microclimate pattern profile, Paris - France



## *Solar Assisted Power Supply for Rail Coaches*

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### **Abstract**

We have examined the feasibility of installing solar photovoltaic modules atop train coaches in India. Most long distance trains of Indian Railways consist of Alstom-LHB (Linke Hofmann Busch) coaches that do not have self-generating systems, making diesel generator cars mandatory to supply the required power for the electrical loads of the coaches. The feasibility of supplementing the diesel generator sets with power from solar photovoltaic modules installed on the coach rooftops has been studied. The area available on the roof of the coach was found to be more than sufficient to meet the electrical lighting load through photovoltaic modules.

For the case study, a typical railway route that covers a distance of 1,800 km has been considered. The saving of diesel was around 90,000 litre per year per train-set. The analysis indicates that the return on investment is around 4 years. In addition, this scheme will reduce the CO<sub>2</sub> emission by 239 tons per year per train. Indian Railways being the largest railway network of the world, operates 160 LHB trains in a day. Hence a significant savings in Diesel and reduction in CO<sub>2</sub> emissions can be achieved.

Keywords: Railway, Solar, Renewable, Energy, Transportation, Sustainable

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## Introduction

The transportation sector is a major contributor to the global CO<sub>2</sub> emission and global warming. Solar power can be used to reduce the CO<sub>2</sub> emissions in buses and trains. The Adelaide City Council introduced all-electric buses in which its batteries were charged by a roof-mounted solar photovoltaic (SPV) system erected at charging stations and has concluded that its cost of operation is far less than diesel powered buses (Adelaide City Council, 2007). In Italy, amorphous silicon modules were installed on five passenger coaches, two locomotives and three freight coaches. (Alessandro Basili, 2005). In 2010, TER-SCNF (Transport Express Régional Société Nationale des Chemins de fer Français), the state-owned railway of France tested a DMU (Diesel Multiple Unit) fitted with Thin-film CIGS (Copper Indium Gallium Selenide) SPV modules. The SPV system of capacity 990W<sub>p</sub> mounted on the rooftop partially supplied power for electrical lighting system inside the DMU (Disasolar, 2012). In 2011, Indian Railways, rail coach at Pathankot was fitted with SPV modules of net capacity of 1 kW<sub>p</sub> to power an electrical load of 420W. Similar attempts were made in Kalka-Simla Mountain Railway (toy-train) to supply power for six LED bulbs of 6W each (Ministry of New and Renewable Energy, 2012). The experiments that were done by Indian Railways was for narrow gauge rail coaches run at a maximum speed of 40 km/h. This paper discusses the feasibility of providing solar power for broad gauge (1,676 mm) LHB coaches being used by the long distance trains of Indian Railways, which generally run up to a maximum speed of 160 km/h.

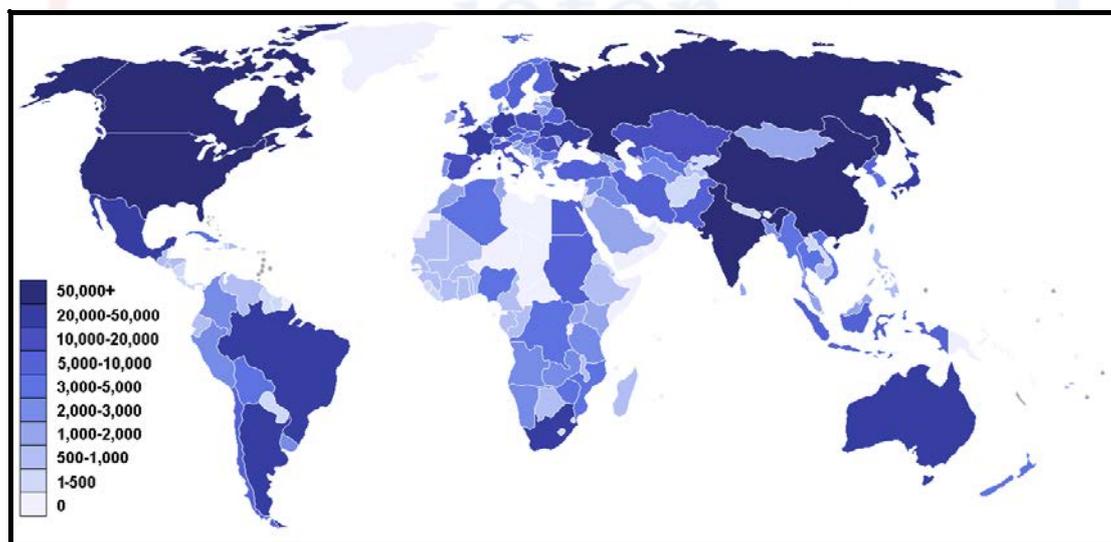


Figure 1: Map describing the length of various railway networks in the world (Wikipedia, 2013)

Figure 1 shows the lengths of railway networks of different countries. It can be seen that United States of America, China, Russia, India and Canada have the longest railway lines. India has the 5<sup>th</sup> largest railway network of the world with a total length of 65,436 km and has been operational since 161 years. It carries 23 million passengers per day scattered over 12,617 trains and remains as the most preferred mode of transportation (Mali, 2014). Figure 2 shows the spotting of various trains of India Railways in which blue and red arrows represent the trains in transit and trains at stations, respectively.

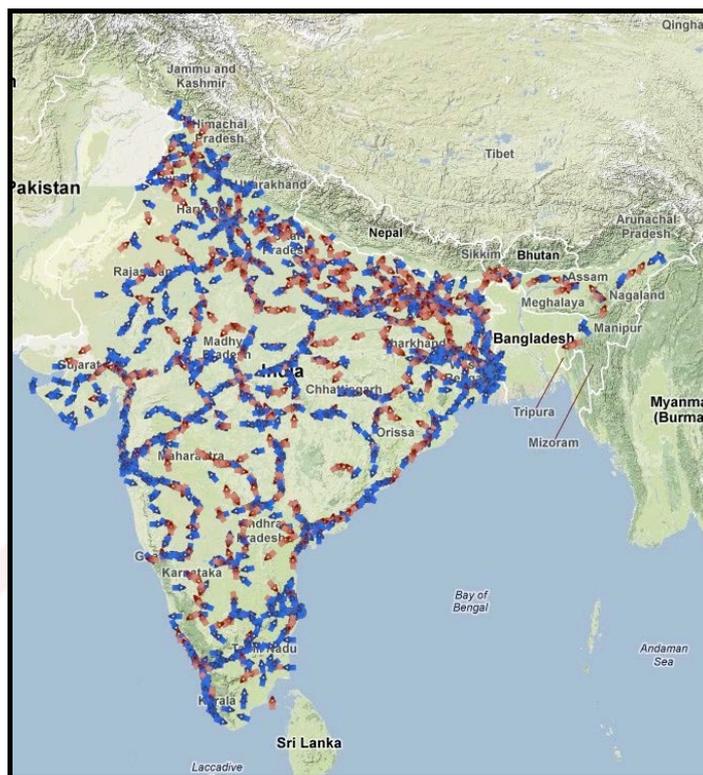


Figure 2: Train spotting of Indian Railways (Ministry of Railways, 2013)

Diesel has been the major source of energy for most of the rolling stock of Indian railways. As shown in figure 3, 70 % of diesel is being consumed in the transportation sector of India, where Indian Railways consume 3.24 % (Ministry of Petroleum & Natural Gas, 2014).

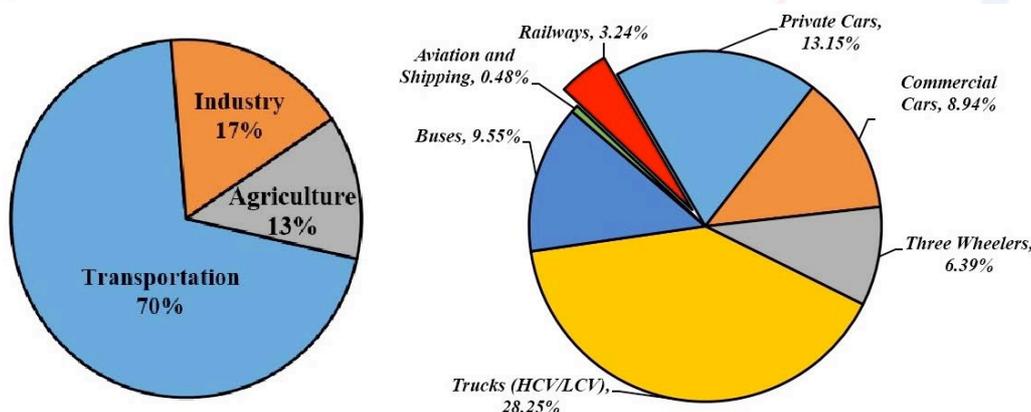


Figure 3: Sectorial Consumption of Diesel in India

### Coaching stock of Indian Railways and its power supply schemes

The coaching stock of Indian Railways includes three versions classified based on the manufacturing units, namely ICF (Integral Coach Factory), RCF (Rail Coach Factory) and LHB (manufacturing license by Linke Hofmann Busch, Germany)(Shravanth Vasisht, Sridhar, & Dhanyavathi, 2011).The total number of passenger coaches being operated in India adds up to 62,924 out of which 5,000 coaches are variants of LHB (Wikipedia, 2014). Since the LHB coaches possess benefits like higher carrying

capacity, lesser weight, low corrosion, low maintenance, good aesthetics, better passenger comfort and safety than the conventional coaches, Indian Railways is slowly migrating from conventional coaches to LHB coaches (Ministry of Railways, 2012).

There are two significant schemes of power supply for the coaching stock of Indian Railways, namely Self-Generation (SG) and End-On Generation (EOG)(Shravanth Vasisht, Sridhar, & Dhanyavathi, 2011), which are adopted by the utility based on the requirement of variants of the coaching stock.

### Self-Generation (SG) Scheme

In SG scheme of power supply, the power required to cater the electrical load in the coach is generated by coupling an alternator to the wheel and axle system of the rail coach by means of a V-belt, as shown in figure 4. The wheel and axle set up acts as the prime mover for the alternator. The output of the alternator is used to charge the battery bank which supplies for the electrical load in the rail coach. The batteries get charged as long as the rail coach is in motion.

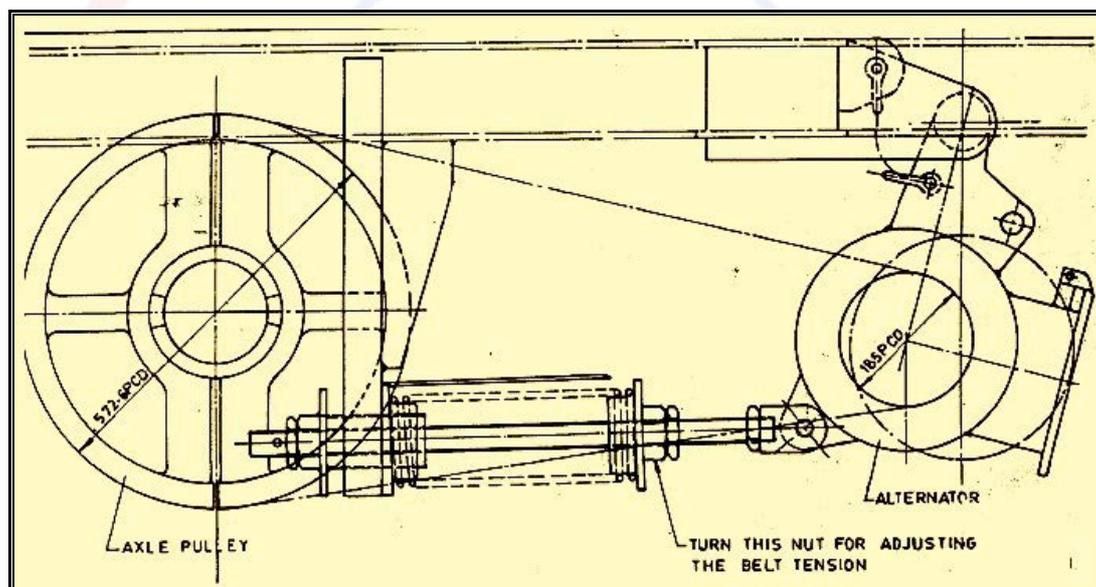


Figure 4: Schematic representation of SG scheme (Shravanth Vasisht, Sridhar, & Dhanyavathi, 2011)

SG system is being used in the conventional rail coaches of Indian Railways and stands as the most environment friendly sources of energy for the rail coaches. In case of outage in the SG system, the required power can be drawn from the adjacent coaches of the rake with the help of the terminals provided on either ends of each coach.

### End-On Generation (EOG) Scheme

EOG scheme of power supply employs two diesel generator sets (DG-Sets) installed in a wagon. This wagon is known as generator car or power car and is coupled on either ends of the rake, as shown in figure 5 (a). The generator cars provide the energy

required for supplying for the electrical load of the entire rake, as shown in figure 5(b).



Figure 5(a): Generator Car or Power Car

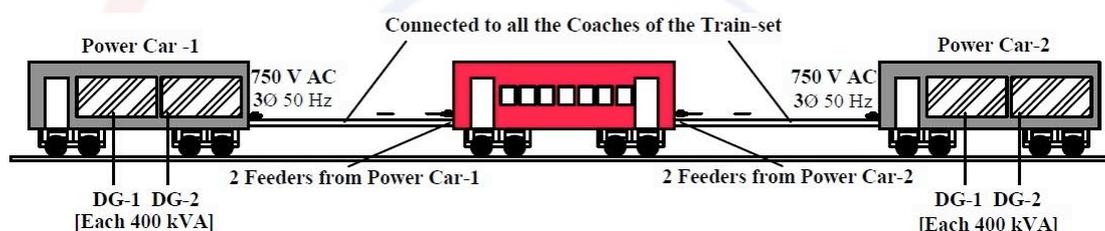


Figure 5(b): Schematic diagram of a rake with EOG scheme of power supply

EOG scheme has been adopted in the LHB variants of coaching stock of Indian Railways. The only demerit of LHB coaches is the consumption of huge volume of diesel for supplying the electrical load. In addition to this, the generator cars produce loud noise which is audible upto a distance of more than 1 km. There is a need to adopt solar power for the coaches in order to reduce the diesel consumption by the LHB coaches, at least for supplementing the electrical power required for the lighting load (Vasisht, Vishal, Srinivasan, & Sheela, 2014). Providing solar power assistance for the LHB rakes would not only reduce the diesel fuel consumption but reduces the CO<sub>2</sub> emission which is one of the major greenhouse gases.

### A Case Study

To check the feasibility of providing solar power assistance for LHB coaches, it is required to know, analyze and evaluate the performance of a train consisting of LHB coaches. For this, one of the first few mixed rake LHB trains (a train with rake composition of both air-conditioned and non-air-conditioned coaches) of the country was selected and details about various types of electrical loads (both heating and lighting circuits), diesel consumptions of the generator cars, fuelling schedules of generator cars and area of roof-top available for installation of SPV modules were collected. The transition from source to destination has been termed as 1 trip. The route taken by the train and other details of the train are as shown in figure 6 and table 1, respectively. It was calculated that the lighting load in the entire rake amounts to

43% of the net electrical load. However, the main focus of this work was to supplement the power source for the electrical lighting circuit in the rake.

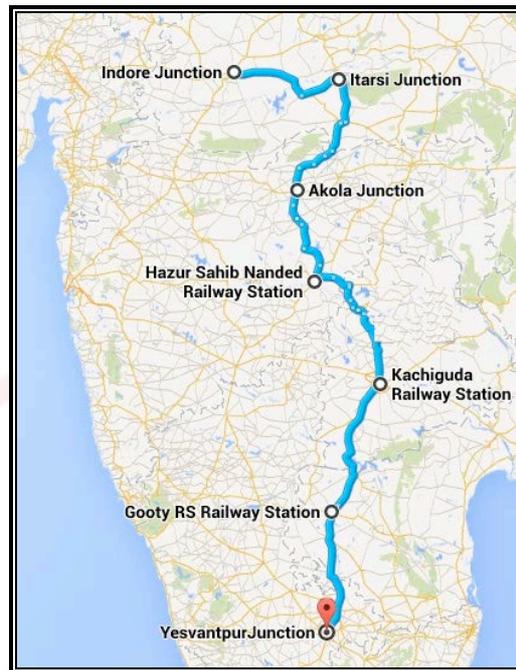


Figure 6: Route map of the train considered for case study

Table 1: Details of the LHB train considered  
(Vasisht, Vishal, Srinivasan, & Sheela, 2014)

Name of the train	Indore – Yeswantpur LHB Express
<b>Rake composition (19 coaches)</b>	
i. No. of air-conditioned coaches	5
ii. No. of non-air-conditioned coaches	13
iii.No. of pantry cars	1
iv. No. of generator cars	2
<b>Distance from source to destination</b>	1,800 km
<b>Duration of 1 Trip (source to destination)</b>	40 hours
<b>Total sunshine period during the trip</b>	15 hours
<b>Electrical load (lighting circuit only)</b>	
i. Total lighting load per coach	4.6 kW
ii. Net lighting load of the rake	90 kW
<b>Details of the fuel used for generator cars</b>	
i. Type of fuel used	Hi-Speed Diesel (HSD)
ii. Price per litre of fuel	US\$ 1.07 (Rs. 66)
<b>Fuel consumption by generator cars for 1 trip</b>	
i. by the net electrical load of the rake	793 gallons (3,000 litre)
ii. by the lighting load of the rake (43% of the net electrical load of the rake)	341 gallons (1,290 litre)

<b>iii. Expenditure on fuel for supplying for electrical lighting load during the trip</b>	US\$ 1,385 (Rs. 85,140)
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It was observed that the train is exposed to sunshine for 15 hours during the trip. This is indeed a good opportunity to harness the solar energy incident on its roof-top. The roof-top layout of the LHB coach along with the region available for placing the SPV modules is shown in figure 7 and calculation for evaluating the feasibility of erecting the SPV modules within the space available is shown in table 2.

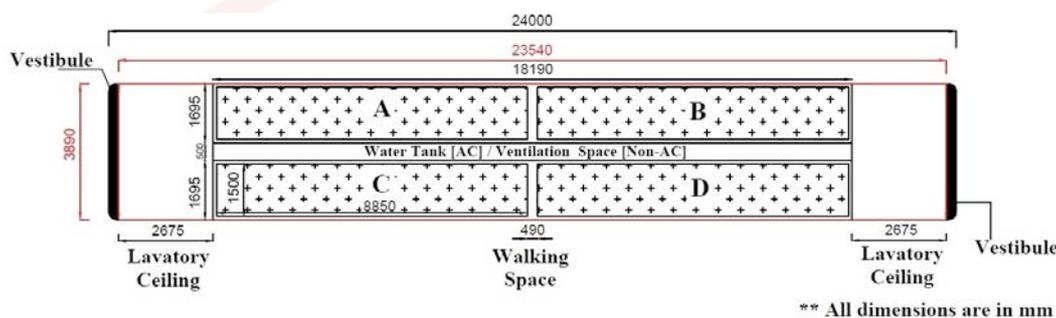


Figure 7: Proposed layout of the roof-top of an LHB coach (Vasisht, Vishal, Srinivasan, & Sheela, 2014)

Table 2: Roof-top area available for the installation of SPV system on one LHB coach

Roof-top area of the LHB coach	
i. Roof-top area available on an LHB coach	93.36 m <sup>2</sup>
ii. Area occupied by air-conditioning units, lavatory ceilings, water tanks. walkways and ventilation vents	31.567 m <sup>2</sup>
iii. Total available area for mounting SPV modules	61.793 m <sup>2</sup>
Solar power potential in an area of 1 m <sup>2</sup>	154 W <sub>p</sub>
Thus, solar power potential in the area available on the roof-top of an coach	61.793 m <sup>2</sup> X 154 W <sub>p</sub> = 9.5 kW <sub>p</sub>
Net solar power potential assuming system efficiency to be 80% and shaded region as 15%	6.5 kW <sub>p</sub>

From tables 1 and 2, it is clear that the solar power potential on the roof-top of one LHB coach is significantly higher than the electrical lighting load of the coach. In order to check the feasibility of installation of SPV system for catering the lighting load, the average daily Global Horizontal Irradiance (GHI) is required to be taken into consideration. Figure 8 describes the trend of daily GHI averaged over different months of the year (Ministry of New and Renewable Energy, 2013). It can be observed that GHI is maximum and minimum during the months March and December, respectively. The estimation of the energy that can be generated from the SPV system and its comparison with the energy consumed by the electrical lighting load of the rake is given in table 3.

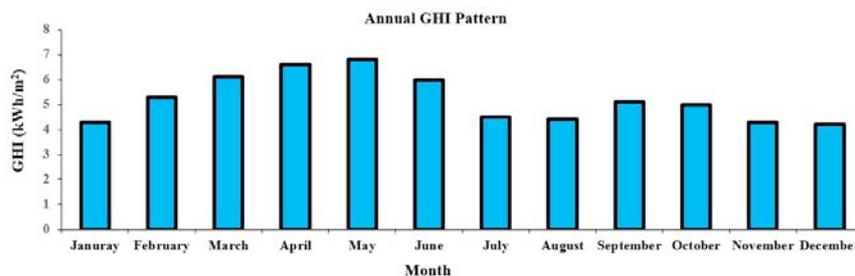


Figure 8: Monthly average daily GHI pattern

Table 3: Solar power electrical generation by SPV system

From table 2, total area available on the roof-top of all the coaches in the rake	1,174 m <sup>2</sup>
Net capacity of SPV system that can be installed on the roof of the rake	6.5 kW <sub>p</sub> X 19 = 123.5 kW <sub>p</sub>
From figure 8, yield of the SPV system when the monthly average daily GHI is i. maximum (March) ii. minimum (December)	6.8 kWh/m <sup>2</sup> X 1,174 m <sup>2</sup> = 7,983 kWh 4.2 kWh/m <sup>2</sup> X 1,174 m <sup>2</sup> = 4,930 kWh
Lowest daily GHI measured in India(Ramachandra, Jaina, & Krishnadas, 2011) Estimated yield of the SPV system for the lowest daily GHI measured	2.5 kWh/m <sup>2</sup> 2.5 kWh/m <sup>2</sup> X 1,174 m <sup>2</sup> = 2,935 kWh
From table 1, energy consumed by the net electrical lighting load of the rake during the sunshine period (15 hours) of 1 trip	90 kW X 15 hours = 1,350 kWh
From table 1, volume of diesel consumed by the electrical lighting load of the rake during the sunshine hours of 1 trip	128 gallons (483 litre)

From table 3, it is clear that the energy that is actually required to supply for the electrical lighting load in the rake can be the comfortably generated from the SPV system even on the days with GHI as low as 2.5 kWh/m<sup>2</sup>. It is also clear from table 3 that the SPV system can support the electrical lighting load in the rake even if 50% of the roof-tops are shaded, thus providing sufficient yield even with diffuse radiation. Hence, seasonal variation would not be a major hindrance.

### Impact of this scheme

The train considered is assumed to undergo a periodic over-haul (POH) stretching up to a maximum duration of 30 days, the train makes upto 188 trips in a year. The utility can reap benefits mentioned in table 4 along with a large reduction in CO<sub>2</sub> emission.

Table 4: Benefits of implementation of this scheme  
(Vasisht, Vishal, Srinivasan, & Sheela, 2014)

From table 1, the maximum number of trips the train can make in an year	188
Volume of diesel that can be annually conserved due to this scheme	23,988 gallons (90,804 litre)
Return on Investment (ROI)	3.38 years
Annual reduction in the CO <sub>2</sub> emitted by one train, considering the amount of CO <sub>2</sub> emitted per litre of diesel burnt as 2.66 kg and factor of combustion as 0.99	239 tonnes

### Requirements for implementation of this scheme

Solar assisted power supply for rail coaches can be implemented if the following requirements are satisfied.

1. SPV modules that are required to be mounted must suit the dimensions of the coach and should be flexible or semi-flexible. These SPV modules can be selected from the models available in the market and arranged suitably to attain the required voltage. A better option would be to manufacture the SPV modules based on the dimensions of the rail coach. In either case, the system voltage of 110 V has to be achieved.
2. A smart central processing unit (CPU) consisting of a power conditioning unit (PCU) is required to be designed. This equipment must be integrated to all the power sources and electrical loads as shown in figure 9 and must be able to
  - a. switch the power source for lighting circuit between EOG and SPV system based on the availability of sunshine
  - b. regulate the charging required for the battery bank depending on the availability of sunshine and previous data recorded by the system
  - c. provide uninterrupted power supply for the net electrical load in the rake by coordinating with all the power sources available and efficiently shift to default (conventional) power supply during faults
  - d. provide real time data of the system to the control room from where the system can be controlled or monitored.
3. The SPV modules are required to be mounted on the structures which can withstand random vibrations and high wind speeds, which would otherwise reflect on the performance of the system.

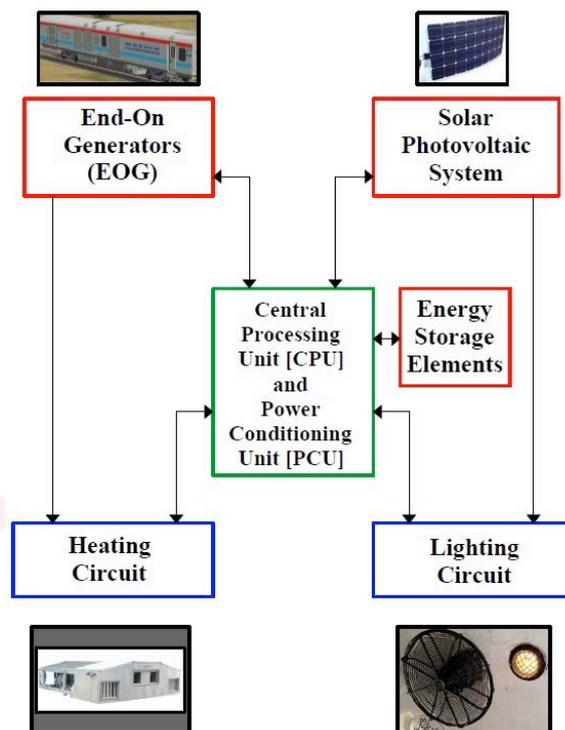


Figure 9: Single line diagram representing the control and coordination required to be done between various power sources and loads

## Conclusion

Indian Railways, being one of the biggest railway networks of the world, operates 160 daily trains consisting of LHB coaches (Ministry of Railways, 2014). It has been calculated that the volume of diesel conserved per year per train is around 23,988 gallons causing a reduction of 239 tonnes of CO<sub>2</sub> being emitted into the atmosphere. These benefits would become significant if all the 160 LHB trains operated in the country are retrofitted with SPV systems on their roof-tops. The approximate annual reduction in the diesel fuel consumption by Indian Railways would amount to 3.8 million gallons leading to a reduction of 38,240 tonnes of CO<sub>2</sub>. This would reduce the overall diesel consumption of Indian Railways along with a reduction in the oil imports by the country. SPV assistance for the existing power supply system would also enable the utility to increase the creature comforts and facilities for the passengers by utilizing the excess energy generated. Estimated return on investment would reach a maximum of 4 years, which would further decrease with the increase in the number of trains fitted with SPV system. The implementation of this scheme on any train can be considered as a wise investment, especially in tropical countries.

## References

Adelaide City Council. (2007). Tindo - The World's First Solar Electric Bus. Adelaide, Australia. Retrieved October 10, 2014, from [http://www.adelaidecitycouncil.com/assets/acc/Environment/energy/docs/tindo\\_fact\\_sheet.pdf](http://www.adelaidecitycouncil.com/assets/acc/Environment/energy/docs/tindo_fact_sheet.pdf)

Alessandro Basili. (2005). Trenitalia, PVTRAIN-The application of innovative photovoltaic technology to. *Layman* , 18. Retrieved October 10, 2014, from [http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n\\_proj\\_id=2061&docType=pdf](http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=2061&docType=pdf)

Disasolar. (2012, November 20). SME awarded for its innovations for future transportation systems. France. Retrieved October 5, 2014, from <http://www.disasolar.fr/wp-content/uploads/2014/07/idtechEx-20-Nov.pdf>

Ministry of New and Renewable Energy. (2012, August). Solar Energy for All. New Delhi, India: Government of India. Retrieved October 10, 2014, from <http://mnre.gov.in/file-manager/akshay-urja/july-august-2012/EN/August%202012%20full%20pages.pdf>

Wikipedia. (2013, October). *List of countries by rail transport network size*. Retrieved October 4, 2014, from Wikipedia: [http://en.wikipedia.org/wiki/List\\_of\\_countries\\_by\\_rail\\_transport\\_network\\_size](http://en.wikipedia.org/wiki/List_of_countries_by_rail_transport_network_size)

Mali, U. (2014, September 21). Analyzing World Largest Railway Network with help of SAP Lumira: Data Geek III Challenge. *SAP Lumira*. Retrieved October 13, 2014, from <http://scn.sap.com/community/lumira/blog/2014/09/21/analyzing-on-world-largest-railway-network-with-help-of-sap-lumira-data-geek-iii-challenge>

Ministry of Railways. (2013, December). *Rail Radar*. Retrieved December 7, 2013, from Railyatri: <http://railradar.railyatri.in/>

Ministry of Petroleum & Natural Gas. (2014). *Press Information Bureau*. New Delhi: Government of India

Shravanth Vasisht, M., Sridhar, B. S., & Dhanyavathi, A. (2011). *Design and development of solar assisted power supply system for multi-services in railways*. Belgaum: Visvesvaraya Technological University.

Wikipedia. (2014, September 2014). *Indian Railways*. Retrieved October 6, 2014, from Wikipedia: [http://en.wikipedia.org/wiki/Rail\\_transport\\_in\\_India](http://en.wikipedia.org/wiki/Rail_transport_in_India)

Ministry of Railways. (2012). *Maintenance Manual for BG Coaches of LHB Design*. New Delhi: Government of India. Retrieved October 05, 2014, from [http://www.rdso.indianrailways.gov.in/works/uploads/File/Maintenance%20Manual%20for%20LHB%20Coaches\(4\).pdf](http://www.rdso.indianrailways.gov.in/works/uploads/File/Maintenance%20Manual%20for%20LHB%20Coaches(4).pdf)

Shravanth Vasisht, M., Sridhar, B. S., & Dhanyavathi, A. (2011). Solar assisted power supply system for multi-services in railways. *Electrical India*, 6.

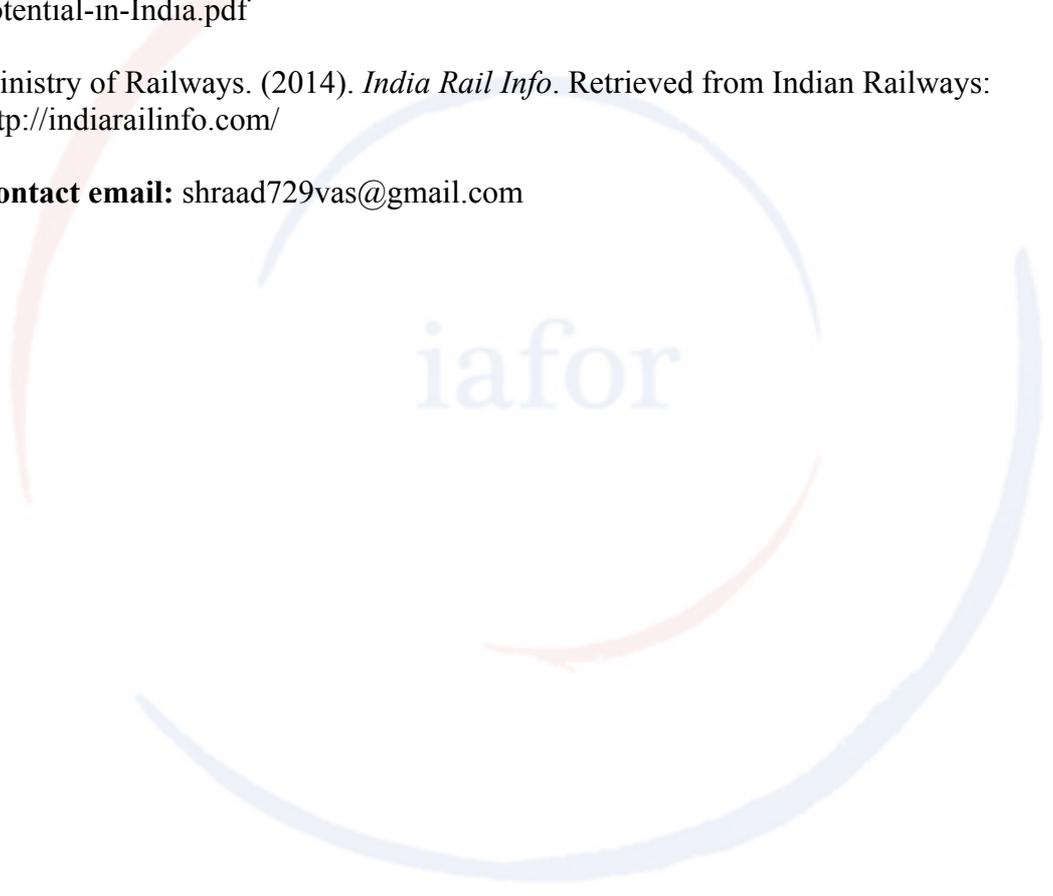
Vasisht, M. S., Vishal, C., Srinivasan, J., & Ramasesha, S. K. (2014). Solar photovoltaic assistance for LHB rail coaches. *Current Science*, Volume 107, Number 2, pg. 255-259. Retrieved October 13, 2014, from <http://www.currentscience.ac.in/Volumes/107/02/0255.pdf>

Ministry of New and Renewable Energy. (2013). *India solar resource maps*. Retrieved from <http://mnre.gov.in/sec/solar-assmnt.html>

Ramachandra, T., Jaina, R., & Krishnadas, G. (2011). Hotspots of solar potential in India. *Renewable and Sustainable Energy Reviews*, 3178-3186. Retrieved October 10, 2014, from <http://edu.2conserve.org/wp-content/uploads/2014/03/Hotspots-of-solar-potential-in-India.pdf>

Ministry of Railways. (2014). *India Rail Info*. Retrieved from Indian Railways: <http://indiarailinfo.com/>

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The logo for iafor (International Association for Energy and Environmental Research) is centered on the page. It features the word "iafor" in a light blue, lowercase, sans-serif font. The text is enclosed within a circular graphic composed of two overlapping, semi-transparent arcs: a red one on the left and a blue one on the right, which together form a partial circle around the text.

***Urban Egalitarianism: The Way Forward to Ensure Sustainable Urban Design,  
Practice and Development in Developing Countries (The Nigerian Case)***

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The North American Conference on Sustainability, Energy & the Environment 2014  
Official Conference Proceedings

**Abstract**

Cities and urban development across the world are entities with high complexity, most especially with the unavoidable ever increasing population which incorporates human diversity in culture, wealth and status. However, rapid urbanization and expansion is today a common phenomenon in many developing countries across the world, this is often characterized by challenges such as slum generation, informality, segregation and unequal distribution of infrastructure and resources among neighborhoods in the cities. Cities in developing nations have continued to grow in fragmentations, making their growth much more than the eyes can see, and the ears can hear and varieties of view-points wanting to be explored in great depth.

In tackling this urban menace, sustainability and urban transformation through policies and strategies seem to be the major focus and agenda among many urban development stakeholders globally. With this development, the environmental and economic sphere of sustainability have been granted higher priority over their social counterpart. However, the key question remains; “who and which group of people” benefit from these new urban spaces which have been proposed or created. Cities and urban spaces are meant to serve their citizenry irrespective of their class and status in the society, a situation where every individual is incorporated and engaged in the decision making and developmental process of the space in which they exist. In achieving this sustainable development and practice goals, this paper presents various integrated approach in which ‘community and neighborhood’ should be placed at the center of sustainability analysis and the discussion of spatial connectivity through urban design, development and practice with cases from Nigerian cities of Lagos and Abuja.

Keywords: sustainability, urban development, segregation, spatial connectivity

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## Introduction

Discussions on the attainments of sustainable urban development and practice has continued to received global recognition, and has remained a major focus among many academic and policy makers circle. These developments have been attributed to the inevitable ever increasing global population and its substantial variability in different regions across the world (UN- Habitat, 2014b). Statistics has reviewed that more than half of the world's population today are concentrated in urban centers across the globe, and these has continued to experience a dramatic increase from 30% in 1950 to 54% in 2014 (UN- Habitat, 2014b). This current statistics concerning the world's population growth and urbanization is also projected to increase by 66% by 2050, making urbanization one of the most challenging issues facing humanity (UNDP, 2006 UN-Habitat, 2014b)

Cities as an engine of development are noted for their complexity and related issues of size, perception, activities, culture and status, but remains homes to multitude of users which have continuously attracted various level of urbanization. For instance, urban population variation across the world have continuously increased by 82% in North America, 80% in Latin America and the Caribbean, 73% in Europe, 40 % in Africa and 48 % in Asia (UN-Habitat, 2014b). In addition, further changes are expected to emerge with major concentration and fastest urbanization growth rate in developing nations across Africa with projections of 56% and Asia with 64% respectively by 2050 (UN-Habitat, 2014b).

In view of this demographic facts, various international forums and reports have recognized both positive and negative benefits associated with urban developmental growth, this ranges from the World Commission on Environment and Development (Brundtland Report) in the 1980s to The Rio+20 United Nations Conference on Sustainable Development in (2012). These forums established the fact that urban development and planning is integrally connected to the three sphere of sustainability: economic, social and environmental. They also highlighted the opportunities of urban growth as that which contribute to economic activities through employment opportunities, commerce and productivity, while serving as the hub that links rural areas and international borders leading into the enormous migration of population (UN- Habitat, 2006, 2007a). However, it is significant to note that the reverse can also be the case with its negative impacts as that which threatens sustainable development such as the intense pressure on existing infrastructural development and public service of energy, water, sanitation, housing and health facilities. Also, are elements of rising inequalities and unequitable share of resources, the inability to manage urban expansion resulting in environmental impacts and sub-standard living conditions (Olotua, 2010).

However, urban sustainability agenda on the global stage have continued to prepare cities for future development in accordance with the benchmark set by the World Commission on Environment and Development (The Brutland Report). This report emphasized the necessity to “meet the needs of the present generation without compromising the ability of future generation to meet their own needs” (WCED, 1987). In addition, subsequent actions are underway such as the planned Third United Nations Conference on Human Settlement (Habitat III) for the year (2016). With this development, further discussions and reports are envisioned towards global

urban sustainability with the aim of deriving new models for urban development and the promotion of equity, welfare, and shared prosperity in this fast rising urban world (UN Habitat, 2014a). However this is important as the recent transformation of cities in developing nations have their national government focusing on economic indicators, the image of its cities, as well as the amount of foreign investors its urban development can attract with a limited attention on the final impact on the larger urban population. Cities and their elements both moving and stationary are perceived differently by its dwellers, as such conveying an image, memory or meaning (Lynch, 1960). In support of this position, this paper presents 'egalitarianism' in the context of urban development and planning as a trend that is required by urban policy makers and stakeholders to actualize a sustainable urban development and practice in developing nations.

### **Urban Transformation in Developing Nations**

In recent years, developing nations have experienced a major transformation in its urban developmental outlook, most importantly from the start of the new millennium year (2000). However, various sustainability reports have identified the important need to recognize and respond to these changes by providing new approaches to tackle any challenges synonymous to urbanization (UN- Habitat 2010, Dixon, 2011). According to demographic statistics *from State of African Cities* (2014), there are over 28 megacities with 453 million dwellers across the world with the fastest growing cities emerging in developing nations with a significant transformation in socio-political, demographical, economical, and technological terms. For instance, Tokyo is today the world 's largest city with an agglomeration of 38 million inhabitants, Delhi with 25 million, Shanghai with and Mexico city 23 million, Lagos, Mumbai and Sao Paulo, each with around 21 million inhabitants all in developing nations (Campbell 2012, UN-Habitat, 2014b).

This urban transitional period has also been historical, most significantly with the advent of the year (2007) which marked the first time in the history of humanity with half of the world's population living in cities. For developing countries, these urban transitional periods have posed numerous urban social and environmental challenges for many of its dwellers, with many of this cities transforming into informal urban expansion, slum formation, urban disintegration and segregation with the neglect of the larger population becoming a common phenomenon. UN Habitat (2010) presented the current state of urban form in many cities in developing nations as that which is developing in two separate 'contrasting' urban developmental patterns. One that is symbolized by poverty, informality, exclusion, and poor quality living environment with little or no infrastructure and services to support the well-being of its inhabitants, and the other with gated communities that is exclusive, formal with more than enough infrastructures and services.

This current urban menace provided a platform for many urban development and sustainability experts to debate on the future of urban planning in developing nations with an objective to meet the demands of the inhabitants and also protect the general environments of this transformed cities (UN-Habitat, 2014). In acknowledgement of this position, the UN-Habitat report on the State of Cities in Developing Countries through an exploratory analysis of the current state and general environment in the cities of Shenyang and Wuhan in China, New Delhi in India, Port Harcourt and

Lagos in Nigeria and Meuraxa in Indonesia all in developing countries as that which lacks the ability to tackle its current challenges characterized by the problems of management, exclusion, inequality, insecurity and environmental degradation; let alone provide solutions for future occurrence. UN-Habitat (2009, 2010) also identified the non-existence of an adequate urban governance policy, participatory urban planning, and the lack of institutional capacity and the high rate of inequality among the different socio-economic population strata as the major factors which has deterred the attainment of sustainable urban development in many developing cities.

In addition, cities in developing nations have urban planning and operational process that is still largely based on the colonial laws in-terms of land tenure systems with regulatory decrees that are one- sided in developmental terms which largely support, protects and tailored made in the interest of the rich or capitalist over that of the urban poor (Aribisala, 2013). Consequently, in the verge of attaining the status of world-class cities, modern urban culture and pattern have been adopted with majority of the planning policies being imported from the developed nations. Examples of this development includes The Eko Atlantic project in Lagos and The Abuja Centenary City which are designed and described as smart modern city which synchronizes the demand of tomorrow's society with a sustainable ecological and socially responsible manner. A springboard and controlling liver for Nigeria's economy and an African epic center of global economic activity where modern beauty will merge with architectural creativity in creating an environment that is alive and productive (Olesin 2013, Adetayo 2014). However many have also argued against the creation of these modern development as that which support spatial segregation, population control and are limited to beautification and decoration of the urban space while the majority of the urban population are evicted without a relocation or compensation plan.



*Land reclamation for the Eko Atlantic Project Lagos, Nigeria.*  
*Source: Eko Atlantic <http://www.ekoatlantic.com/media/image-gallery/>*

Indeed, it is important to ask the key question of how sustainable is this present urban planning practice, and if these current city development provides adequate solutions to the current urban challenge being faced in many cities in developing countries. According to Lynch (1960) who argued that not only is the city an object to be perceived, but remains a product of many builders that is constantly modified to suit

their purpose. However Allen (2009) thoughts concerning urban planning policies is that which is determine by the viability of any given practice, policy or trend ‘for or against’ any urban sustainability, as it is important to reflect on its relationship with all spheres of sustainability (economic, social, environmental) of the built environment. As such, the sustainability of any city depends on its capacity and the livability of all city dwellers through an efficient urban infrastructure and built environment. In recognition of this position, urban planning and practice have been recognized by the World Urban Campaign as the instrument which determines the sustainability of any city by the promotion of a participatory engagement, strategic thinking, vision building and territorial coordination which must be clearly understood in the context of the area been examined (UN-WUF, 2004). Reports from the Second and Third World Urban Forum in Barcelona and Vancouver (2004, 2006) reinvented the functions of urban planning and practice with wide acceptance and a consensus from planning experts and stakeholders with the establishment of the 10 principles:

- The promotion of sustainable development
- Achieving integrated planning
- Integrate planning with budget
- Planning with partners and stakeholders
- Meeting the subsidiary principles
- Ensuring accessibility to land promoting
- Market responsiveness
- Developing appropriate planning tools
- Be pro-poor and inclusive
- Recognition of cultural diversity.

Many researchers and built environments experts during this forum emphasized the need to continuously update urban planning process and policies of cities, as they remain the key instruments to bridge the gap between the two urban groups of the rich and the poor as well as achieving inclusive, participatory and culturally meaningful cities.

### **Sustainability and Urban Planning Process**

The concept and definition for sustainability have been presented from both implicit and explicit characterization by various references and reports. An implicit characterization of sustainable urban planning from the perspective of showing higher priority or concern for a particular or some aspect of sustainability over the other (Holland 1995, Dillard et al, 2009, Pole'se & Stren 2000). Further explicit view-point has also been offered with the derivation of an appropriate solution from a broader perspective of enumerating all aspects of sustainability that is vital (Lombardi & Basden, 1997). However, international forums on sustainability agenda have continued to present a holistic structure to harmonize the diverse interest towards sustainable planning and design for cities (WCED 1987, UNCHS 1996, LCSEC 2007, UNCSD, 2012). This integrated approach unifies all interest in urban developmental procedures with the need to ensure an inclusive and participatory process that involves all stakeholders in the determination of the built environment and also the livelihood of its inhabitants from a long-term approach.

Planning procedures plays a vital role in urban development designs and formation through an outlined analysis and evaluation of all current and eventuated challenges on the basis of real world case studies and planning examples. In support of this argument, the global report on Human Settlement (2009) identified series of factors which impacts on the current state of the sustainable urban and living conditions of many city dwellers across the world. This include demographic challenge in the case of rapid urbanization as previously stated, democratization opportunities through the awareness of social and economic rights, economic challenge and its connection with the uncertainty of future economic growth, and social and spatial inequality resulting in urban sprawl and informal urbanization. In reference to this challenges, urban planning fundamentals urge to be reinvented by concerned stakeholders whereby the new imperatives and demand on policies and strategies are derived with an appropriate solution through contextualized information, communication tools, with an inclusive modelling method been finalized by design and implementation. Urban planning and practice of 21st century cities must also transform these key challenges into opportunities by creating cities that work for all its citizenry in- respective of their status by:

### **Tackling Informality Instead of Contrasting It**

The form of any city is largely determined by its urban development and practice; this is evident with the current state of transformation been experienced in many cities across developing nations. Cities such as Lagos, Abuja and Nairobi among many others have urban practices and developments characterized by contrasting neighborhood settings (UN-Habitat, 2014a). The wide gap between various class and social strata in the society remains a major factor that influences urban divide, exclusion, and contrasting neighborhood settings in many of these cities. However, UN- Habitat (2010) identified the enforcement of negative regulatory laws as a control mechanism been utilized to tackle urban informality at all cost in cities in developing countries, which was also argued to be a major factor leading into acquisition and sub-division. Many urban dwellers in these regions of the world are subjected to high level of rejection and neglect, as the level of inequality has continued to rise without much concern and attention from policy makers and city developers with supportive strategies in the provision of an inclusive city for all (UN-Habitat, 2014a).

In achieving an inclusive urban space, effective urban planning developmental practice can be utilized as a tool to achieve the much anticipated inclusion as well as reverse the trend of informality and the growth in slum development. However it is significant to note that the transformation for better outcomes does not happen automatically, as appropriate policies that support the needs and living conditions of the urban poor must be implemented with emphasis on the importance of every individual and their community. This creates a balance between urban growth and sustainability with key elements such as the restructuring of institutions, equity in resource allocation, leadership re-development and political vision and value as well as effective implementation and monitoring. UN-Habitat (2010) also identified the strategic use of planning tools through improved urban governance as a critical element in tackling contrasting neighborhoods. It is also considered as the foundation for urban planning approach that is switched from a 'command and control' model to that which incorporates an inclusive and participatory process. This can become a

reality by first providing a strategic plan for the equal provision of infrastructure guided by land development or land re-adjustment as a possible solution to an upgrade for informal settlements. Urban planning process must be participatory through meaningful and collective engagement with the involvement of the general public in all the decision making process, implementation and monitoring. Secondly, the collaboration between private and public sector, community based groups, and international development partners must also be encouraged as an avenue which can strengthen the legitimacy of planning and regulatory system with the aim of achieving progress through adequate standards and regulations. Thirdly, legislative and policy framework through institutional processes are vital procedures in achieving sustainable cities and spatial planning. This facilitate the intersectional coordination and position urban planning at the intersection of public policy and resource allocation For instance, in the case of cities such as Kusumu, Kenya's third largest city, where data gathering process and surveys provided planners with an up-date information concerning the needs of the residents with the utilization of a city-wide Geographic Infrastructure System to ensure the effective planning for their slums (UN-Habitat, 2014a). Through this, urban planning becomes tools for local democracy and inclusive governance which responds to the needs of the city dwellers rather than regulates it. Furthermore, participatory planning empowers communities with an outcome of a better spatial design that is responsive to the needs of different urban groups which obviously impacts on the quality of life.

### **Urban Development and the Quality of Life for All**

The term 'quality of life' for city dwellers across the world has often been discussed, debated with various interpretations and meaning in response to urban developmental challenges. In the desire to interpret the urban quality of life concept in a particular place, person or group, many research and report have based their ideology of the quality of life on human satisfaction with different elements of cost and living conditions with access to basic goods, service, infrastructure and public amenities (UN- Habitat, 2012/2013). Also identified are the equity and respect for diversity and cultural identities, and land use pattern within local level with an objective of meeting the diversity of needs and expectation of the citizenry (UN- Habitat 2012/2013, Haman Serag et al 2013). According to Nobel Laureate Amartya Sen, the quality of life of an individual is determined by various opportunities open to such person and their freedom to choose from these many opportunities (UN Habitat, 2012/2013). As such, Haman Serag et al (2013) further presented the view point that urban quality of life is a multi-dimensional concept which is analyzed in accordance to place and societies. Using this perspective, he also argued that the urban quality of life cannot be understood from one view point, but that which incorporates over dimensions that are inter-related and dependent on each other. Seven main dimensions were identified as that which contributes to the realization of any urban quality of life, these are:

- **The physical:** This takes into account the sustainability of the urban fabric, through planning, provision and management of the city layout, services and infrastructure.
- **The social:** The promotion of social justice, equity and interaction for urban dwellers to interact with the access to the freedom of choice while participating actively in their respective communities.

- **Psychological:** The creation of an urban environment that recognize opinions of every citizen in-terms of identity and sense of place.
- **Economic :** The creation of an urban space as a place for activities that support human development through job creation and the promotion of local business opportunities while encouraging mixed use development.
- **Political:** The democratization of urban policies that promotes integration with the involvement of every stakeholder in the community in decision making.
- **Mobility:** This focus on accessibility and transportation issues with the provision of a network interconnecting streets through friendly pedestrian and cycle pathway to reduce traffic load, minimize air pollution and also encourage walking.
- **Environment:** The provision of natural landscaped natural green area distributed equally within every neighborhood in an urban area.

Haman Serag et al (2013) argument on sustainable urban development identified the improvement of the quality of life of every citizenry as vital in any sustainability agenda with the emergence of new urban planning theories such as new urbanism, smart growth, urban village and intelligent urbanism. These urban theories further promoted the urban quality of life concept with the consideration of the seven identified dimensions in the design of buildings, neighborhoods and cities that focus on the sense of community and place, along with people's needs and well-being.

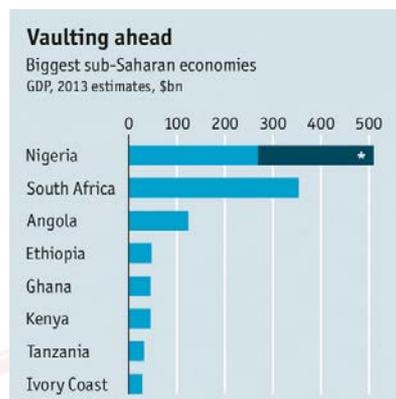
In recent times, efforts have also shifted from the definition to the measurement of quality of life with a presumed argument that individuals are the best judges of their life conditions by providing relevant information about a crucial component of social change through values, beliefs, and the motivation of the ordinary citizen (Haman Serag, et al 2013).

However, quality of life underpins the functionality of any city which its notion is at the crossroad of all policies and actions. For instance, human development capacity and economic growth of a city is enhanced by means of empowerment of its citizens through the equal and accessible opportunities been provide. Also the improvement of the quality of life and living condition for every urban dweller is largely based on the urban planning and design process which is vital in the provision of adequate infrastructure and services of public transport, housing, public space, and drainage system to support the well-being of every citizenry. According to the UN- Habitat Survey (2011), this identified security, human right, and housing with basic facilities as well as employment with a decent salary as the most important factors. In view of these positions, it is obvious that the quality of life of every group in an urban development is an essential element in the determination of how sustainable a city can be, which has made the fulfillment of needs and well-being a burning issue globally.

### **Urban Politicking in Nigerian Cities**

Urbanization rate in Nigerian cities is one of the highest in the world couple with the demographic fact of being the most populous black nation on earth, with an urban development pattern that takes the form of a central core with peripheral area that are suburban with peri-urbanization (UN-Habitat, 2014b). Recent economic growth in Nigeria with its emergence as Africa's largest economy in 2014 is marked with trends

of imported developmental models of revitalization, renewal and redevelopment in its urban growth (Dobbs, 2014).



*IMF National Statistic on Biggest Sub-Saharan Economics*

*Source: The Economist: <http://www.economist.com/news/finance-and-economics/21600734-revised-figures-show-nigeria-africas-largest-economy-step-change>.*

This initiative have recorded both successes and failures from various quarters of the society, one with creative and ambitious development that focus on certain class of groups in the society with a strong political and economic tool to secure foreign investment, promote international attention and indeed signaling a new economic awakening and pride for the country (Adetayo, 2014). While the other is the promotion of urban development away from the major population concentration, with a disconnection driven by negative policies and control system leading into subdivision, segregation, forced eviction and social inequity (Bean, 2011). The community power structure of Nigerian cities is that which the business and elicit group determine and regulate all the major urban planning decisions on behalf of millions of other city inhabitants (Aribisala, 2013).

The implication of this divergent circumstance in shaping urban development outcome is evident in the current urban development and practice of Lagos, Port-Harcourt and Abuja in Nigeria. Discussions from the 2012 United Nations Conference on Sustainable Development established the need of achieving an equilibrium in global urban development with an integrated equitable delivery and access to land, housing, basic services and infrastructures. In creating such equilibrium in the context of Nigeria's urban development and practice, it is important to first examine the objectives of the current urban policies and development with the key question of to 'whose advantage and benefits' are the current developmental policies and plan. As such, there exists a complex sociological problem of trying to strike equilibrium between the power groups in the society and among other groups. According to Branne (1956), in the attempt to operate a planning machinery in a society with a kind of balancing scale between the state and the individual, the major challenge remains how to maintain an 'equilibrium' in which all goals through its planning process must be geared towards. For instance in the case of Lagos, West African commercial hub and Africa's largest city with an estimated population of 21 million residents, the planning and regulatory efforts of the city authority have been routinely thwarted by economic and political intervention (Olesin,2013). Hence,

suggesting a capitalist undertone leading to a highly unequal urban divide segregated by class and social strata. A typical case is the example of the forced eviction and destruction of urban slum and informal settlements such as Makoko, and Badia both slum community on the edge of Lagos. Various reports and publications have argued that the eviction exercise was not aimed at achieving sustainable development for Lagos, but was undertaken as a result of the increase in land value and its proximity to highbrow neighborhoods areas of Victoria Island, Ikoyi and Lekki, while paving way to planned communities with adequate infrastructures far beyond the reach of the initial occupiers and settlers (Bean, 2011).

### **The Makoko Saga**

Makoko, a fishing community which consist of dozens of stilt structures built over Lagos lagoon is habituated by very poor urban dwellers struggling to contain a rapidly expanding population (Bean, 2011). This slum settlement provides its residents with shelter to live and work with the lagoon serving as the main source of livelihood from the sale of fish to the rest of the city of Lagos. However, the government of Lagos has unfortunately identified the growth of this neighborhood as illegal and dangerous, as the unhealthy environment continuously expands causing water contamination and flooding as a result of the lack of sanitation and waste management.



*Makoko Lagos Lagoon Slum Development*

*Source: BBC News: <http://www.bbc.co.uk/news/world-africa-18872929>*

The Lagos city urban development administration commenced the demolition of Makoko following a 72 hours advance notice of eviction with more than 30,000 residents evicted and displaced into a worse living condition with no assistance for relocation (Beski, 2012). Argument in support of the slum clearing action by the government was an effort to clean up Lagos, as the unwholesome structures constitute an ‘environmental nuisance’, security risk, an impediment to the economic and gainful utilization of the waterfront. In addition, Makoko was also identified as a slum that is easily visible from the Third Mainland Bridge which connects Lagos mainland to the city’s rich and business districts, and its scenery does not represent Lagos as a true emerging world class city in positive light (Bean 2011, Adeoye 2012, Fortin 2012, Beski, 2012).

## **The Abuja Land Swap Concept**

In tackling the challenges of rapid urbanization in the city of Abuja most importantly with the provision of public infrastructure, new policy of land swap concept was initiated by the Abuja urban development authority with an objective to ensure comprehensive development of districts in line with the Abuja master-plan and also generate secondary investment (Ibezim-Ohaeri, 2013). This concept awards large hectares of greenfield lands to competent private developers for the provision of public infrastructure. More specifically, the land swap initiative is to give an investor a particular percentage of land in a district in exchange for the provision of infrastructure earmarked for the district. According to Abuja city development authority, the land swap initiative have presented an incentivized solution to the persisting urban challenge characterized by pressure on existing infrastructure and the lack of funds with the primary objective of fast- tracking housing and infrastructural development. However majority of Abuja urban dwellers in the concerned satellite towns and villages have argued that the ‘land swap initiative’ lacks an inclusive participatory process in its formation, as aggrieved indigenous communities fault the public private partnership model as that which excludes the involvement of the communities in the redevelopment intervention. In addition, there are concerns that the contractual relationship between the Federal Capital Development Authority (FCDA) and private developers does not outline community roles and benefits under the project (Ibezim-Ohaeri, 2013). Hence, making the continued existence of the original settlers and owners of the land in the transformed neighborhood a dream that will may never come through.

## **Conclusion**

The connection between an urban space and its occupants cannot be overemphasized as ‘equality and justice’ is required in Nigeria’s urban development as the framework where communal engagement and collaboration occurs in creating sustainable urban development, rather than solving a challenge with the emergence of another.

## Reference

Allen A. (2009). Sustainable Cities or Sustainable Urbanization. Taken from the Summer 2009 edition of UCL's Journal of Sustainable Cities. [www.ucl.ac.uk/sustainable-cities](http://www.ucl.ac.uk/sustainable-cities).

Adeoye G. (2012). Lagos State Government Defends Makoko Demolition. July 19<sup>th</sup> 2012 Daily Times Nigeria.. <http://www.dailytimes.com.ng/article/lagos-state-government-defends-Makoko-demolition>. Accessed August 27<sup>th</sup> 2014.

Adetayo O. (2014). Abuja's N3trn Ambitious City within the City. The Punch Newspaper. July 10, 2014.<http://www.punchng.com/feature/nations-capital/abujas-n3trn-ambitious-city-within-the-city/> . Accessed August 27<sup>th</sup> 2014.

Aribisala F. (2013). Warning: Poor People Are Not Wanted in Lagos Mega-City. The Vanguard Newspaper. September 17, 2013. <http://www.vanguardngr.com/2013/09/warning-poor-people-are-not-wanted-in-lagos-megacity/>. Accessed 5<sup>th</sup> September 2014.

Branne R. (1956). Towards a Theory of Urban Planning Standards. Massachusetts Institute of Technology. Department of City and Regional Planning.

Bean A. (2011). Protest Continue after Demolition of Coastal Slum in Lagos. July 25<sup>th</sup> 2011. IHC <http://intlhc.org/blog/protests-continue-after-demolition-of-coastal-slum-in-lagos>. Accessed 5<sup>th</sup> September 2014.

Beski D.(2012). Lagos Makoko Slums Knocked Down in Nigeria. BBC World News. <http://www.bbc.co.uk/news/world-africa-18870511>. Accessed 5<sup>th</sup> September 2014.

Campbell J. (2012). This is Africa's New Biggest City: Lagos, Nigeria Population of 21 Million . The New York Times. July 12, 2012

Dillard J., Dujon V., King C., 2009.Understanding the Social Dimension of Sustainability. New York: Routledge.

Dixon T. (2011). Sustainable Urban Development to 2050: Complex Transition in the Built Environment of Cities. Oxford Institute for Sustainable Development, Oxford Brooks University.

Dobbs R. Fiorini R. Leke A. Suleiman A. Thompson F. Wright D.(2014). Nigeria Renewal: Delivering Inclusive Growth in Africa's Largest Economy. Mckinsey Global Institute. May 2014.

Fortin J. (2012). The 'Poor Man's Venice': Nigeria Demolishes Makoko in Lagos, Evicting Thousands. International Business Times. <http://www.ibtimes.com/poor-mans-venice-nigeria-demolishes-makoko-lagos-evicting-thousands-723329> July 17<sup>th</sup> 2012. Accessed August 24<sup>th</sup> 2014.

GPHCDA (2014). Greater Port-Harcourt City Development Authority. <http://www.gphcity.com/>. Accessed August 29<sup>th</sup> 2014.

Holland A. (1995). The Use and Abuse of Ecological Concepts in Environmental Ethics, Biodiversity and Conservation, vol.4, pp.812-826.

Hamam S. Ahmed S. Elsayed F. Sarah A. (2013). Principle of Urban Quality of Life for a Neighborhood. Housing and Building National Research Centre Journal 2013 Volume (9) 86-92

Ibezim-Ohaeri V. (2013). Spaces for Change, Abuja Land Swap Initiative : The Challenges Within. Policing the policy Series / Volume 9. May 2013.

Lynch K. (1960). The Image of the City. Massachusetts Institute of Technology. MIT Press.

Lombardi P.L. and Brandon P.S., (1997) Toward a Multimodal Framework for Evaluating the Built Environment Quality in Sustainability Planning, in Brandon et al. (eds.), Evaluation in the Built Environment for Sustainability, E&FN SPUN, Chapman & Hall, London, pp.6-21.

Lombardi P.L. (1999). Understanding Sustainability in the Built Environment. A Framework for Evaluation in Urban Planning and Design. Department of Surveying, University of Salford, U.K.

LCSEC (2007). Leipzig Charter on Sustainable Europe Cities . 2<sup>nd</sup> May 2007. [http://ec.europa.eu/regional\\_policy/archive/themes/urban/leipzig\\_charter.pdf](http://ec.europa.eu/regional_policy/archive/themes/urban/leipzig_charter.pdf) Accessed August 24<sup>th</sup> 2014.

Olotuah A. (2010). Housing Development and Environmental Degeneration in Nigeria. Department of Architecture, Federal University of Technology, Akure, Nigeria. The Built Environment Review. Volume 3, 2010

Olesin A. (2013). Eko Atlantic City as Benchmark for Urban Renewal. National Mirror Newspaper. February 25, 2013.

Pole'se M., Stren R., 2000. The Social Sustainability of Cities: Diversity and the Management of Change. Canada: University of Toronto Press.

UNCHS (1996). United Nations Conference on Human Settlement, The Indicators Programme: Monitoring Human Settlements for the Global Plan of Action, Paper - United Nations Conference on Human Settlement (Habitat II), Istanbul, June 1996.

United Nations World Urban Forum (2004). 13-17 September 2004, Barcelona, Spain. <http://ww2.unhabitat.org/wuf/2004/>. Accessed August 24<sup>th</sup> 2014.

United Nations WUF III (2006). World Urban Forum. Vancouver, Canada. June 19-23, 2006. [http://ww2.unhabitat.org/wuf/2006/wuf\\_story12.asp](http://ww2.unhabitat.org/wuf/2006/wuf_story12.asp) . Accessed August 24<sup>th</sup> 2014.

UNCSD (2012). United Nations Conference on Sustainable Development Rio+ 20. 20-22 June 2012 Rio de Janeiro Brazil [www.uncsd2012.org](http://www.uncsd2012.org). Accessed August 10<sup>th</sup> 2014.

UN HABITAT (2006/2007). State of The World Cities: The Millennium Development Goals and Urban Sustainability, 30 Years of Shaping The Habitat Agenda. USA : Earthscan [www.unhabitat.org](http://www.unhabitat.org). United Nations Human Development Programme.

UNDP (2006). World Urbanization Prospective and Human Development Report New York: United Nation Publication. Department of Economic and Social Affair (Population Division).

UN HABIATAT(2009). Annual Report 2008. Nairobi: UNON/Publishing. [www.unhabitat.org](http://www.unhabitat.org). United Nations Human Development Programme.

UN- HABITAT (2010a). The State of African Cities. Governance, Urban Inequality and Urban Land Markets. Nairobi: UNON/Publishing. [www.unhabitat.org](http://www.unhabitat.org). United Nations Human Development Programme.

UN-HABITAT (2010b). Planning Sustainable Cities: Practice and Perspective. Nairobi : UNON/Publishing. [www.unhabitat.org](http://www.unhabitat.org) United Nations Human Development Programme.

UN-HABITAT (2012/2013). State of The World Cities: Prosperity of Cities. New York: Routledge. [www.unhabitat.org](http://www.unhabitat.org) United Nations Human Development Programme.

UN-HABITAT (2014a). The State of African Cities: Re-imaging Urban Transition. Nairobi: Michael Jones. [www.unhabitat.org](http://www.unhabitat.org) United Nations Human Development Programme.

United Nations (2014b). World Urbanization Prospects: The 2014 Revision. The United Nations Department of Economic and Social Affairs.

WCED (1987). World Commission on Environment and Development, Our Common Future (The Brundtland Report), Oxford University Press, Oxford.

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***An Experimental Study on Coupling DCMD  
with SGSP through Its Wall Heat Exchanger***

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**Abstract**

The interest of using solar powered membrane distillation systems for desalination is growing worldwide due to the membrane distillation (MD) attractive features. This study experimentally investigates utilization of direct contact membrane distillation (DCMD) coupled to a salt-gradient solar pond (SGSP) for sustainable freshwater production and reduction of brine footprint on the environment. A model for heat and mass flux in the DCMD module and a thermal model for an SGSP are developed and coupled to evaluate the feasibility of freshwater production. Experiments are conducted at RMIT University renewable energy laboratory using SGSP wall heat exchanger. The feed stream of 1.3% salinity is heated up by the wall heat exchanger and circulated through MD module then injected back to an evaporation pond. Also, a heat recovery system (Heat Exchanger) is used to back up heat from the outlet brine stream of DCMD and use it as preheating for inlet feed stream flow. Results are compared and shown that if the flow is laminar, the connecting DCMD module to the SGSP could induce marked concentration and temperature polarisation phenomena that reduce fluxes. Therefore turbulence has to be created in the feed stream to reduce polarisations and the brine is recirculated after passing through the heat exchanger to reduce the environmental footprint.

Keywords: Solar Membrane Distillation, Solar desalination, DCMD & SGSP desalination, Membrane mass flux.

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## 1. Introduction:

Since 1950, the growth of global demand for freshwater has increased dramatically and approximately doubled every 15 years. This growth has reached a point where today existing freshwater resources are under great stress, and it has become both more difficult and more expensive to develop new freshwater resources. One particular issue is that a large proportion of the world's population (approximately 70 %) settles in coastal zones [1]. The current mean population density at coastlines is almost  $100 \text{ hab}/\text{km}^2$ , and it is over 2.5 times the global average and embraces 45% of the global population [2]. Many of these coastal regions rely on underground aquifers for a substantial portion of their freshwater supply. Specifically, if an aquifer is overdrawn, it can be contaminated by an influx of seawater or salts and, therefore, requires a treatment or purification. About 450 million people in 29 countries face severe water shortage; about 20% more water than is now available will be needed to feed the additional three billion people by 2025 [3]. Furthermore, the world health organization (WHO) reported that 20% of the world population already has inadequate drinkable water. Even though the two third of the planet is covered with water, 99.3 % of this water either has high salinity or not accessible ( Ice caps ) [4]. So the combined effects of increasing freshwater demand, population growth and seawater intrusion into coastal aquifers are stimulating the need for desalination. The desalination is a process of removing salts and other minerals from a saline water solution producing fresh water, which is suitable for human consumption, agriculture and industrial use. The desalination system usually consists of three main parts; water source which may be brackish or sea water, desalination unit and energy source which is playing the key role in evaluating the desalination plant performance.

The aim of producing water at less energy consumption has led to promising solution which is solar desalination as most of countries have unlimited seawater resources and also a good level of solar energy. However, the strong potential of solar energy to seawater desalination process is not yet developed at the commercial level [5]. Solar desalination is an environmental friendly and cost saving process competitive with other conventional desalination techniques [6]. Also, the utilization of low-temperature membrane distillation (MD) coupled to a renewable energy source can be sustainable solution for the water and energy scarcity. Membrane distillation is a process working on the principle of phase change or vapour-liquid interface that has the capability to grow into a viable tool for solar water desalination. Direct contact membrane distillation (DCMD) is a configuration of MD where warmer feed solution is in direct contact with one side of a microporous hydrophobic membrane and cold water (permeate) is in direct contact with the opposite side of the membrane (Fig. 1) [7].

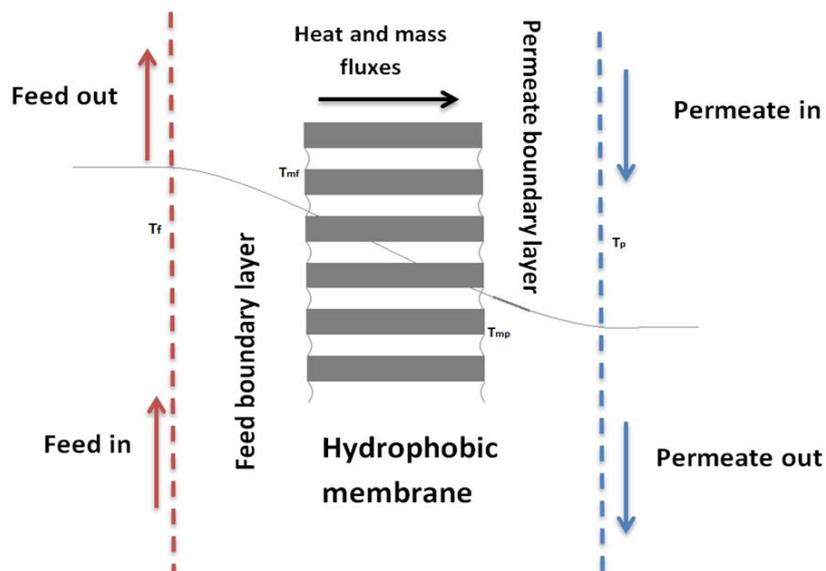


Fig. (1) Thermal boundary layer on the membrane surface

DCMD uses hydrophobic microporous membrane where only volatile components can be transported through the membrane pores. The driving force is the vapour pressure difference that is resulted from temperature difference across the membrane. The water mass flux is driven by simultaneous heat and mass transfer and resulted in highly pure permeate water [8]. DCMD is one of the simplest configurations of MD; it requires only a membrane module, low-grade heat source, and two low-pressure pumps to pass the liquids over the membrane. The simplicity of this configuration makes it highly suitable for application in remote locations where technical and sustainable solutions is not available and the capital cost is low compared to other membrane systems driven by renewable energy.

An ideal method for providing a sustainable source of heat energy for the DCMD system is a salinity-gradient solar pond (SGSP) [9]. It comprises of three thermal layers (Fig. 2): the upper convective zone (UCZ), the non-convective zone (NCZ), and the lower convective zone (LCZ). The UCZ is relatively thin layer of cold and fresh water. The convection can be suppressed within the pond water by NCZ which consists of salt gradient, and thus, the NCZ acts as insulation layer for the LCZ.

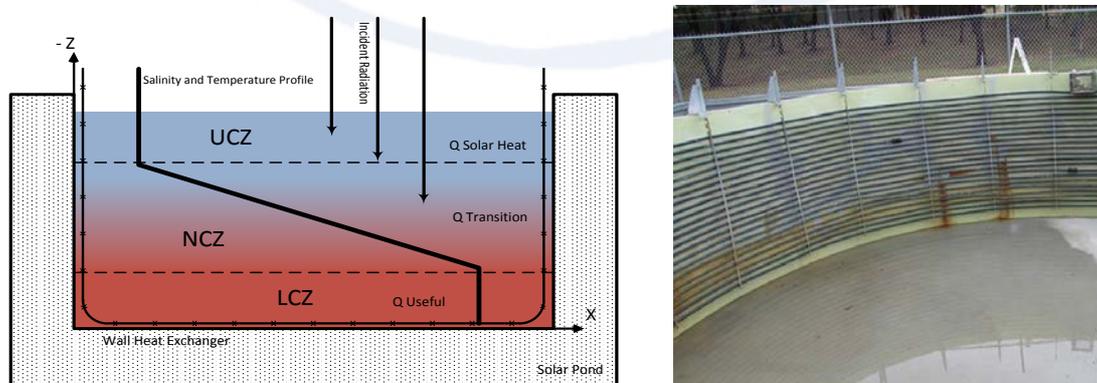


Fig.2. schematic diagram of salinity-gradient solar pond and in-pond heat exchanger pipe

At the LCZ layer, the salt concentration and temperature have the highest values and working as a heat energy storage. In fact, the solar radiation penetrates the pond's upper layers then passes through NCZ then reaches the LCZ and heats up the highly concentrated brine. The LCZ can reach temperatures greater than 90°C and the useful heat can be used directly for low-temperature thermal applications. SGSP has been used previously to provide heat energy for desalination and it was found to be amongst the most cost-effective alternative energy systems for desalinating water process [10]. In 1987, the most notable work began with solar pond of 3000 m<sup>2</sup> in El Paso, Texas, USA. At this site, a small multi-effect, multi-stage flash distillation unit with a brine concentration and recovery system, and a 2.94 m<sup>2</sup> air-gap MD (AGMD) unit were tested in conjunction with the solar pond to evaluate the performance and the reliability of this technology. These desalination units were selected as they are usually operated with low grade temperature source and therefore, are more suitable to operate with the thermal energy generated by solar ponds [11]. The multieffect, multi-stage unit produced an average water amount of 3.3 L/min, which was comparable to a water production of 1.6\*10<sup>-3</sup> m<sup>3</sup> per day per m<sup>2</sup> of SGSP. However, this unit required large amount of electricity to operate the system at approximately 30 kPa and a temperature higher than 60°C to start the desalination process. Using AGMD, a maximum flux of 6.7 (L/m<sup>2</sup>/hr) and a water production of 0.158\*10<sup>3</sup> m<sup>3</sup> per day per m<sup>2</sup> of SGSP, was achieved [11]. This maximum water production was obtained with a temperature difference of 41 C across the membrane module. Moreover, the water production significantly decreased when the system operates at lower temperature difference across the membrane. Most commercial MSF units operate with a top brine temperature of 90 – 110°C heated by steam while the solar pond operates in the range of 30 – 95 °C. Therefore, in solar pond assisted MSF systems, the first stage of the MSF heat exchangers is changed to liquid-liquid heat exchanger instead of steam-liquid heat exchanger. Some selected solar pond assisted desalination plant research studies are listed in Table 1.

Table (1) Selected SGSP &amp; MD desalination systems

Ref.	Mod./exp.	Location / Radiation / W/m <sup>2</sup>	SGSP size m <sup>2</sup>	Desalination method	Capacity	Cost (\$/M3)
[12]	Model	Tripoli, Libya 350	70000	MSF	1238 - 1570 m <sup>3</sup> /day	1.8
[13]	Model	Dead sea/Jordan 200-500	3000	MSF	6 m <sup>3</sup> /day	Na
[14]	Experiment	Ancona, Italy	625	MED	30 m <sup>3</sup> /day	Na
[11]	Model	Walker, NV, USA	Na	DCMD	2.7*10 <sup>-3</sup> m <sup>3</sup> /day/m <sup>2</sup> of SGSP	Na
[10]	Model	Gabès, Tunisia/ 588 - 1085	Na	VMD	71 L/hr/m <sup>2</sup>	Na

In fact, MD desalination requires thermal and mechanical energy; therefore it is similar to the solar assisted MSF/MED process, which could use low grade heat from solar pond, electricity from a PV system or the power grid. Regarding MD energy consumption and cost, researchers are not completely agreed about its preferability. Some consider that MD from an energy consumption perspective is unfavourable when compared with MED and MSF because of the additional resistance to mass transport and reduced thermal efficiency (due to heat conductivity losses) [8]. In contrast, others claim that comparing to MSF plants, the MD energy consumption is similar but the pumping power is less [15]. However, by using new materials and optimizing the MD configuration, the temperature and concentration polarization salt solution can be simultaneously reduced in the DCMD [16], which might potentially reduce the cost. In addition, MD uses robust and cheap membranes, which means that MD could save on the usage of chemical and the saline water pretreatment costs compared to RO [8]. Some selected solar assisted MD seawater desalination systems can be seen in Table 1, in which most solar assisted MD systems operates at temperatures less than 80°C. However, modelling results have shown that combining solar collectors with the MD system could achieve a higher membrane permeate flux [17]. Although, there are many cost estimation reports about MD desalination, there are only a few on solar MD desalination costs. Banat et al. estimated the produced water cost by \$15/m<sup>3</sup> for a 100 l/d system using a 10 m<sup>2</sup> membrane and 5.73 m<sup>2</sup> flat panel collectors (FPC). Also, the cost was \$18/m<sup>3</sup> for a 500 l/day system using FPC–PV driven MD, 40 m<sup>2</sup> membranes and 72 m<sup>2</sup> FPC [18]. The study showed that by increasing the plant life time and the reliability, the cost could be further reduced.

Overall, solar assisted MD is still under development stage. Reports on novel processes, experimentally confirmed modelling and pilot plant evaluations continue to appear in the literature [5]. MD has some disadvantage compared to MED and MSF of additional resistance to mass transport by the membrane. However, this disadvantage can be overcome since the MD materials develop lower cost and/or by using more area for heat and mass transfer. In addition, it could be used for highly concentrated saline water treatment or high recovery, that RO could not handle, which normally require high energy consumption.

## 2. MD theoretical approach:

In MD, the driving force for water vapour transfer through the membrane pores is the temperature difference between the feed/membrane interface temperature ( $T_{mf}$ ) and the permeate/membrane interface temperature ( $T_{mp}$ ). This generates a vapour pressure difference between both membrane sides which forces the vapour molecules to travel through the membrane pores and condensate at cold membrane side.

### 2.1 Flow Mechanisms:

There are three basic mechanisms of mass flow inside the membrane wall, which are Knudsen diffusion, Poiseuille flow and molecular diffusion. In Knudsen diffusion, the pore size is too small, and the collision between molecules can be neglected. Furthermore, the collision between sphere molecules and the internal walls of the membrane is the dominant mass transport form. Molecular diffusion occurs if the pore size is big comparing to the mean free path of molecules and they move corresponding to each other. The flow is considered Poiseuille (viscous flow) if the

molecules act as continuous fluid inside the membrane pores. In general, different mechanisms occur simultaneously (Knudsen, Poiseuille and Molecular diffusion) inside the membrane if the pore size is less than 0.5  $\mu\text{m}$  [19].

## 2.2 Knudsen number:

It is a governing quantity of the flow mechanism inside the membrane pores which is the ratio between the mean free path of the transported molecules and the pore size of the membrane. It is as follow:

$$kn = \frac{S}{d} \quad (1)$$

S is the mean free path of the transferred gas molecule and d is the mean pore diameter of the membrane.

S is calculated from:

$$S = \frac{k_B T}{\sqrt{2} \pi P d_e^2} \quad (2)$$

The pore sizes of the most membranes are in the range of 0.2 -1.0  $\mu\text{m}$ . The mean free path of water vapour is 0.11  $\mu\text{m}$  at feed temperature of 60°C. Therefore  $kn$  is the range of 0.11-0.55[19].

The different flow mechanisms inside the membrane pores can be identified by Knudsen number ( $kn$ ):

$kn < 0.01$	Molecular diffusion
$0.01 < kn < 1$	Knudsen-molecular diffusion transition mechanism
$kn > 1$	Knudsen mechanism

## 2.3 Mass Flux (J):

As shown in figure (1), vapour is transferring from feed side of the membrane to the permeate side by pressure difference force which is resulted from the temperature difference between two sides. The mass transfer may be written as a linear function of the vapour pressure difference across the membrane, given by:

$$J = C_m (P_1 - P_2) \quad \text{kg/m}^2/\text{sec} \quad (3)$$

Where  $J$  is the mass flux,  $C_m$  is the membrane distillation coefficient, and  $P_1, P_2$  are the partial pressure of water vapour evaluated at the membrane surface temperatures  $T_1, T_2$ .

$C_m$  for Knudsen flow mechanisms:

$$C_m^k = \frac{2\varepsilon r}{3\tau\delta} \left( \frac{8M}{\pi RT} \right)^{1/2} \quad (4)$$

$C_m$  for molecular diffusion

$$C_m^D = \frac{\varepsilon PD}{\tau\delta P_a RT} \quad (5)$$

$C_m$  for Knudsen-molecular diffusion transition mechanism:

$$C_m^C = \left[ \frac{3}{2} \frac{\tau\delta}{\varepsilon d} \left( \frac{\pi RT}{8M} \right)^{1/2} + \frac{\tau\delta P_a RT}{\varepsilon PD M} \right]^{-1} \quad (6)$$

$D$  is the diffusion coefficient of the vapour in the air.  $P$  is the pressure at  $\bar{T}$  and can be found using Antoine equation:

$$P^{\square} = \exp\left(23.238 - \frac{3841}{\bar{T}-45}\right) \quad (7a)$$

( $\bar{T}$ ) is the average membrane temperature.

The vapour pressure decreases with increasing of feed water salinity according to Raoult's law as follow [4]:

$$P_c^v = (1 - x_c)P^v \quad (7b)$$

Where  $x_c$  is the weight fraction of salt in water.

#### 2.4 Heat Flux (q):

The heat transfer models of MD can be summarized as follows:

- Convective heat transfer from the feed side to the membrane surface boundary layer:

$$q_f = h_f(T_f - T_{mf}) \quad (8)$$

Where  $q_f$  is the feed heat flux ( $W/m^2$ ) and  $h_f$  is the heat transfer coefficient ( $W/m^2.K$ ).

- Heat flux through the membrane which includes conduction heat flux through the solid material of the membrane  $k_m \frac{dT}{dx}$ , and the latent heat transfer as a convection by water vapour through the pores  $JH_v$ :

$$q_m = JH_v + k_m \frac{dT}{dx} \quad (9)$$

$H_v$  is the vaporisation enthalpy of water evaluated at the mean temperature  $\frac{T_{mf}+T_{mp}}{2}$ , and the second term is the conduction heat loss through the membrane material.

Finally, heat is transferred through the permeate boundary layer to the permeate water by convection.

$$q_p = h_p(T_{mp} - T_p) \quad (10)$$

At steady state:

$$q_f = q_m = q_p \quad (11)$$

The overall heat transfer coefficient can be determined by:

$$U = \left[ \frac{1}{h_f} + \frac{1}{\frac{k_m}{\delta_m} + \frac{JH_v}{T_{mf} - T_{mp}}} + \frac{1}{h_p} \right]^{-1} \quad (12)$$

The rate of total heat transferred through the membrane is:

$$q_t = U (T_f - T_p) \quad (13)$$

The feed flow energy balance is:

$$q_f = \dot{m}_f c_p (T_{f,in} - T_{f,out}) \quad (14)$$

The thermal efficiency of the MD system is:

$$E_t(\%) = \frac{JH_v A}{Q_t} * 100 \quad (15)$$

The thermal efficiency is the ratio between the water heat energy consumption to generate vapour and the total heat energy supplied to the system. Whereas, heat conduction through membrane solid, is considered heat loss and it should be minimised.

To be more adequate, the efficiency should include both thermal and electrical energy (pumps) thus GOR (Gained Output Ratio) can define it as:

$$GOR = \frac{JH_v A}{E_T + E_E} \quad (16)$$

To determine heat transfer coefficients of the boundary layers at both membrane sides the average bulk temperature of feed side  $\frac{T_f + T_{mf}}{2}$ , and at permeate side  $\frac{T_{mp} + T_p}{2}$  of the membrane should be used. Graetz-Leveque correlation is recommended [20]:

$$Nu = 1.86 \left( Re P_r \frac{d_h}{L} \right)^{0.33} \quad d_h = \frac{4A_c}{P_e} \quad (17)$$

This correlation can be used for laminar flow ( $Re < 2100$ ).

In contrast, next correlation can be applied for turbulent flow ( $2500 < Re < 1.25 * 10^5$  and  $0.6 < P_r < 100$ ).

$$Nu = 0.023 Re^{0.8} P_r^n \quad (18)$$

Where n is equal to 0.4 for heating, and 0.3 for cooling [21].

The dimensionless groups, Nusselt number ( $Nu$ ), Reynolds number ( $Re$ ) and Prandtl number ( $P_r$ ) can be calculated straightforwardly using the available physical data of feed and permeate fluid.

At both sides of the membrane where the vapour-liquid interface takes place; there is a thermal boundary layer which its temperature differs from the bulk stream. This difference is described as temperature polarisation coefficient (TPC).

$$TPC = \frac{T_{mf} - T_{mp}}{T_f - T_p} \quad (19)$$

The iterative method by a computer software (MATLAB®) is applied to predict  $T_{mf}$  and  $T_{mp}$ . By entering the geometry and fluid properties, the software calculates the boundary heat transfer coefficients those to be used with other correlations. Then it uses the values of  $T_{mf}$  and  $T_{mp}$  which are initially assumed equal to the bulk temperature  $T_f$  and  $T_p$  respectively, to determine the new values of  $T_{mf}$  and  $T_{mp}$  by a number of iterations. Equations (21) and (22) are used to predict both temperatures. Once the surface temperatures  $T_{mf}$  and  $T_{mp}$  are determined, the software calculates the rest of required parameters. Please refer to the appendix (A) as an example of those values.

To determine the evaporation latent heat:

$H_v$  is evaluated at  $T$

$$T = \frac{T_{mf} + T_{mp}}{2} \quad (20)$$

From heat balance through the membrane and boundary layers:

$$T_{mf} = \frac{h_m(T_p + (h_f/h_p)T_f) + h_f T_f - JH_v}{h_m + h_f(1 + h_m/h_p)} \quad (21)$$

$$T_{mp} = \frac{h_m(T_f + (h_p/h_f)T_p) + h_p T_p + JH_v}{h_m + h_p(1 + h_m/h_f)} \quad (22)$$

Where 
$$h_m = \frac{k_m}{\delta_m} \quad (23)$$

### 3. SGSP heat extraction:

A salinity gradient solar pond of 50 m<sup>2</sup> located at RMIT Bundoora east campus, Australia, in renewable energy laboratory field was used to connect with DCMD module to work as heat energy source. The pond was designed with a depth of 2.05 m. The bottom storage zone was designed to be 0.56 m thick, the gradient zone 1.34 m thick and the top convective zone 0.15 m thick. The rate of heat extraction from this pond through its wall heat exchanger is given by:

$$\dot{Q} = A_o \cdot U \cdot LMTD \quad (24)$$

Where A<sub>o</sub> is the external surface area of the heat exchanger pipe, U is the overall heat transfer coefficient based on the external surface area (in W/m<sup>2</sup> °C) and LMTD is given by

$$LMTD = \frac{[T_o - T_i]}{\ln[(T_{po} - T_i)/(T_{po} - T_o)]} \quad (25)$$

Where T<sub>i</sub>, T<sub>o</sub> and T<sub>po</sub> are the temperature of the inlet and outlet of the wall heat exchanger and solar pond, respectively.

The rate of extracted thermal energy is given by:

$$\dot{Q} = \dot{m}_f * C_p * (T_{po} - T_{pi}) \quad (26)$$

Where  $\dot{m}$  is the mass flow rate (in kg/s) and C<sub>p</sub> is the specific heat of the circulating saline water (in J/kg °C) through the pipe.

The solar pond efficiency can then be calculated by:

$$e_{sp} = \frac{\dot{m} * C_p * (T_{po} - T_{pi})}{G * A_{sp}} \quad (27)$$

Where G is the solar radiation at the surface of the pond (in W/m<sup>2</sup>) and A<sub>sp</sub> is the area of solar pond.

Therefore, the overall heat transfer coefficient of the in-pond heat exchanger pipe can be found from equation (24).

$$U = \frac{\dot{Q}}{A_o * LMTD} \quad (28)$$

### 4. Water production and heat energy recovery:

After DCMD operational parameters were selected (e.g., feed and permeate velocity, partial pressure of air entrapped in the pores) and the SGSP specifications (e.g., surface area, thickness of each zone) were determined, the performance of the coupled DCMD/SGSP system was evaluated. Specifically, heat extracted from the SGSP,

water mass flux, and energy required for permeate water production through the membrane were determined. The necessary membrane surface area to use all the energy collected in the SGSP was also determined. In addition, the required membrane area  $A_{DCMD}$  ( $m^2$ ) for the DCMD module, when the heat extracted from the SGSP is used without losses, can be found by equating the energy stored in the SGSP with the energy consumed by the DCMD module. Thus:

$$(A_{SP} * q_{use}) * e_{sp} = A_{DCMD} * q_m \quad (29)$$

Where  $A_{SP}$  ( $m^2$ ) is the surface area of the SGSP.

The water flow produced by DCMD module,  $q_m$  ( $m^3/s$ ), is given by:

$$q_m = \frac{J * A_{DCMD}}{\rho} \quad (30)$$

Fig. 3 shows the DCMD module and the SGSP coupling. The feed solution to the membrane module was saline water which is taken from the evaporation pond that is located beside the solar pond. The concentration of this feed solution typically is about 1.3 % (13 g/l). The heat extracted from the solar pond in the NCZ was transferred to the feed solution using the in-pond heat exchanger with effectiveness between 35 and 40 %, and it was assumed that there were no heat losses in the coupled system. Therefore, the average feed temperature was assumed to be equal to the temperature in the LCZ which is considered as  $T_{sp}$ , i.e.,  $T_{f\text{ inlet}} = T_{sp} = T_L$ , where  $T_L$  is the LCZ temperature. Also, a stainless steel cross flow heat exchanger (fig.3 HE1) was connected to the DCMD module and the evaporation pond to exchange heat between the outlet fresh water that is slightly hot and cold inlet feed water. In this way, the average permeate temperature was consistency kept stable at temperature ranging from 20 °C to 23 °C. Furthermore, for energy conservative purpose, second heat exchanger (Fig.3 HE2) was installed to recover heat from the hot feed water exiting the MD module and preheat the feed water that enters the in-pond heat exchanger pipe in the solar pond.

## 5. Experiment and procedures:

The experiments were carried out in renewable energy laboratory at RMIT Bundoora east campus at the months of May and June. Tests were performed using a PTFE membrane manufactured by Membrane Solution (80 % porosity, 210  $\mu m$  thickness, 0.22  $\mu m$  nominal pore size). This membrane was inserted between two symmetrical plastic blocks creating two channels of 2 mm gap at both sides and was sealed by rubber cord. Also, the membrane was supported by plastic net spacer of 1 mm thickness at both sides. As it can be seen from figure (4), the 0.1074  $m^2$  (0.235m W\* 0.475 m L) flat membrane module has inlet and out let permeate and hot saline water. Both are flowing in counter directions and Figure (3) shows the used setup and the schematic diagram of the experiment.

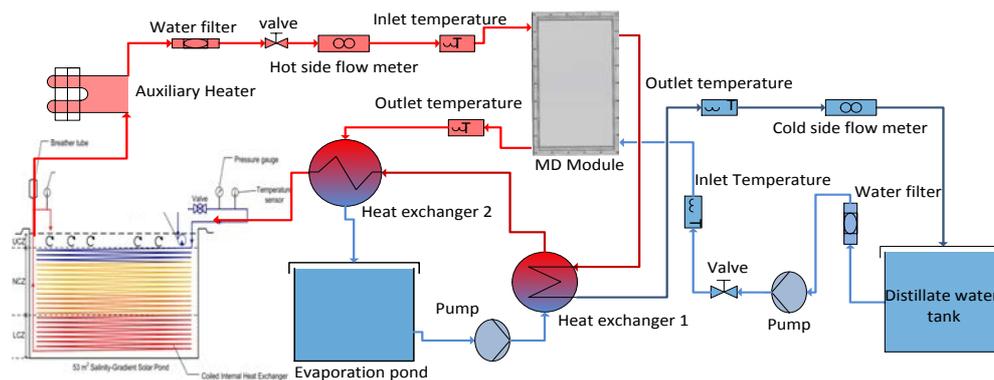


Fig.(3a) the schematic diagram of experimental set-up

The 1.3 % solution of saline water is pumped from the evaporation pond at low temperature and enters the first heat exchanger after passing through water filter unit. In this stage it works as a cooling fluid that removes a certain amount of heat gained by outlet permeate water throughout the MD module. Then the saline water goes through the second heat exchanger where it gains a portion of heat that is exchanged with hot saline water coming from the MD module feed outlet. This preheating process can achieve up to 50% of heat recovery from the total heat energy gained by the feed saline water. By this point, the saline water enters the in-pond heat exchanger (figure 2) to be heated to the maximum temperature which is almost equal to the solar pond temperature. The in-pond heat exchanger is a plastic coiled pipe fixed to the wall by a stainless steel frame (Fig. 2) since the plastic tubing is ideal for the highly corrosive environment. It is made of reinforced polyethylene pipe (32 mm OD, 3 mm thick). The frame allows the pipe to move freely in the circumferential direction for any contraction and expansion. There are 22 rows of tubes and the total length of the pipe is 560 m. The thermal conductivity of the polyethylene pipe is 0.37 W/m/ °C. Temperature measurements were made at inlet and outlet of the MD module and 6 different thermocouples used through the set-up. Also, in MD process the membrane wetting is not allowed, therefore the conductivity of the permeate water was periodically measured in order to ensure that there was no penetration of the feed solution through the membrane pores. Finally, the saline water reaches the solar pond temperature and it is ready to flow through the membrane module to conduct the distillation process.

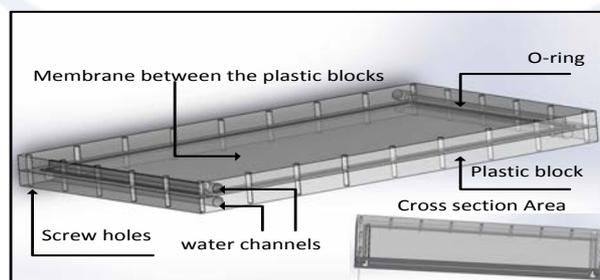


Fig.(4) Flat plat DCMD module and crosssectional area of the plastic blocks

The flows of 10 l/min for feed side solution and 4 l/min for permeate water were recirculating at the two sides of the membrane in counter current directions. The temperatures of the bulk liquid phases are measured at the hot entrance ( $T_{f1}$ ), the cold entrance ( $T_{p1}$ ), the hot exit ( $T_{f2}$ ) and the cold exit ( $T_{p2}$ ), of the membrane module. These temperatures will be different from the temperatures at the hot and cold

membrane surfaces  $T_{mf}$  and  $T_{mp}$ , respectively. Also, the solar pond temperature and the temperature of feed saline water that is coming out from the second heat exchanger are measured. All measurements were monitored by data acquisition system brought by DataTaker<sup>®</sup>. Also, to determine the water mass flux by this experimental set-up, permeate water continuously collected in the distillate reservoir, and the corresponding distillate flux was measured by an electronic scale. Finally, the recirculation flow rates on both membrane surfaces were 10 l/min at feed side and 4 l/min at permeate side.

## 6. Results and Discussion.

### 6.1 DCMD performance:

Fig. 5 shows an example of the variation of the temperature during the distillation process at different points in the set-up. These temperatures used to determine the operational parameters of the DCMD module and its performance. Also, the mathematical model was used to predict the permeate water mass flux and heat flux across the membrane as well as the heat energy consumption and heat recovery by the heat exchanger (second HE).

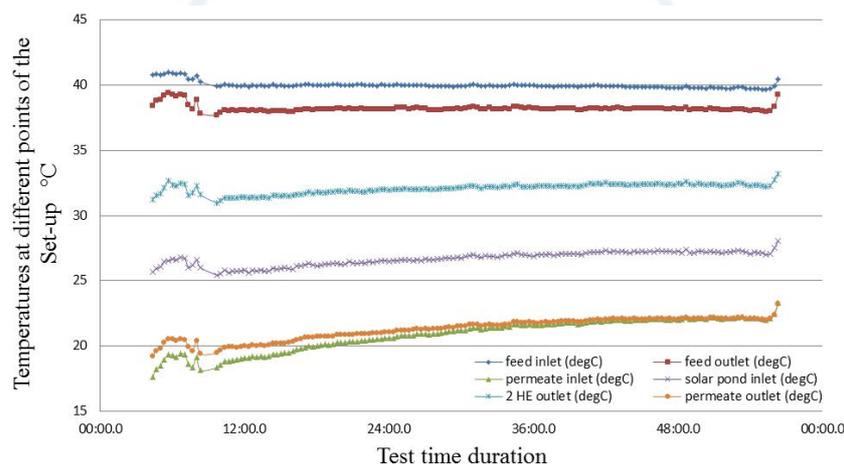


Fig (5) variation of solution temperatures at different location of the Set-up with test time duration

Fig. 6 represents the predicted and experimental fluxes of pure water at various feed temperatures when the system was in transient flow regions ( $2100 < Re < 4000$ ). The experimental data corresponded fairly well with the flux estimated from the Knudsen diffusion model. However, it can be seen that the experimental data was in good agreement with the mathematical model limits since the estimated result was lower by 15 % in average. The tortuosity factor ( $\tau$ ) plays a vital role in determining the mass transport mechanism. In this work, the tortuosity of 1.5 was employed and it was derived from the correlation proposed by Khayet [22]. It can be concluded that Knudsen diffusion was the dominant mechanism in mass transfer across the membrane and it has been found that its values ranged between 7 and 12. Also, TPCs ranged between 0.34 and 0.38 at velocity 0.354 m/s (transient region). Therefore, larger amount of heat was required to vaporize water at the membrane surface. This contributed to the large difference in temperature between the bulk feed stream and the membrane surface, and the pronounced effect of temperature polarization.

Whereas, the increase in heat transfer coefficient in boundary layer might be induced by the high cross flow velocity which will result in the decrease in temperature difference between bulk streams and membrane surfaces.

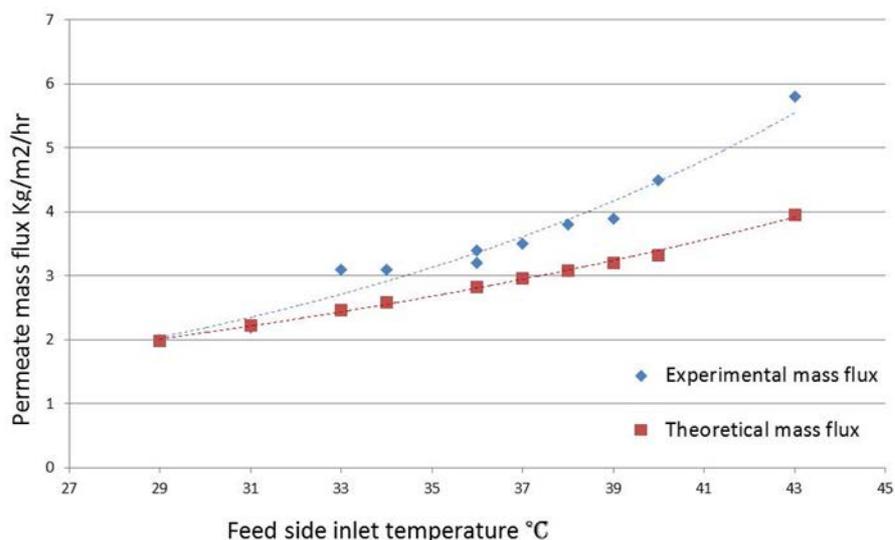


Fig. (6) Mass flux (J) variation with temperature difference and inlet feed water temperature across the membrane

Furthermore it can be seen in Fig 6 that the higher the feed temperature, the higher the permeate flux (see also Fig. 8). At highest temperature (45 °C), the influence of temperature on the permeation flux was more significant compared with that of low temperature (29 °C) since the vapour pressure at an exponential function with temperature.

The combined effect of the temperature difference between the feed and permeate channels,  $T_f$  and  $T_p$ , respectively, and the feed inlet temperature of saline water,  $T_{in}$  °C, on the performance of the DCMD module is presented in Fig. 7. A permeate temperature of an average between 20°C and 23°C and feed temperatures between 30°C and 45°C were utilized. These temperatures were available at the LCZ layer of the solar pond. They were depended on the season time which was May and June. A feed concentration of 1.3 % (13 g /L), which is approximately the total dissolved solids concentration in the evaporation pond, was used. Also, the evaporation pond was used as a brine discharge destination. When the temperature at the feed water was high and decreased (Fig. 7), the water and heat fluxes decreased. The continuing decrease in these fluxes is nonlinear and started from high value of 6 l/m<sup>2</sup>/hr to 2 l/m<sup>2</sup>/hr at the end of June. The high mass flux occurs because high velocity flow is used, producing more solution mixing in the channels and reducing the thermal boundary layer thickness [20]. Subsequently,  $T_{fm}$  and  $T_{pm}$  approach  $T_f$  and  $T_p$ , respectively, and maximizing the temperature and vapour pressure differences across the membrane. This increases the driving force as well as the conductive heat flux across the membrane material. It is also found that the transmembrane coefficient is almost about 0.001 kg/m<sup>2</sup>/Pa/hr for this type of PTFE membranes.

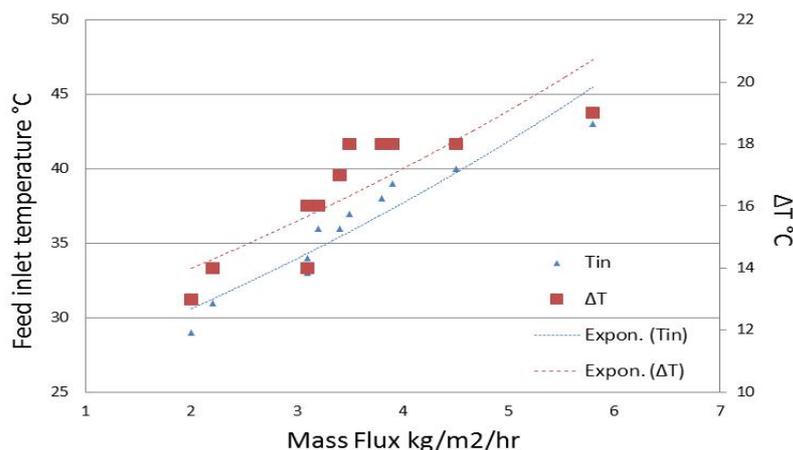


Fig. (7) vapour mass flux (J) variation with temperature difference and inlet feed water temperature across the membrane

For feed side water velocity equal to 0.36 m/s ( $Re_f = 2540$  and  $Re_p = 560$ ), the water flux of 6 l/m<sup>2</sup>/hr was achieved and it was around the average of some reported values [5]. The increased water flux also increases convective heat flux because more water vapour crosses the membrane.

## 6.2 Energy consumption:

The permeation mass flux significantly decreases with the inlet feed temperature ranges from 45 to 30 °C, which result in an increase in thermal energy consumption. The decrease of the total thermal capacity entering the channels, results in a decrease of the bulk temperature difference across the membrane. According to Eq. (13) this effect leads to a lower driving force. Also, the temperature polarisation is reduced by an enhanced heat transfer in the thermal boundary layers, thus a higher interfacial temperature difference needs to be used. Fig (8) shows how the energy consumption of this system varies with inlet feed temperature and ranges from 13000 kj/kg to 6000 kj/kg. It has been observed that the heat energy consumption was higher at lower feed inlet temperature than that at higher inlet feed temperature. The higher total energy demand is not completely compensated by higher inlet temperatures from an energetic point of view. The higher thermal energy input and the heat transfer are not sufficient to rise up the vapour driving forces accordingly. Furthermore, the used preheating system achieved significant heat energy recovery ranges between 40% and 60% of the total heat energy gained from the solar pond. This heat used to preheat the saline solutions that is entering the in-pond heat exchanger and cooling down the outlet hot saline water that is exiting the MD module and discharging into evaporation pond.

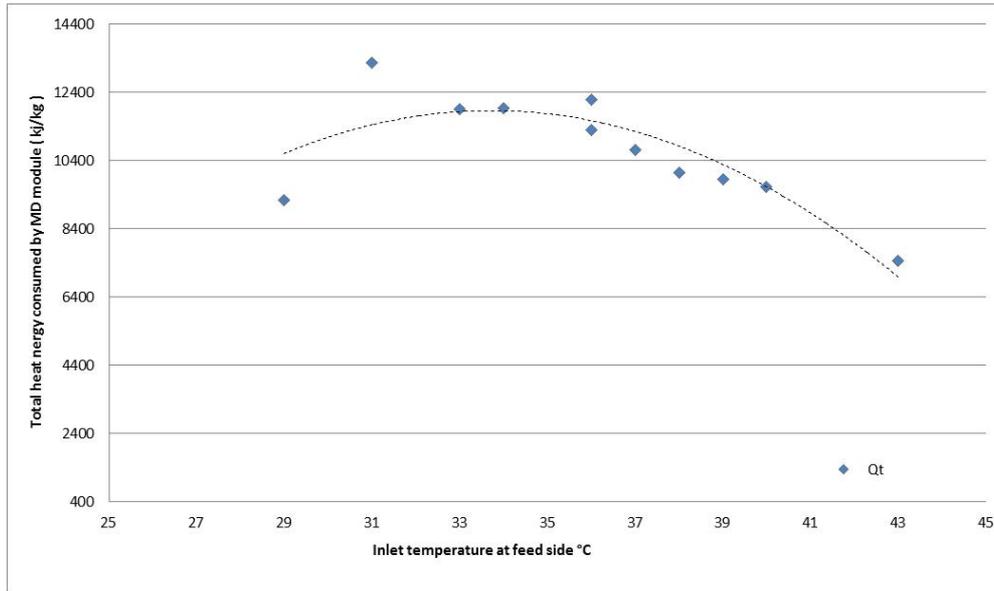


Fig. (8) total heat energy consumption by MD membrane module ( $q_t$ ) variation with inlet feed water temperature ( $T_{in}$ )

### 6.3 SGSP performance:

Fig (9) shows a typical solar radiation on the horizontal surface of the solar pond on hourly bases. The average daily radiation was at  $310 \text{ W/m}^2$  and the maximum was at  $700 \text{ W/m}^2$ . The heat exchanger pipe is circulating around the pond wall extracting the heat from the NCZ layer. This method of heat extraction achieve an efficiency of 30% for this solar pond as some researchers claim [9]. For other conditions, the efficiency were either temporarily raised (if the amount of extracting energy is more than the incoming solar radiation corresponding to cloudy days) or decreased due to fluctuating solar radiation. Also note that if the heat gains (during winter months) from the surrounding walls are included, this would reduce the average efficiencies further.

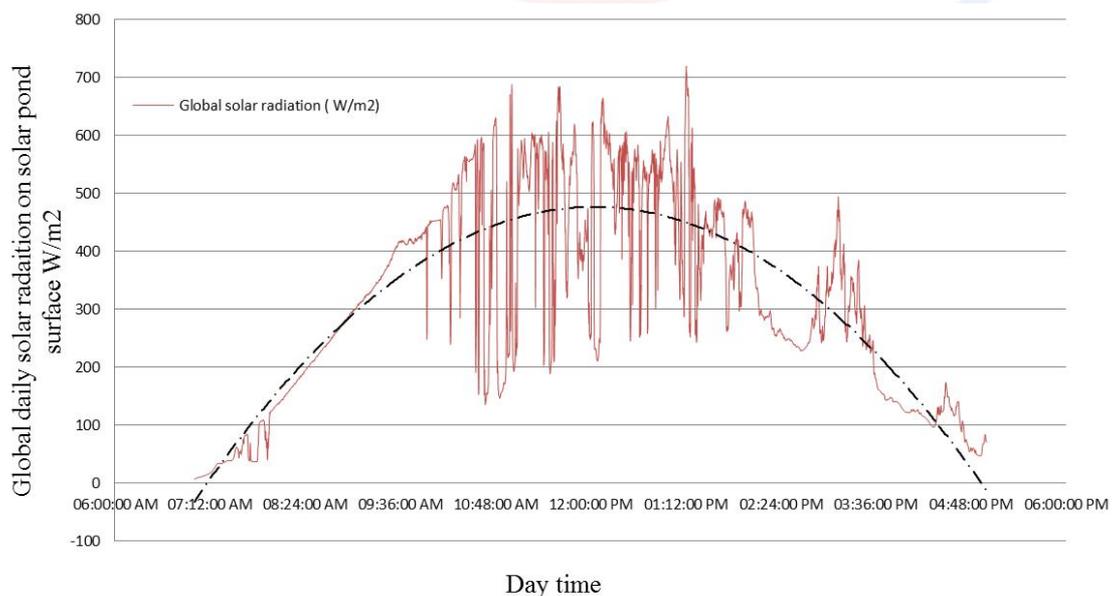


Fig. (9) Typical daily solar radiation on the horizontal surface of the solar pond

Therefore, if the efficiency of 30% is considered and the average daily radiation is  $310 \text{ W/m}^2$ , the amount of energy that can be delivered by this solar bond will be about 4.7 KW. This is applying only for winter season (April to June) and the performance can be improved by conduct the experiment in summer time.

It can be seen in Fig (10) the temperature gradient profile which was taken during heat removal and approximated by a 2nd order polynomial trend line due to the fluctuations caused by heat losses and convective currents. On 23th April 2014, when heat extraction has just started, the temperature gradient near the top of the NCZ was high ( $35^\circ\text{C/m}$ ) whereas at the bottom of the NCZ, was very low. However, the temperature gradient profile can be reversed, as predicted by Andrews and Akbarzadeh [9]. At the top of the LCZ, the temperature gradient was low ( $5^\circ\text{C/m}$ ), as compared to other cases. The small temperature gradient at the surface means that there is very little heat loss by conduction to the UCZ.

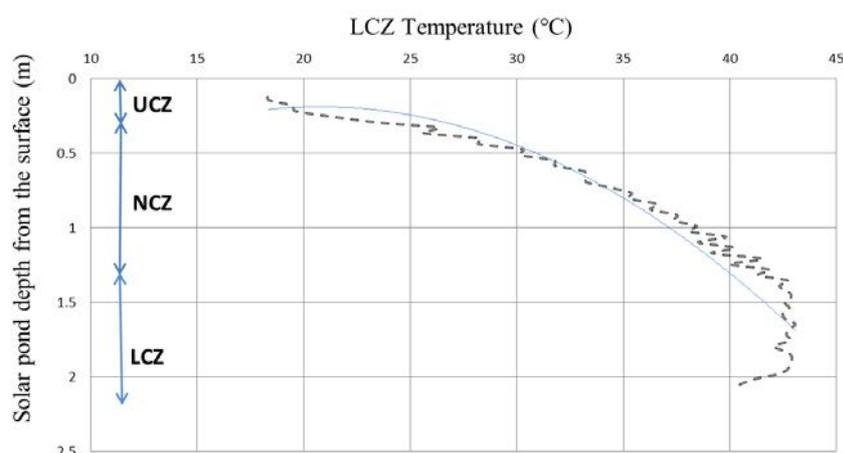


Fig. (10) Temperature variation with depth of SGSP at different layers

#### 6.4 Water production by SGSP:

The performance of the coupled DCMD/SGSP through the In-pond heat exchanger system for the typical operating conditions, i.e.,  $T_f = 30$  or  $45^\circ\text{C}$ , is shown in Fig (9). The performance is presented as a function of the temperature in the LCZ. At higher LCZ temperature, the outlet temperature of the IHE and the temperature difference across the DCMD membrane are higher, result in higher permeate flux. At the end of the season the temperature of saline water exiting the in-pond heat exchanger approached LCZ temperature which means the heat transfer and heat loss was very small.

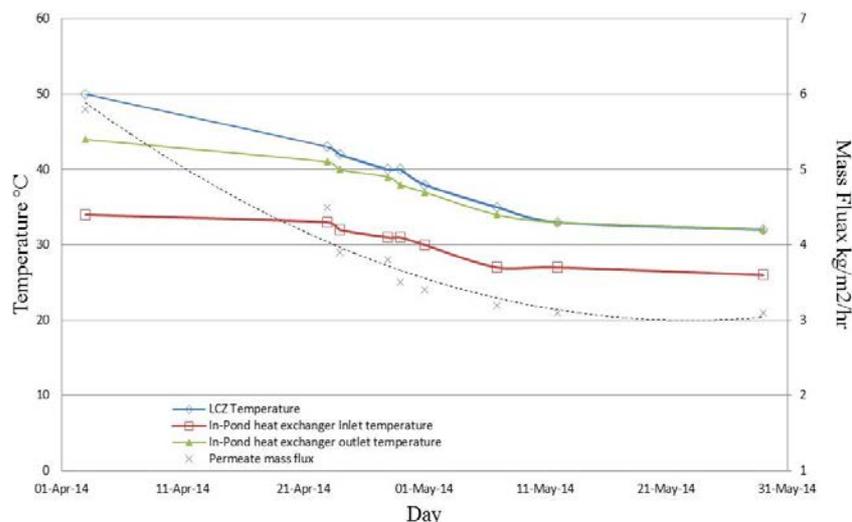


Fig. (10) mass flux across the membrane (J) variation with LCZ temperature and inlet; outlet in-pond heat exchanger pipe

Moreover, because of winter season is approaching the LCZ temperature decreases gradually and this affects the feed temperature. Eventually, the vapour pressure on the feed side and the permeate water flow decrease. Thus, as shown in Fig 10, the highest water flow obtained in the DCMD module occurs when the feed side is at 46°C and the temperature at the LCZ is 50°C. At these conditions, and when treating a feed solution with a salinity of 1.3%, the coupled system delivers  $1.2 \cdot 10^{-3} \text{ m}^3$  of fresh water per  $1 \text{ m}^2$  of membrane and  $1 \text{ m}^2$  SGSP. If higher temperatures in the LCZ are used, the coupled system produces larger water permeation flux. However, lower temperature in the LCZ would decrease the heat energy transfer to the feed saline water flowing in the IHE pipe as well as the feed inlet temperature of the DCMD module.

## 7. Conclusion:

This study experimentally investigates utilization of direct contact membrane distillation (DCMD) coupled to a salt-gradient solar pond (SGSP) through its wall heat exchanger for sustainable freshwater production and reduction of brine footprint on the environment. The experimental data corresponded fairly well with the flux estimated from the Knudsen diffusion model as it was the dominant mass flux mechanism. The fluxes are nonlinear and started from high value of  $6 \text{ l/m}^2/\text{hr}$  to  $2 \text{ l/m}^2/\text{hr}$  at the end of June and the trans-membrane coefficient was about  $0.001 \text{ kg/m}^2/\text{pa}/\text{hr}$ .

The energy consumption of this system varies with inlet feed temperature and ranges from  $13000 \text{ kJ/kg}$  to  $6000 \text{ kJ/kg}$  and the extra heat exchanger recover 40 % to 60 % of this energy and use it as a preheating system. This energy can be provided by solar pond which receives an average daily radiation at  $310 \text{ W/m}^2$  in winter season.

Finally, when treating a feed solution with a salinity of 1.3%, the coupled system delivers  $1.2 \cdot 10^{-3} \text{ m}^3$  of fresh water per  $1 \text{ m}^2$  of membrane and  $1 \text{ m}^2$  SGSP. It is important to note that the cost of this system is feasible, since it uses renewable thermal energy to drive the desalination process. Further studies and experiments will be conducted in summer season and an economic analysis needs to be conducted to

determine the economic aspects of using solar pond as a heat energy source for MD distillation.

**Nomenclature:**

$C_{ap}$	Specific heat coefficient (J/Kg.K)
$C_m$	Membrane mass flux coefficient ( $kg/m^2 \cdot Pa \cdot h$ ).
$d$	Membrane pore diameter (m).
$d_e$	Collision diameter of the water vapour and air ( $2.64 * 10^{-10} m$ and $3.66 * 10^{-10} m$ )
$h_f$	Heat transfer coefficient at feed side ( $W/m^2 \cdot K$ ).
$h_p$	Heat transfer coefficient at permeate side ( $W/m^2 \cdot K$ ).
$h_m$	Heat transfer coefficient of the membrane ( $W/m^2 \cdot K$ ).
$J$	Total mass flux of the membrane ( $kg/m^2/h$ ).
$k_B$	Boltzmann constant ( $1.380622 * 10^{-23} J/K$ )
$M$	Molecular weight (kg/mol).
$\dot{m}_f$	Hot feed flow rate (kg/s)
$P$	Average pressure inside the membrane pores (Pa)
$P_a$	Entrapped air pressure ( $P_a$ ).
$P^v$	Vapour pressure at given salinity (Pa)
$P_1$	Vapour pressure at feed membrane surface ( $P_a$ )
$P_2$	Vapour pressure at permeate membrane surface ( $P_a$ )
$R$	Gas constant (J/Kg.K).
$T$	Absolute temperature inside the membrane pores (K)
$T_f$	Bulk feed side temperature (K).
$T_p$	Bulk permeate side temperature (K).
$\tau$	Membrane tortuosity.
$\delta$	Membrane thickness (m).
$\varepsilon$	Membrane porosity.

Appendix (A)

<b>Vmf = 0.3546099 [m/sec]</b>
<b>Ref = 2540.6449191 [DL]</b>
<b>hf = 2892.3968473 [w/m2.k]</b>
<b>Vmp = 0.1418440 [m/sec]</b>
<b>Rep = 560.3420445 [DL]</b>
<b>hp = 898.6778082 [w/m2.k]</b>
<b>Path Length = 0.0000019 [m]</b>
<b>Knudsen Number =</b> <b>8.5392279 [DL]</b>
<b>Hv = 2418500.0000000 [J/Kg]</b>
<b>U = 447.0013711 [w/m2.k]</b>
<b>qt = 13410.0411338 [w/m2]</b>
<b>EE = 0.2905636 [DL]</b>
<b>TPC = 0.3480575 [DL]</b>
<b>T1 = 318.3636925 [k]</b>
<b>T2 = 307.9219676 [k]</b>

**P1 = 9770.48718792 [Pa]**

**P2 = 5592.05872615 [Pa]**

**Cm = 0.0000002453**

**[kg/m<sup>2</sup>.pa.sec]**

**J = 0.00161111 [kg/m<sup>2</sup>.sec]**



## References

1. Ranjan, P., et al., *Global scale evaluation of coastal fresh groundwater resources*. Ocean & Coastal Management, 2009. **52**(3–4): p. 197-206.
2. Mee, L., *Between the Devil and the Deep Blue Sea: The coastal zone in an Era of globalisation*. Estuarine, Coastal and Shelf Science, 2012. **96**(0): p. 1-8.
3. Hanjra, M.A. and M.E. Qureshi, *Global water crisis and future food security in an era of climate change*. Food Policy, 2010. **35**(5): p. 365-377.
4. Qtaishat, M.R. and F. Banat, *Desalination by solar powered membrane distillation systems*. Desalination, 2013. **308**(0): p. 186-197.
5. Li, C., Y. Goswami, and E. Stefanakos, *Solar assisted sea water desalination: A review*. Renewable and Sustainable Energy Reviews, 2013. **19**(0): p. 136-163.
6. Farahbod, F., et al., *Experimental study of a solar desalination pond as second stage in proposed zero discharge desalination process*. Solar Energy, 2013. **97**(0): p. 138-146.
7. El-Bourawi, M.S., et al., *A framework for better understanding membrane distillation separation process*. Journal of Membrane Science, 2006. **285**(1–2): p. 4-29.
8. Al-Obaidani, S., et al., *Potential of membrane distillation in seawater desalination: Thermal efficiency, sensitivity study and cost estimation*. Journal of Membrane Science, 2008. **323**(1): p. 85-98.
9. Leblanc, J., et al., *Heat extraction methods from salinity-gradient solar ponds and introduction of a novel system of heat extraction for improved efficiency*. Solar Energy, 2011. **85**(12): p. 3103-3142.
10. Mericq, J.-P., S. Laborie, and C. Cabassud, *Evaluation of systems coupling vacuum membrane distillation and solar energy for seawater desalination*. Chemical Engineering Journal, 2011. **166**(2): p. 596-606.
11. Suárez, F., S.W. Tyler, and A.E. Childress, *A theoretical study of a direct contact membrane distillation system coupled to a salt-gradient solar pond for terminal lakes reclamation*. Water Research, 2010. **44**(15): p. 4601-4615.
12. Agha, K.R., *The thermal characteristics and economic analysis of a solar pond coupled low temperature multi stage desalination plant*. Solar Energy, 2009. **83**(4): p. 501-510.
13. Saleh, A., J.A. Qudeiri, and M.A. Al-Nimr, *Performance investigation of a salt gradient solar pond coupled with desalination facility near the Dead Sea*. Energy, 2011. **36**(2): p. 922-931.
14. Caruso, G. and A. Naviglio, *A desalination plant using solar heat as a heat supply, not affecting the environment with chemicals*. Desalination, 1999. **122**(2–3): p. 225-234.
15. Alklaibi, A.M. and N. Lior, *Membrane-distillation desalination: Status and potential*. Desalination, 2005. **171**(2): p. 111-131.
16. Francis, L., et al., *Material gap membrane distillation: A new design for water vapor flux enhancement*. Journal of Membrane Science, 2013. **448**(0): p. 240-247.
17. Ali, M.T., H.E.S. Fath, and P.R. Armstrong, *A comprehensive techno-economical review of indirect solar desalination*. Renewable and Sustainable Energy Reviews, 2011. **15**(8): p. 4187-4199.
18. Banat, F. and N. Jwaied, *Economic evaluation of desalination by small-scale autonomous solar-powered membrane distillation units*. Desalination, 2008. **220**(1–3): p. 566-573.

19. Alkudhiri, A., N. Darwish, and N. Hilal, *Membrane distillation: A comprehensive review*. *Desalination*, 2012. **287**(0): p. 2-18.
20. Srisurichan, S., R. Jiratananon, and A.G. Fane, *Mass transfer mechanisms and transport resistances in direct contact membrane distillation process*. *Journal of Membrane Science*, 2006. **277**(1-2): p. 186-194.
21. Incropera, F.P. and P.I. Frank, *Fundamentals of heat and mass transfer*, ed. D.P. DeWitt. 2002, New York: New York : Wiley.
22. Khayet, M., *Membranes and theoretical modeling of membrane distillation: A review*. *Advances in Colloid and Interface Science*, 2011. **164**(1-2): p. 56-88.





## ***Renewable Energy Policies: A Comparison of Global and Turkish Perspectives***

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### **Abstract**

Sustainability concerns resulting from the consumption of natural resources, life-threatening levels of pollution, global warming, climate change and the ever increasing worldwide energy use have brought renewable energy sources to forefront. Given the possibility of depletion of fossil fuels in the near future; the utilization of clean and renewable energy sources have become inevitable. Consequently, countries have developed government policies and adopted respective regulations to ensure the production and use of renewable energy and promote the respective new investments. This has been realized both individually and also as a part of global organizations and networks some of which can be listed as the Organisation for Economic Co-operation and Development (OECD), European Union (EU), United Nations (UN) and International Energy Agency (IEA).

Turkey is a developing country with a substantial amount and wide range of renewable energy sources, and it is located in an advantageous geographical position that enables their effective utilization. However, because of the rapid increase in the energy consumption and the inefficient use of resources, it remains to be an energy importing country with more than half of its energy being met externally. Hence, a detailed review and evaluation is conducted in this study on the current literature, projects, binding regulations, incentives, and pricing mechanisms together with the respective energy statistics to analyze and compare the renewable energy policies in Turkey with those adopted worldwide. Ultimately, the goal is to make certain suggestions and lay out possible solutions regarding Turkey's energy problems.

Keywords: Renewable Energy, Renewable Energy Policies, Literature Survey, Turkish Renewable Energy Sector, Sustainability.

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## Introduction

Renewables have become the fastest growing source of world energy with their share of electric power generation increasing from 10 percent to 15 percent in 2010 while the fossil fuel sources grew 3 or 4 percent (EIA, 2012). The reason behind this is the concern for sustainability resulting from factors including but not limited to the depletion of natural resources, life-threatening levels of pollution, global warming, climate change and the ever increasing worldwide energy consumption (Komor and Bazilian, 2005; Apergis and Payne, 2010). The Renewable Energy Working Party of the International Energy Agency (IEA) has provided the following definition (IEA, 2013a):

*“Renewable Energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly or indirectly from the sun, or from heat generated deep within the earth. Included in the definition is energy generated from solar, wind, biofuels, geothermal, hydropower and ocean resources, and biofuels and hydrogen derived from renewable resources.”*

In line with the above definition, renewable energy sources can be classified under the following categories (IEA, 2013a):

- Hydro,
- Geothermal,
- Solar,
- Tide/Wave/Ocean,
- Wind,
- Solid biofuels, biogases, liquid biofuels, and
- Renewable municipal waste.

The effective utilization of the above-listed sources is critical across the world, where 1.3 billion people still do not have access to modern sources of energy (WEF, 2013). Societies have much to gain from the effective use of renewable energy with certain issues to consider while making this happen (see Table 1).

<b>Advantages</b>	<b>Disadvantages</b>
Provides low operating and maintaining costs Provides long life period Service cost is low Reliable source Induces technology development Fosters regional development Provides efficient energy production and safety Generates revenue and tax Creates new employment opportunities Protects environment and saves environmental protection costs Enhances living conditions It is waste-free	High up-front investment Entails long-term planning Entails long-term agreements Entails multidisciplinary involvement Could involve resettlement Entails new legal codes Excessive competition

Table 1: Advantages and disadvantages of renewable energy cont. (Gökmen and Temiz, 2015)

Advantages	Disadvantages
Improves air quality Preserves ecosystems Helps slow down climate change	

In order to make use of these advantages and to address the critical issues, countries have developed government policies and adopted respective regulations to ensure the production and use of renewable energy and promote the respective new investments. This has been realized both individually and also as a part of global organizations and networks such as the Organisation for Economic Co-operation and Development (OECD), European Union (EU), United Nations (UN) and IEA.

In the last decade, there has been a significant shift in the world toward emerging markets and consequently energy demand; in that, while the developed world used two thirds of world oil in 2000, by 2011 this was split about evenly between developed and developing countries (WEF, 2013). This shift is estimated to continue with virtually all growth from here on being expected in emerging market nations (WEF, 2013), and thus, the energy consumption and production in developing countries have become much more critical. Turkey is one of these developing countries with a substantial amount and wide range of renewable energy sources, and it is located in an advantageous geographical position that enables their effective utilization (Baris and Kucukali, 2012; Benli, 2013; Yuksel and Kaygusuz, 2011). However, because of the rapid increase in the energy consumption (Ozturk et al., 2009) and the inefficient use of resources, Turkey remains to be an energy importing country with more than half of its energy being met externally (Kaya, 2006; Yuksel and Kaygusuz, 2011; Benli, 2013). Figure 1 and Figure 2 clearly depict this situation.

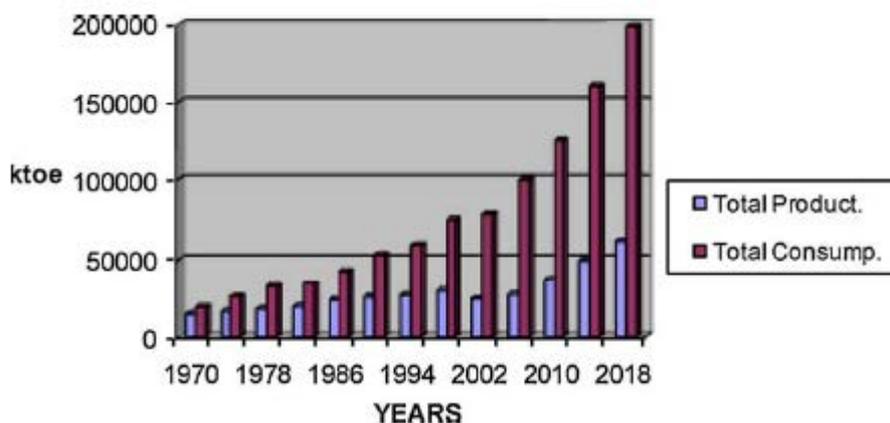
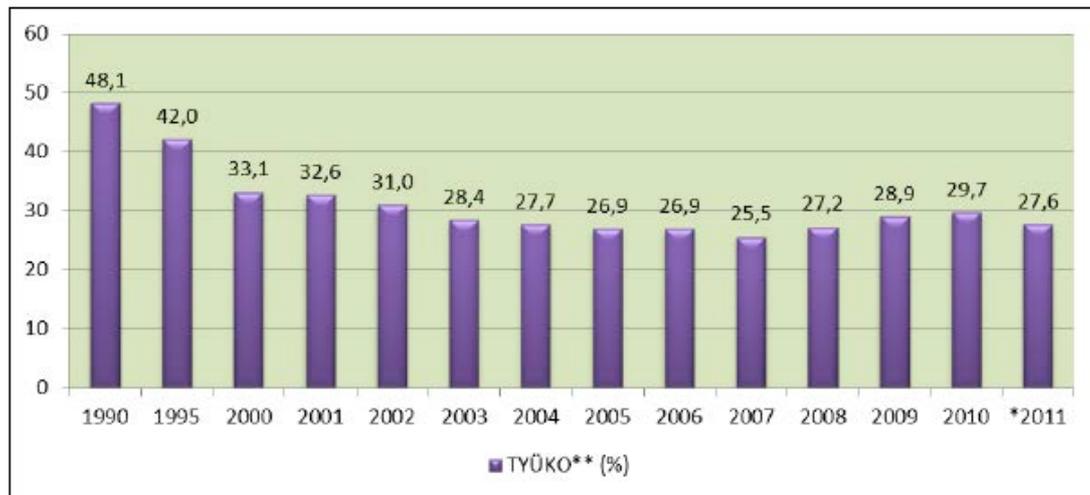


Figure 1: Total energy consumption and production in Turkey (Yuksel and Kaygusuz, 2011)



- An estimated value has been provided for 2011.

Figure 2: Percentage of energy demand met by indigenous production (MMO, 2012)

In order to form a general perspective on the energy situation in Turkey, the following numerical information has been provided (WWF-Türkiye, 2011; MMO, 2012):

- Turkey is Europe's 6<sup>th</sup> largest energy market,
- Projected annual growth of the electricity demand is 7%,
- Hydropower constitutes 98% of the renewable energy,
- In 2008, imported primary energy supply was 73%,
- In 2009, the energy generated from fossil fuels was 81%,
- As of 2009, the share of renewable energy in electricity generation was 19%,
- Between 2000 and 2010 Turkey's primary energy production has reached from 81.2 Mtoe to 109.3 Mtoe with an increase of 34.6%,
- In the period up to 2020, the annual average of Turkey's primary energy production is expected to increase by 4%,
- Between 2000 and 2010 Turkey's installed capacity of electricity has reached from 27,264 MW to 53,051 MW with an increase of 94.6%, and during the same period electricity consumption has reached from 128.3 billion kWh to 229.3 billion kWh with an increase of 78.8%.

The above-mentioned facts also prove that although there has been an increase in Turkey's primary energy production, this is far from meeting the accelerating demand. Thus, there is an urgent need to increase the quality, quantity and diversity of the renewable energy sources. This is only possible by effective renewable energy policies, which constitute a "highly complex policy subsystem that lies at the intersection between environmental policy, economic policy, and energy policy" (Yi and Feiock, 2014). Consequently, a detailed review and evaluation have been conducted in this study on the current literature, projects, binding regulations, incentives, and pricing mechanisms together with the respective energy statistics to analyze and compare the renewable energy policies in Turkey to those adopted worldwide. Ultimately, the goal is to make certain suggestions and lay out possible solutions regarding Turkey's energy problems. To this end, the second part of the study provides a comparative analysis of renewable energy use throughout the world. The third part summarizes the global energy policies under four headings, namely

those adopted in OECD countries, non-OECD countries, EU and Turkey. Finally, the possible solutions are suggested in the conclusions part.

### Comparative Analysis of the Renewable Energy Use around the World

This section provides a brief analysis on the comparison of renewable energy use in Turkey with Africa, Asia, China, Latin America, Middle East, OECD and World Total. The purpose is to lay out the current situation of renewable energy use in Turkey on a general basis and also by source. To this end, Figure 3 and Figure 4 depict the renewable energy use throughout the years 2006 and 2010 and the corresponding five year averages of specific renewable energy categories, respectively. The analysis in this section is from a previous study carried out by the authors, wherein the data was taken from OECD sources.

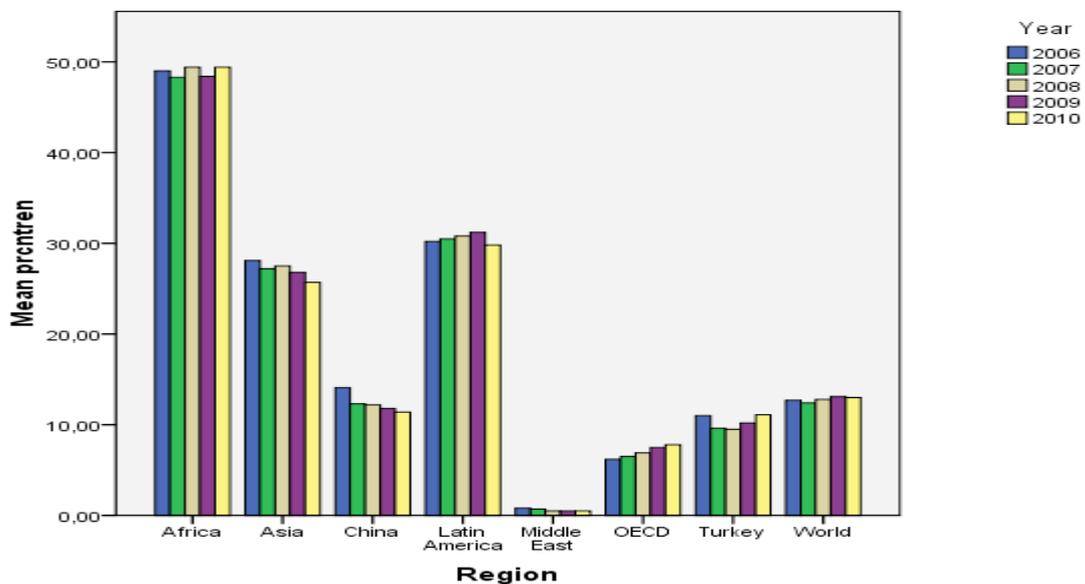


Figure 3: Renewable energy use throughout the world (Selam et al., 2014)

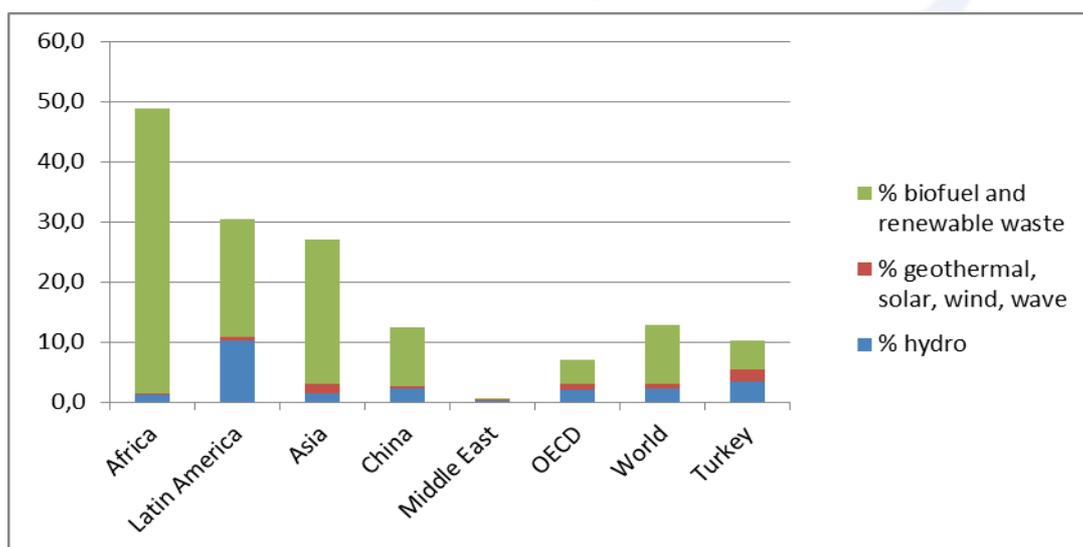


Figure 4: Worldwide Renewable Energy Use (five year averages by type) (Selam et al., 2014)

In Figure 3 and Figure 4, it can clearly be seen that the percentage of renewable energy use in Africa has reached up to 50%, which is significantly above the world average. This is due to the fact that mostly organic non-fossil fuels are used in African countries. The Middle East, which is the center of fossil fuels, is expectedly where renewable energy has the lowest share. As for the OECD countries, the renewable energy use is close to the world average with hydro; geothermal, solar, wind and wave; biofuels and renewable waste have almost equal shares. China has also caught up with the world average in terms of renewable energy use. As for Turkey, it approaches the world average in renewable energy use most of which is hydro, biofuels and waste. Selam et al. (2014) have also compared renewable energy use in Turkey with that of OECD and concluded that it is slightly above OECD Total, OECD Americas and OECD Asia Oceania and slightly below OECD Europe between the years 2006 and 2010. However, the renewable energy use excluding hydro is below the general average, which indicates that a significant amount of the energy production in Turkey is from hydroelectric sources. Considering the rich amount of renewable energy sources, it is clear that energy policies promoting the effective and efficient use of other renewable energy sources besides hydro are inevitable.

### **Energy Policies: Global and Turkish Perspectives**

In this section, the renewable energy policies of certain selected countries have briefly been summarized. This evaluation has been presented under the main headings of OECD and non-OECD countries, EU and Turkey. The EU has especially been included in the analysis because Turkey is in the accession process to the EU. Thus, the energy policies should be compatible with those of the EU member countries.

### **Renewable Energy Policies of OECD**

OECD has been established in 1961 with the aim of “promoting policies that will improve the economic and social well-being of people around the world” (OECD, 2014). Currently, there are 34 member countries spanning the globe, from North and South America to Europe and the Asia-Pacific region (OECD, 2014). Turkey is one of the founding members.

In 2010, 18% of the world population lived in the OECD with 74% of the world gross domestic product (GDP) being created in its 34 member countries. The TPES of the OECD in 2010 represented about 44% of global energy supply, while the total energy production constituted 30% of the global energy production (IEA, 2012a). Due to the reasons stated in Table 1, the OECD countries have adopted certain energy efficiency policies such that each government made its own decision regarding the measures to be taken and their implementation (Saidel and Alves, 2003). These measures fall under the following basic categories (Saidel and Alves, 2003):

- restrictive regulations,
- information to the public,
- creation of market asymmetries,
- funding/loans programs and
- state capital/private capital partnerships.

The evolution of the renewable energy policies in OECD countries can be viewed in Figure 5.

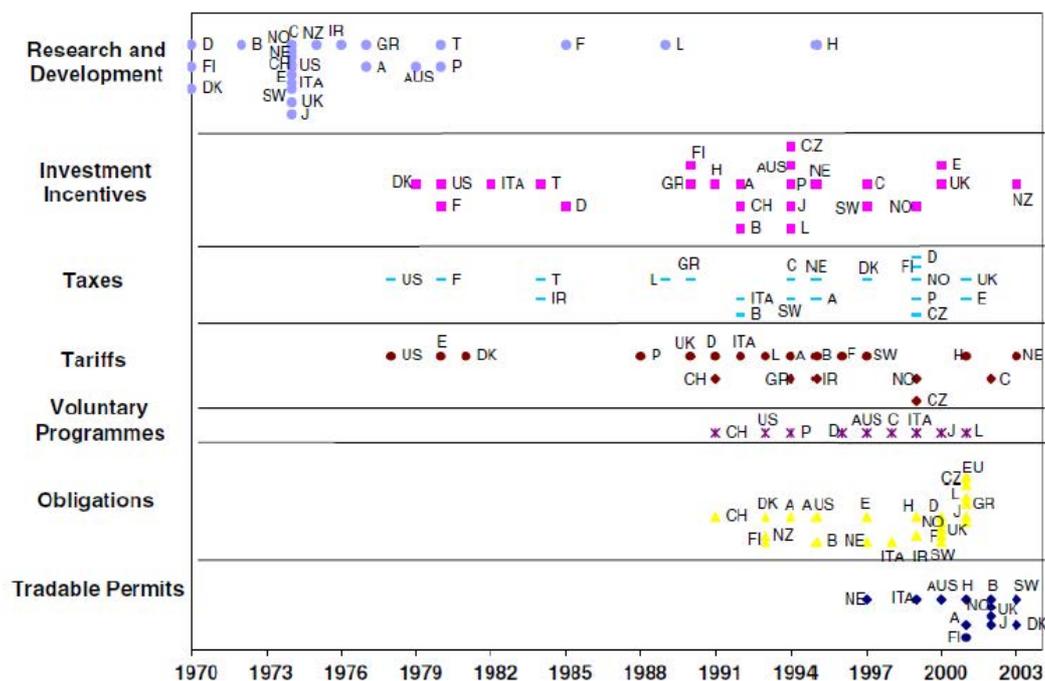


Figure 5: Patterns of policy adoption in selected OECD countries (Nicolli and Vona, 2012)

### Renewable energy policies of some non-OECD countries

In 2007, OECD decided to invite some countries like Chile, Israel and Russia to open discussions for the membership of the organization and offered “enhanced engagement” program to Brazil, China, India, Indonesia and South Africa (OECD, 2014).

China is world’s largest energy producer and emitter of greenhouse gases. Therefore, China focuses on efforts in energy conservation, efficiency in energy utilization and emission reduction. According to China’s Energy Policy Report (2012) some of these efforts can be summarized as the following:

- Various energy-saving renovations are implemented;
- Efforts have been made to support new and renewable energy developments;
- Improvements have been made in civil energy use conditions (energy service level, access to natural gas and electricity, combined heat and power projects etc.);
- Environmental protection has been increased.

The country’s energy consumption per-capita is low and decreasing every year. The energy consumption for every 10 000 yuan of GDP decreased by 20.7% from 2006 to 2011 (China's Energy Policy, 2012). China aims to increase the use of non-fossil fuels by developing new and renewable energy sources by the end of the 12<sup>th</sup> Five-Year Plan. It is the leading renewable energy producer in the world with the world’s richest hydropower resources, and currently less than 30% of its resources have been utilized

(Liu, 2013; China's Energy Policy, 2012). These resources can help China to achieve the goal of increasing the non-fossil energy consumption share to 15% by 2020. Chinese government wants to provide hydropower development by using local resources and local employment, obtaining local economic development and protecting local environment. China is also the fastest growing wind power market in the world (Hanna, 2010). Thus, the aim is to encourage R&D studies in wind-power equipment production, improve the standards and control in the sector, optimize the wind power production and develop offshore wind farms. China has rich solar energy resources too. During the 12<sup>th</sup> Five-Year Plan, China will promote and encourage the solar-power development with the construction of power stations, solar power generation projects, efforts to generalize solar heating, cooling, water heaters and industrial applications of solar energy. Another energy policy of China is to make nuclear power plants safer and more efficient (China's Energy Policy Report, 2012). Especially after the nuclear disaster in 2011, there have been comprehensive safety controls and inspections for nuclear power plants in China. Finally, studies have been conducted to benefit from the biomass potential in rural areas, which is also one of the primary sources of renewable energy (Meisen and Hawkins, 2014).

Russia has rich oil and coal reserves, but the depletion danger led the country to the development of the renewable energy sector. Russia has wind, hydro, solar, geothermal and biomass energy sources in various regions. Current discussions emphasize the need for decentralized and smaller projects to develop renewable energy. There are several reasons for the low level of renewable energy in Russia, some of which are as follows (Bächtold, 2012):

- Traditional energy sources are easily available with low costs in Russia.
- The government imposes high export duties to keep the energy prices low in the country's market. Any increase in energy prices can deteriorate the life conditions of the people because of the severe climate in Russia.
- Scarce government subsidies and tax incentives cause an inconsistent legal base.
- The awareness of the population about renewable energy is weak.

India faces an emerging supply-demand imbalance situation with the increases in total electricity demand, which resulted from the economy, life conditions, urbanization and energy access in the country (MNRE, 2011). Thus, renewable energy has become a necessity for India and establishing a sustainable energy base has gained significance since early 1970s. According to the report of Ministry of New and Renewable Energy in India (MNRE, 2011), MNRE is the only ministry in this area in the world. In addition to the implementation of various comprehensive programs, MNRE supports research and development of new and renewable energy technologies, products and services.

Brazil is one of the countries that make use renewable energy effectively. Some highlights regarding renewable energy in Brazil are listed as the following (IEA, 2012b):

- Brazil and the United States are the largest biofuel producers. Brazil also aims to be the largest exporter of biofuels (mainly ethanol) in the world.

- 37% of the road transport demand in Brazil is expected to be met by biofuels by 2035.
- One of the targets of the ten-year plan for energy expansion is for renewables to account nearly 80% of the total installed capacity in 2020. It is expected to be met by mainly hydropower followed by wind power and biomass.

### **Renewable energy policies of the EU**

Environmental concerns, supply security and competitiveness considerably affected the EU policies especially those related to the renewable energy sector, resulting in an effective renewable energy policy since 1997 (EWEA, 2011). The Renewable Energy Directive 2009/28/EC set forth a European framework for the promotion of renewable energy by 2020 through mandatory national renewable energy targets (EC, 2013a). Thus, the current policy of the EU for 2020 aims at 20% substitution of fossil fuels (coal, oil, gas and nuclear) by renewable energy resources that include biomass and waste, hydro-, geothermal-, solar-, and wind power (Krozer, 2013). The other targets for 2020 are greenhouse gas emission reductions of 20% relative to emissions in 1990 and 20% savings in energy consumption compared to projections (EC, 2013b). Consequently, 19.9% of the absolute European energy generation in the EU27 in 2009 was produced by renewables, with hydro-power taking the lead (11.6%), followed by wind (4.2%) (Fouquet, 2013).

Each member of the EU has decided on its own strategies to meet the above-stated energy targets and published these in Renewable Energy Action Plans (NREAP) between July 2010 and January 2011 as required by the EU (Directive 2009/28/EC) (Kitzing et al., 2012). The most common renewable energy sources (RES) support strategies implemented in the EU can be listed as the following (Kitzing et al., 2012):

- Feed-in tariffs; guaranteed prices (FIT)
- Feed-in premiums; production premiums (FIP)
- Tender schemes (TND)
- Quota obligations with tradeable green certificates (TGC)
- Investment grants (INV)
- Fiscal measures (tax incentives, etc.) (TAX)
- Financing support (loans, etc.) (FIN)

Recently, there have been efforts regarding an integrated policy framework for the period up to 2030 with the following targets (EC, 2014):

- reducing EU domestic greenhouse gas emissions by 40% below the 1990 level by 2030,
- increasing the share of renewable energy to at least 27% of the EU's energy consumption by 2030,
- realizing 30% energy savings,
- establishing a market stability reserve at the beginning of the next ETS (Emissions Trading System) trading period in 2021,
- developing a set of key indicators to assess progress over time and provide a factual basis for policy action as needed and

- establishing a new governance framework based on national plans for competitive, secure and sustainable energy.

### Renewable energy policies of Turkey

The energy consumption in Turkey is constantly increasing due to the economic growth, increasing population, migration from rural regions to urban and/or tourism Regions (Kotcioğlu, 2011), and thus, it is in a position to import over 70% of its primary energy supply (with oil and natural gas having the biggest shares) (Kaya and Kılıç, 2012). The renewable energy potential (hydropower, solar, biomass and wind power) is sufficient enough to overcome the energy dependency (Kotcioğlu, 2011), but it has not been efficiently utilized, leaving the country with an urgent need for effective energy policies. Figure 6 depicts the renewable energy supply and projections for the future in Turkey.

Renewable energy sources	2000	2005	2010	2015	2020
Primary energy supply					
Hydropower (ktoe)	2656	4067	4903	7060	9419
Geothermal, solar and wind (ktoe)	978	1683	2896	4242	6397
Biomass and waste (ktoe)	6457	5325	4416	4001	3925
Renewable energy production (ktoe)	10,091	11,074	12,215	15,303	19,741
Share of total domestic production (%)	38	48	33	29	30
Share of TPES (%)	12	12	10	9	9
Generation					
Hydropower (GWh)	30,879	47,287	57,009	82,095	109,524
Geothermal, solar and wind (GWh)	109	490	5274	7020	8766
Renewable energy generation (GWh)	30,988	47,777	62,283	89,115	118,290
Share of total generation (%)	25	29	26	25	25
Total final consumption					
Geothermal, solar and wind (ktoe)	910	1385	2145	3341	5346
Biomass and waste (ktoe)	6457	5325	4416	4001	3925
Renewable total consumption (ktoe)	7367	6710	6561	7342	9271
Share of total final consumption (%)	12	10	7	6	6

Figure 6: Renewable energy supply and projections for the future in Turkey (Toklu, 2013)

Recently, energy efficiency has become a significant issue in the government's agenda, and Energy Efficiency Strategy Paper has been published in February 2012 (IEA, 2013b). This strategy and the Energy Efficiency Law (2007) are examples of the actions taken to form a legal and institutional framework to support energy efficiency with a predicted amount of 40 300 toe (involving total government support of TRY 8 900 000) total energy savings between the years 2009 and 2013 (IEA, 2013b). Some of the other significant legislative milestones are summarized as follows (Simsek and Simsek, 2013; Bölük, 2013; PwC, 2012):

- Law No. 4283 (Law on Building and Operating of Electricity Generation Plants by BOT Model and Regulation of Energy Marketing), wherein the participation of the private sector in building and operating energy plants was accepted;
- Electricity Market Law No. 4628 and electricity market licensing regulation (2001) (amended by Law no: 5784 in 2008), encouraging electricity generation from renewable energy sources;
- Law on Utilization of Renewable Energy Resources for the Purpose of Generating Electrical Energy-No. 5346 (2005), with the aim of expanding the use of renewable energy used to generate electrical energy and to ensure an increase and diversification in the use of renewable energy without disturbing free market conditions [amended by Law Regarding the Amendment in the Law of Utilization of Renewable Energy Resources for the Purpose of Generating Electricity (Law no: 6094) in December 2010, establishing Turkey’s Renewable Energy Support (YEK) Mechanism];
- Law on Geothermal Resources and Natural Mineral waters-No. 5686 (2007), setting forth rules to protect and produce geothermal and natural mineral water resources;
- Strategy Plan 2010–2014 (2010), covering the period between 2010 and 2014, with the aim of ensuring that the share of renewable resources in electricity generation is increased by up to at least 30% by 2023; and
- Renewable Energy Law (2011), setting forth new incentives for renewable energy productions.

Figure 7 depicts the incentive mechanisms ruled out by the above-mentioned laws. Also, in order to make a comparison, the energy policies in the high income countries and those in the upper-middle income countries (including Turkey) can be viewed in Figure 8 and Figure 9, respectively.

Incentive Mechanism	Incentives	
Investment incentive	<u>Licensing</u> i) Installed capacity of 500 kW is exempted from licensing and setting up a company ii) Only 1 % of licensing cost is paid by corporate entities applied to get a license and these entities do not pay annual licensing cost for the first eight years. iii) Priority is ensured for system connection	
	<u>Land appropriation</u> i) Real properties either regarded as forest or private property of Treasury are leased or right of easement or usage permits are given to such properties ii) 85 % of discount is given to rent, right of easement and usage permits and Forest Villagers Development Revenue, Forestation and Erosion Control Revenues are not demanded during the first 10 years	
Feed-in Tariff	Government guarantees to buy electricity generated for 10 years offering a feed-in Tariff	
	Feed-in Tariff Amounts: USD \$ cent	
	Hydropower	7.3
	Wind Energy	7.3
	Geothermal	10.5
	Biomass	13.3
	Solar Radiation	13.3
Tax exemptions and cuts	Special consumption tax exemption is applied for 2% biodiesel blending.	
Premium	Premium is given for oil seeds.	

Figure 7: Incentive mechanisms ruled out by Law No:4628, 5346, 6094 and 4760 (Bölük, 2013)

	REGULATORY POLICIES AND TARGETS						FISCAL INCENTIVES				PUBLIC FINANCING	
	Renewable energy targets	Feed-in tariff/premium payment	Electric utility quota obligation/RPS	Net metering	Biofuels obligation/mandate	Heat obligation/mandate	Traded REC	Capital subsidy/grant, or rebate	Investment or production tax credits	Reductions in sales, energy, CO <sub>2</sub> , VAT, or other taxes	Energy production payment	Public investment loans, or grants
<b>HIGH INCOME COUNTRIES \$\$\$\$</b>												
Australia	●	○			○		●	●			●	
Austria	●	●			○		●	●			●	
Barbados	●			●							●	
Belgium	●		○	○	●		●	●			●	●
Canada	○	○	○	○	●		●	●	●		●	●
Croatia	●	●			●						●	
Cyprus	●	●			●		●				●	
Czech Republic	●	●			●		●	●		●	●	
Denmark	●	●		●	●		●	●		●	●	●
Estonia	●	●			●		●				●	
Finland	●	●			●		●			●	●	
France	●	●			●		●	●	●	●	●	●
Germany	●	●			●	●	●	●		●	●	●
Greece	●	●			●		●	●		●	●	
Hungary	●	●			●		●			●	●	
Ireland	●	●			●	○	●				●	●
Israel	●	●	●		●	●	●	●	●	●	●	●
Italy	●	●	●		●	●	●	●		●	●	●
Japan	●	●	●		●		●	●			●	
Luxembourg	●	●			●		●	●		●	●	
Malta	●	●		●			●	●		●	●	
Netherlands	●	●		●	●		●	●		●	●	
New Zealand	●				●		●			●	●	
Norway	●				●		●	●		●	●	
Oman							●	●		●	●	●
Poland	●		●		●		●	●		●	●	●
Portugal	●	●	●	●	●	●	●	●	●	●	●	●
Singapore	●			●							●	●
Slovakia	●	●					●			●		
Slovenia	●	●					●			●		●
South Korea	●		●	●	●	●	●	●	●	●	●	
Spain <sup>2</sup>	●	●		●	●	●	●	●	●	●	●	
Sweden	●		●		●		●	●	●	●	●	
Switzerland	●	●					●	●		●	●	
Trinidad and Tobago	●							●		●		
United Arab Emirates	○		○			○				○	○	○
United Kingdom	●	●	●		●	●	●	●	●	●	●	○
United States		○	○	○	●	○	○	●	●	●	●	●

Figure 8: Renewable Energy Support Policies (High Income Countries) (REN21, 2013)

The analysis of Figure 7, Figure 8 and Figure 9 clearly reveals that Turkey mostly has regulatory policies such feed-in tariff and biofuel obligations as opposed to some other countries (e.g. United States, China and the EU countries), where support tools including fiscal incentives (i.e. capital subsidy, grant or rebate, energy production payment) and public finances (i.e. public investment loans or grants and competitive public bidding) are also widely used to support renewable energy (PWC, 2012; Bölük, 2013).

	REGULATORY POLICIES AND TARGETS							FISCAL INCENTIVES				PUBLIC FINANCING	
	Renewable energy targets	Feed-in tariff/premium payment	Electric utility quota obligation/RPS	Net metering	Biofuels obligation/mandate	Heat obligation/mandate	Tradable REC	Capital subsidy grant, or rebate	Investment or production tax credits	Reductions in state, energy, CO <sub>2</sub> , VAT, or other taxes	Energy production payment	Public investments, loans, or grants	Public competitive bidding/tendering
<b>UPPER-MIDDLE INCOME COUNTRIES \$\$\$</b>													
Algeria	●	●										●	
Argentina	●	●			●			●	●	●	●	●	
Belarus										●			
Bosnia and Herzegovina	●	●						●				●	
Botswana	●							●		●			
Brazil	●			●	●	○		●		●	●	●	
Bulgaria	●	●			●			●		●	●	●	
Chile	●		●	●		●		●		●	●	●	
China	●	●	●		●	●		●		●	●	●	
Colombia	●				●					●			
Costa Rica	●			○									
Dominican Republic	●	●		●		●		●	●	●		●	
Ecuador		●								●	●		
Grenada	●			●						●			
Iran		●								●		●	
Jamaica	●			●	●				●			●	
Jordan	●	●		●	●					●	●	●	
Kazakhstan		●					●						
Latvia	●	●			●					●	●	●	
Lebanon	●			●		●				●	●		
Libya	●									●			
Lithuania	●	●	●		●	●					●		
Macedonia	●	●											
Malaysia	●	●	●		●					●	●	●	
Mauritius	●	●											
Mexico	●			●		●			●		●	●	
Montenegro	●	●											
Palau	●		●										
Panama		●		●				●		●	●	●	
Peru		●			●					●	●	●	
Romania	●		●		●		●			●	●		
Russia	●							●					
Serbia	●	●						●					
South Africa	●							●		●	●	●	
St. Lucia	●			●									
Thailand	●	●			●					●	●		
Tunisia	●			●				●		●	●		
Turkey	●	●			●			●			●	●	
Uruguay	●	●		●	●	●		●		●	●	●	

Figure 9: Renewable Energy Support Policies (Upper-Middle Income Countries) (REN21, 2013)

Ozturk et al. (2009) summarize Turkey’s energy policy as follows:

- Meeting long-term demand using public, private, and foreign capital,
- Accelerating privatization activities in the energy sector,
- Taking into consideration supply costs of energy imports,
- Meeting demand as much as possible through indigenous resources,
- Diversifying energy supplies and avoiding dependence on a single source or country,
- Adding new and renewable sources (geothermal heat, solar, wind, etc.) as soon as possible to the energy supply system,

- Ensuring sufficient, reliable and economic energy supplies on time,
- Ensuring energy security of supply,
- Implementing measures for energy efficiency,
- Planning energy research and development activities to meet requirements,
- Minimizing losses in energy production, transmission, distribution and consumption and
- Protecting the environment and public health in the production of energy.

The above-stated principles are also covered in the Strategy Plan 2010-2014, where the following targets are set for 2023-the 100<sup>th</sup> anniversary of Turkish Republic (the Vision 2023 Programme) (Kabakçı and Tanuğur, 2010; Yarbay et al., 2011; Erdal, 2012):

- To be able to make complete use of potential of indigenous coal and hydraulic resources,
- To make maximum use of renewable resources and increase their share to 30%,
- To incorporate nuclear energy into electricity generation within the period until 2020 and
- To secure rapid and continuous improvement in energy efficiency in a way that parallels EU countries.

In order to make maximum use of renewable resources as stated in the Strategic Plan, all the potential renewable energy types should be utilized. Renewable energy supply in Turkey is mostly hydropower and biomass, but air pollution concerns and deforestation have resulted in a decrease in the biomass use, changing the composition of the renewable energy supply in favor of wind energy (Kotcioğlu, 2011; Toklu, 2013). There is a significant potential for wind power development in Turkey (Kotcioğlu, 2011), which should effectively be utilized in the near future due to the fact that between 22.5TWh and 4 5.0TWh of electricity must be generated from renewable energy sources other than hydropower in the next decade to fill the demand gap (Melikoglu, 2013). It is estimated that this gap can be diminished by wind and solar energy if the investments are carried out as planned and the goals in Vision 2023 agenda can be achieved (Melikoglu, 2013). Consequently, the following causes of failure should be overcome for the renewable energy projects to be successful (Bezir et al., 2009):

- In many renewable energy projects, premature technologies which were still under research were used.
- The design of many projects did not allow sufficient, long-term maintenance.
- Many renewable energy projects were either demonstration projects, or for other reasons not replicated.
- Renewable energy technologies are often simply too expensive to be used in Turkey, where financial resources are limited.
- There is a lack of detailed renewable energy resource assessments and databanks particular to Turkey (Simsek and Simsek, 2013).
- Turkish bureaucracy is an important handicap for foreign investors (Toklu, 2013).

In its report on Turkish Renewable Energy Policies, IEA has made certain recommendations, which should be taken into consideration to address the above-stated issues. These are (IEA, 2009):

- Continue efforts to ensure a predictable and transparent support framework to attract investments, while creating technology-specific incentives that will decrease over time.
- Design the feed-in tariff to be as flexible and predictable as possible and assess the options to introduce further flexibility in support mechanisms, such as premium on wholesale price.
- Continue efforts to ensure smooth integration of new renewable electricity capacity into the grid.
- Continue efforts to remove non-economic barriers to renewable energy development.
- Consider stronger policy support for the wider use of solar and geothermal heat and biofuels for transport in a sustainable and cost-effective way.
- Expand the partnerships with the private sector through increased use of collaboration for energy R&D.

## Conclusions

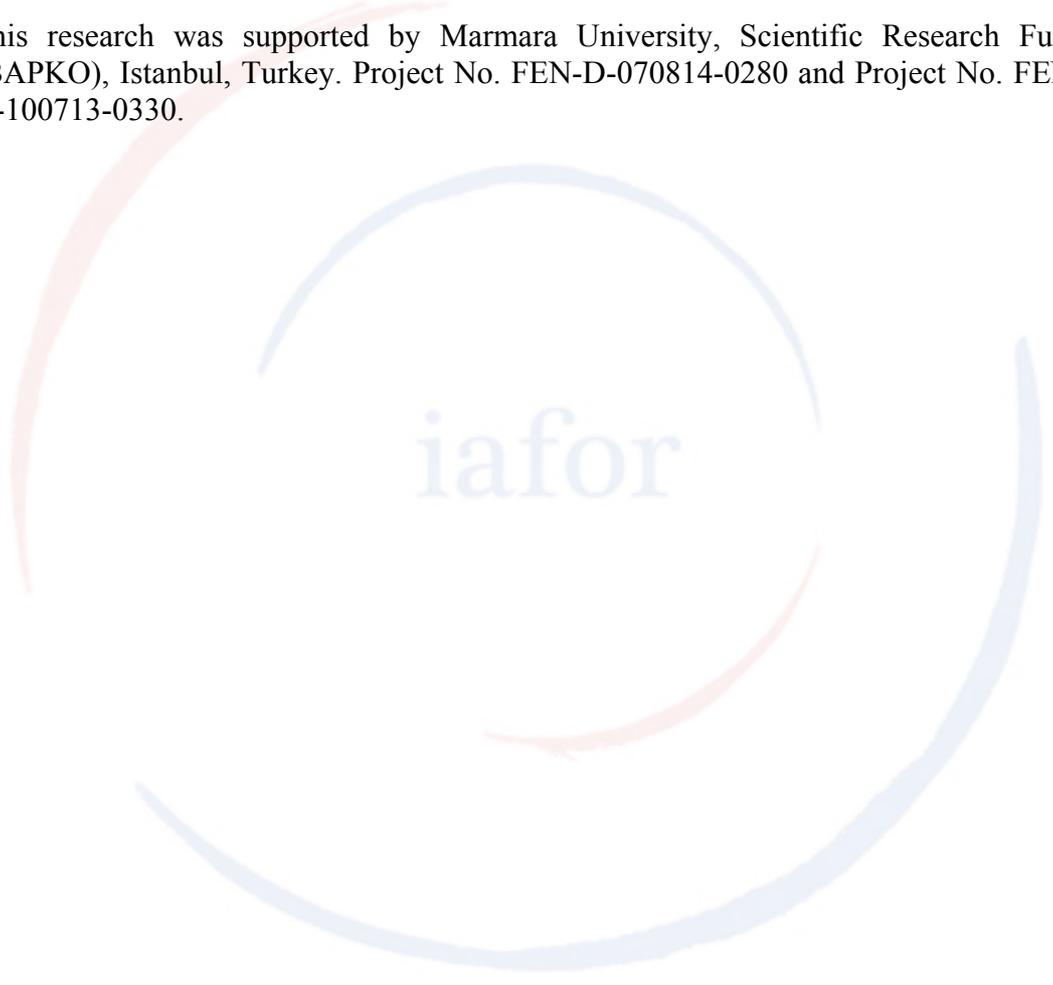
Turkey is a developing country with a substantial amount and wide range of renewable energy sources, but because of the rapid increase in the energy consumption and the inefficient use of resources, it remains to be an energy importing country with more than half of its energy being met externally. Thus, there is an urgent need for effective energy policies. To this end, a detailed review and evaluation has been conducted in this study on the current literature, projects, binding regulations, incentives, and pricing mechanisms together with the respective energy statistics to analyze and compare the renewable energy policies in Turkey with those adopted worldwide. As a result, the following suggestions and possible solutions have been reached:

- Binding legislation should be developed and taken into effect for all sources of renewable energy (as opposed to the current situation of the sole coverage of wind and geothermal in regulations).
- Licensed investments have to be finalized as soon as possible.
- Nuclear power plants should not be seen as a solution. (Due to the absence of basic laws, the lack of technical knowledge and experience etc.)
- R&D and technology investments should be valued (especially for converting energy resources into utilizable energy or into energy).
- Renewable energy investments should be supported by effective economic incentives.
- The necessary actions should be taken (such as the acceleration of exploration activities) for the utilization of geothermal energy potential.
- Development of regional renewable energy-related projects should be promoted as well as global ones and international collaborative efforts should be supported.
- Partnerships with the private sector should be expanded through increased use of public-private partnerships for energy R&D.

- Financial competitiveness of renewable energy sources must be enhanced.
- Simultaneous growth of renewable energy sources should be realized.
- The administrative process should be facilitated and technical difficulties should be removed for the efficient grid connection of these sources.
- The bureaucratic difficulties should be addressed to increase foreign investments.
- At the present the most significant renewable energy sources are biomass and hydropower in Turkey; however, this is expected to change in favor of solar and wind energy due to environmental concerns and resource scarcity.

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## References

- Apergis, N., Payne, J.E. (2010). Renewable energy consumption and economic growth: Evidence from a panel of OECD countries. *Energy Policy*, 38, 656-660.
- Baris, K., Kucukali, S. (2012). Availability of renewable energy sources in Turkey: Current situation, potential, government policies and the EU perspective. *Energy Policy*, 42, 377-391.
- Bächtold, J. (2012). Russia-Renewable Energy. Swiss Business Hub Russia. [http://www.s-ge.com/suisse/export/fr/filefield-private/files/53139/field\\_blog\\_public\\_files/14171](http://www.s-ge.com/suisse/export/fr/filefield-private/files/53139/field_blog_public_files/14171), Moscow (02.10.2014)
- Benli, H. (2013). Potential of renewable energy in electrical energy production and sustainable energy development of Turkey: Performance and policies. *Renewable Energy*, 50, 33-46.
- Bölük, G. (2013). Renewable Energy: Policy Issues and Economic Implications in Turkey. *International Journal of Energy Economics and Policy*, 3, 153-167.
- China's Energy Policy (2012). China's Energy Policy 2012. [http://www.gov.cn/english/official/2012-10/24/content\\_2250497.htm](http://www.gov.cn/english/official/2012-10/24/content_2250497.htm) (06.10.2014).
- Bezir, Ç.N., Öztürk, M., Özek, N. (2009). Renewable energy market conditions and barriers in Turkey. *Renewable and Sustainable Energy Reviews*, 13, 1428-1436.
- EC (European Commission) (2013a). Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - Renewable Energy Progress Report. Brussels:EC.
- EC (European Commission) (2013b). Green Paper - 2030 framework for climate and energy policies. Brussels:EC.
- EC (European Commission) (2014). [http://ec.europa.eu/clima/policies/2030/index\\_en.htm](http://ec.europa.eu/clima/policies/2030/index_en.htm) (12.10.2014).
- EIA (U.S. Energy Information Administration Office) (2012). Annual Energy Outlook 2012 with Projections to 2035. [www.eia.gov/forecasts/aeo](http://www.eia.gov/forecasts/aeo) (02.04.2013).
- Erdal, L. (2012). Renewable Energy Investments and Potential for Green Jobs in Turkey. *Sosyal ve Beşeri Bilimler Dergisi*, 4, 171-181.
- EWEA (The European Wind Energy Association) (2011). EU Energy Policy to 2050-Achieving 80-95% emissions reductions. Brussels: EWEA.
- Fouquet, D. (2013). Policy instruments for renewable energy - From a European perspective. *Renewable Energy*, 49, 15-18.
- Gökmen, A., Temiz, D. (2015). The Importance and Impact of Fossil and Renewable

Energy Sources in Turkey on Business and the Economy. *Energy Sources, Part B: Economics, Planning, and Policy*, 10, 14-20, DOI: 10.1080/15567249.2010.497795.

Hanna, N. (2010). *Investing in Wind Power: A concise guide to the technologies and companies for investors*. Great Britain: Harriman House Ltd.

IEA (International Energy Agency) (2009). *Energy Policies of IEA Countries - Turkey 2009 Review*. Paris: IEA.

IEA (International Energy Agency) (2012a). *Energy Balances of OECD Countries - IEA Statistics*. Paris: IEA.

IEA (International Energy Agency) (2012b). *World Energy Outlook 2012*. Paris: IEA.

IEA (International Energy Agency) (2013a). *Renewables Information - IEA Statistics*. Paris: IEA.

IEA (International Energy Agency) (2013b). *Energy Policy Highlights*. Paris: IEA.

Kabakci, S.B., Tanugur, Y. (2010). Waste in the Renewable Energy Legislations of European Union, United States and Turkey. In: 10<sup>th</sup> International Conference on Clean Energy (ICCE), September 15-17, East Mediterranean University and University of Miami, Farnagusta, North Cyprus.

Kaya, D. (2006). Renewable energy policies in Turkey. *Renewable and Sustainable Energy Reviews*, 10, 152-163.

Kaya, D., Çanka Kılıç, F. (2012). Renewable Energies and Their Subsidies in Turkey and some EU countries- Germany as a Special Example. *J. Int. Environmental Application & Science*, 7, 114-127.

Kitzing, L. Mitchell, C. Morthorst, P.E. (2012). Renewable energy policies in Europe: Converging or diverging? *Energy Policy*, 51, 192-201.

Komor, P., Bazilian, M. (2005). Renewable energy policy goals, programs, and technologies. *Energy Policy*, 33, 1873-1881.

Kotcioğlu, İ. (2011). Clean and sustainable energy policies in Turkey. *Renewable and Sustainable Energy Reviews*, 15, 5111-5119.

Krozer, Y. (2013). Cost and benefit of renewable energy in the European Union. *Renewable Energy*, 50, 68-73.

Liu, Z. (2013). *Electric Power and Energy in China*. Singapore: Wiley.

Meisen, P., Hawkins, S. (2014). *Renewable Energy Potential of China: Making the Transition from Coal-Fired Generation*. Global Energy Network Institute (GENI). <http://www.geni.org/globalenergy/research/renewable-energy-potential-in-china/Renewable%20Energy%20Potential%20in%20China.pdf> (06.10.2014).

Melikoglu, M. (2013). Hydropower in Turkey: Analysis in the view of Vision 2023. *Renewable and Sustainable Energy Reviews*, 25, 503-510.

MMO (2012). Türkiye'nin Enerji Görünümü. TMMOB Makine Mühendisleri Odası Raporu (MMO/588) (Genişletilmiş İkinci Baskı). Ankara: MMO.  
[http://www.mmo.org.tr/resimler/dosya\\_ekler/dd924b618b4d692\\_ek.pdf](http://www.mmo.org.tr/resimler/dosya_ekler/dd924b618b4d692_ek.pdf) (01.05.2013).

MNRE (Ministry of New and Renewable Energy, Government of India) (2011). Strategic Plan for New and Renewable Energy Sector for the Period 2011-17. [http://mnre.gov.in/file-manager/UserFiles/strategic\\_plan\\_mnre\\_2011\\_17.pdf](http://mnre.gov.in/file-manager/UserFiles/strategic_plan_mnre_2011_17.pdf) (06.10.2014).

Nicolli, F., Vona, F. (2012). The Evolution of Renewable Energy Policy in OECD Countries: Aggregate Indicators and Determinants. <https://ideas.repec.org/p/fce/doctra/1213.html> (01.10.2014).

OECD (The Organisation for Economic Co-operation and Development) (2014). Members and Partners, <http://www.oecd.org/about/membersandpartners> (06.10.2014).

Ozturk, M., Bezir, N.C., Ozek, N. (2009). Hydropower–water and renewable energy in Turkey: Sources and policy. *Renewable and Sustainable Energy Reviews*, 13, 605-615.

PwC (PricewaterhouseCoopers) (2012). Turkey's Renewable Energy Sector from a Global Perspective. [https://www.pwc.com.tr/tr\\_TR/tr/publications/industrial/energy/assets/Renewable-report-11-April-2012.pdf](https://www.pwc.com.tr/tr_TR/tr/publications/industrial/energy/assets/Renewable-report-11-April-2012.pdf) (12.08.2014).

REN21 (Renewable Energy Policy Network for the 21<sup>st</sup> Century) (2013). Renewables 2013 Global Status Report. [http://www.ren21.net/portals/0/documents/resources/gsr/2013/gsr2013\\_lowres.pdf](http://www.ren21.net/portals/0/documents/resources/gsr/2013/gsr2013_lowres.pdf) (05.02.2014).

Saidel, M.A., Alves, S.S. (2003). Energy efficiency policies in the OECD countries. *Applied Energy*, 76, 123-134.

Selam, A.A., Özel, S., Arnoğlu Akan, M.Ö. (2014). Turkey's Position Among the OECD Countries Within the Context of Renewable Energy Utilization. *Dumlupınar University Journal of Social Sciences EYI 2013 Special Issue*, 317-334.

Simsek, H.A., Simsek, N. (2013). Recent incentives for renewable energy in Turkey. *Energy Policy*, 63, 521-530.

Toklu, E. (2013). Overview of potential and utilization of renewable energy sources in Turkey. *Renewable Energy*, 50, 456-463.

WEF (World Economic Forum) (2013). Energy Vision 2013 Energy Transitions: Past and Future. Geneva: WEF.

WWF-Türkiye (World Wide Fund for Nature-Türkiye) (2011). Yenilenebilir Enerji Geleceği ve Türkiye. WWF Rapor, <http://www.yesilekonomi.com/files/yenilenebilir-enerji-gelecegi-turkiye.pdf> (12.04.2013).

Yarbay, R.Z., Güler, A.Ş., Yaman, E. (2011). Renewable Energy Sources and Policies in Turkey. In: Proceedings of the 6<sup>th</sup> International Advanced Technologies Symposium (IATS'11), May 16-18, Elazığ, Turkey, 185-190.

Yi, H., Feiock, R.C. (2014). Renewable Energy Politics: Policy Typologies, Policy Tools, and State Deployment of Renewables. The Policy Studies Journal, 42, 391-415.

Yuksel, I., Kaygusuz, K. (2011). Renewable energy sources for clean and sustainable energy policies in Turkey. Renewable and Sustainable Energy Reviews, 15, 4132-4144.

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*An Evaluation of Renewable Energy Indicators  
within the Sustainability Framework*

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The North American Conference on Sustainability, Energy & the Environment 2014  
Official Conference Proceedings

**Abstract**

Environmental concerns such as security of available resources, global warming, greenhouse effect, Carbon and Nitrogen emissions force governments to take preventive actions and make restrictive regulations. One way to provide a clean environment for the future generations is to promote the usage of renewable energy sources and development of renewable energy technologies. In this perspective the researchers used different methods and indicators to evaluate governments and their policies on renewable energy.

In this study, a two-phased taxonomy framework is designed to evaluate renewable energy. The framework has two dimensions; these are general and sustainability dimensions, respectively. For the general dimension three properties are defined, which are global, economic and usage. Sustainability dimension has its own well-known aspects which are environmental, economical and social ones. Each indicator provided from the literature is classified by two properties from each dimension, providing six indicator types. The literature is surveyed with this point of view and a two-phased framework for the indicators that are used evaluate renewable energy is proposed. It is seen that some of these indicators can be easily reached from organizations (OECD, IEA, World Bank, etc.) statistical data, where as some are computed by using these data.

This framework and indicators hereby are presented to provide a basis for researchers who aim to evaluate renewable energy usage. The proposed framework constitutes initial step of an ongoing research project to classify the world countries in the context of renewable energy approach by using data mining techniques.

Keywords: Renewable Energy, Sustainability, Energy Taxonomy, Literature Survey

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## Introduction

Environmental concerns such as security of available resources, global warming, greenhouse effects, Carbon and Nitrogen emissions force governments to take preventive actions and make restrictive regulations. One way to provide a clean environment for the future generations is to promote the usage of renewable energy sources and development of renewable energy technologies. Long-term initiatives are also a source of motivation for governments to use renewable energy. Energy and oil price volatility makes it difficult to make investment decisions for them. Because energy is a fundamental economic input – for transportation, agriculture, industry and other sectors, low energy prices decrease production costs. Countries are also being exposed to economic and political changes outside the country borders (price hikes, supply shortages) because of dependency on foreign energy sources and security of energy supply.

Sustainability is defined as meeting the needs of the present without compromising the ability of future generations to meet their own needs (Our Common Future, 1987). One interpretation of that definition, in the context of electricity, is to transition away from fossil fuels entirely – due to their carbon emissions and their finite supply (Komor & Bazilian, 2005). Kyoto carbon targets are important in for governments and they intend to reduce their carbon emissions. It is known that over one-third of the greenhouse gas reduction opportunities are identified in the electricity production sector (IEA, 2003). Fossil fuel burning emits various compounds such as SO<sub>x</sub> and NO<sub>x</sub> that contribute to local and regional air quality problems (Komor & Bazilian, 2005).

In this perspective the researchers used different methods and indicators to evaluate governments and their policies on renewable energy. Some methods used in evaluation of renewable energy are:

- DEA (Chien & Hu, 2007, Wang et al., 2012),
- Granger causality tests (Jinke et al., 2008; Apergis & Payne, 2010; Nazlioglu et al., 2011),
- Empirical studies, interviews (Hirschl, 2009; Martins & Pereira, 2011; Nagy & Körmendi, 2012),
- General evaluations (Valentine, 2011; Baris & Kucukali, 2012),
- Other (Liddle, 2012; Reuter et al, 2012), etc.

## Renewable Energy and Sustainability

The definition below is given for Renewable Energy and Sources by The Renewable Energy Working Party of the International Energy Agency (OECD/IEA, 2012).

*“Renewable Energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly or indirectly from the sun, or from heat generated deep within the earth. Included in the definition is energy generated from solar, wind, biofuels, geothermal, hydropower and ocean resources, and biofuels and hydrogen derived from renewable resources.”*

The renewable energy sources are classified by OECD with the given definitions:

**“Hydroelectricity:** Hydroelectricity refers to potential and kinetic energy of water converted into electricity in hydroelectric plants.

**Geothermal:** Energy available as heat emitted from within the earth's crust, usually in the form of hot water or steam. It is used for electricity generation, heat production for sale to third parties or directly as heat in its primary form.

**Solar energy:** Solar radiation exploited for electricity generation and hot water production. Passive solar energy for direct heating, cooling or lighting of dwellings or other buildings is not included.

**Tide / wave / ocean:** Mechanical energy derived from tidal movement, wave motion or ocean current and exploited for electricity generation.

**Wind:** Kinetic energy of wind exploited for electricity generation by wind turbines.

**Biofuels and Renewable Waste:** Includes solid biofuels, biogases, liquid biofuels, and the renewable portion of municipal waste.”

Energy sector was one of the first in using the term “sustainable development” in order to turn the related economic activity into green energy (Sheinbaum-Pardo, 2012). According to “Annual Energy Outlook 2012 with Projections to 2035” which is published by U.S. Energy Information Administration Office, (2012) renewable energy is the fastest growing source of marketed energy. While the fossil fuels share in electricity production is increased between 3% and 4%, the renewable energy share is increased from 10% to 15% in 2010 (Annual Energy Outlook, 2012).

In order to maintain economic growth and provide economic opportunity to citizens which are a vital role of governments, economic sectors such as energy have a significant public sector presence (Komor & Bazilian, 2005). Apart from the recent escalation in energy prices, the dependency on foreign energy sources for petroleum, global climate change, and carbon emissions, government policies (such as renewable energy production tax credits, rebates for the installation of renewable energy systems, renewable energy portfolio standards, and the establishment of markets for renewable energy certificates by various states) has also critical effects on the increasing growth of renewable energy (Bowden & Payne, 2010).

There are a vast range of potential renewable energy programs, ranging from low-cost, low-intervention education programs; to regulatory-based and high intervention forced investments, and many ways to classify renewable energy programs, including demand versus supply, regulatory versus incentive-based, by degree of market intervention, etc (Komor & Bazilian, 2005). In Figure 1 Renewable Energy Goals, Programs, and Technologies for Ireland can be found. There is various programs to promote the usage and development of renewable energy. Strategic Assessment Framework for the Implementation of Rational Energy (SAFIRE) computer model devised by Energy for Sustainable Development Ltd (ESD, UK) was one of them which elaborates development scenarios for renewable energy calculate their financial, environmental and social implications (Oniszk-Popawska et al, 2003).

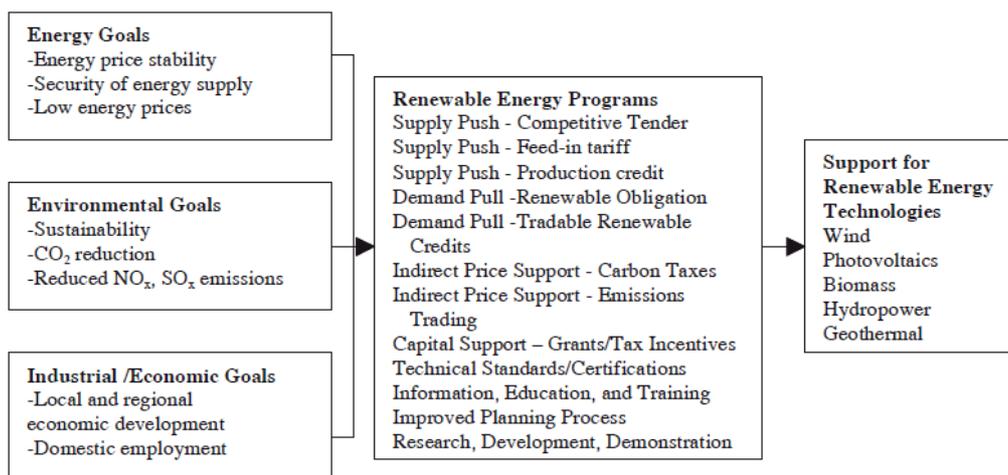


Figure 1. Ireland Renewable Energy Goals, Programs, and Technologies (Komor & Bazilian, 2005)

Owing to the significance of renewable energy around the world, International Energy Agency and OECD, measures the usage of energy and share of renewables annually (Selam et al., 2014). In Figure 2 renewable energy shares for Africa, Asia, China, Latin America, Middle East, OECD countries, Turkey and the World is given for years between 2006 and 2010.

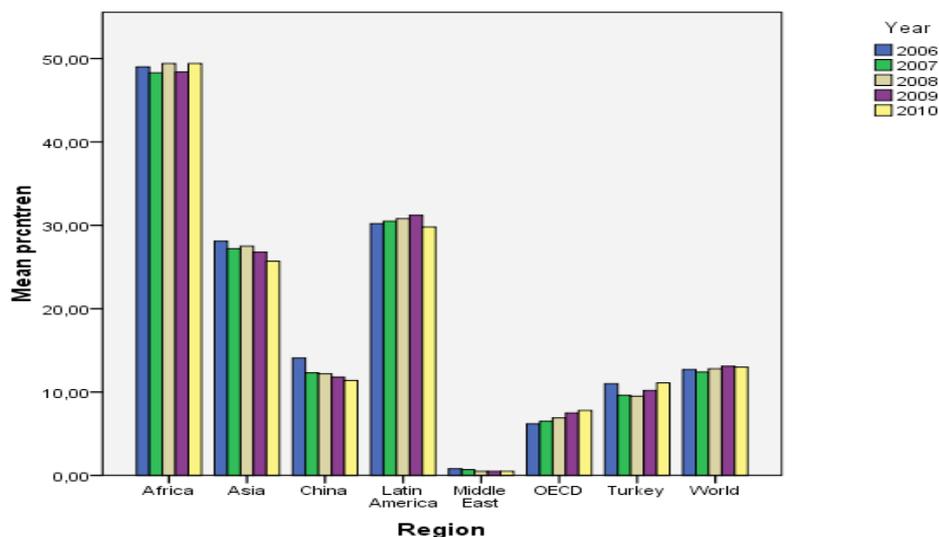


Figure 2. Renewable Energy Share for the World and some important regions (%) (Selam et al., 2014)

Besides, renewable energy is measured with three main categories which are hydro; geothermal, solar, wind, ocean, and tide; biofuels, and renewable waste, respectively. In Table 1 renewable energy usage percentages can be found according to average share of main categories between years 2006 and 2010.

Table 1. Average Renewable Energy Usage for the World and some important regions (%) (Selam et al, 2014)

Region	% Renewable	% Hydro Share	% Geothermal, Solar, Wind Tide & Ocean Share	% Biofuels and Renewable Waste Share
Africa	48,9	1,3	0,2	47,4
Latin America	30,5	10,3	0,5	19,7
Asia	27,1	1,5	1,6	24,0
China	12,4	2,3	0,4	9,7
Middle East	0,6	0,2	0,2	0,2
OECD	7,0	2,1	1,0	3,9
World	12,8	2,3	0,7	9,8
Turkey	10,3	3,5	1,9	4,9

### Indicator Taxonomy and Selection

In this study, a two-phased taxonomy framework is designed to evaluate renewable energy. The framework has two dimensions; these are general and sustainability dimensions, respectively. For the general dimension three properties are defined, which are global, economic and usage. Sustainability dimension has its own well-known aspects which are environmental, economical and social ones (Sheinbaum-Pardo et al., 2012).

The indicators hereby have been selected from a variety of articles about renewable energy evaluation. The most frequent and accessible indicators are selected among each group. For the second selection process brainstorming activities and debates have been held among the researchers. The list is eliminated and 14 final indicators have been determined.

Each indicator provided from the literature is classified by two properties from each dimension, providing six indicator types. The literature is surveyed with this point of view and a two-phased framework for the indicators that are used evaluate renewable energy is proposed. The indicator taxonomy under this framework is given in Table 2.

It is seen that some of these indicators can be easily reached from organizations (OECD, IEA, World Bank, Eurostat, World Energy Council etc.) statistical data, where as some are computed by using these data. Data is collected and published yearly for world countries under certain classifications by such organizations.

Table 2. Indicator Taxonomy

General Dimension	Sustainability Dimension
Global	Environmental
Economic	Economic
Usage	Social

## Energy Indicators

The general information, unit and definition about the selected indicators are referred from the World Bank, World Development Indicators (2014). Apart from that information, literature is surveyed with the aim of analyzing how the selected indicators are used for energy and sustainability evaluation.

The Total Primary Energy Supply (TPES) is the most frequent and basic indicator used to evaluate energy among researchers. This value is calculated by  $TPES = \text{Indigenous production} + \text{imports} - \text{exports} - \text{international marine bunkers} - \text{international aviation bunkers} \pm \text{stock changes}$  (World Bank, 2014). In other words, this value provides a country's energy usage. Geller et al., (2006), used TPES in the form of "TPES/GDP" to evaluate OECD energy intensity trends. Similarly, Liddle (2012) used TPES in the same form for the econometrics of endogenous structural breaks to examine changes in energy intensity trends in OECD countries over 1960-2009.

The next two indicators, "of which renewables" and "share of renewables in TPES" are related. The former is the Mtoe value of primary energy supply which is obtained by renewable energy, and the latter is the percentage of it in TPES. Renewable energy is used as a variable to estimate the Technical Efficiency Score of OECD and non-OECD countries in regression analysis (Chien & Hu, 2007). In a study to examine the relationship between renewable energy consumption and economic growth, Apergis and Payne (2010) used Granger Causality Tests for growth for a panel of twenty OECD countries over the period 1985-2005. They also conducted the same test for 6 Central American countries over 1980-2006.

In more detailed researches share of main fuel categories in total renewables are investigated. These categories are hydro; geothermal, solar, wind, tide; biofuels and renewable waste as a percentage of renewable energy. In a prior study the importance of renewable energy is mentioned for the entry of Poland to European Union (Wohlgemutha & Wojtkowska-Lodej, 2003).

Share of hydro fuel in renewable energy and share of geothermal, solar, tide and wind (GSTW) fuel in renewable energy are two other variables in Chien and Hu's (2007) article where Technical Efficiency Score is estimated. Renewable energy sources are used to analyze the Mexican energy policy with the methodological framework for sustainable energy development (Sheinbaum-Pardo et al., 2012). This methodology is proposed by the Economic Commission for Latin America and the Caribbean and takes renewable energy sources as a general sustainability indicator for the energy sector (Sheinbaum-Pardo et al., 2012).

The two other vital energy sources are natural gas and nuclear energy. Both of the indicators are given in the form of % in TPES. In 2010, world Total Primary Energy Supply (TPES) was 12 782 Mtoe, of which 13,0%, or 1 657 Mtoe, was produced from renewable energy sources (Renewables, 2012). The shares of other energy sources were as follows: 32,2% oil, 27,3% coal, 21,6% natural gas and 5,6% nuclear energy (Renewables, 2012). In this context, natural gas is being used more than renewable energy and nuclear is nearly used as half percent of renewable energy.

Two important indicators in energy evaluation are electricity production; total and from renewable resources. The most commercial type of electricity production mostly relies on rotating turbines attached to electrical generators. It is a continuous process of generating electric power from various renewable and nonrenewable energy sources. Nonrenewable energy sources include coal, oil, gas, nuclear power which raise environmental concerns. On the other hand, hydropower, geothermal, solar, wind, tide, biomass and biofuels are considered as clean, sustainable and renewable energy sources. Wohlgemutha & Wojtkowska-Lodej (2003) studied on electricity industry restructuring approaches employed in the European Union and Poland with a focus on the promotion of the use of renewable-energy sources for electricity generation. In another study, Baris and Kucukali (2012) examined the availability and potential of renewable energy sources in Turkey and assessed government policies, financial and environmental aspects utilizing electricity production and renewable energy sources as significant parameters.

PPP, GDP is gross domestic product converted to international dollars using purchasing power parity rates (World Bank, 2014). In the study of Chien and Hu (2007), GDP is used as an output variable of DEA where they aimed to analyze the effects of renewable energy on the technical efficiency of 45 economies. Apergis and Payne (2011) also used GDP while conducting Granger Casualty Tests to analyse the relationship between renewable energy consumption and economic growth for OECD countries over the period 1985-2005.

Population is one of the development indicators among the world. Instead of separately, population can be used calculate ratios with some other indicators. Labor force participation rate is the proportion of the population ages of 15 and older which is economically active: all people who supply labor for the production of goods and services during a specified period (World Bank, 2014). Capital and labor force are used as the control variables for the panel of fourteen OECD countries during the period 1980-2007 in the empirical model to determine the direction causality between nuclear energy consumption and economic growth in OECD countries (Nazlioglu et al., 2011). Apergis and Payne (2011) have also used labor force in their article when conducting Granger Causality Tests. Labor force has also been a variable to estimate Technical Efficiency Scores in Chien and Hu's (2007) research.

Most of the literature on renewable energy includes carbon dioxide emissions (CO<sub>2</sub>). World Bank (2014) defines CO<sub>2</sub> emissions as follows: "Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring." In this study CO<sub>2</sub> emissions are taken as kg per 2011 PPP \$ of GDP.

One of the principal environmental goals of Ireland is to reduce carbon emissions and other atmospheric pollutants such as NO<sub>x</sub> and SO<sub>x</sub> and encourage "emission free" renewable energy generation (Komor & Bazilian, 2005). Especially, electricity production sector focus on CO<sub>2</sub> emissions to mitigate climate change (Komor & Bazilian, 2005). According to Jinke et al. (2008) the world energy economy is carbon based and CO<sub>2</sub> emission is obviously linked to economic growth. Also Jinke et al. (2008) suggest the major OECD or non-OECD countries (especially China, India and South Africa) to make efforts to reduce their CO<sub>2</sub> emissions resulted from coal consumption. Hirschl (2009) analyze renewable energy policy at the international

level and provide content analyses of numerous official documents and information obtained through interviews with different experts. Some notes from the article are as follows: i) As CO<sub>2</sub>-based projects, renewable energy projects yield lower reduction quantities than the industrial projects aiming other greenhouse gases with much higher CO<sub>2</sub> equivalents. ii) Although in theory, the increase in CO<sub>2</sub> prices can provide a boon to investors in renewable energy, experiences in the emissions trading market show that the stability of the price developments has not been sufficient for satisfactory investment security and investment incentive (Hirschl, 2009).

Energy consumption in transport is represented by the consumptions of petrol and diesel oil. In our study, fuel prices and road sector energy consumption are also taken into account. The fuel prices are represented as the pump price for gasoline (US\$ per liter) and pump price for diesel fuel (US\$ per liter) (World Bank, 2014). World Bank calculates these pump prices by taking the pump prices of the most widely sold grades of gasoline and diesel fuel and converting them from local currency to U.S. dollars. Road energy consumption is used as a % of total energy consumption. World Bank definition of road sector energy consumption is as follows: “the total energy used in the road sector including petroleum products, natural gas, electricity, and combustible renewable and waste”. According to Strategic Assessment Framework for the Implementation of Rational Energy (SAFIRE) computer model, database of the model include fuel sector data containing fuel prices and each fuel’s share in the individual sectors (Oniszk-Poplawska et al., 2003). As well as road energy consumption, fuel prices play a vital on the energy sector. Especially depletion of fossil fuels have important effect on fuel prices which lead the sector to the biofuels.

## **Conclusion**

Each indicator provided from the literature is classified by two properties from each dimension, providing six indicator types. The literature is surveyed with this point of view and a two-phased framework for the indicators that are used evaluate renewable energy is proposed. This framework and indicators hereby are presented to provide a basis for researchers who aim to evaluate renewable energy usage.

Finally, the 14 selected indicators can be classified as energy-based indicators (TPES, of which renewables, share of renewables, share of main fuel categories, share of natural gas, share of nuclear energy, electricity production, road energy consumption), economy-based indicators (GDP, population, labor force participation rate, pump prices for gasoline and diesel fuels) and environment-based indicator (CO<sub>2</sub> emissions). The increasing usage of energy-based indicators leads researcher to the assessment of renewable energy around the world. Economy-based indicators are also widely used to evaluate countries. Reduction of CO<sub>2</sub> emissions is emphasized in most of the studies in the literature as an objective for using renewable energy.

The proposed framework constitutes the initial step of an ongoing research project to classify the world countries in the context of renewable energy approaches by using data mining techniques. In Table 3 selected indicators can be found with their dimensions assigned hereby and a detailed description from the World Bank is provided.

Table 3. Selected Indicators

Indicator Name	Indicator Unit	General Dimension	Sustainability Dimension	Definition
TPES	Mtoe	Usage	Economic	Consists of: Indigenous production + imports - exports - international marine bunkers - international aviation bunkers +/- stock changes
Of which renewables	Mtoe	Usage	Environmental	Primary energy supply from renewables
Share of renewables in TPES	% in TPES	Usage	Environmental	Percentage of renewable energy in TPES
Share of main fuel categories in total renewables	% in renewables	Usage	Environmental	a- Hydro b- Geothermal, solar, wind, tide c- Biofuels and renewable waste
Share of natural gas	% in TPES	Usage	Environmental	Primary energy supply from natural gas
Share of nuclear energy	% in TPES	Usage	Environmental	Primary energy supply from nuclear energy
Electricity production	kWh	Usage	Economic	Electricity production is measured at the terminals of all alternator sets in a station.
Electricity production from renewable sources	kWh	Usage	Environmental	Electricity production from renewable sources includes hydropower, geothermal, solar, tides, wind, biomass, and biofuels.
GDP, PPP	constant 2011 international \$	Economic	Economic	PPP GDP is gross domestic product converted to international dollars using purchasing power parity rates.
Population	Midyear estimates	Global	Social	Total population is based on the de facto definition of population, which counts all residents regardless of legal status or citizenship.
Labor force participation rate, total	% of total population ages 15+	Global	Social	Labor force participation rate is the proportion of the population ages 15 and older that is economically active.
CO <sub>2</sub> emissions	kg per 2011 PPP \$ of GDP	Global	Environmental	CO <sub>2</sub> emissions are those stemming from the burning of fossil fuels and the manufacture of cement.
Road sector energy consumption	% of total energy consumption	Usage	Environmental	Road sector energy consumption is the total energy used in the road sector including petroleum products, natural gas, electricity, and combustible renewable and waste.
Pump price for gasoline & diesel fuel	US\$ per liter	Economic	Environmental	Fuel prices refer to the pump prices of the most widely sold grade of gasoline & diesel fuel.

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## References

- Apergis, N. & Payne, J.E. (2010). Renewable energy consumption and economic growth: Evidence from a panel of OECD countries. *Energy Policy*, 38, 656-660.
- Baris, K. & Kucukali, S., (2012). Availability of renewable energy sources in Turkey: Current situation, potential, government policies and the EU perspective. *Energy Policy*, 42, 377-391.
- Bowden, N. & Payne, J. E. (2010). Sectoral analysis of the causal relationship between renewable and non-renewable energy consumption and real output in the US, *Energy Sources, Part B: Economics, Planning, and Policy*, 5, 400-408.
- Chien, T., & Hu, J.L. (2007). Renewable energy and macroeconomic efficiency of OECD and non-OECD economies. *Energy Policy*, 35, 3606-3615.
- Geller, H., Harrington, P., Rosenfeld, A.H. Tanishima, S., Unander, F. (2006). Polices for increasing energy efficiency: Thirty years of experience in OECD countries, *Energy Policy*, 34, 556-573.
- Hirschl, B. (2009). International renewable energy policy - between marginalization and initial approaches, *Energy Policy*, 37, 4407-4416.
- IEA (International Energy Agency), 2003. *Energy Policies of IEA Countries, Ireland 2003 Review*, OECD/IEA, Paris, France. Available at [www.iea.org](http://www.iea.org)
- Jinke, L., Hualing, S., Dianming, G. (2008). Causality relationship between coal consumption and GDP: Difference of major OECD and non-OECD countries, *Applied Energy*, 85, 421-429.
- Komor, P. & Bazilian, M. (2005). Renewable energy policy goals, programs, and technologies, *Energy Policy*, 33, 1873-1881.
- Liddle, B. (2012). Breaks and trends in OECD countries' energy-GDP ratios. *Energy Policy*, 45, 502-509.
- Martins, F.R., & Pereira, E.B. (2011). Enhancing information for solar and wind energy technology deployment in Brazil, *Energy Policy*, 39, 4378-4390.
- Nagy, K. & Körmendi, K. (2012). Use of renewable energy sources in light of the "New Energy Strategy for Europe 2011-2020", *Applied Energy*, 96, 393-399.
- Nazlioglu, S., Lebe, F Kayhan, S. (2011). Nuclear energy consumption and economic growth in OECD countries: Cross-sectionally dependent heterogeneous panel casuality analysis. *Energy Policy*, 39, 6615-6621.
- OECD/IEA, (2012). *Renewables Information 2012*. ISBN 978-92-64-17388-0.
- Onizsk-Poplawska, A., Rogulska, M., Wisniewski, G. (2003). Renewable-energy developments in Poland to 2020, *Applied Energy*, 76, 101-110.

Reuter, W. H., Szolgayová, J., Fuss, S., Obersteiner, M. (2012). Renewable energy investment: Policy and market impacts, *Applied Energy*, 97, 249-254.

Selam, A.A., Özel, S., Arıoğlu Akan, M.Ö. (2014). "Turkey's Position Among the OECD Countries Within the Context of Renewable Energy Utilization", *Dumlupınar University Journal of Social Sciences (EYI 2013 Special Issue)*.

Sheinbaum-Pardo, C., Ruiz-Mendoza, B.J., Rodriguez-Padilla, V. (2012). Mexican energy policy and sustainability indicators, *Energy Policy*, 46, 278-283.

United Nations, (1987). *Report of the World Commission on Environment and Development: Our Common Future*. Accessible at <http://www.un-documents.net/our-common-future.pdf>

U.S. Energy Information Administration Office, (2012), *Annual Energy Outlook 2012 with Projections to 2035*, U.S. Department of Energy, Office, Washington, DC 20585. Accessible at [www.eia.gov/forecasts/aeo](http://www.eia.gov/forecasts/aeo)

Valentine, S. V. (2011). Japanese wind energy development policy: Grand plan or group think?, *Energy Policy*, 39, 6842-6854.

Wang, Z.-H., Zeng, H.-L., Wei, Y.-M., Zhang, Y.X. (2012). Regional total factor energy efficiency: An empirical analysis of industrial sector in China, *Applied Energy*, 97, 115-123.

Wohlgemutha, N., Wojtkowska-Lodej, G. (2003). Policies for the promotion of renewable energy in Poland, *Applied Energy*, 76, 111-121.

World Bank, 2014. World Development Indicators. Accessible at <http://data.worldbank.org/indicator>

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***Field Test for the Conversion Efficiency Determination of High Concentrating  
Solar Cells with Fresnel Lenses in a Tropical Location***

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**Abstract**

Field test for the conversion efficiency determination of high concentrating solar cells with fresnel lenses in a tropical location was conducted at the top of NRRU Science Center Building, Nakhon Ratchasima, Thailand . The five of square shape of 5.5 mm x 5.5 mm. mutijunction solar cells were series connected to be a module. Each cell was fabricated with 100 suns silicon-glass fresnel lens for a concentrating purpose. We also determined the conversion efficiency of 160 watts peak monocrystalline silicon solar cell panel for a comparing purpose. All of solar cell module, solar cell panel, pyrhelimeter, pyranometer and light sensor were set up on the dual axes sun tracker. Data were gathered every 2 minutes all day from November 2013 to May 2014 via the automatic data logging system. The results have presented that the average conversion efficiencies of high concentrating solar cell module with fresnel lenses and of the 160 watts peak monocrystalline solar cell panel were 20.36 % and 14.12 % respectively, while, the average output powers per unit area of them were 9,652.89 watt/m<sup>2</sup> and 78.43 watt/m<sup>2</sup> respectively. It is clearly seen that, in terms of conversion efficiency and output power per unit area, the advantage of high concentrating solar cell with fresnel lens module significantly better than the typical monocrystalline solar cell panel. Economical aspect, the dominant of high concentrating solar cell with fresnel lens module, it will be significantly reduce the land investment cost and also encouraging in use of solar cell in urban and rural in spite of under the tropical location of Thailand.

Keywords : concentrating solar cells, conversion efficiency, fresnel lens, tropical location

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## Introduction

Renewable energy sources are of increasing interest, especially with a combination of tightness in world oil supply and problems with global warming. Solar cells, in particular, have attracted much attention due to their relative simplicity of operation in converting solar energy directly to electrical energy (Green 1998). Commercially, three types of silicon solar cell were used: monocrystalline, polycrystalline and amorphous (Messenger and Ventre 2004) with the conversion efficiency under the STC condition reach to 25%, 19% and 6% respectively (Wikipedia 2014). However, under the outdoor condition, the conversion efficiency of these solar cells significantly drop. Individual solar cells combine to form a solar cell panel (Goswami, Kreith et al. 2000). Typically, to maximize the average solar energy incident onto solar cells for the whole year, solar cell panels are conventionally set up as fixed panels facing south for the northern hemisphere location. A latitude tilt angle  $\pm 15^\circ$  to  $25^\circ$  is widely used to maximize solar energy incident onto solar cells as the seasons change (D. Partain 1995). To enhance the conversion efficiency of these solar cells, the single axis or dual axis sun tracking system was employed to increase the conversion efficiency about 20%-30% (Markvart and Castaner 2003).

Recently, the high efficiency multijunction solar cell was reported on the conversion efficiency under the STC condition with non-concentrating system reach to over 30%. For only this conversion efficiency of the multijunction solar cell, it is not enough to compete to the typical solar cells due to the cost per efficiency ratio is greater (Wikipedia 2014). So, multijunction solar cells were used for incorporate to the concentrating system such as lens or mirror (Nilsson 2005) that attached to the dual axis tracker which concentrates the sunlight onto the cell (Luque and Andreev 2007), the most extreme conversion efficiency of the multijunction solar cell reach to 44.7% (under 297.3 suns) (Casey 2013). The conversion efficiency of multijunction solar cells vary as the concentration ratio (CR) of light onto the cell, cell temperature, optical of concentration system etc. The clear sky of most direct radiation and low temperature will give rise the high conversion efficiency such as in Spain, USA and Australia. Similar limitation to typical solar cells, under the outdoor condition, the conversion efficiency of multijunction solar cells drop due to many factors.

In spite of the cloudy sky of most diffuse radiation and high temperature that will drop down the conversion efficiency of the cells such as in Thailand, Malaysia and Vietnam, there were rarely outdoor researchs that reported on the conversion efficiency of multijunction solar cells with concentrating system. In contrast, instead of typical solar cells using, the use of high efficiency multijunction solar cell incorporate to concentrating system should be boost the conversion efficiency of cells to compensate the disadvantages of the cloudy sky and high temperature. The most dominant of this high concentrating solar cell system is the reduction on the land use due to its has a very small size cell that need very small area to install compare with the typical solar cell system. So, I have decided to do the field test research to determine the conversion efficiency of multijunction solar cell incorporate to concentrating system (under 100 suns) via fresnel lens and dual axis tracker to justify or make a decision on using this system in a tropical location like in Thailand.

## Background

### Multijunction solar cells

Typical, commercially, solar cells made of one p-n junction silicon that have a specific band gap to capture specific photon energy. So, most of photon energy from the sun are lost. Then, it effects to the conversion efficiency limitation. To capture photon energy from the sun as much as possible, multijunction solar cells were designed and fabricated. The different type of III-V materials which have different band gap were layered from high band gap energy to low band gap energy from top to bottom of each multijunction solar cell respectively as shown in figure1. The reason for this is that the excess photon energy from the top layer penetrates to the middle and then to the bottom of multijunction solar cell. The consequent is of dominantly increase the conversion efficiency of multijunction solar cells compare with typical solar cells. However, to date, the cost-efficiency ratio of multijunction solar cells is too high compare with typical solar cells. So, economically, multijunction solar cells were suggested to work with concentration system and dual sun tracker for enhancing the maximum performance. To date, the conversion efficiency of the multijunction solar cell reaches to 44.7% (under 297.3 suns) (Casey 2013).

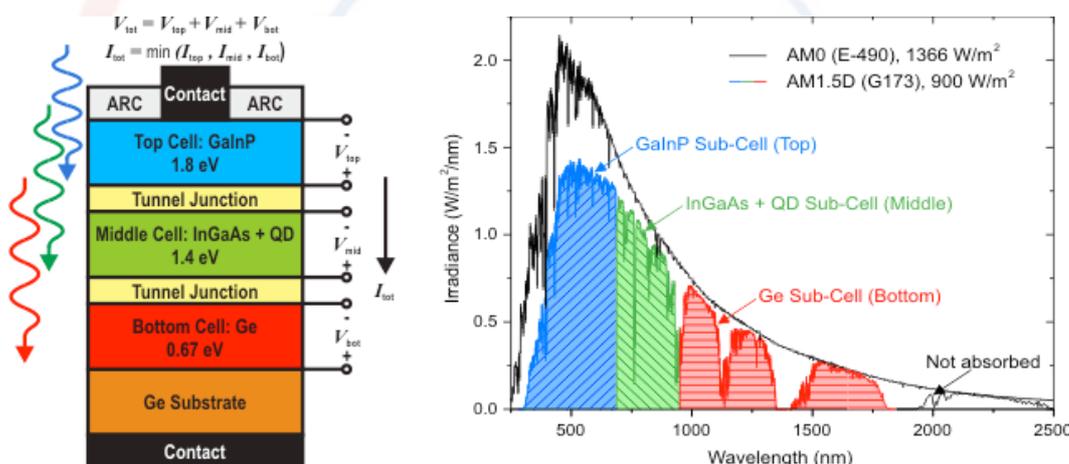


Figure1. Multijunction solar cell structure and spectral irradiance-wavelength graph (Solar PV, 2014)

### Concentration system

Concentration sunlight via some optics such as fresnel lens or parabolic mirror onto a small area solar cell is popularly called concentrated photovoltaic (CPV). CPV can significantly increase the conversion efficiency of multijunction solar cells(44.7%) compare to non-concentrated multijunction solar cells(over 30%)(Wikipedia 2014) and conventional silicon solar cells(25%) due to its photon fluxes are more consolidated. The dominant benefit of CPV is of using only small amount materials to fabricate very small solar cells compare to conventional solar cells. So, CPV can save the environment, land cost, installing cost, labor cost etc. However, CPV needs the multijunction solar cell, lens or parabolic mirror, direct sunlight, cell cooling, sun tracker that increasing in overall cost compare to conventional solar cells. For competition, CPV must be enhanced the performance on increasing conversion efficiency of multijunction solar cell and lower its cost as soon as possible. We can be

categorized the CPV type based on the level of sunlight concentration (unit: suns) in to 3 types: low concentration (sunlight concentration 2-100 suns) that no need to active cool and active sun tracker, medium concentration (sunlight concentration 100-300 suns) that need to active or passive cool and dual sun tracker. The last one: high concentration (sunlight concentration 1,000 suns or more) that need to active cool and active dual sun tracker. Figure2. was shown about some examples of CPV optics. The more lower or higher concentrations and the more higher temperature can be make low conversion efficiency of multijunction solar cell. The optimum concentration is around 500 suns as shown in figure3.

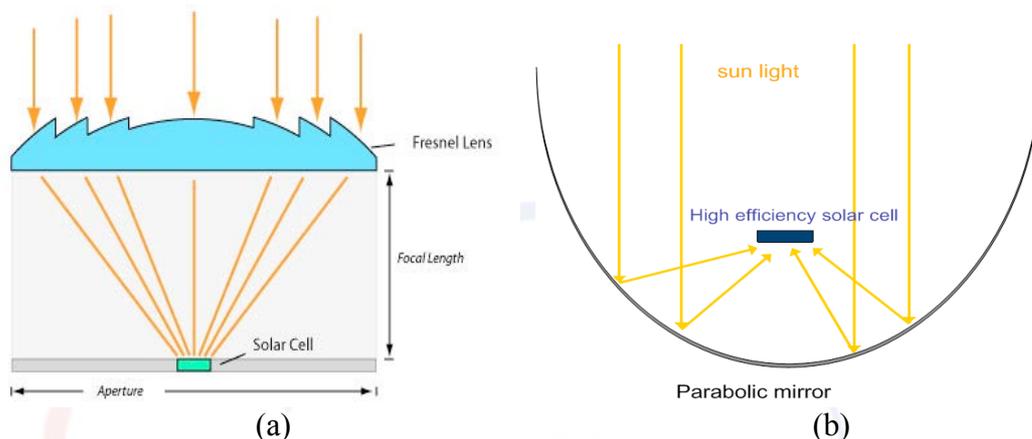


Figure2. Concentration by lens(a) (Concentrated Photovoltaic Technology, 2014) and concentration by parabolic mirror (b)(Liang, 2010)

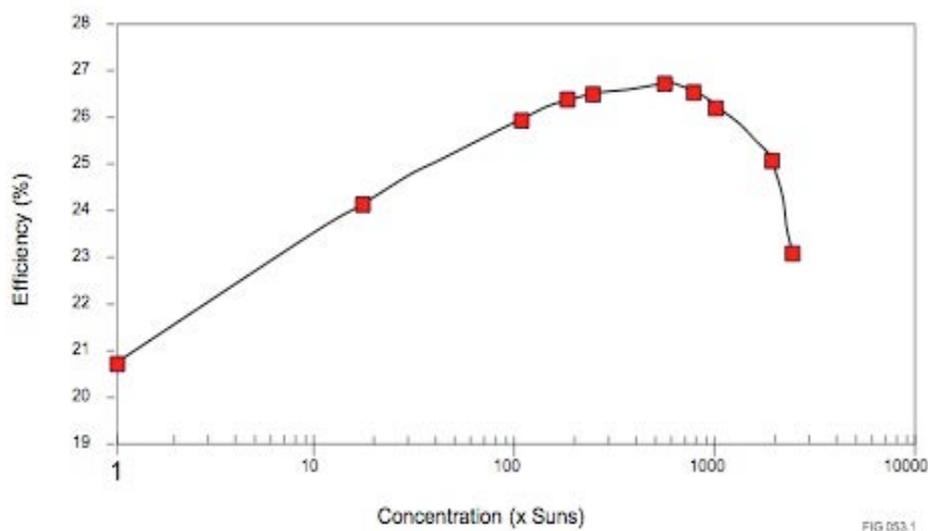


Figure3. Effect of concentration ratio on conversion efficiency of solar cell (McConnell and Fthenakis, 2012)

## Performance and economical analyses of the system

### 1) Conversion efficiency of solar cell ( $\eta$ )

The average conversion efficiency for each solar cell module can be determined by equations 1 to 2. Note that we define both  $\Delta t$  and  $dt$  as time intervals between data points. Economically, we favorite high conversion efficiency from solar cell.

$$\text{Efficiency}_{av} = \frac{\text{Total Energy Output in time T}}{\text{Total Energy Input in time T}} \times 100\% \quad (1)$$

Thus,

$$\text{Efficiency}_{av} = \frac{\int_0^T \text{Power Output}_{ins} dt}{\int_0^T \text{Power Input}_{ins} dt} \times 100\% \quad (2)$$

where  $\text{Efficiency}_{ins}$  = instantaneous conversion efficiency for each solar cells module.

$\text{Power Output}_{ins}$  (W) = instantaneous electric power output from the solar cell module.

$\text{Power Input}_{ins}$  (W) = instantaneous power incident on solar cell module.

$\text{Efficiency}_{av}$  = average conversion efficiency for each solar cell module over an extend time interval T.

### 2) Concentration ratio (CR)

The parameter used to quantify the amount of refractive area of lens or reflective area of mirror that receive sunlight energy flux input onto each aperture(A) per a small area of each solar cell is called the concentration ratio. It is determined using equation 3(Nilsson 2005). The more concentration ratio of solar cell system the more of solar flux intensity onto solar cell.

$$\text{CR} = A/a \quad (3)$$

### 3) Cost-efficiency ratio (CE)

This parameter used to quantify the cost of investment in solar cell system (C) per conversion efficiency ( $\eta$ ) of solar cell. It is determined using equation 4. The lower cost-efficiency ratio of the solar cell system the more benefit of that solar cell system.

$$\text{CE} = C/\eta \quad (4)$$

### 4) Payback period (PP)

Payback period is the time in which the initial cash outflow of an investment is expected to be recovered from the cash inflows generated by the investment. It is one of the simplest investment appraisal techniques. It is determined using equation 5. The lower payback period the more benefit of that solar cell system.

$$\text{Payback Period} = \frac{\text{Initial Investment Cash}}{\text{Inflow per Period}} \quad (5)$$

When cash inflows are uneven, we need to calculate the cumulative net cash flow for each period and then use the following formula for payback period:

$$\text{Payback Period} = A + \frac{B}{C}$$

In the above formula,

**A** is the last period with a negative cumulative cash flow;

**B** is the absolute value of cumulative cash flow at the end of the period A;

**C** is the total cash flow during the period after A

### Climate conditions of the experimental site

The experimental site was located in Nakhon Ratchasima, a northeastern province of Thailand. Thailand is located between latitude 5° 37' N and 20° 27' N, and between longitude 97° 22' E and 105° 37' E. Thailand is geographically divided into 4 regions: Northern, Northeastern, Central and Southern regions. A map of Thailand and neighbouring countries is shown in Figure4.

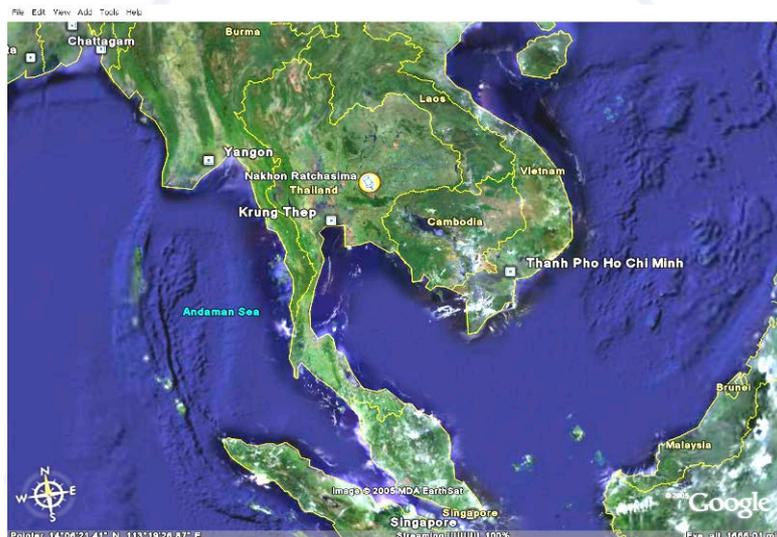


Figure4. Map of Thailand. (Google 2014)

Thailand has 3 seasons: rainy (from mid-May to mid-October), winter (from mid-October to mid-February) and summer (from mid-February to mid-May). The climate of Thailand, a tropical country, is mainly affected by the two monsoon winds: the Southwest and Northeast. The Southwest monsoon comes from the Indian Ocean in May. As a result, clouds and rains spread widely around the country until the end of the rainy season in October. The Northeast monsoon comes from the mainland of China in October. Consequently, dry and cold weather with a clear sky widely appears around the country until the end of winter in February. However, the east coast of the Southern region experiences heavy rain at this time due to moisture from the Gulf of Thailand. A period of the transition of the monsoons, from the Northeast to the Southwest occurs in February. The weather then becomes hot and humid around the country until the end of summer in May. The hottest months of the year

are from March to May. There are many climate parameters which characterise the general weather for each season in Thailand, such as cloudiness, surface wind, surface temperature, rainfall, relative humidity etc. (TMD 2014)

Table 1. Climatological information of Nakhon Ratchasima, Thailand (WMO 2014)

Month	Mean Daily Minimum Temperature (°C)	Mean Daily Maximum Temperature (°C)	Mean Total Rainfall (mm)	Mean Number of Rain Days
Jan	17.9	30.9	5.9	0.9
Feb	20.5	33.6	17.8	2.2
Mar	22.8	35.8	37.1	5.1
Apr	24.5	36.6	63.5	7.7
May	24.7	35.1	140.5	13.8
Jun	24.8	34.4	108.3	13.3
Jul	24.3	33.9	113.7	13.5
Aug	24.2	33.2	146.2	16.4
Sep	23.7	32.2	221.6	18.1
Oct	22.9	30.9	143.4	12.2
Nov	20.5	29.7	27.3	4
Dec	17.6	29.1	2.8	0.7

## Methods

The methods for this research were done as following steps;

1. Series connected the five 5.5 cm x 5.5 cm multijunction solar cells together (with built in heat ventilation substrate that further attach to the heat sink for each cell).
2. Fabricated each multijunction solar cell to receive the expected 100 suns concentrated sunlight from each fresnel lens.
3. Installed the module which composes of a set of multijunction solar cell and a set of fresnel lens onto the rack of dual axis sun tracker.
4. Installed a 160 watts monocrystalline solar cell panel as a comparative cell onto the rack of dual axis sun tracker.
6. Installed the pyrheliometer and pyranometer onto the rack of dual axis sun tracker to measure the direct and diffuse solar fluxes incident onto these solar cells.
7. Installed the light sensor on the dual axis sun tracker to sense and control for a precision tracking.
8. Connected wires from all of the system to the data loggers for data gathering

purpose.

9. Set up the data loggers to collect the data every 2 minutes for 6 months.
10. Collected data were calculated to determine the average conversion efficiency and average output power per unit area of a set of multijunction solar cell module and a comparative monocrystalline solar cell panel.



Figure5. System set up and installation

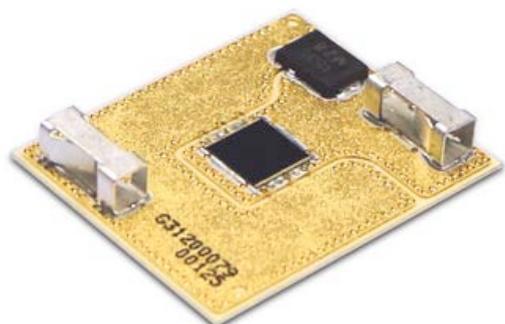


(a)

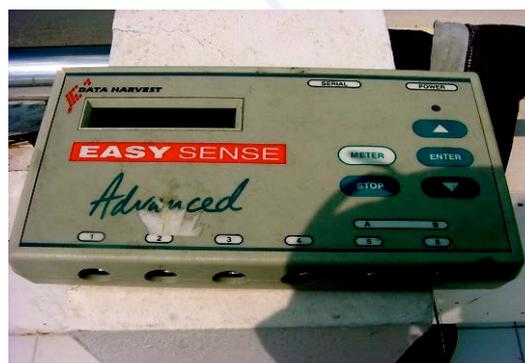


(b)

Figure6. The SK01-D pyranometer (a) and DN5-E pyr heliometer (b) set up



(a)



(b)

Figure7. The 5.5 cm x 5.5 cm CTJ multijunction solar cell (a) (Suncore 2014) and data logger (b)

## Result and discussion

### Conversion efficiency

#### 1) Overall average conversion efficiency

The result for overall average conversion efficiency of multijunction solar cell module (100 suns) and a comparative monocrystalline silicon solar cell panel (160 watts) were 20.36% and 14.12% respectively. We clearly seen that the performance of 100 suns concentrated of sunlight via fresnel lenses onto multijunction solar cells significantly greater than monocrystalline silicon solar cell panel. In spite of a cloudy and overcast sky in a tropical location site, the CPV system was still shown a good performance although it has lower performance than in the clear sky, dry weather and

cool temperature location. To increase the performance of multijunction solar cells module, the increment of concentration ratio for the system is recommended.

### 2) Monthly average conversion efficiency

The result for monthly average conversion efficiency of multijunction solar cell module and a comparative monocrystalline silicon solar cell panel was presented in figure8. We found that, every month except for in April 2014, the performance of 100 suns concentrated of sunlight via fresnel lenses onto multijunction solar cells greater than monocrystalline silicon solar cell panel. Especially, in winter (from November to February), the performance of 100 suns concentrated of sunlight via fresnel lenses onto multijunction solar cells dominantly greater than monocrystalline silicon solar cell panel. The average conversion efficiency in winter of multijunction solar cell module and a comparative monocrystalline silicon solar cell panel were 20.94% and 13.31% respectively. The low temperature incorporate to the very clear sky in winter must be influent in both of solar cells performance. The average conversion efficiency in summer of multijunction solar cell module and a comparative monocrystalline silicon solar cell panel were 16.48% and 15.19% respectively. Critically, we have seen that the average conversion efficiency in summer of multijunction solar cell module a few more than a comparative monocrystalline silicon solar cell panel. The high temperature incorporate to the cloudy and overcast sky in summer must be influent in both of solar cells performance.

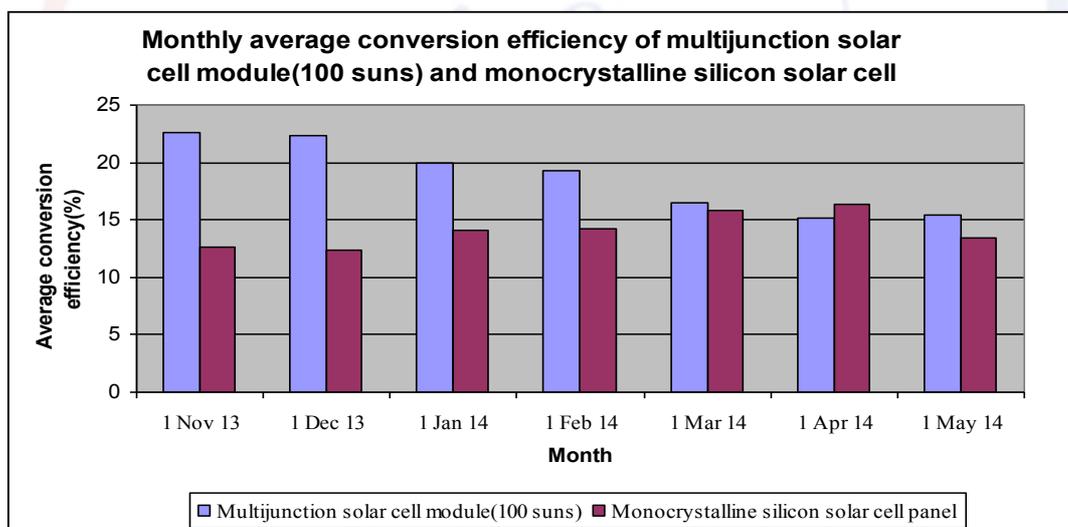


Figure8. Monthly average conversion efficiency of multijunction solar cell module and a comparative monocrystalline silicon solar cell panel

### 3) Average output power per unit area

The average output powers per unit area of multijunction solar cell module and a comparative monocrystalline silicon solar cell panel were 9,652.89 watt/m<sup>2</sup> and 78.43 watt/m<sup>2</sup> respectively. Economical aspect, the dominant of high concentrating solar cell with fresnel lens concentrating system module, it will be significantly reduce the land investment cost and also encouraging in use of solar cell in urban and rural in spite of under the tropical location of Thailand and neighbouring.

## **Conclusion**

The field test for the conversion efficiency determination of 100 suns concentrated via fresnel lenses onto the multijunction solar cells in Nakhon Ratchasima, Thailand as a tropical location was shown the satisfactory result. The average conversion efficiency of multijunction solar cell module was significant greater than a comparative monocrystalline silicon solar cell panel with the 20.36% and 14.12% performances respectively. Especially, the performances of both solar cells were better in winter than in summer because of sky condition and temperature. The average output powers per unit area of multijunction solar cell module and a comparative monocrystalline silicon solar cell panel were 9,652.89 watt/m<sup>2</sup> and 78.43 watt/m<sup>2</sup> respectively. The result was presented the possibility to use concentrating solar cell system via fresnel lens in the tropical area although lesser performance than the clear sky and low temperature location. To increase the performance of multijunction solar cells module, the increment of concentration ratio for the system is recommended.

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## References

- Casey, T. (2013). "Cost Of Solar Set To Plummet With New 44.7% Efficiency Record." Retrieved 15 June, 2014, from <http://cleantechnica.com/2013/09/24/new-solar-cell-efficiency-record-of-44-7-set/>.
- D.Partain, L., Ed. (1995). Solar Cells and Their Applications. Concentrator Modules Using Multijunction Cells. New York, A Wiley-Interscienc Publication.
- Google (2014). Map of Thailand
- Goswami, D. Y., F. Kreith, et al. (2000). Priciples of Solar Engineering. Philadelphia, Taylor&Francis.
- Green, M. A. (1998). Solar Cells. New South Wales, The University of New South Wales.
- Luque, A. L. and V. M. Andreev, Eds. (2007). Concentrator Photovoltaics. Multijunction Concentrator Solar Cells. Heidelberg, Springer.
- Markvart, T. and L. Castaner, Eds. (2003). Practical Handbook of Photovoltaics: Fundamentals and Applications High-efficiency concentrator silicon solar cells. Oxford, Elsevier Advanced Technology.
- Messenger, R. A. and J. Ventre (2004). Photovoltaic Systems Engineering. Florida, CRC Press.
- Nilsson, J. (2005). Optical Design and Characterization of Solar Concentrators for Photovoltaics. Lund, KFS KB.
- Suncore. (2014). "CPV Technology." Retrieved 20 July, 2014, from <http://www.suncorepv.com/index.php?m=content&c=index&a=lists&catid=82>
- TMD. (2014). "Weather." Retrieved 6 May, 2014, from <http://www.tmd.go.th/index.php>.
- Wikipedia. (2014). "Multijunction photovoltaic cell." Retrieved 18 August, 2014, from [http://en.wikipedia.org/wiki/Multijunction\\_photovoltaic\\_cell](http://en.wikipedia.org/wiki/Multijunction_photovoltaic_cell).
- WMO. (2014). "Climatological Information of Nakhon Ratchasima, Thailand " Retrieved 3 July, 2014, from [https://www.wmo.int/pages/index\\_en.html](https://www.wmo.int/pages/index_en.html).
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***Improving Energy Scavenging Capacity via a  
Vertically Configured Closed-Circuit PRO System***

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**Abstract**

A novel configuration for a closed-circuit PRO (CPRO) system is described. The CPRO system enables fluid flow in both the draw and feed channels using gravitational potential energy. The new PRO system is designed to store gravitational potential energy derived from input thermal energy for use in fluid circulation, thereby bypassing the need for circulation pumps. As a result the novel PRO system can recover a significant amount of the 66% of energy typically unavailable for external use. The new PRO system is self-cleaning with all salt (in the draw solution, having leaked through the membrane) washed into the distillation unit. Circulation of distilled water is accomplished using stored gravitational potential energy. Circulation of the saline solution is accomplished using a gravitationally powered volumetric mass transfer process without significant loss of internal pressure. A laboratory test device was constructed and operated. Its top performance is evaluated at a recovery of 67.0% of the energy potential.

Keywords: pressure retarded osmosis, vertical closed circuit pressure retarded osmosis

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## Introduction

Pressure retarded osmosis (PRO) systems are energy-transforming devices capable of transforming thermal energy into pressurized water using differences in solute concentration of solutions. The resulting pressurized water can then be used to generate power (McGinnis, 2008). This process occurs via a flow of liquid through a semi-permeable barrier through which water or other solvent passes through more readily than salts or other substances that may be dissolved in the solvent (Kaleda, 2011). If the solution on one side of the barrier has a higher dissolved solute concentration than that on the other side of the barrier, solvent moves through the barrier in the direction of the more highly concentrated solution. At the same time, solute moves across the barrier toward the lower concentration solution. Because the rate of movement of solute is much slower than that of solvent, a pressure difference between the two sides may evolve in the relatively short term, enabling work to be done.

Closed-circuit PRO (CPRO) systems are PRO systems in which the high pressure, medium concentration solution moves through a power generator and on into a separator. The separator removes the solvent from the solute by some means, typically through thermal distillation, and returns the two streams of liquid to the membrane assembly (Efraty, 2014 and Alfaee 2012). Such a system can be run virtually indefinitely with no influx of either salt or water. The CPRO system must utilize energy to do the separation; this energy drives the pressurization and whatever work might be undertaken with the pressurized water. A typical use of CPRO systems is transformation of waste, parasitic, or unwanted heat into electrical power: energy scavenging.

In CPRO systems, high pressure solution is used to power circulation pumps that move the high and low concentration solutions from the distiller to the membrane chamber. It is also used to generate electrical power. A ratio of 33% electricity production to 66% circulation pump power is typical for many systems (Hong et. al, 2013). The use of two thirds of the energy potential in internal operation is a strong limiting design element of the system.

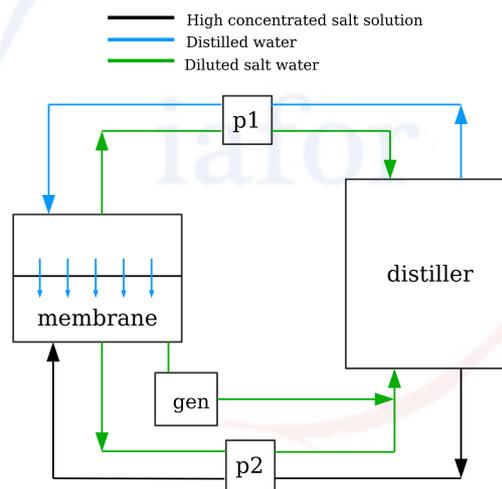
The built world consists of a myriad of opportunities for energy scavenging in cases where the thermal gradient one has to work with is of the order of  $10 - 20^{\circ}C$  (Air Vent, 2014). Structures such as sheds, attics, and others can routinely generate relatively small thermal gradients that themselves represent a significant amount of energy opportunity. Capturing this energy could enable low energy devices that could provide communication, sensor activation, and other low wattage opportunities that might be useful in remote areas or in the wake of a calamity.

If CRPO systems are to be used for energy acquisition, it is desirable to use systems with superior energy recovery to that of conventional CPRO system. Reducing the internal power utilization of the device enhances the amount of energy available for external use. This paper presents work we've done on a vertically oriented CPRO system (VCPRO) which reduces the energy expenditures due to pumping through pressure pumps and thereby enhances the amount of energy that can be delivered.

The remainder of the paper is organized as follows. Section 2 describes the system and provides a theoretical analysis of its performance characteristics. Section 3 describes the experiments undertaken with the system and provides their experimental data. Section 4 gives a discussion of the system, experimental designs, and potential future improvements to the system. Section 5 concludes.

## Enhancing recovered energy using a vertical layout for a CPRO System

A typical CPRO system involves four principle parts: a means of separating solvent from solution (typically a distiller), a membrane assembly, a generator, and one or more pressure pumps capable of using high pressure to drive the circulation of the draw solution and the distilled solvent. In general, the power required to carry out the circulation of the draw solution and the feed solution (distillate) is drawn off of the pressurized and diluted draw solution downstream from the membrane assembly. This limits the overall power that can be harvested.



**Figure 2.1:** The horizontal arrangement of the CPRO.

### The vertically oriented CPRO system (VCPRO)

We developed an alternative organization for the CPRO system in which the parts of the system are laid out vertically, as in Figure 2.2. This system eliminates the need for pressure pumps using a system of valves, conduits, and vertical drops to circulate the different water sources.

#### General Design Strategy

In energy harvesting, some form of relatively low concentration untapped energy is acquired and transformed to another form that is easily usable (Miller, 2006). In

our system, the energy we are interested in acquiring is thermal energy. While the transformation of this energy into a usable form is expected to yield a small return for scavenged energy due to the low temperature gradients generally available and the concomitant thermodynamic limitations<sup>1</sup>, improvements in distillation technology (which are not an explicit goal of this study) can be used to increase the recovered energy significantly.

The VCPRO system recovers energy by using thermal energy and relatively small thermal gradients to distill water. This water moves as vapor up a gravitational potential, acquiring gravitational potential energy. The water then condenses and is collected in a water reservoir, with excess water (beyond the reservoir's capacity) continuing on into a membrane assembly. The brine is retained by the distiller. The membrane assembly contains two chambers in contact across an osmosis membrane. The brine is used to fill one chamber while the distillate fills the other chamber. As a result of the differing concentrations, the brine is pressurized as the distillate moves via forward osmosis through the membrane. The pressurized fluid flows from the membrane assembly to a generator where it can be used to generate electrical power. The fluid then flows back into the distiller. Periodically the water retained in the reservoir is released into the distilled water side of the membrane assembly, forcing the water already there out into the distiller. This cleans the distilled water side of the membrane and recovers the salt that has flowed through the membrane. The cycle continues as long as a thermal gradient at the distiller side is maintained.

## Detailed Description

Our distiller comprises two principle parts: an evaporator (1) and a condenser (9). The evaporator is an acrylic vertically elongated chamber principally made from two coaxial acrylic tubes, closed at both ends. A vacuum is retained between the two tubes, insulating the two from one-another. Heat is absorbed through a copper tube attached to the bottom of the inner acrylic tube. Vapor generated as the water evaporates, fills the distiller, and travels to the condenser, which is located between the evaporator (1) and the reservoir (3). In our laboratory model, the condenser (9) is a long copper tube.

The distiller is directly connected to three other parts of the apparatus: the reservoir (3), the generator (2), and the membrane assembly (6) through a set of valves. Liquid enters the distiller from two of these three sources and leaves the distiller as vapor and distilled water. Liquid entering the distiller from the generator (2) comes through the top of the evaporator (1) while liquid from the membrane assembly's inner chamber (4) enters through the side of the evaporator (1). The distiller is connected to the membrane assembly's outer chamber (5) via valves V6 and V7 connected to two locations at the bottom of the evaporator (1). These valves can be used to transfer dilute water from the outer membrane assembly chamber to the distiller using a mass transfer process driven by the relative densities of the liquids in the membrane assembly and the evaporator. One connection from the outer chamber of the membrane assembly (5) to the evaporator (1) is

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<sup>1</sup>i.e. Carnot efficiency limitations

connected to an internal tube that extends partway into the evaporator. When the valves V6 and V7 are opened, the heavier concentrated water in the evaporator can displace the lighter liquid in the membrane assembly's outer chamber, restoring the draw solution to a high concentration.

The reservoir (3) accepts water from the condenser and stores it. Beyond a maximum capacity, additional water deposited in the reservoir flows through to the connecting tubing joining the reservoir and the membrane assembly. The valve at the bottom of the reservoir (V2) can be opened to drain the reservoir. Both pathways bring distilled water into the membrane assembly's inner chamber (4). If the reservoir and the connecting tubing are sufficiently full of water, draining the reservoir deposits water into the distiller through valves V2, V3, V4, and V8. This effectively "cleans" this side of the membrane and recovers salt that may have passed through the membrane into the inner chamber.

The membrane assembly (6) comprises two chambers defined by two coaxial acrylic cylinders. Accordingly, these are an inner chamber (4) and an outer chamber (5). The two are separated by a cylindrical cellulose acetate membrane<sup>2</sup> supported by the inner acrylic cylinder. The inner chamber contains a low concentration solution derived from distilled water; the outer chamber is filled with a draw solution (NaCl solution, in this study). The top of the inner chamber has a port which can be connected to the output of the reservoir. The bottom of the inner chamber is connected to the side of the evaporator (1) through valves V8 and V3. Distilled water can flow freely through the interior chamber from valve V4 to valve V8. The outer chamber (5) is connected to the collector (7) and the generator (2) through valve V5 and the pressure relief valve (8). It is also connected to the evaporator (1) through valves V6 and V7, as described above; these valves are vertically separated with one near the top of the outer chamber (5) and the other near the bottom. Pressurized water flows through valve V5 and on through the pressure relief valve (8) before continuing on to the generator (2). In our study, the generator is bypassed.

(8) is a one-way pressure relief valve which opens at a pressure differential of 33.9 kPa. Water pumped through the valve may be measured at the collector (7), providing a measure of the amount of available energy at this point. Subsequent models will eliminate this pressure valve, utilizing the power generator (2). Water pumped through this valve is drained back into the distiller from the top of the evaporator (1).

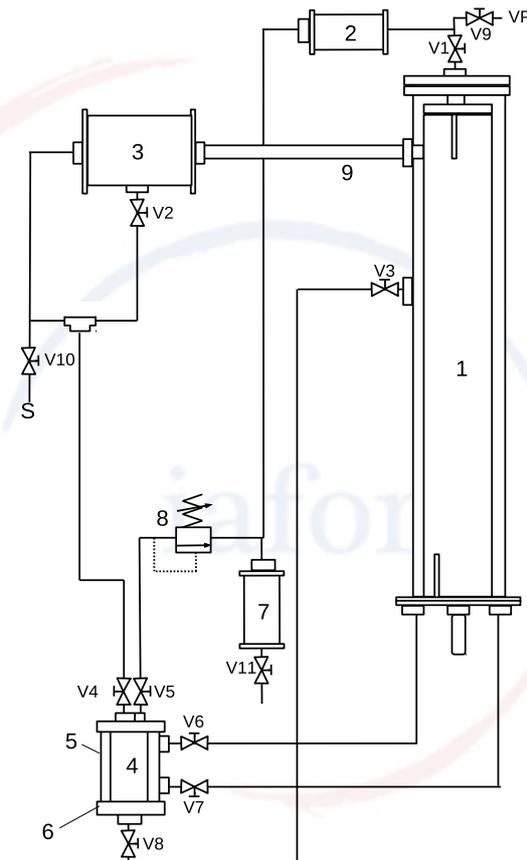
Water flowing through the membrane dilutes the solution in the membrane assembly's outer chamber. As a result, it is necessary to periodically restore its concentration. This is accomplished by opening the two valves (V6 and V7) on the side. This step reduces the pressure in the membrane assembly's external chamber, but maintains the pressure between the membrane assembly and the generator; normal flow will be restored when the pressure within the membrane assembly is restored. As the diluted water is less dense than the solution in the distiller, it is relatively bouyant and is displaced by the heavier and more concentrated brine

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<sup>2</sup>We obtained cellulose acetate membrane material from standard GE modules, model TFM-18.

that results from utilizing the distiller. This restores the concentration of the draw solution and the functionality of the device.

Salt passes through the membrane into the membrane assembly's inner chamber. The solution therein becomes increasingly saline over time. It is necessary to wash out the inner chamber periodically. This is accomplished by opening V3, V4, V8, and V2. The water in the reservoir naturally drains through the membrane assembly and into the distiller due to its height. The process washes out salt in the membrane assembly's internal chamber and recovers it in the distiller.



**Figure 2.2:** The vertical arrangement of the CPRO. The vertical CPRO consists of four principle parts: (1 and 9) the distiller, (2) power generator, (3) the reservoir, and (6) the membrane assembly.

In this figure, the evaporator (1) is vertically elongated, enabling the vapor from the first of what can be several stages to travel vertically prior to condensation. The energy may then be used for subsequent stages in complex distillation processes. In our laboratory scale device, the vertical lift is limited. However, in larger devices the vertical lift desired can be significant.

## Reduced Carnot efficiency due to vertical orientation

In order to reduce the thermal energy required to pre-heat the distiller so as to begin distilling water, the entire distiller is evacuated and the rarified atmosphere

is replaced with water vapor using a steam injection procedure. This effectively transforms the distiller into a heat pipe<sup>3</sup>. As a result, the transfer of thermal energy is extremely fast and requires no priming. The vertical height of the distiller affects the pressure (and therefore temperature) differential between the elevated condenser and the distiller; the Carnot efficiency is necessarily reduced as a result of the height related temperature difference.

In order to determine the scale of the temperature difference, we can model the column of vapor as incompressible gas of density  $\rho_g$ . In this case, the pressure exerted by the column of gas is given by

$$P_c = \rho_g g h. \quad (1)$$

As a result, if the temperature at the bottom of the column is given by  $T_h$ , the temperature at the top of the column is given by Antoine's equation as

$$P_t = e^{\left(A - \frac{B}{C + T_h}\right)} - \rho_g g h. \quad (2)$$

where  $A$ ,  $B$ , and  $C$ , are experimentally determined constants. Therefore, the temperature at the top of the column will have cooled to

$$T'_h = \frac{B}{A - \log\left(e^{\left(A - \frac{B}{C + T_h}\right)} - \rho_g g h\right)} - C.$$

The resulting Carnot efficiency is limited by  $e = \frac{T'_h - T_l}{T_l}$ .

## Overall energy efficiency

We can model the function of the distiller as follows. Given a quantity of heat  $\Delta Q_{in}$ , a quantity of water  $\Delta V_{in}$  is generated. This is given by

$$\Delta V_{in} = \kappa \frac{\Delta Q_{in}}{H_v(T, M)} \quad (3)$$

where  $H_v(T, M)$  is the heat of vaporization of water at the temperature and molarity<sup>4</sup>, and  $\kappa$  is a proportionality constant which captures the efficiency and the multiplicative effect of the distiller. For a single stage system, this is necessarily lower than 1. For more complex systems, such as multi-effect distillation MED systems, this can be significantly higher than 1<sup>5</sup>.

Of the water that is generated by the distiller, some proportion of it is used to clean the system while the remaining water may be used to clean the membrane's inner

<sup>3</sup>A *heat pipe* is also known as a *Perkin's tube*.

<sup>4</sup>The heat of vaporization can be viewed as essentially constant, despite the elevated molarity, if the heat of vaporization as a function of mass refers only to the mass of the water being evaporated rather than as a function of the mass of the entire quantity of water and salt contained therein.[?]

<sup>5</sup>Values of  $\kappa$  of up to 23 have been reported, though at high temperature[?, ?].

chamber. The frequency of cleaning depends on the concentration of the external solution, the operating pressures and temperatures, and the kind of membrane being used. Based on these characteristics, we can determine the proportion of water  $\chi$  used for washing the membrane interior and the proportion of water  $(1 - \chi)$  of water used for power production.

The distilled water is deposited in the membrane chamber where it passes through the membrane by forward osmosis, generating a stream of water pressurized to a pressure

$$P_{out} \leq \pi = iRMT. \quad (4)$$

Here  $M$  denotes the molarity of the water on the other side of the membrane,  $R$  is the gas constant,  $i$  is the Van t'Hoff factor,  $\pi$  is the osmotic pressure, and  $T$  is the temperature. The amount of energy in the stream is equal to

$$E_{out} = \Delta V_{in} P_{out} (1 - \xi) \leq \Delta V_{in} i (1 - \xi) RMT = \kappa \frac{\Delta Q_{in} i (1 - \xi) RMT}{H_v(T)}. \quad (5)$$

The rate of water pumping may be obtained using

$$J_w = A(\pi - \Delta P) \quad (6)$$

where  $A$  is the membrane surface area and  $\Delta P$  is the pressure difference between the sides of the membrane.  $J_w = \frac{dV_{out}}{dt}$ . As  $\frac{dV_{out}}{dt} \leq \frac{dV_{in}}{dt}$ ,

$$\frac{dE_{out}}{dt} = \frac{dV_{out}}{dt} P_{out} \leq \frac{dV_{in}}{dt} P_{out} = \kappa \frac{i(1 - \xi) RMT}{H_v(T)} \frac{dQ_{in}}{dt}. \quad (7)$$

We can rate the amount of output power as the ratio of the amount of power recovered and the maximum amount of power recovered

$$e = 1 - \xi. \quad (8)$$

## Experimental Procedures

We constructed and operated a laboratory scale model consisting of the primary structures described above in Section 2.1. Referring to Figure 2.2, we describe here the procedures used during the evaluation of the VCPRO system.

### Preparation

This procedure is used to prepare the device with an internal wet vacuum, enhancing the distillation process. The evaporator (1) was initially filled with saturated NaCl solution, the internal chamber of the membrane assembly (4) was filled with distilled water, and the external chamber of the membrane assembly (5) was filled with solution drained from the evaporator (1). A vacuum pump connected to valve V9 evacuated the air within the system whilst steam was injected from the hot water reservoir connected to valve V10 in order to force out any remaining air that otherwise would not have been evacuated. While the vacuum pump was on, only V11 was closed. Once the pump was turned off, valves V2, V3, V6, V7, V8, V9, V10, and V11 were closed and steam injection was ceased.

## Distillation/Pressurization/Work

The copper tube connected to the bottom of the evaporator (1) was heated to a temperature of ambient plus  $16 - 20^{\circ}C$ , which, in turn, heated the saline solution in the evaporator (1) and caused water to evaporate. The water condensed in the copper pipe (9) and traveled through it to the reservoir (3). Water additionally condensed in the tubing leading to the membrane assembly (6). The water that entered the membrane assembly did so through its inner chamber (4). There was a net movement of water across the osmosis membrane from the inner chamber (4) to the outer chamber (5). Pressure forced saline solution from the membrane assembly (6) to the evaporator (1). Valves V1 and V5 were open, and valves V2, V3, V4, V6, V7, and V8 were closed.

The pressure generated by the osmotic action in the membrane chamber (6) was measured by the pressure relief valve (8) which required a minimum pressure of  $33.9\text{ kPa}$  to open. Work was estimated by calculating the product of the pressure required to open the valve and the volume of water that passed through the valve and was collected in the collector (7).

### “Recharge”

This procedure exchanges the locations of the solutions in the outer chamber of the membrane assembly (5) and the evaporator (1), taking advantage of their relative densities. By closing valve V5 and opening valves V6 and V7, we connected the evaporator (1) and the outer chamber of the membrane assembly (5). The heavier and more concentrated saline solution of the evaporator (1) moves through the tubing and displaces the lighter and less concentrated solution in the outer chamber of the membrane assembly (5). Simultaneously, the lighter and less concentrated solution of the outer chamber of the membrane assembly (5) traveled through the tubing to the evaporator (1), filling the volume vacated by the more concentrated solution. This process is a natural result of gravitational action and requires no external intervention. The completion of this process restores the concentration gradient across the membrane.

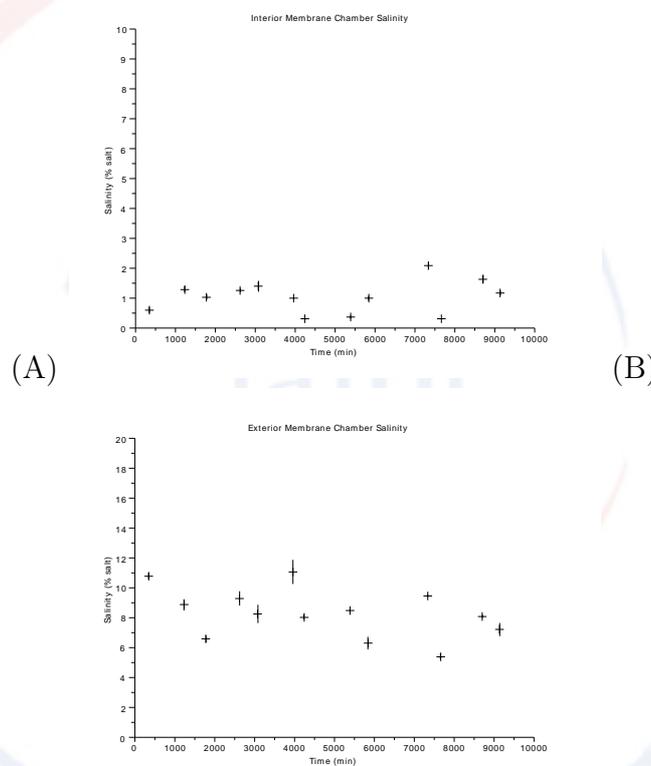
### Cleaning

This procedure is necessary to clean the slightly saline solution that results on the “clean” side of the osmosis membrane from the movement of salt through the membrane. In this procedure, valves V2, V3, and V8 are opened. The distilled water in the reservoir (2) drains into the inner chamber of the membrane assembly (4), through valves V3 and V8 and their connecting tubing, and into the evaporator (1). This effectively washes the slightly salty solution out of the inner chamber of the membrane assembly (4) and recovers the salt in the evaporator (1). After the procedure is completed, valves V2, V3, and V8 are closed.

## Data and analysis

### Salinity measures

We measured the salinity of both the interior and exterior chambers of the membrane assembly. During the experimental run, a collecting chamber was added to the exterior membrane chamber, allowing the pressurized water to be collected. Every 10 hours, we released the vacuum and measured the volume of solution that had pooled in the collector. We also drained just enough distilled water from the interior of the membrane chamber to measure its salinity. The salinity of each sample was measured three or four times with a salinity probe<sup>6</sup>.



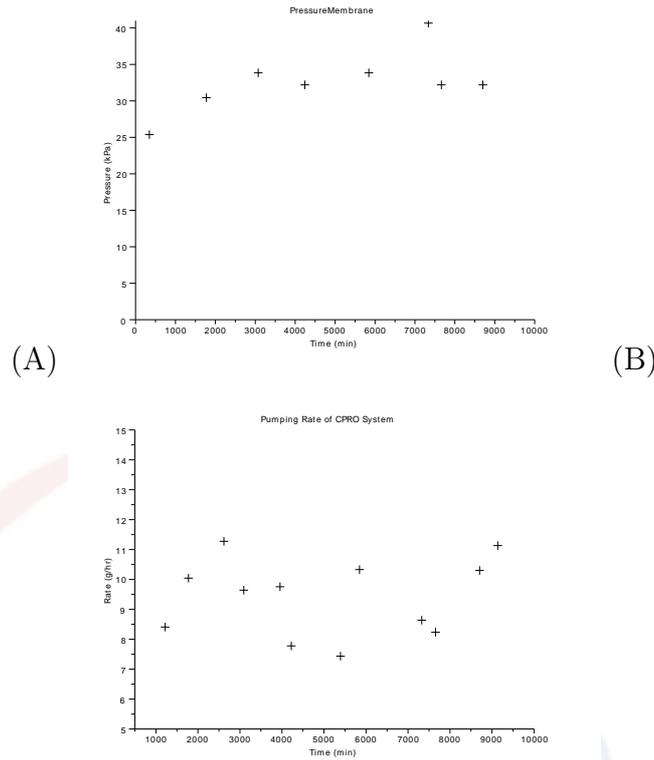
**Figure 4.1:** The variation of the salinities in the internal chamber (A) and external chamber (B) of the membrane assembly during a one-week operational run.

The data thus obtained are given in Figure 4.1. Notably, the variation of the salinities is limited, and the salinities vary around a relatively constant set point over a nearly one-week period.

### Power Output

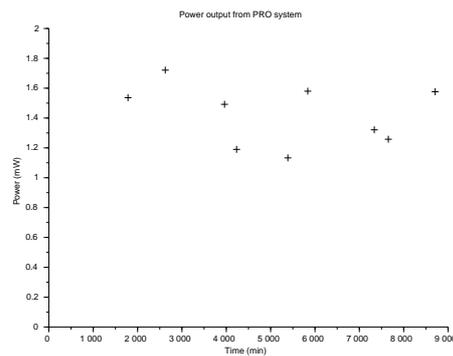
We measured the pressure of the external membrane chamber and the pumping volume during the same period. These data are depicted in Figure 4.2.

<sup>6</sup>We used a model CDH45 salinity probe manufactured by Omega.



**Figure 4.2:** The system pressure (A) and the pumping rate (B) during a one-week operational run of the VCPRO system.

These data can be combined to determine the power output of the VCPRO system. The power output is depicted in Figure 4.3.



**Figure 4.3:** The power output of the VCPRO system during a one-week operational run.

Notably, the power output varies around a relatively constant output averaging  $1.48 \pm 0.28 \text{ mW}$ .

A pressure relief valve was used to regulate the internal pressure in the place of the generator. This allowed the system to pressurize as it might while using a generator.

## Efficiency measures

There are two distinct areas of efficiency in this device. The first area of efficiency results from the generation of water from the input heat. A thermal, one-stage distillation device has a maximal water output of

$$V_{max} = \gamma \frac{\Delta E}{H_v} \quad (9)$$

given an energy input of  $\Delta E$  and an efficiency coefficient of  $\gamma$ . In our laboratory model, we measured our efficiency as  $0.52 \pm 0.012$ . As a result, we report our efficiencies as a ratio of the measured distillation conversion to the maximum in equation (9).

The overall efficiency of the device is the ratio of the energy in to the energy out. In our device, we input  $15W$  and produced approximately  $1.48 \pm 0.035 mW$ . This gives an efficiency of  $9.87 \times 10^{-3}\%$ . Since the Carnot efficiency is limited to  $6.49\%$ , this represents a corrected efficiency of the PRO system alone of  $0.152\%$ .

When we compare our system, which was limited to a total pressure of  $33kPa$  to the maximal energy output given by  $i\Delta MRT\Delta V$ , we find that our system produced  $9.42 \pm 0.236\%$  of the maximal total energy possible.

## Discussion

The goal of the VCPRO system is to enable the acquisition of an increased portion of energy generated through the osmotic process through the elimination of the power consumption of the pumping systems. This is possible through the creation of an alternative circulation process in which gravitational potential energy is used in lieu of internally generated energy. As a result, the increased energy output is limited by  $1 - \xi$ , as given in (8).

Our experimental analysis of the device centered around the creation of sustainable operating conditions within the device. As our data indicates, the internal conditions surrounding the membrane, the inner and outer chamber concentrations, the pressures in these chambers, and the power output, were all consistent. In particular, the values of these measurables varied around a stable point, generating time-based variations with a flat trendline. As a result, we infer that the operation of the VCPRO system is stable and can output energy on a continual basis.

Our system utilized a custom pressure relief valve which enabled liquid flow at high pressures. The pressure relief opened at a pressure of approximately  $33 kPa$ . This is well below the theoretical maximum pressure of the system given the saline concentrations on either side of the membrane. This pressure was chosen so as to ensure that the membrane and membrane chamber remained intact. As the chamber itself is constructed from acrylic pieces fused together with acrylic cement or epoxy and the membrane is not rated for high pressure, we chose to limit

the pressure during these runs. More robust membrane chambers and membranes would enable higher pressures and therefore greater energy generation.

During our test of the VCPRO system, we recharged the system and cleaned the system two times daily during the first half of the run and then reduced that to once daily during the second part of the run. As can be seen in Figure 4.1, a slight change in the concentrations inside and outside the membrane result as compared to earlier in the run. Despite this, our device continued to pump pressurized water at a power rating averaging  $1.48 \pm 0.28$  *mW* throughout the run. This rate of generation of pressurized water was too small to utilize for electrical power generation; a subsequent study may utilize pooling to enable power generation.

The number of recharge cycles can be used to estimate the amount of water used for recharging as compared to the amount pumped. The amount of water pumped per day is approximately  $240 \frac{mL}{day}$ . Each recharge cycle consumed approximately 118.2 *mL*. As a result, cleaning our system twice daily produced a yield of 50.4% while lowering the cleaning cycle to once daily produced a yield of 67.0%. As this number is a function of the salt flux through the membrane, it is expected that lower salt fluxes will produce higher energy yields resulting from longer pumping periods between cleaning events.

The increase of energy recovery of our VCPRO system more than doubles the reported yields of systems employed elsewhere commercially or academically. Though our yields are quite low for systems employing single-stage distillers, the system is simple, employs few moving parts (excluding the generator), and can passively generate power based on low temperature gradients. Since thermal gradients of this magnitude exist in many structures in the built world including homes, storage facilities, and office buildings, the potential for its use as a secondary, nearly passive source of power is reasonable. The system described here is not likely to require frequent maintenance, making it suitable for use in the developing or developed world.

## Conclusions

This paper describes a novel closed pressure retarded osmosis (CPRO) device. The current device is novel in that its vertical configuration removes the need for pressure pumps that generally absorb a significant amount of energy in a standard pressure retarded osmosis (PRO) system or a CPRO system. We described here the implementation of a laboratory scale vertical closed pressure retarded osmosis system (VCPRO). In our laboratory scale device, regeneration of brine concentration after dilution by effluent is accomplished using gravitational cycling. Cleaning of the feed solution is similarly accomplished using gravitational cycling. These two procedures maintain the concentration gradient across the membrane, enabling continued operation. The brine and distilled water sources are regenerated in the distiller which itself is driven by thermal gradients not exceeding  $30^{\circ}C$ . These thermal gradients may be routinely found in much of the built world, indicating that there is a significant potential for energy scavenging using this and

related systems.

This device operates with two unusual conditions. First, the membrane has saline water on one side and distilled water on the other side. The use of distilled water operating in a forward osmosis process is likely to extend the operating lifetime of the membrane to as many as twenty years (Desormeaux, 2014). At the same time, the device is operated at relatively low pressure on the distilled water side. This low pressure is an inhibiting factor for bacterial growth, and serves to limit fouling of the membrane. As a result of these two conditions, this device is a good choice for use in areas where replacement parts might be unavailable or infeasible. In particular, we believe that this device is a good choice for use in the developing world where replacement parts may be difficult or impossible to obtain.

We have not integrated an electrical power generator in the current system; we shall do so in the future so as to evaluate the theoretical and actual electrical power yields of the system. The new system will include a much larger membrane surface so as to enable a large flow rate under pressure. Future studies of this system will also include the integration of the system in a built structure, such as a shed or an attic. It is expected that the thermal gradients between such a structure and the outside world may exceed fifteen degrees resulting in a continual and permanent source of electricity.

## Acknowledgments

We would like to acknowledge the contribution of Ms. E. Jung who worked with us in constructing and testing the initial prototype.

## References

Alfaee, A. (2012) Forward Osmosis: Potential use in Desalination and Water reuse. *Journal of Membrane and Separation Technology*, 1, pp. 79-93.

Al-Shammiri, M. and Safar, M. (1999) Multi-effect distillation plants: state of the art. *Desalination*, 126, pp. 45-59.

Burgess, G. and Lovegrove, K. (2005) Solar thermal powered desalination: membrane versus distillation technologies. *Proceedings of the 43rd Conference of the Australia and New Zealand Solar Energy Society*, Dunedin.

Desormeaux, E. (2014), private communication.

Efraty, A. (2014). US Patent Application No. 20140007564. Washington, DC: U.S. Patent and Trademark Office.

Hong, S., Ryoo, W., Chun, M., Lee, S., and Chung, G. (2013). Desalination and Water Treatment: Numerical studies on the pressure-retarded osmosis (PRO) system with the spiral wound module for power generation. *Desalination and Water Treatment*, pp. 1-9. DOI: 10.1080/19443994.2013.821041

Kaleda, M. (2011). US Patent Application No. 20110044824. Washington, DC: U.S. Patent and Trademark Office.

McGinnis, R. and Elimelech, M. (2008) Global challenges in energy and water supply: the promise of engineered osmosis. *Environmental Science & Technology*, 42, pp. 8625-8629.

Miller, J. and Evans, L. (2006) Forward Osmosis: A new approach to water purification and desalination. Sandia Report, SAND2006-4634, Sandia National Laboratories, California.

Principles of Attic Ventilation, informational pamphlet from Air Vent, Inc. Downloaded from <http://www.airvent.com/pdf/literature/PAVbooklet.pdf> on 9 Sept. 2014.

Sharqawy, M., Lienhard, J., and Zubair, S. (2010) The thermophysical properties of seawater: A review of existing correlations and data. *Desalination and Water Treatment*, 16, pp. 354-380.



## ***Hospital Waste Management in Ondo State South West Nigeria***

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### **Abstract**

This study investigates the waste management practices in some selected hospitals in the densely populated regions of Ondo state. Five (3 public and 2 privates) hospitals were assessed, wards ranges from 2 to 10 and number of beds ranges from 12 to 84. This study shows complete absence of medical waste tracking, monitoring and testing programme in all the hospitals. In addition, institutionalized medical waste management plan were also absent from all the hospitals, only one had an abatement facility in form of mini-incinerator. However, open dump sites were seen within some of the hospital premises. Medical waste generation rates ranged between 0.38kg/bed/day and 0.97kg/bed/day to 0.7kg/bed/ward/day and 4.38 kg/bed/ward/day, while on average, a generation rate of 0.676kg/bed/day and 2.51kg/bed/ward/day were obtained. More so, it was also observed that numerous kinds of wastes generated were not separated into different bins but disposed in the same refuse bins. The most predominant methods of waste treatments practiced at the hospitals were burning and burial. All hospitals and other medical institutions in the state engage the services of the state government waste disposal board for their final collection and disposal of waste as there are no private waste contractors in the state.

Keywords: medical waste, disposal bin, incinerator, open dump, ward

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## Introduction

Municipal solid waste (MSW) generation is fast becoming a major challenge across the globe. MSW is the collection of all waste by both private and public authorities ranging from household (domestic), commercial, institutions and to industrial sources (Linderhof et al, 2001). In a bid to curb the increasing rate of MSW, implementation of waste minimization programme was made (Visvanathan and Tränkler, 2003). Currently, researches have shown problems of co-disposal of municipal solid waste like hospital waste with pathogenic and infectious materials; commercial wastes like used oil, batteries and paints; inorganic industrial wastes like acids, heavy metals, and asbestos; and organic industrial wastes like solvents, pesticides, have particular hazards on the waste pickers (scavengers) and people living within the dump site areas (Basse et al, 2006). Solid waste in Nigeria poses many environmental problems, such as blocking of waterways and drainage channels (resulting to flooding), air pollution (offensive odours), and contaminants dangerous to public health. Many developing countries like Nigeria, India, Cameroon, Malaysia etc. employed open dumps usually referred to as landfills for their solid waste disposal (Aderogba & Afelumo, 2012). However, waste depositions in open dumps results in uncontrolled emission of landfill gas (methane) which do not only pollutes the environment but also affects human's health (EPA, 2012).

Medical establishment such as hospitals, medical institutes and laboratory are among the largest creation of MSW on a per capita basis. World Health Organization (WHO, 2007) revealed that the aim of health-care establishment to its worker, patients and the public is to make medical waste management safe and sustainable. However, health-care waste can result in serious harm if not managed correctly. For instance, WHO (2000) estimated that injections with contaminated syringes caused 21 million hepatitis B virus (HBV) infections (32% of all new infections), two million hepatitis C virus (HCV) infections (40% of all new infections) and 260 000 HIV infections (5% of all new infections). In addition, health-care activities generate significant amounts of hazardous waste such as mercury and expired pharmaceuticals, as well as large amounts of general waste (WHO, 2007).

In Nigeria, solid waste management started in the early 1970s as a result of crude oil discovery which in turn led to urbanization and industrialization and has resulted to increase in the volume of waste generated. Thus, in 1977 Lagos State Refuse Disposal Board (LSRDB) was instituted as the first waste management outfit in West Africa (LAWMA, 2013). In addition, Federal Environmental Protection Agency (FEPA) classified health care (medical) waste in Nigeria as infectious waste which include, culture and stock of infectious agents, pathological waste, waste from surgery or autopsy that were in contact with infectious agents, sharps (hypodermic needles, syringes, scalpel blades), waste from human blood and products of blood and laboratory waste (Basse et al., 2006). WHO (1999) defines Health Care Waste (HCW) as the total waste stream from a healthcare or research facility that includes both potential risk waste and non-risk waste materials. In addition, medical waste can also be defined as any solid waste generated in the diagnosis, treatment, or immunization of human beings or animals, in related research, production or testing's, of biological form from all types of health care institutions, including hospitals, clinics, doctor (dental and veterinary doctor) offices, and medical laboratories (Manyele, 2004).

The aim of this study is to study investigates the waste management practices in some selected hospitals in the densely populated regions of Ondo state, South West Nigeria.

## **Materials and methods**

### **Study Area**

This study was conducted in Ondo State, South West geopolitical zone in Nigeria. The state covers an area of 15,195.2 square kilometers and a latitude of 7<sup>0</sup> 10” north and longitude of 5<sup>0</sup> 05” East. This shows that the state lies entirely in the tropics. It occupies an area of 14, 788.723 square kilometres with estimated population of 3,460,877 (Nation Population Census, 2006) and a population density of 218 people per square kilometer. The state accounts for 2.5% the country’s population. The temperature throughout the year ranges from 21°C to 30°C with humidity relatively high. The annual rainfall varies from 2,000mm in the southern parts to 1,150mm in the northern areas. The rainfall decreases in amount and distribution from the cost to hinterland. Figure I show the map of Ondo State and its various local government areas.

**Methodology:** Five different hospitals were selected for this study; 2 privates and 3 public. These hospitals are located in different local government area of the state. Study commenced with the current state of waste management to recycling and disposal activities in each hospital. Information on each hospital was confirmed from the directors of the hospital by interviews. Furthermore, the use of structured questionnaires, one on one discussions and participant observed strategy was employed. This study lasted for 6 months July to December 2013. The questionnaires simple and objective questionnaire based on the guidelines of the safe management of waste from health care facilities (WHO, 1999) were self-administered and interviews were conducted among officers in charge of medical waste in each hospital. Health care managers, nurses, nursing assistants and waste handlers within and outside the hospitals were among those interviewed. The questionnaires contained information on medical waste generation, segregation, collection, storage, transportation, treatment and final disposal.

### **Ethnic consideration**

Permission was obtained from Ondo State Hospital Board Management Akure, Ondo State and also each hospital before conducting the research.



**Figure 1:** Map of Ondo State (Source: ond\_map.png)

**Table 1:** Statistics of Surveyed Hospitals

Hospital	Description	Type	Number of wards	Numbers of beds
Hospital A	Located in a medium to high densely populated area of Ikare of the metropolis. The treat both general and few specialized case	Public	10	84
Hospital B	It is located in the low to medium densely populated area of the state, Iwaro-Oka. It treats general cases.	Public	5	28
Hospital C	It is located at the outskirts of the ancient town of Owo Kingdom. Owo is a densely populated area. It treats general cases.	Public	4	16
Hospital D	A specialist hospital located in medium to high densely populated area of the state capital in Akure. It treats both	Private	6	27

	general and specialized cases.			
Hospital E	Located in medium to high densely populated great of the state capital in Akure. It treats general cases.	Private	2	12

## Results

Table 2 shows the characterization of waste in the hospitals while table 3 shows the waste management practices used each hospital. The hospitals were measured with three principal criteria as stipulated in the National Guidelines for the presence or absence of a tracking programme, monitoring and testing and the existence of any Medical Waste Management Plan (MWMP) in place.

Medical waste generation in each hospital (kg/bed day and total waste generated in kg/day) is shown on Table 4. Medical waste generation ranged between 0.38kg/bed/day and 0.97kg/bed/day to 0.7kg/bed/ward/day and 4.38 kg/bed/ward/day, while on average, a generation rate of 0.676kg/bed/day and 2.51kg/bed/ward/day were obtained.

### Internal Medical Waste Collection and Storage

In the studied hospitals, the cleaners and nursing assistance are responsible for the collection of medical waste from wards to the various storage centres in all the hospitals. Collections of medical waste from the wards to the deposal centres are done mostly three times daily. The frequency of waste collection from internal storage facilities by external waste collectors is irregular. Many of the cleaners confirmed that general collection by Waste Management Board could be once or twice a week in private while in public hospitals it is sometime collected once in a month or even once in more than a month. Summary of waste collection frequency is shown on Table 5

Table 2: Solid waste compositions from the hospitals

Contaminated waste	Description
Domestic waste	Food leftover, used toiletry, food container and used office papers.
Glass	Pasteur pipettes and broken glasses, disposable culture dishes, specimen containers.
Sharps	Disposable needles & syringes, scalpel blades
Waste from surgery and autopsy	Soiled dressings, sponges, drapes, lavage Tube, drainage sets, under pads and surgical gloves.
Pharmaceutical wastes	Expired drugs and chemicals or spoilt and contaminated drugs.
Dialysis unit wastes	Tubing, filters, disposable sheet, towels, gloves, aprons, and laboratory coats.
Contaminated equipment	Equipment used in patient care, medical

Other types of waste

laboratories, research

Specimen containers, slides and cover slips,  
disposable gloves, lab coats and aprons.  
Cultures, stocks of infectious agents from clinic  
research



**Table 3:** Medical Waste Management Consideration

Designation	Hospital type	Tracking program	Monitoring & Testing	Abatement facility	*MWMP
Hospital A	Public	Absent	Absent	None	Absent
Hospital B	Public	Absent	Absent	None	Absent
Hospital C	Public	Absent	Absent	None	Absent
Hospital D	Private	Absent	Absent	Mini incinerator needle	Absent
Hospital E	Private	Absent	Absent	None	Absent

\*MWMP: Medical Waste Management Plan

**Table 4:** Medical Waste Generation in Surveyed Hospitals

Designation	Hospital type	Number of beds	Total waste done (kg/day)	Generation rate kg/bed/day	Generation rate kg/ward/day
Hospital A	Public	84	54.0	0.64	1.80
Hospital B	Public	28	10.5	0.38	0.70
Hospital C	Public	16	15.3	0.96	3.80
Hospital D	Private	27	26.3	0.97	4.38
Hospital E	Private	12	5.6	0.47	1.87
Total	5	167	111.7	0.68	2.51

**Table 5:** Frequency of Waste Disposal in Various Hospitals

Hospital	Hospital type	Total waste generated/day	Frequency of disposal	Frequency of collection per day
Hospital A	Public	54.0	Twice in a month	Three
Hospital B	Public	10.5	Once in a month	Three
Hospital C	Public	15.3	Specific	Three
Hospital D	Private	26.3	Twice in a week (Monday & Tuesday)	Three
Hospital E	Private	5.3	Once in a week Tuesday	Six

## **Waste Treatments and Disposal**

The most prevailing method of waste treatments practiced at the hospitals were burning and burial of medical waste. It was also observed that no medical infectious waste was excluded from these practices. In addition, another common practice noted at some of the hospitals was the disposal of infectious and regulated waste types seen on open land within the hospital premises and canal very close by. This kind of practice is a very poor medical waste management practices which usually pose as risk to public health within and outside the hospitals. Only one of the private hospital visited had a mini-incinerator used for disinfecting used needles and it is the most outstanding out of the five. None of the hospital engaged the service of environmental officers to oversee their treatment and disposal of its medical waste. More so, hospitals employ the services of public waste collectors for their waste collection and final disposal to government authorized dumps.

## **Discussion and Conclusion**

Waste management practices in each hospital as revealed in this study shows complete absence of medical waste tracking, monitoring and testing programme in all the hospitals. More so, institutionalized medical waste management plan were also absent in any of the hospital. From the observation regulated domestic waste constitutes more than 50% of the total medical waste stream. More so, it was observed from this study that none of the hospitals keep the records of waste generated either as volume or weight. Waste can be measured in two ways; volume and weight. However, weight has advantages over volume because of its consistency and accuracy. Linderhof et al., (2001), did a study on volume and weight and they reported that weight is effective and cheaper in pricing than the volume from composted waste and other non-recyclable waste.

In addition, it was observed that dump sites are located within some of the hospital premises. Since the hospitals had no waste data, many of the bins were therefore weighted and generated data were recorded and evaluated. This may not be accepted as an absolute value for the entire metropolis due to existence of multiplicity of healthcare facilities within mega city. The total volume of medical waste generated in all the hospitals was 111.7kg/day. This translates to 2.73kg/bed month and calculated total waste volume of 3,351kg/month by all hospitals. Because of the poor policy on medical generation in the state it was difficult to get the volume of infectious waste, sharp and chemical waste. This result is similar to the ones obtained by Longe and Williams (2006) and Bassey et al., (2006). More so, the result shows that the hospital visited do not follow the guidelines on health care waste management as shown by Mokuolu (2009).

The study also revealed poor handling of waste by the workers an act very dangerous for health staff dealing with waste because they are exposed to high occupational and health hazards. The most important steps in reducing the volume of hazardous/infectious waste from other municipal solid waste is by waste minimization and segregation (Mukuolu, 2009). This method will enable each hospital to know the volume of waste generated and it will make assessment more accurate. In addition, the separation method should be accompanied by the use of labelled or coloured bin bags and boxes for collecting sharps. Longe et al., (2006) revealed that separation of

hazardous/infectious waste from other kind of waste is the right step to reducing health risk.

Although the public hospitals visited employed the use of colour coding bin system which is in contrast to the private ones, but the method is poorly handled. The coloured bins and how they are used are; green disposal bins for collection of sanitary pad; red bins for collection of sharps; blue bins for collection of blood stained cottons, gauze and bandage. Thus it was observed that some hospitals had the coloured code system bins but do not follow it uses accordingly. In one of the hospital, sharps (e.g. needles) were seen stored in medical waste boxes prior to treatment and before final disposal.

One of the barriers to medical waste coding system in State is that there is no uniformity in the hospitals colour coding system. This is similar to Longe et al., (2006) that the existing national Guideline is silent about it this important aspect of the MSWM. Waste collection frequency days should be reviewed, because generated medical waste in various hospital were left for days even weeks around the hospital premises. These poor practices should be looked into not only by the hospital staff but also the Ministries of Environment and Health. However, these unpleasant practices are common with the public hospitals. This could be as a result of the numbers of patients that visits the government (public) hospitals and also because many of the hospitals are less funded by the government such that the hospital management needs to generate fund to run the hospitals. In contrast, the private hospitals stood out because they employ the service of Government Waste Authorities adequately, pay as you throw (PAYT). But in the public hospitals, one of the areas visited was still waiting for the waste authorities to come collect the waste expect the government to pay since they themselves are owned by Government.

In conclusion, this research has revealed some of the dangers associated with medical or healthcare waste in our hospital and environment at large, it therefore necessary that the authorities in charge of should enforce the healthcare waste management plan so that the society can be free from risk associated with medical waste and our environment can be a sustainable place for all.

### **Recommendations**

Licensed private waste collectors services should be encouraged and employed in the state. This will help the quick collection of waste and the frequency of waste collection in hospitals will improve. There should be adequate legal backing and sanction in the case of non-compliance by erring hospitals, health institutions and clinic of treatment dealing with infectious and sharps wastes. Also, there should be availability of adequate monitoring facilities. With this, the control of medical waste can be fully achieved. Finally, medical waste handlers within health care facilities should be trained on methods and new techniques of medical waste management and in hazardous effects of medical waste using WHO guidelines.

## References

- Aderogba, K. A and Afelumo, A. A. (2012). Waste Dumps and their Management in Lagos Metropolis. *International Journals of Learning and Development* Volume 2 No. 1 page 1-16.
- Bassey, B. E., Benka-Coker, M. O., and Aluyi, H. S. A. (2006). Characterization and management of solid medical wastes in the Federal Capital Territory, Abuja Nigeria. *African Health Sciences* 2006; 6(1): 58-63
- Environmental Protection Agency, (2012). Issues updated, Achievable Air Pollution Standards for Oil and Natural Gas. Retrieved from: <http://www.epa.gov/airquality/oilandgas>.
- Lagos State Waste Management Authority (LAWMA, 2013). Who we are [http://www.lawma.gov.ng/insidelawma\\_whoare.html](http://www.lawma.gov.ng/insidelawma_whoare.html)
- Lehman, S. (2010). Resource recovery and material flows in the city: Zero waste sustainable consumption as paradigms in urban development. *Sustainable Development Law and Policy*, 11, 28-38.
- Linderhof, V., Kooreman, P., Allers, M. and Wiersma, D. (2001). Weight-based pricing in the collection of household waste: the Oostzaan case. *Resource and Energy Economics*, 23:359–371.
- Longe, E. O. and Williams, A. (2006). A preliminary study on medical waste management. Management of solid medical wastes in the Federal Capital Territory, Abuja Nigeria.
- Manyele, S.V. (2004). Medical Waste Management in Tanzania: Current situation and the way forward. *African Journals on Environmental Assessment Management*. 8 (1): 74-99.
- Mokuolu, O. A. (2009). Health-Care Waste Management. Seminar presented in Society for Quality in Health-Care in Nigeria. Retrieved from [http://www.Sqhn.org/./HCWM\\_SQHN](http://www.Sqhn.org/./HCWM_SQHN)
- Ondo State Diary (2012) produced by Ondo State Ministry of Information.
- Visvanathan C. and Tränkler J. (2003). Municipal Solid Waste Management in Asia- A Comparative Analysis, *Workshop on Sustainable Landfill Management Chennai, India*, pp. 3-15
- World Health Organization. (1999). Health Care wastes. Available at [http://www.who.int/water\\_sanitation\\_health/Environmental\\_sanit/MHCWHanbook.htm](http://www.who.int/water_sanitation_health/Environmental_sanit/MHCWHanbook.htm). Retrieved from [http://www.who.int/water\\_sanitation\\_health/Environmental\\_sanit/MHCWHanbook.htm](http://www.who.int/water_sanitation_health/Environmental_sanit/MHCWHanbook.htm).

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## ***Human Right to Water: Public Policies and Warranty of Adequate Food in Brazil***

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### **Abstract**

This work intends to approach the human right to water, established as an essential component of the adequate food, knowing that the lack of drinking water covers more than 1.4 billion people around the world, according the United Nations (UN), 36 million of them only in Latin America, as data from World Bank in 2014. In Brazil, although it is provided implicitly in several written rights, such as the right to life, to food and to a balanced environment, the right of access to drinking water is worrying. Although it owns 60% of the Amazon Basin, which drains by a fifth of the volume of freshwater in the world, more than 55% of Brazilian cities may have deficits in water supply in 2015, according to data the National Water Agency (ANA), what has been happening in recent years so frequently in big cities like São Paulo. This study also aims to evaluate the treatment given by the Brazilian government to the warranty of the access of the water as a way to provide food security to people with less purchasing power. To achieve this goal, we will seek to discuss the adequate nutrition as a social right already enshrined in the Brazilian Constitution since 2010, having in the water the essential component for an adequate alimentation and to the assurance of the access to this right and ensuring access to that right under the public policies of the Brazilian government. Keywords: Human right to water; adequate food; public policy; food security



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## **Introduction**

Although it has been subject of declaration of the United Nations in 1992, the human right to water is still not officially contemplated in the most important statements of rights of the Planet. The absence of legal provision contributes to the Nations fail to consider the priority of supply, in a very serious moment in the world where the lack of access to safe drinking water still reaches over 1.4 billion people, according to the United Nations (UN), while 2.5 billion people are still without access to improved sanitation and only 63% of the population has access to sanitation in good conditions, according to the United Nations Children's Fund (UNICEF) report.

As a component of human nutrition, water must be understood as essential to the adequate satisfaction of the nutritional needs of the human being and, therefore, treated with the same level of demand for a dignified survival. In this respect, it should be addressed by the public policies of governments, endowed with drinkability and continuous supply.

In Brazil, where there are still thousands of people without access to safe drinking water in cities and in rural areas, the possibilities of natural uptake are reduced every year, due to weather problems and the lack of sufficient investments to improve the area.

This study examines the potential and the regulatory legislation of the water in Brazil, and public policies aimed at providing potable water in sufficient quantity in the context that is considered indispensable to nutrition and, therefore, part of the human right to adequate food.

### **I. Human Right to Water - The Construction of a New Right**

The rights of man are historical rights born in certain circumstances (Bobbio, 1992), characterized by struggles in defense of new freedoms against old powers, and born gradually, not all at once, neither once and for all. The world produced through the ages almost a dozen normative documents of protection of human rights until the emergence of the Universal Declaration of Human Rights in 1948: still in the Middle Ages, Magna Carta (1215), and later, the Petition of Right (1628), the Habeas Corpus Act (1679) and the Bill of Rights (1689); after this, the Virginia Declaration of Rights (1776), the Declaration of the Rights of Man and of the Citizen (1789); and in the twentieth century, the Declaration Of Rights Of The Working And Exploited People (1918), at the beginning of the Soviet Union. Consequence of the Declaration of 1948, the UN General Assembly redacted the International Covenant on Social, Economic and Cultural Rights and the International Covenant on Civil and Political Rights, prioritizing the principle of freedom (1966), then the Vienna Declaration and Programme of Action (1993) and the Rome Statute, later responsible for creating the International Criminal Court (1998) (Comparato, 2010)

However, in all these documents, the right to potable water was not specifically included, although the Universal Declaration of Human Rights refers in art. 25, the right to a standard of living that will ensure health and well being to the family, including food, among others (UNITED NATIONS, 2014).

The concern of the United Nations on this issue led the organization to, among other actions, edit, in 1992, the Universal Declaration of Water Rights, considering water as part of the heritage of the planet and assigning to everybody the responsibility for its conservation, and in 2010, the Organization issued a Resolution declaring as a human right clean and safe water and sanitation (UNITED NATIONS, 2014).

Although it seems to be infinite to human, animal and plant life, because it covers two thirds of Earth's surface, the sufficiency of water for the Planet has been reason for restlessness and insecurity to keep the biological balance of humans. Lack of access to safe drinking water still reaches more than 1.4 billion people worldwide, according to the United Nations (UN), and they are 36 million only in Latin America, where 45% of water is lost before reach the consumer, according to data collected by the organization with the World Bank (World Bank, 2014).

The future seems even more uncomfortable: World Energy Council estimates that water consumption in Latin America must raise 330% until 2050, due to the increase of energy generation expected in 550%, with a similar situation in Africa, where energy production will grow 700% and the water use 500% in the same period. The demand for water will increase due to the cooling of nuclear plants and fuel extraction and refining besides hydroelectric power plants (WORLD ENERGY COUNCIL , 2014).

A report from the United Nations Children's Fund (UNICEF, 2012) in 2012 found that only 63% of the world population has access to sanitation in good condition. That number is expected to reach only 67% by 2015, according to estimates of the organ, far from the 75% targeted by MDG (Millennium Development Goals). Worldwide, the agency estimates that 2.5 billion people are still without access to an improved sanitation.

In Brazil, 19 million people who live in urban areas don't reach drinking water. Another 21 million people that live in rural areas also don't access clean water. Furthermore, only 46% of Brazilian households are endowed with sewage collection service (FUNASA, 2010).

Therefore, it is notorious that one of the main and most serious environmental problems the world faces, because it is extremely limiting, is the shortage of drinking water, which, together with bad distribution, the unconscious use and several forms of pollution leads the impairment of life on Earth. The desertification and water shortages are the most serious problems to be faced by Third World countries this decade, when one fifth of the world's population humanity today no longer has access to drinking water (SANTOS, 2001). Therefore, it is a reality that shows the emergence and thus requires the regulation of a new fundamental right: the right of access to drinking water.

The right to water is provided implicitly in many of the rights protected by laws such as the right to life, to enjoy a standard of living adequate for health and human welfare, to protection against diseases and to access to food. All of these rights already ensured in the legal system reinforce the need for States to recognize water as a fundamental human right. In the globalized world, international debates have emphasized the importance of recognizing access to water as a right of the person in

equitable access to a minimum quantity, once it is indispensable as a condition for accessing other human rights, such as, right to good quality of life, to health and welfare, as well as to civil and political rights.

Some Latin American countries already provide the right to water in their Constitutions. This is the case of Ecuador, whose 2008 Constitution (ECUADOR, 2008) contemplated the so-called "Good Living" (as they call in their native indian language, Sumak Kawsay) as the new basis of the ethics of development, characterized by values such as sovereignty, legal equity, equality and the rights of nature (WOLKMER ET AL, 2012). The document registered in its 3rd. article, the guarantee of the right to water, among others, as an obligation of the state towards its citizens. Bolivia has equally included in its 2009 Constitution, the guarantee to every one of the fundamental right to water, prohibiting the concession or privatization of its exploration and distribution (bolivia, 2009).

In Brazil, although it is provided implicitly in several positivized rights, such as the right to life, to food and to a balanced environment, the right to drinking water is not provided in the law explicitly.

## **1.2. Human Right to Adequate Food (HRAF)**

Established since the Universal Declaration of Human Rights, the right to food was the object of the United Nations Special Rapporteur on the Right to Food in 2002, which is taken as a human right inherent to everyone, who should have regular, permanent and unrestricted access (UNITED NATIONS, 2014). Food can be defined as any solid or liquid substance which can be ingested by a person using it to satisfy their physiological needs (NUÑES SANTIAGO, 1992). Internationally, the International Covenant on Economic and Social Rights recognizes by its States Parties the fundamental right of all people to be protected from hunger, assuming these States the task of promoting actions to improve the production, conservation and distribution of food.

In Brazil, the Federal Constitution inserted the right to food in its 6th. article, by the Amendment number 64 of 2010. Before that, the HRAF was implicit in other constitutional provisions such as the right to health, to the minimum wage, to social assistance, to education, to school feeding, to land reform, among others. There is also in article 1st. III, human dignity as one of the fundamental principles of the Federative Republic of Brazil.

The report of the National Council for Food and Nutrition Security (CONSEA), in 2010, states that the HRAF is realized when every person has guaranteed and uninterrupted access to adequate and healthy food for own and sustainable means. The strategies for achieving the HRAF are many and presuppose the guarantee of other human rights. It is responsibility of the United Federation States the obligations to respect, protect, promote and provide human rights, since it is up to them to guard and the execution of the state budget. Thus, the obligation to ensure the realization of the HRAF implies in allocating public budgets and implement universal public policies that include progressively (and primarily) the population vulnerable to hunger and poverty.

### **1.3. Water as a component of the adequate food**

Water is indispensable as an essential component to adequate food. Great part of food contains high levels of water, but its consumption can't be ignored, considering only food, because water is necessary to every body function. The lack of water causes more intense effects in the body to perform certain tasks than any others. It is the most present inorganic constituent living matter: about 60% of a man's weight is constituted by water and in certain aquatic animals, this percentage reaches 98% (VON SPERLING, 1992).

The body has no conditions to storage water, so the amount of water lost must be replaced to ensure the proper functioning of the body and the maintenance of health. It is also because of this that the nutrition without the consumption of water does not complete the requirements of the body, being insufficient just the water contained in certain kinds of food. Water carries nutrients such as amino acids, glucose and vitamins, and is the medium in which all chemical reactions occur, having among its functions in humans to maintain the (internal) core temperature during exercises (GOWDAK, 2010). The water, therefore, includes all the items that make up an appropriate diet and can't be divorced from this, so that the access to clean water and food in good quality implies in achieving the basic needs of life's maintenance in human beings.

## **II. Water Geography in Brazil**

Brazil boasts a privileged position in relation to water resources in the world. The country holds 12% of the fresh water on the planet, considering the average annual flow of its rivers, 180 thousand cubic meters per second. Brazil holds 60% of the Amazon basin, which flows around a fifth of the volume of freshwater in the world. But the amount varies according to the region.

It means that even in areas of high river water availability, such as the Amazon (74% of total) there are periods of drought. Even more serious is the situation of the semiarid part of some regions in which the phenomenon of drought has great influence on water availability and life quality. The Amazon region holds 73.6% of the national surface water resources and only 5% of the population (BRAGA JÚNIOR ET AL, 2008)

### **2.1. Drainage basins**

A drainage basin or watershed is an area of natural uptake of precipitation water that converges the flow to a single exit point. It consists of a set of surface sections and a drainage network formed by streams of water that converge to result in a single bed in its discharge, or to the point where all the discharge converges the basin (TUCCI ET AL, 1997).

The country has eight major river basins and it is divided into 11 regions, as envisaged in the resolution n. 32/2003, of the National Water Resources Council, comprising the basins of each region. Brazilian states have different divisions for their territories for the purpose of water resources management, applying different criteria.

São Paulo has 22 units of river management, Paraná, 15, Minas Gerais, 36, among others.

Studies of the National Water Agency (ANA) in 2004 on demand and availability of water, demonstrated the existence of serious problems of supply for several uses, from high demands on the availability of water and courses whose quality is compromised by pollution. This increases the marginal cost in order to answer urban demands in metropolitan areas, especially in face of the need to bring water to the needy region of neighbor watersheds. At least two metropolitan regions in Brazil, São Paulo and Rio de Janeiro use water to their populations that are brought from transpositions of neighbor basins.

Thus, the water management in Brazil faces the challenge of managing the demand as well as increasing the supply and assurance of provision in hydrographic areas with low water availability, added with the need for better quality and reduced domestic and industrial pollution. In the field of the industrial pollution the system of control has reduced the rates through fines, but the same does not occur with domestic pollution produced by sanitation companies, which do not take the account of treating more than 15% of the sewage toilets before discard them in urban rivers. In addition, the country struggles with diffuse source pollution, in urban and rural areas, also a problem yet to be solved (BRAGA JÚNIOR ET AL, 2008).

## **2.2. Groundwater**

Brazil has underground water reserves yet to be exploited. It owns a part of the Guarani Aquifer, the largest source of fresh groundwater border in the world. The Guarani Aquifer System spreads over an area of approximately 1.1965 million sq. km. It is located in east central portion of the South American continent, and it is distributed through the territory of four countries: Argentina, Paraguay, Uruguay, and Brazil, where it is located the largest portion, 71% of the total, equivalent to approximately 840 800 sq. km.

The aquifer is dispersed across eight Brazilian states: Mato Grosso do Sul, Rio Grande do Sul, São Paulo, Paraná, Goiás, Minas Gerais, Santa Catarina and Mato Grosso. The sandy rocks are intersected by basaltic rocks and the sandy part has between 200 and 800 feet thick, reaching up to 1,800 feet deep, emerging in various parts of the region which it stretches. This depth causes a significant variation in water temperature, emerging in places at 65 degrees Celsius and in others in ambient temperature, hovering near 20 degrees Celsius (RIBEIRO, 2008).

## **2.3. Water crisis**

Although it holds a privileged position in the world due to its water potential, more than 55% of Brazilian cities may have deficits in water supply in 2015, according to data from a study conducted in 2011 by the National Water Agency (ANA), what has been happening in recent years so frequently in big cities like São Paulo. The study shows that 84% of the cities require urgent investments to adapt their production systems of drinking water, and 16% need new springs (ANA, 2014). The same study shows that investments in the Southeast and Northeast regions are over 16.5 billion dollars and the lack of works in fountains and distribution systems may cause a

breakdown in the supply of the region, which must focus 72% of the Brazilian population in 2025.

The water supply and sewerage services in the great Brazilian urban concentrations present precarious conditions, due to the excess of domestic and industrial pollution, occurrence of contamination of water sources when there are urban flooding, besides the increasing demand for water (TUCCI ET AL, 2000). This leads to a severe reduction of water levels in the near future. The table in the result of the deficient management by local authorities and the absence of integrated perception of the environment, which leads to degradation of the quality of people's lives, aggravating the diseases and creating a collapse of the activities of trade and industry (PESCE ET AL, 2000).

There is water shortage in many cities of the country, caused by reduced levels of the sources of supply. São Paulo, the largest city in Brazil, with an estimated population of 43.6 million inhabitants, faces one of the greatest periods of water restrictions in its history. The authorities do not assume but consumers perceive important changes in the quality and quantity of water reaching to their homes (IDEC, 2014).

### **III. Public Policies of Access to Water and the Warranty of Adequate Food in Brazil**

#### **3.1. Treatment and distribution of water policy**

Drinking water reaches Brazilians' homes in urban areas through the supply made by government-owned corporations in cities and states, but in some of them, this task falls to private sanitation companies. The water is taken from natural springs, in adequation to quality potability standards required by Brazilian rules, and then transported to the cities and towns, according to their needs.

##### **3.1.1. Brazilian legislation**

Brazil has one of the most advanced legal systems of the world with regard to water management. The Brazilian Water Law (Law No. 9433/1997), which created the National Water Resources Policy, considers water as a public good and as a limited resource and endowed with value. Among other things, the Act disposes about the granting of rights of use of natural water resources for the economic activities that require large amount of water.

The National Water Resources Policy (PNRH), established by the Water Law, established as a main objective, to ensure to current and future generations the necessary water availability, in appropriate standards of quality for the respective uses in addition to prevention and defense against critical hydrological events and sustainable development, promoting the rational and integrated use of water resources.

The Act also establishes standards to ensure civil, criminal and administrative supervision, including the obligation to compensate damages, responsibility for criminal acts and fines. But still forms of realization of the fundamental right to water are to be instituted, imposing positive benefits to the State, are such, basic sanitation,

provision of safe drinking water in sufficient quantity and the assurance that in situations of scarcity, priority use of water resources will be effectively for human consumption and watering livestock.

The Water Resources Policy also established the position of the "paying user", which affords the payment for the use of waterways to launch effluents (liquid discharges), as industries or cities that throw their effluents in rivers or lakes. Payment is made according to the type and quantity of effluent released. The user also has to respect the rules that ensure the preservation of national water resources, classified by the National Environmental Council (CONAMA) in nine classes of freshwaters, brackish and salt marshes throughout the national territory, as are its main uses.

### **3.1.2. National Sanitation Plan**

Approved at the end of 2013, the National Council of Cities, the National Sanitation Plan (PLANSAB) provides an integration of basic sanitation services, four components: drinking water supply, sanitation sewage, street cleaning and solid waste management, and drainage and management of urban storm water. As ensured in the Law of National Guidelines of Sanitation (Law 11,445/2007), the PLANSAB should be reviewed annually and revised every four years.

It is the first Plan built in a democratic and participatory way between government, society and public and private agents operating in the water sector, and the representation of the United Nations in Brazil. There was a participation process coordinated by the Ministry of Cities and an Interagency Working Group (GTI) established by the Presidency of the Republic, and also approved by the National Health Council (CNS), the National Water Resources Council (CNRH), National Environmental Council (CONAMA) National Council of Cities (Concidades).

The goal is to invest 508.5 billion reais in works of drinking water supply, collection and treatment of sewage and waste, and in actions of drainage in the period from 2014 to 2030. Investments shall be afforded in 59% by the Federal Government, with the remaining 41% under the responsibility of state and local governments, providers of sanitation services, private sector and international organizations, among others. The PLANSAB expects to achieve in the next 20 years 99% coverage in drinking water and 92% in sanitation, besides the universalization of collection of solid waste in urban areas and the lack of landfills or open dumps across the country sky BRASIL, MINC, 2014).

### **3.2. Access to water and assurance of adequate food**

The access to clean drinking water is still poor in Brazil, more in some regions than in others, considering the factors regularity, quality and quantity. Data from the Brazilian Institute of Geography and Statistics (IBGE) show that the water supply in permanent households was 81.4% in 2010 (IBGE, 2014), with the goal of reaching 84% in 2015, which is already impaired by the lack of investments, pollution and inadequate management that compromises springs. Inequalities between peripheral regions and major cities persist and it can be observed numbers slightly above 30% of water supply and sanitation among the poor.

It is verified that the progress in the access to improved drinking water sources in Brazil is very slow compared to population growth and other indexes. In the period from 1991 to 2010, the raise in the number of people with access to treated water supply per household was only 13%, jumping from 68 to 81% in urban areas and there are still 33 cities across the country that do not count on network water supply. In the same period, the Brazilian population grew twice, 26%, from just over 140 million to over 190 million people.

The United Nations, in the United Nations Special Rapporteur on the Right to Food (UNITED NATIONS, 2014), refers to the availability, quality and accessibility of food to meet the requirement of an adequate feeding. The Organization refers to the economic and physical accessibility and stability of the food supply. It is considered that people should have access to resources needed for an adequate nutrition throughout all the year and it has to be available to all people, whether healthy or sick, infants, prisoners, among others, and for those living in areas of difficult access, as armed conflicts, natural disasters, wars and indigenous villages. Moreover, it implies in availability and access to food in a stable manner, on a regular and ongoing way throughout the year.

Despite of that, and all the legal structure the country has in relation to water as a component of adequate nutrition, public policies that aim to guarantee these rights in Brazil are still not enough to prevent that a relevant part of the population be deprived of such access, because even when there is supply, in many regions of the country it has no accessibility and quality throughout the whole year.

During periods of drought the supply is reduced and the quality is compromised. Data from National Statistics Institute, show that in the other regions, the supply is available for only part of the population, and in others, this service simply does not exist yet.

## **Conclusion**

The study served to demonstrate that, although water is an essential component to the adequate food, its regulation as a human right is far from being realized. Under the provision of drinking water in the world, it was found a worrying situation, especially in Brazil, where there are large amounts of water, but in remote areas, far from urban centers, where access is still precarious in many cities.

Not only in Brazil, but in a considerable part of Nations, it is seen that the Millennium Goals, established by the United Nations regarding to improving the supply of potable water, will not be achieved. Holder of most of the Guarani Aquifer, one of the world's largest underground reservoirs, and even with investments in public policies in recent years, including the establishment of the National Basic Sanitation Plan, Brazil still needs to invest large sums to equip sufficiently the system of collection, treatment and supply of drinking water for its inhabitants.

The Brazilian government has not, therefore, achieving the obligation to ensure the human right to adequate food, once water, one of its main components, is not yet available to all the inhabitants.

## References

- BANCO MUNDIAL. *O que faz o mundo perder 260 bilhões por ano?* Disponível em: <<http://blogs.worldbank.org/latinamerica/es/o-que-custa-ao-mundo-us-260-bilh-es-por-ano>>
- BOBBIO, N. *A era dos direitos*. Rio de Janeiro: Campus, 1992, p. 5.
- BOLÍVIA. CONSTITUCIÓN POLÍTICA DEL ESTADO PLURINACIONAL, 2009.
- BRAGA JÚNIOR, B.; FLECHA, R.; PENA, D.; KELMAN, J. Pacto federativo e gestão de águas. *Estudos Avançados*, v. 22, n. 63, São Paulo, 2008. Dossiê Água.
- BRASIL. AGÊNCIA NACIONAL DE ÁGUAS (ANA). Disponível em: <<http://www2.ana.gov.br>>
- ECUADOR. CONSTITUCIÓN DE LA REPÚBLICA. 2008.
- BRASIL. FUNASA. *Sistema Nacional de Informação sobre Saneamento Básico – 2010*. Disponível em: <[http://www.funasa.gov.br/site/wp-content/uploads/2013/05/marcelo\\_de\\_paula.pdf](http://www.funasa.gov.br/site/wp-content/uploads/2013/05/marcelo_de_paula.pdf)>. Acesso: 10.07.2014.
- BRASIL. MINISTÉRIO DAS CIDADES. Plano Nacional De Saneamento Básico – Plansab. Disponível em: Acesso em 15.07.2014. <<http://www.mma.gov.br/cidades-sustentaveis/item/485-plano-nacional-de-saneamento-b%C3%A1sico>>.
- COMPARATO, F.. *Afirmção histórica dos direitos humanos*. 7. ed. São Paulo: Saraiva, 2010, p. 57 e ss.
- GOWDAK, M. et al. Nutrição aplicada à atividade física. In:
- NEGRÃO, C.; BARRETO, A. (Org.) *Cardiologia do Exercício: do Atleta ao Cardiopata*. 3. ed. Barueri-SP: Manole, 2010.
- IBGE – Instituto Brasileiro de Geografia e Estatística. Estimativa Censo Demográfico 2010. Disponível em: <<http://www.ibge.gov.br/estadosat/perfil.php?sigla=sp>>
- IDEC LISTA EVIDÊNCIAS DE RACIONAMENTO DE ÁGUA EM SP E COBRA ALCKMIN, ARSESP E SABESP. *Revista Carta Capital*. 30.07.2014. Disponível em: <<http://www.cartacapital.com.br>>
- NUÑES SANTIAGO, B. *Derecho alimentario*. Buenos Aires: Abeledo-Perrot, 1992.
- PESCE, S.; WUNDERLIN, D. *Use of water quality indices to verify the impact of Cordoba City (Argentina) on Suquia River*. *Water Res.* 2000; 34(11):2915–26.
- RIBEIRO, W. Aquífero Guarani: gestão compartilhada e soberania. In *Estudos Avançados*. São Paulo, n v. 22, n. 64, dez.2008.

SANTOS, B. *Crítica da razão indolente: contra o desperdício da experiência* . 3 ed. São Paulo: Cortez, 2001, p 24.

TUCCI, C.; HESPANHOL, I.; CORDEIRO NETTO, O. *A gestão da água no Brasil: uma primeira avaliação da situação atual e das perspectivas para 2025* [relatório]. Global Water Partnership: 2000. Disponível em: <<http://www.bvsde.paho.org/bvsacd/cd17/cenarioges.pdf> >.

TUCCI, C. *Hidrologia: ciência e aplicação*. 2.ed. Porto Alegre: ABRH/Editora da UFRGS, 1997. (Col. ABRH de Recursos Hídricos, v.4).

UNICEF. *Progress on Drinking Water and Sanitation 2012*. Disponível em: <<http://www.unicef.org/media/files/JMPreport2012.pdf>>

VON S. *Princípios Básicos do Tratamento de Esgotos*, DESA-UFGM, Belo Horizonte, 1996.

WOLKMER, M. O “novo” direito humano à água. In WOLKMER, A.; LEITE, J. (Orgs.). *Os “novos” direitos no Brasil*. São Paulo: Saraiva, 2012, p. 215.

WORLD ENERGY COUNCIL. Disponível em:< <http://www.worldenergy.org/>>

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## *Attribution Analysis at Member State Level of Percent Changes in European Carbonization Index*

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### **Abstract**

Since the beginning of the Industrial Revolution, emissions of CO<sub>2</sub> due to human activities have led to a marked increase in atmospheric concentrations of long-lived gases, leading to a worrisome global warming. In recent years, with a view to contribute to design suitable policies to control those emissions, numerous environmental studies have analyzed the trends in gas emissions and their main drivers. In this paper we explore in detail the trend of carbonization as a driving force for CO<sub>2</sub> emissions in the EU Member States. By implementing the so-called Sato-Vartia logarithmic mean Divisia index (LMDI-II) method, we factorize the emission change in the EU for the 2000-2010 period. Results point to the carbonization effect, along with the intensity effect, as one of the most relevant factors. Then, relying on the so-called attribution analysis (Choi and Ang, 2012; Fernández González et al., 2013) we present a new theoretical framework that enables attribution of percent changes in the carbonization index to individual EU Member States. This deeper study shows the strong concentration of this reducing influence in some big economies, with Germany, the United Kingdom, France and Italy contributing by more than 50%. Furthermore, adding Spain and Poland, the total contribution exceeds 75% of total change. Findings in this paper suggest that efforts should focus on strategies aiming at encouraging innovation, adaptation to more efficient and environmentally friendly technologies, research for higher quality energies, lower carbon fuel substitution and instalment of abatement technologies like carbon capture and storage.

**Key words:** Attribution analysis, LMDI method, emission coefficient index, European study.

**JEL:** C43 (Index numbers aggregation), O52 (Europe), Q43 (Energy and macroeconomy), Q51 (Environmental effects), Q58 (Government policy).

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## 1. Introduction

Climate change usually refers to the ongoing rise in global average temperature near Earth's surface, causing an increase in the frequency and severity of natural disasters. It is mostly caused by increasing concentrations of GHG in the atmosphere of which carbon dioxide is the most significant one. Climate change and global warming presents a serious problem since it bring changes in acidification, temperature and level of the oceans, frequency and severity of droughts and floods, Arctic sea ice and glacier extent, and it poses new challenges for humanity, affecting our own health and safety.

Global primary energy use has traditionally involved a dependence on fossil fuels sources: first, coal and steam, and then, oil and natural gas. Although deforestation, industrial processes, and some other agricultural practices also emit gases into the atmosphere, the majority of GHG come from burning fossil fuels to produce energy. Despite of the increasing use of non-fossil fuel sources (nuclear, hydro-energy and others like geothermal, solar, tidal, wind, wood and waste) to produce energy, reductions in the fuels emission coefficient and the energy intensity are still considered key elements to combat global warming.

Emission coefficient denotes the declining average carbon intensity of primary energy over time. Although intensities are currently increasing in some developing regions (World Energy Outlook 2004 -IEA, 2004), the replacement of fuel towards lower carbon content ones and more efficient technologies such as capture and storage of gases has brought lower carbon intensities.

Given global concerns about environmental issues and the consequent agreements signed by many countries (e.g., the Kyoto Protocol, 1997; and Doha Amendment to the Kyoto Protocol, 2012), a large number of environmental studies have emerged in recent years. Following different approaches, numerous authors have dealt with factorization and analysis of aggregate CO<sub>2</sub> emissions. Index decomposition analysis (IDA) is a leading theoretical framework that is heavily used in environmental and energy studies. It involves decomposing the variation of an aggregate variable relying on economic indexes<sup>1</sup>. From both theoretical and applied perspectives, the logarithmic mean Divisia index (LMDI) method reported in Ang and Choi (1997) is widely accepted and it has likely emerged as the preferred in most factorization studies. Among others, numerous are its advantages, profusely demonstrated in Ang and Liu (2001): it leads to exact decomposition, it is consistent in aggregation, it handles zero values effectively, it satisfies both factor and time reversal test, and there exists a simple formula relating additive and multiplicative decompositions<sup>2</sup>. Authors like Ang et al. (1998), Nag and Parikh (2000), Ramírez et al. (2005), Ma and Stern (2008), Liao and Wei (2010), Sahu and Narayanan (2010), Hammond and Norman (2012) and Shahiduzzaman and Alam (2012) have applied this method in order to decompose changes in a number of environmental and energy aggregates.

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<sup>1</sup> Thus, the methodological problems of this analysis are similar to those of the index numbers indicated by Fisher (1927) and Diewert (1980).

<sup>2</sup> This fact makes redundant both forms of decomposition. In this paper, we opted for multiplicative approach since we are interesting in percentual interpretations.

Recently, in order to further analysis in real energy intensity trend, Choi and Ang (2012) proposed a new decomposition approach, the so-called *attribution analysis of IDA*. Based on the exhaustive LMDI method, their proposal enables the assessment of individual sector to the percentual change in real energy intensity. In this paper we extend this analysis, analysing the emission coefficient index tendency and assessing the contribution of individual regions to percentual changes in it. This will allow us a deep analysis of the emission coefficient influence on CO<sub>2</sub> emission changes, identifying those regions in which environmental strategies are yielding to significant outcomes.

The goal of this paper is twofold. First, we aim at analyzing in detail trend of emission coefficient (or carbonization) index in the EU in the last decade. This objective will be achieved through decomposing changes in CO<sub>2</sub> emissions into several factors, namely energy intensity, emission coefficient (or emission coefficient), structural change and economic activity. This decomposition will be carried out in IDA framework, particularly through the implementation of the Sato-Vartia logarithmic mean Divisia index (LMDI-II) method. Findings will help in energy and environmental policies planning.

Second, we intend to quantify and analyze individual Member State contributions to percent changes in the emission coefficient factor. In order to achieve this target, following the attribution analysis firstly introduced in Choi and Ang (2012) and later expanded in Fernández González et al. (2013), we derive and develop an adequate methodology to carry out this study. Results will show those countries in which energy and environmental strategies should be reformulated in order to achieve more favorable emission coefficient.

In Section 2, we display the methodology necessary to achieve the objectives. Section 2.1 reviews the multiplicative LMDI-II decomposition method, showing its suitable use in order to factorize changes in CO<sub>2</sub> emissions in relation to alternative. In Section 2.2 and based on an attribution analysis, we derive a new methodology that enables the assignment of emission coefficient factor percent changes to individual Member States.

Section 3 analyzes the emission coefficient index trend by economic sector and Member State. In Section 3.1, we decompose changes in EU CO<sub>2</sub> emissions into several factors: energy intensity, emission coefficient, European production structure and economic activity. Section 3.2 implements the attribution analysis presented in Section 2.2 in order to identify those largest contributor countries to percentual changes in the index.

Finally, the last section collects the main conclusions of the paper, setting key recommendations in order to control CO<sub>2</sub> emissions in the EU.

## **2. Methodology**

In Section 2.1 we review the multiplicative LMDI method introduced by Ang and Choi (1997) to factorize changes in an environmental aggregate. Specifically, we focus on the so-called Sato-Vartia LMDI (LMDI-II) method since it involves a genuine geometric mean, ensuring a weights sum equal to unity. Moreover, we

consider both periodwise (single-period) and time series (multi-period) implementations of LMDI-II.

Then, in Section 2.2, based on the attribution analysis of IDA reported by Choi and Ang (2012) and extended by Fernández González et al. (2013), we present and develop an extension for further analysis in emission coefficient factor. Actually, we seek for quantifying contribution of individual regions to its percentual changes. This means a significant added value, since findings and environmental action lines would be individually suited to each region. Again, for further study, we take into account both single-period (*periodwise*) and dynamic or multi-period (*time series*) decomposition.

## 2.1. LMDI-II method

Adapting this method to present case, changes in aggregate CO<sub>2</sub> emissions may be decomposed into the following predetermine factors:

- (a) Emission coefficient or carbonization effect, i.e., impact of specific carbon emissions per unit energy on emissions. It evaluates fuel quality, fuel switching (fuel substitution) and the installation of abatement technologies;
- (b) Intensity effect, i.e., impact of energy requirements per unit value added on emissions. It involves the energy consumption related to some variables like energy prices, energy conservation and energy-saving investments, structure and the efficiency of the energy systems, technological choices and socio-economic behaviour;
- (c) Structural effect, i.e., impact of production structure. It measures changes due to the relative position of sectors/regions in an economy; and
- (d) Activity effect, i.e., impact of economic growth. Assuming a constant (average) coefficient between GDP and CO<sub>2</sub> emissions, it is regarded as the theoretical CO<sub>2</sub> emissions caused by economic activities (Sun, 1999).

Given the following variables, evaluated at time  $t$ :

- $G_t$  : aggregate CO<sub>2</sub> emissions,
- $G_{i,t}$  : CO<sub>2</sub> emissions from region  $i$
- $E_t$  : total energy consumption,
- $E_{i,t}$  : energy consumption in region  $i$ ,
- $Y_t$  : Gross Domestic Product,
- $Y_{i,t}$  : production of region  $i$ ,
- $C_{i,t}$  : emission coefficient of in region  $i$  ( $C_{i,t}=G_{i,t}/E_{i,t}$ ),
- $S_{i,t}$  : product share in region  $i$  ( $S_{i,t}= Y_{i,t}/Y_t$ ),
- $I_{i,t}$  : energy intensity in region  $i$  ( $I_{i,t}=E_{i,t}/Y_{i,t}$ ).

Where data are disaggregated by region, aggregate CO<sub>2</sub> emissions may be expressed as follows:

$$G_t = \sum_{i=1}^k \frac{G_{i,t}}{E_{i,t}} \frac{E_{i,t}}{Y_{i,t}} \frac{Y_{i,t}}{Y_t} Y_t = \sum_{i=1}^k C_{i,t} I_{i,t} S_{i,t} Y_t \quad (1)$$

where the summation  $i$  is taken over the  $k$  regions, and being the sum of all regions the predefined geographic area under study.

Considering infinitesimal periods, dividing by  $C_t$  and integrating on both sides with respect to time  $t$  in  $[0, T]$  yields:

$$\ln(G_T/G_0) = \int_0^T \sum_i^k \frac{C'_{i,t} I_{i,t} S_{i,t} Y_t}{G_t} + \int_0^T \sum_i^k \frac{C_{i,t} I'_{i,t} S_{i,t} Y_t}{G_t} + \int_0^T \sum_i^k \frac{C_{i,t} I_{i,t} S'_{i,t} Y_t}{G_t} + \int_0^T \sum_i^k \frac{C_{i,t} I_{i,t} S_{i,t} Y'_t}{G_t} \quad (2)$$

where  $C'_{ijt}$ ,  $I'_{i,t}$ ,  $S'_{i,t}$  and  $Y'_t$  are, respectively, the first derivatives of  $C_{i,t}$ ,  $I_{i,t}$ ,  $S_{i,t}$  and  $Y_t$  with respect to time.

Denoting by  $(R_{tot})_{0,T}$  the total effect between periods 0 and  $T$  ( $(R_{tot})_{0,T} = G_T/G_0$ ), with  $(R_{emf})_{0,T}$ ,  $(R_{int})_{0,T}$ ,  $(R_{str})_{0,T}$  and  $(R_{act})_{0,T}$  being, respectively, the estimated emission coefficient, intensity and structural effects, respectively, Equation (2) above may be transform into any of the following two forms:

$$(R_{tot})_{0,T} = e^{\left( \int_0^T \sum_{i=1}^k \frac{G_{i,t}}{G_t} (C'_{i,t}/C_{i,t}) dt \right)} e^{\left( \int_0^T \sum_{i=1}^k \frac{G_{i,t}}{G_t} (I'_{i,t}/I_{i,t}) dt \right)} e^{\left( \int_0^T \sum_{i=1}^k \frac{G_{i,t}}{G_t} (S'_{i,t}/S_{i,t}) dt \right)} e^{\left( \int_0^T \sum_{i=1}^k \frac{G_{i,t}}{G_t} (Y'_t/Y_t) dt \right)} \quad (3)$$

$$(R_{tot})_{0,T} = e^{\left( \int_0^T \sum_{i=1}^k (C'_{i,t} I_{i,t} S_{i,t} Y_t / G_t) dt \right)} e^{\left( \int_0^T \sum_{i=1}^k (C_{i,t} I'_{i,t} S_{i,t} Y_t / G_t) dt \right)} e^{\left( \int_0^T \sum_{i=1}^k (C_{i,t} I_{i,t} S'_{i,t} Y_t / G_t) dt \right)} e^{\left( \int_0^T \sum_{i=1}^k (C_{i,t} I_{i,t} S_{i,t} Y'_t / G_t) dt \right)} \quad (4)$$

Transforming the above path integrals into parametric ones, Liu et al. (1992) derive (3) and (4) into general parametric Divisia methods I (PDM-I) and II (PDM-II), respectively. Therefore, ocusing on the PDM-II effects may be estimate through the following expressions:

$$(R_{emf})_{0,T} = e^{\left[ \sum_{i=1}^k \frac{G_{i,0}}{G_0} + \beta_i \left( \frac{G_{i,T}}{G_T} - \frac{G_{i,0}}{G_0} \right) \ln \left( \frac{C_{i,T}}{C_{i,0}} \right) \right]} \quad (5)$$

$$(R_{int})_{0,T} = e^{\left[ \sum_{i=1}^k \frac{G_{i,0}}{G_0} + \beta_i \left( \frac{G_{i,T}}{G_T} - \frac{G_{i,0}}{G_0} \right) \ln \left( \frac{I_{i,T}}{I_{i,0}} \right) \right]} \quad (6)$$

$$(R_{str})_{0,T} = e^{\left[ \sum_{i=1}^k \frac{G_{i,0}}{G_0} + \beta_i \left( \frac{G_{i,T}}{G_T} - \frac{G_{i,0}}{G_0} \right) \ln \left( \frac{S_{i,T}}{S_{i,0}} \right) \right]} \quad (7)$$

$$(R_{act})_{0,T} = e^{\left[ \sum_{i=1}^k \frac{G_{i,0}}{G_0} + \beta_i \left( \frac{G_{i,T}}{G_T} - \frac{G_{i,0}}{G_0} \right) \ln \left( \frac{Y_T}{Y_0} \right) \right]} \quad (8)$$

where  $\beta_i$  denotes given weight of region  $j$  from period 0 to period  $T$ , and being  $0 \leq \beta_i \leq 1$ .

Considering the logarithmic mean weight function proposed in Ang and Choi (1997)<sup>3</sup>

$$L(G_{i,0}, G_{i,T}) = \frac{(G_{i,T} - G_{i,0})}{\ln(G_{i,T}/G_{i,0})}$$

and normalizing it to fulfill the partition-of-unity property, the following weight function is obtained:

$$w_{i,0-T}^* = \frac{L(G_{i,0}, G_{i,T})}{\sum_{i=1}^k L(G_{i,0}, G_{i,T})}, \quad i=1,2,\dots,k \quad (9)$$

where  $w_{i,0-T}^*$  denotes the normalized weight of region  $j$  between periods 0 and  $T$ .

In addition, also intermediate periods between 0 and  $T$  may be considered, leading to time series decomposition. This type of decomposition likely entails more accurate results than periodwise since it uses a larger volume of information. Besides, it makes possible the detection of structural breaks, different phases or time patterns in the estimated effects.

Denoting  $(C_{tot})_{0,T}$  as the cumulative change in CO<sub>2</sub> emissions from 0 to  $T$ ,  $(C_{emf})_{0,T}$  the estimated cumulative emission coefficient effect from 0 to  $T$ ,  $(C_{int})_{0,T}$  the estimated cumulative intensity effect from 0 to  $T$ ,  $(C_{str})_{0,T}$  the estimated cumulative structural effect by from 0 to  $T$  and  $(C_{act})_{0,T}$  the estimated cumulative activity effect by from 0 to  $T$ , we obtain:

$$(C_{tot})_{0,T} = (R_{tot})_{0,1} (R_{tot})_{1,2} \dots (R_{tot})_{T-1,T} \quad (10)$$

$$(C_{emf})_{0,T} = (R_{emf})_{0,1} (R_{emf})_{1,2} \dots (R_{emf})_{T-1,T} \quad (11)$$

$$(C_{int})_{0,T} = (R_{int})_{0,1} (R_{int})_{1,2} \dots (R_{int})_{T-1,T} \quad (12)$$

$$(C_{str})_{0,T} = (R_{str})_{0,1} (R_{str})_{1,2} \dots (R_{str})_{T-1,T} \quad (13)$$

<sup>3</sup> This weight function leads to a complete decomposition, i.e., no deviation from the target value is observed:  $(R_{sd})_{T-1,T} = 1$ .

$$(C_{act})_{0,T} = (R_{act})_{0,1} (R_{act})_{1,2} \dots (R_{act})_{T-1,T} \quad (14)$$

## 2.2. Attribution analysis of the Divisia emission coefficient index

Once a predefined factor is isolated through any decomposition technique, contribution of each individual attribute (i.e., each economic sector or region) to its overall percentual change may be advised through an attribution approach. Based on Choi and Ang (2012) and interested in emission coefficient index study, we propose and develop the methodology set out below.

A Divisia index of emission coefficient (in log-change form) from period 0 to period  $T$  may be expressed as a geometric mean index:

$$\ln(R_{emf})_{0,T} = \ln\left(\frac{R_{emf T}}{R_{emf 0}}\right) = \sum_{i=1}^k w_i \ln\left(\frac{C_{i,T}}{C_{i,0}}\right) \Leftrightarrow (R_{emf})_{0,T} = \prod_{i=1}^k \left(\frac{C_{i,T}}{C_{i,0}}\right)^{w_i} \quad (15)$$

By defining the unknown parameters  $\pi_i$  as in Equation (20) below, the geometric index is converted into an arithmetic mean<sup>4</sup>, and the following expression is obtained:

$$\frac{R_{emf T}}{R_{emf 0}} = \frac{\sum_{i=1}^k \pi_i C_{i,T}}{\sum_{i=1}^k \pi_i C_{i,0}} \quad (16)$$

By defining  $a_{i,0} \equiv \frac{\pi_i I_{i,0}}{\sum_{g=1}^k \pi_g I_{g,0}}$ ,  $a_{i,T} \equiv \frac{\pi_i I_{i,T}}{\sum_{g=1}^k \pi_g I_{g,T}}$ , using the identity

$\sum_{i=1}^k \sum_{j=1}^l (a_{i,T} - a_{i,0}) = 0$  and applying the definition of logarithmic mean, the following two identities are derived (Balk, 2004):

$$\sum_{i=1}^k L(a_{i,T}, a_{i,0}) \ln\left(\frac{a_{i,T}}{a_{i,0}}\right) = 0 \quad (17)$$

$$\ln\left(\frac{a_{i,T}}{a_{i,0}}\right) = \ln\left(\frac{C_{i,T}}{C_{i,0}}\right) - \ln\left(\frac{R_{emf T}}{R_{emf 0}}\right) \quad (18)$$

Inserting (18) in (17) and solving the equation in  $\ln\left(\frac{R_{emf T}}{R_{emf 0}}\right)$ , we obtain the following alternative log-change expression for  $(R_{emf})_{0,T}$ :

<sup>4</sup> Attribution analysis requires an arithmetic mean index. Choi and Ang (2012), relying on an identity derived by Balk (2004), transformed the Divisia or geometric mean index into an arithmetic mean formula.

$$\ln\left(\frac{R_{emf,T}}{R_{emf,0}}\right) = \sum_{i=1}^k \frac{L(a_{i,T}, a_{i,0})}{\sum_{g=1}^k L(a_{g,T}, a_{g,0})} \ln\left(\frac{C_{i,T}}{C_{i,0}}\right) =$$

$$\sum_{i=1}^k \frac{\pi_i L(C_{i,T}, C_{i,0}(R_{emf})_{0,T})}{\sum_{g=1}^k \pi_g L(C_{g,T}, C_{g,0}(R_{emf})_{0,T})} \ln\left(\frac{C_{i,T}}{C_{i,0}}\right) \quad (19)$$

Comparing weights of the two log-change forms in (15) and (19), we obtain:

$$\pi_i = \frac{w_i}{L(C_{i,T}, C_{i,0}(R_{emf})_{0,T})} \quad (20)$$

Replacing (20) in (19), the right-hand side is the same as the log change form in (15). Hence, (20) is so-called as the ‘‘Reinsdorf formula’’ (Reinsdorf, 1996) since it provides a link between geometric and arithmetic mean indices and it.

Since Montgomery-Vartia index is not a genuine geometric mean, the above attribution analysis is based in Sato-Vartia index. That is, it is built on the LMDI-II method.

Finally, attributions of emission coefficient index in LMDI-II<sup>5</sup> will be given by the following formula:

$$\left(\frac{R_{int,T}}{R_{int,0}} - 1\right) = \sum_{i=1}^k \sum_{j=1}^l a_{ij} \left(\frac{C_{ij,T}}{C_{ij,0}} - 1\right) \quad (21)$$

where

$$a_i = \frac{\pi_i C_{i,0}}{\sum_{g=1}^k \pi_g C_{g,0}} = \frac{\frac{w_i C_{i,0}}{L(C_{i,T}, C_{i,0}(R_{emf})_{0,T})}}{\sum_{g=1}^k \frac{w_g C_{g,0}}{L(C_{g,T}, C_{g,0}(R_{emf})_{0,T})}} \quad (22)$$

and  $a_i$  may be interpreted as the relative weight of component  $i$  in region  $j$ . It measures the degree of influence of this component on the total. It is readily checked

$$\text{that } \sum_{i=1}^k a_i = 1.$$

Again a multi-period attribution analysis is also indicated if intermediate period information is available. Upon the basis of the following definition of chain real

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<sup>5</sup> The presented analysis is built on the LMDI-II method since Montgomery-Vartia index is not a genuine geometric mean but Sato-Vartia index.

energy intensity index, cumulative emission coefficient effect may be expressed as follows:

$$(C_{emf})_{0,T} = (R_{emf})_{0,1} (R_{emf})_{1,2} \dots (R_{emf})_{T-1,T} \quad (23)$$

And the following difference representation is readily obtained:

$$\begin{aligned} (C_{emf})_{0,T} - 1 &= \frac{R_{emf T}}{R_{emf 0}} - 1 = \frac{R_{emf T}}{R_{emf 0}} - \frac{R_{emf 0}}{R_{emf 0}} = \\ &\left( \frac{R_{emf T}}{R_{emf 0}} - \frac{R_{emf T-1}}{R_{emf 0}} \right) + \left( \frac{R_{emf T-1}}{R_{emf 0}} - \frac{R_{emf T-2}}{R_{emf 0}} \right) + \left( \frac{R_{emf T-2}}{R_{emf 0}} - \frac{R_{emf T-3}}{R_{emf 0}} \right) + \dots + \\ &\left( \frac{R_{emf 1}}{R_{emf 0}} - \frac{R_{emf 0}}{R_{emf 0}} \right) = \quad (24) \\ &\frac{R_{emf T-1}}{R_{emf 0}} \left( \frac{R_{emf T}}{R_{emf T-1}} - 1 \right) + \frac{R_{emf T-2}}{R_{emf 0}} \left( \frac{R_{emf T-1}}{R_{emf T-2}} - 1 \right) + \frac{R_{emf T-3}}{R_{emf 0}} \left( \frac{R_{emf T-2}}{R_{emf T-3}} - 1 \right) + \dots + \\ &\frac{R_{emf 0}}{R_{emf 0}} \left( \frac{R_{emf 1}}{R_{emf 0}} - 1 \right) \end{aligned}$$

Therefore:

$$(C_{emf})_{0,T} - 1 = \frac{R_{emf T}}{R_{emf 0}} - 1 = \sum_{t=1}^T \frac{R_{emf T-t}}{R_{emf 0}} \left( \frac{R_{emf T}}{R_{emf T-t}} - 1 \right) \quad (25)$$

This expression shows that the percent change in the above chain index is a cumulative sum of single-period percent changes multiplied by  $\frac{R_{emf t-1}}{R_{emf 0}}$ .

Inserting (21) in (25), the following expression for multi-period attribution analysis of Divisia chain indices is obtained:

$$\left( \frac{R_{emf T}}{R_{emf 0}} - 1 \right) = \sum_{t=1}^T \frac{R_{emf t-1}}{R_{emf 0}} \left( \frac{R_{emf t}}{R_{emf t-1}} - 1 \right) = \sum_{i=1}^k \sum_{t=1}^T \frac{R_{emf t-1}}{R_{emf 0}} (a_i)_{t-1,t} \left( \frac{C_{i,t}}{C_{i,t-1}} - 1 \right) \quad (26)$$

where

$$(a_i)_{t-1,t} = \frac{\frac{(w_i)_{t-1,t} C_{i,t-1}}{L(C_{i,t}, C_{i,t-1} (R_{emf})_{t-1,t})}}{\sum_{g=1}^k \frac{(w_g)_{t-1,t} C_{g,t-1}}{L(C_{g,t}, C_{g,t-1} (R_{emf})_{t-1,t})}} \quad (27)$$

The value of  $\frac{R_{emf\ t-1}}{R_{emf\ 0}}(a_i)_{t-1,t} \left( \frac{C_{i,t}}{C_{i,t-1}} - 1 \right)$  in (26) may be interpreted as the contribution of sector  $i$  in region  $j$  during period  $[t-1, t]$ , evaluated from the base period 0.

### 3. Empirical Analysis

In this section we analyze in detail the evolution of the aggregate CO<sub>2</sub> emissions in the EU from 2000 to 2010, quantifying its drivers and paying particular attention to emission coefficient factor impact. Analysis is done in two phases.

First, in order to identify and quantify driving forces under changes in EU CO<sub>2</sub> emissions, we implement multiplicative LMDI-II method at country disaggregation level. Second, with the objective of deeper exploration in the emission coefficient trend, we implement an attribution analysis. The goal is exploring attribution to percentual changes in the corresponding emission coefficient index of each Member State.

Time series data on CO<sub>2</sub> emissions (in thousand tonnes of CO<sub>2</sub> equivalent), energy consumption<sup>6</sup> (in million tonnes of oil equivalent) and value added in real terms (in euro at basic prices in purchasing power parity) for both sector and country, were obtained from the Publications Office of the European Union (Eurostat -European Commission, 2014). We considered the following sectors<sup>7</sup>: Agriculture, Industry (including energy and manufacturing industries, industrial processes and construction), Transport and Others (includes residential and commercial).

#### 3.1. Decomposition of changes in EU CO<sub>2</sub> emissions

Multiplicative LMDI-II method is implemented to factorize changes in EU CO<sub>2</sub> emissions. In addition, single-period/periodwise (with the immediately preceding period taken as base year) and multi-period/time series decomposition (with the initial year chosen as base) are carried out in each case, leading to simple and cumulative factor estimations.

Based on 27 Member States ( $i=1,\dots,27$ ) disaggregation, results from both periodwise and time series decomposition forms are reported in Table 1.

From 2000 to 2010, EU aggregate CO<sub>2</sub> emissions experienced a decrease of 6.11%. Two effects have contributed to this reduction: intensity (10.68%) and emission coefficient (7.1%) effect. This means innovation, technical change, adaptation to more efficient technologies in EU Member States, but also the use of less contaminant energies and the installation of capture and storage of gas emissions have lower CO<sub>2</sub>

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<sup>6</sup> Primary energy and its conversion are not really transparent to the consumers. Determining the emission coefficient as a ratio of total CO<sub>2</sub> emissions per primary energy unit would remove from the analysis the actual point of consumption and interactions between the energy system and the economy. By contrast, final energy is directly consumed and it represents the actual energy requirements.

<sup>7</sup> Subject to availability of data for the studied area, we leave for future work an analysis at more disaggregated levels. Hopefully, this will provide further insights in order to effectively improve governance at these finer levels.

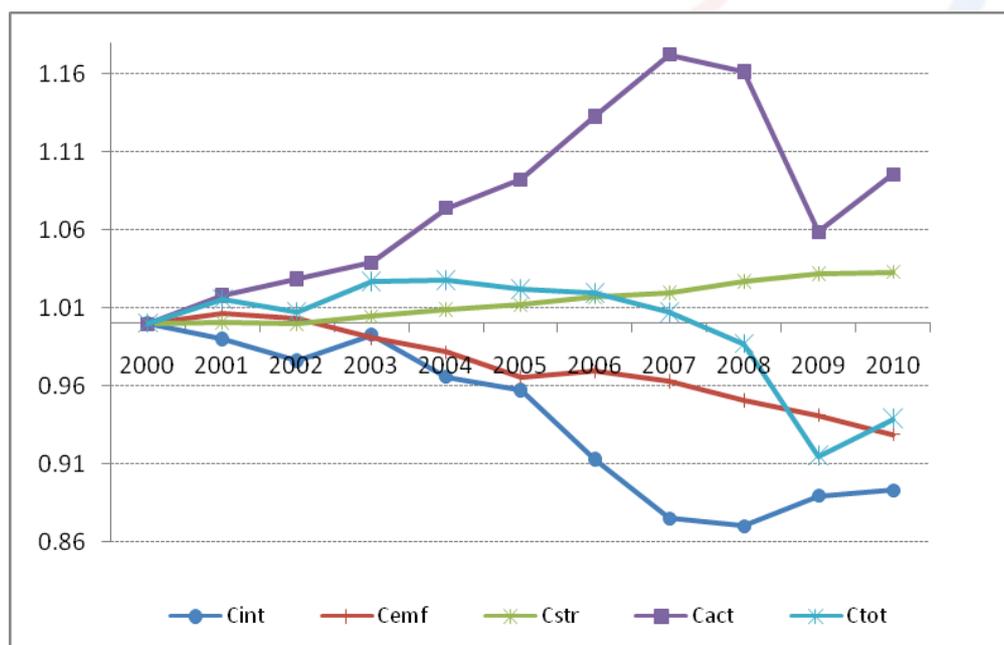
emissions. On the contrary, structural and activity effects contributed to increase CO<sub>2</sub> emissions by 3.29% and 9.54%, respectively. That is, changes in the EU production structure towards more polluter countries and the growing economic activity in them enhanced CO<sub>2</sub> emissions in the EU.

**Table 1.** Periodwise and time series decomposition results of changes in CO<sub>2</sub> emissions in the EU when aggregating by Member States, 2000-2010<sup>a</sup>.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
LMDI	$R_{int}$	$R_{emf}$	$R_{str}$	$R_{act}$	$R_{tot}$	$C_{int}$	$C_{emf}$	$C_{str}$	$C_{act}$	$C_{tot}$
2000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
2001	0.9901	1.0062	1.0011	1.0182	1.0154	0.9901	1.0062	1.0011	1.0182	1.0154
2002	0.9857	0.9964	0.9993	1.0104	0.9917	0.9759	1.0027	1.0003	1.0287	1.0070
2003	1.0173	0.9880	1.0043	1.0100	1.0195	0.9929	0.9906	1.0046	1.0390	1.0266
2004	0.9728	0.9912	1.0045	1.0335	1.0010	0.9658	0.9819	1.0092	1.0739	1.0277
2005	0.9912	0.9837	1.0029	1.0169	0.9944	0.9573	0.9658	1.0121	1.0921	1.0219
2006	0.9540	1.0037	1.0048	1.0370	0.9977	0.9133	0.9694	1.0169	1.1324	1.0195
2007	0.9583	0.9935	1.0026	1.0348	0.9878	0.8752	0.9631	1.0196	1.1718	1.0071
2008	0.9946	0.9872	1.0073	0.9906	0.9799	0.8705	0.9508	1.0270	1.1609	0.9868
2009	1.0221	0.9900	1.0048	0.9120	0.9273	0.8897	0.9413	1.0320	1.0587	0.9150
2010	1.0039	0.9870	1.0009	1.0347	1.0261	0.8932	0.9290	1.0329	1.0954	0.9389

<sup>(a)</sup> Columns (1)-(5) report periodwise results (the base year is the immediately preceding year), whereas columns (6)-(10) display time series results (with 2000 being the base year).

Anyway, a detail annual exploration indicates some changes in behaviour patterns. Figure 1 shows evolution of each individual effect, assisting in detection of any trend change along the studied period.



**Figure 1.** Multiplicative decomposition results of changes in CO<sub>2</sub> emissions in the EU when aggregating by Member States (base year = 2000).

Attending to Figure 1, we may distinguish two main phases. From 2000 to 2007, CO<sub>2</sub> emissions increased with some fluctuations but always being superior to 2000 level. In this phase, particularly in its first years, only intensity effect lowered emissions, adding emission coefficient effect from this point onwards. Respect to the activity effect showed a positive influence, with a significant increase in such influence from 2002. Meanwhile, structural effect displays a positive, slight but increasing impact on CO<sub>2</sub> emissions.

The second phase goes from 2007 to the end. In this interval, CO<sub>2</sub> emissions experienced a drop, reaching levels below 2000. Drivers of this reduction were the significant shrink in economic activity impact (despite its recovery in 2010) and the increasing negative contribution of emission coefficient influence. Meanwhile, structural effect still increases its positive impact and the intensity effect undergoes a turnaround reducing its contribution to the control of emissions. The global economic and financial crisis in these years may explain lower economic growth (even negative in some countries) and slowdown in the investment efforts of new and more efficient technologies.

A global analysis of Figure 1 indicates an aggregate CO<sub>2</sub> emissions reduction in the EU from 2000 to 2010. However, comparing the situation between defined phases, this reduction was mainly a result of lower economic activity. This fact implies the need to review the environmental strategies performed and the need to promote alternatives for better control of emissions<sup>8</sup>.

### 3.2. Attribution analysis of emission coefficient index

Attribution analysis method is implemented to quantify contribution of individual Member State to percent changes in EU emission coefficient or emission coefficient index (Sections 3.2.1 and 3.2.2, respectively). In addition, periodwise (with the immediately preceding period taken as base year) and time series decomposition (with the initial year chosen as base) are carried out in each case, leading to direct and cumulative attributions.

Based on 27 Member States ( $i=1, \dots, 27$ ) disaggregation, attribution analysis results from periodwise form are reported in Table 2 and Figure 2. The first presents  $a_j$  values (%) and the second relates to individual contribution to those changes.

**Table 2.** Periodwise attribution results ( $a_i$ ) of each Member State to percentual changes in emission coefficient factor in the EU (2000-2010)<sup>a</sup>.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$a_i$	Belgium	Bulgaria	CzechR.	Denmark	Germany	Estonia	Ireland	Greece	Spain
2000-2010	0.0292	0.0116	0.0297	0.0135	0.2078	0.0038	0.0123	0.0247	0.0745

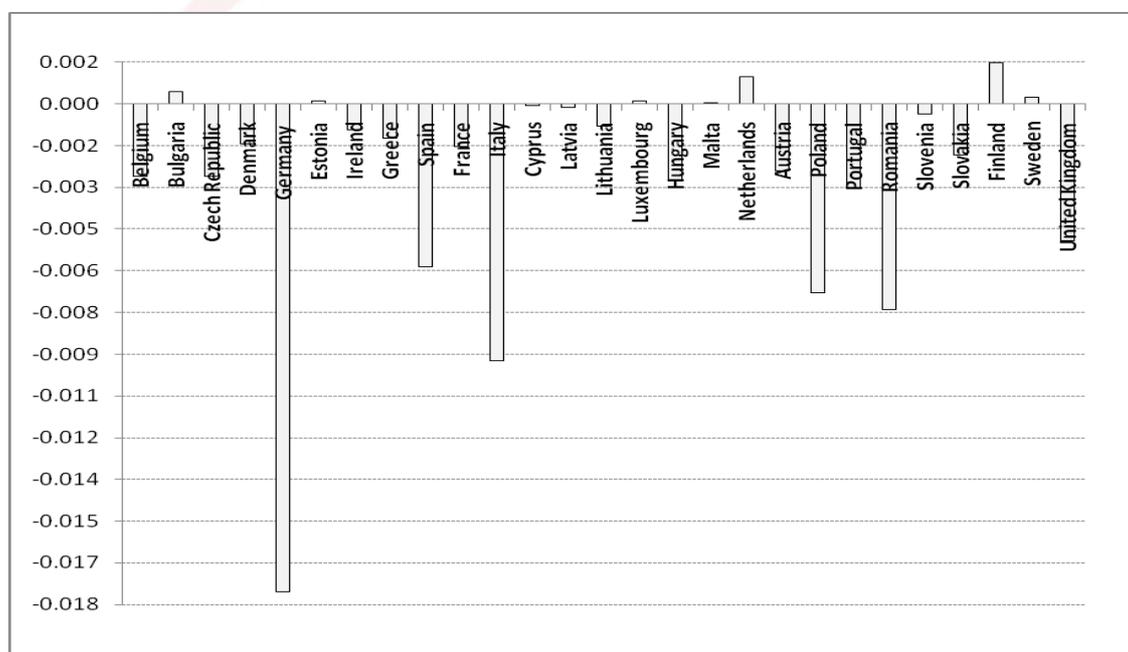
<sup>8</sup> Analogous studies like Paul and Bhattacharya (2004) or Parikh et al. (2009) for Indian case, Ozawa et al. (2002) for Mexico, Zafrilla et al. (2012) for Spain, Jung et al. (2012) for South Korea, Hatzigeorgiou et al. (2008) for Greece or Hammond and Norman (2012) for the United Kingdom also lead to similar outcomes.

	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
$a_i$	France	Italy	Cyprus	Latvia	Lithuania	Luxemb.	Hungary	Malta	Netherl.
2000-2010	0.1032	0.1103	0.0020	0.0022	0.0039	0.0022	0.0151	0.0006	0.0418

	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
$a_i$	Austria	Poland	Portugal	Romania	Slovenia	Slovakia	Finland	Sweden	UK
2000-2010	0.0172	0.0813	0.0160	0.0276	0.0040	0.0099	0.0136	0.0129	0.1295

(a) The sum of columns (1-27) gives the unity.



**Figure 3.** Periodwise contribution of each Member State to percentual changes in emission coefficient factor in the EU from 2000 to 2010.

As it is commented above (Table 1 and Figure 1), emission coefficient index fell from 2000 to 2010. According to Figure 2, most of the Member States have contributed to this reduction. Specifically, big Western economies like Germany, Italy, the United Kingdom and Spain and in a lesser extent some Central and Eastern European ones like Romania, Poland and Hungary have been the largest contributors. By contrast, some small Western Members like Netherlands, Finland, Luxembourg and Malta, and some few ex-communist ones like Bulgaria and Estonia provides contributed to increase the index.

A deeper analysis is displayed in Tables 3 and 4, reporting results from time series attribution analysis of changes in emission coefficient index.

**Table 3.** Time series attribution results ( $a_i$ ) of each Member State to percentual changes in emission coefficient factor in the EU (base year = 2000).<sup>a</sup>

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$a_i$	Belgium	Bulgaria	CzechR.	Denmark	Germany	Estonia	Ireland	Greece	Spain
2001	0.0292	0.0118	0.0292	0.0134	0.2069	0.0037	0.0127	0.0250	0.0757
2002	0.0286	0.0117	0.0290	0.0134	0.2063	0.0037	0.0125	0.0251	0.0764
2003	0.0290	0.0120	0.0295	0.0133	0.2073	0.0037	0.0127	0.0250	0.0777
2004	0.0285	0.0120	0.0296	0.0133	0.2067	0.0036	0.0126	0.0247	0.0789
2005	0.0278	0.0123	0.0294	0.0133	0.2042	0.0104	0.0126	0.0247	0.0794
2006	0.0282	0.0127	0.0292	0.0135	0.2062	0.0037	0.0128	0.0252	0.0774
2007	0.0279	0.0127	0.0287	0.0136	0.2043	0.0037	0.0120	0.0258	0.0794
2008	0.0292	0.0124	0.0294	0.0136	0.2041	0.0037	0.0126	0.0255	0.0779
2009	0.0288	0.0117	0.0296	0.0136	0.2040	0.0038	0.0128	0.0261	0.0762
2010	0.0292	0.0116	0.0297	0.0135	0.2078	0.0038	0.0123	0.0247	0.0745

	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
$a_i$	France	Italy	Cyprus	Latvia	Lithuania	Luxemb.	Hungary	Malta	Netherl.
2001	0.1076	0.1105	0.0019	0.0020	0.0034	0.0020	0.0147	0.0006	0.0420
2002	0.1078	0.1114	0.0019	0.0020	0.0035	0.0020	0.0150	0.0005	0.0421
2003	0.1064	0.1116	0.0019	0.0020	0.0036	0.0021	0.0148	0.0005	0.0419
2004	0.1054	0.1119	0.0019	0.0020	0.0036	0.0021	0.0147	0.0005	0.0419
2005	0.1035	0.1113	0.0019	0.0021	0.0038	0.0022	0.0149	0.0005	0.0420
2006	0.1042	0.1128	0.0019	0.0020	0.0039	0.0022	0.0153	0.0005	0.0410
2007	0.1044	0.1125	0.0019	0.0020	0.0041	0.0022	0.0153	0.0005	0.0405
2008	0.1040	0.1114	0.0019	0.0020	0.0041	0.0022	0.0155	0.0006	0.0405
2009	0.1039	0.1109	0.0020	0.0021	0.0039	0.0022	0.0154	0.0006	0.0417
2010	0.1032	0.1103	0.0020	0.0022	0.0039	0.0022	0.0151	0.0006	0.0418

	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
$a_i$	Austria	Poland	Portugal	Romania	Slovenia	Slovakia	Finland	Sweden	UK
2001	0.0158	0.0758	0.0159	0.0265	0.0038	0.0092	0.0137	0.0130	0.1340
2002	0.0161	0.0750	0.0159	0.0267	0.0039	0.0091	0.0139	0.0129	0.1335
2003	0.0163	0.0751	0.0158	0.0264	0.0039	0.0093	0.0137	0.0126	0.1319
2004	0.0165	0.0762	0.0158	0.0264	0.0039	0.0093	0.0138	0.0126	0.1312
2005	0.0169	0.0748	0.0156	0.0262	0.0040	0.0095	0.0134	0.0125	0.1308
2006	0.0169	0.0764	0.0156	0.0267	0.0040	0.0096	0.0138	0.0126	0.1316
2007	0.0170	0.0774	0.0156	0.0265	0.0041	0.0095	0.0138	0.0126	0.1319
2008	0.0170	0.0783	0.0157	0.0269	0.0041	0.0097	0.0137	0.0125	0.1315
2009	0.0172	0.0799	0.0158	0.0271	0.0041	0.0097	0.0133	0.0126	0.1311
2010	0.0172	0.0813	0.0160	0.0276	0.0040	0.0099	0.0136	0.0129	0.1295

<sup>(a)</sup> The sum of columns (1-27) gives the unity.

As Table 1 reports, emission coefficient effect fell along the period 2000-2010, with some exceptional years: 2001 and 2006. According to Table 5, time series attribution results show again negative contribution of the majority of the Member States, contributing so to reduce emission coefficient index. Specifically, big Western economies and most ex-communist countries participated in this decrement. Further analysis of Tables 4 and 5 brings interesting outcomes. First, Eastern and Central Member States, particularly Poland, Hungary, Romania and Slovakia, significantly increased their contribution to emission coefficient reduction. Second, France, Estonia and Spain are countries whose contribution is rapidly changeable. Third, Germany is the biggest contributor to changes in emission coefficient to the extent that its positive attribution in 2001 led to emission coefficient index increase. Finally, Western developed countries like Sweden, Netherlands and Finland exhibit poor even none improvement in emission coefficient reduction along the studied period.

**Table 4.** Contribution of each EU Member State to global change in emission coefficient effect from 2001 to 2010, (base year = 2000).<sup>a</sup>

Year	(1) Belgium	(2) Bulgaria	(3) Czech R.	(4) Denmark	(5) Germany	(6) Estonia	(7) Ireland	(8) Greece	(9) Spain
2001	-0.0002	0.0004	-0.0004	0.0003	0.0071	-	-	-	-
2002	0.0009	0.0000	-0.0008	0.0003	0.0052	0.0002	0.0003	0.0001	0.0000
2003	-0.0002	0.0001	-0.0020	0.0010	-0.0039	0.0001	0.0001	0.0000	-
2004	0.0006	-0.0004	-0.0022	-0.0002	-0.0072	0.0001	0.0001	0.0000	-
2005	0.0009	-0.0010	-0.0020	-0.0013	-0.0092	0.0009	0.0000	0.0008	0.0002
2006	-0.0006	-0.0013	-0.0011	0.0000	-0.0105	0.0000	0.0001	0.0000	0.0001
2007	-0.0009	-0.0005	0.0001	-0.0009	-0.0104	0.0000	0.0000	-	-
2008	-0.0025	-0.0004	-0.0020	-0.0015	-0.0086	0.0001	0.0000	0.0000	0.0004
2009	-0.0023	0.0001	-0.0022	-0.0013	-0.0090	-	-	-	-
2010	-0.0026	0.0004	-0.0026	-0.0014	-0.0175	0.0000	-	-	-

9 3 9

Year	(10) France	(11) Italy	(12) Cyprus	(13) Latvia	(14) Lithuania	(15) Luxemb.	(16) Hungary	(17) Malta	(18) Netherlands
2001	-0.0024	0.0007	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0006
2002	-0.0039	0.0001	0.0000	0.0001	-0.0001	0.0001	-0.0009	0.0001	0.0005
2003	-0.0027	0.0008	0.0000	0.0000	-0.0003	0.0001	-0.0003	0.0001	0.0001
2004	-0.0016	0.0009	0.0000	0.0001	-0.0003	0.0002	-0.0006	0.0001	-0.0002
2005	-0.0017	0.0007	0.0001	0.0002	-0.0004	0.0002	-0.0010	0.0001	-0.0020
2006	-0.0016	0.0002	0.0000	0.0000	-0.0006	0.0002	-0.0018	0.0001	-0.0005
2007	-0.0038	0.0007	0.0001	0.0002	-0.0008	0.0001	-0.0023	0.0001	0.0006
2008	-0.0034	0.0001	0.0001	0.0000	-0.0008	0.0001	-0.0029	0.0001	0.0012
2009	-0.0010	0.0008	0.0000	0.0002	-0.0008	0.0001	-0.0031	0.0001	0.0004
2010	-0.0016	0.0002	0.0001	0.0001	-0.0008	0.0001	-0.0028	0.0000	0.0010

	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)
Year	Austri	Polan	Portuga	Romani	Sloveni	Slovaki	Finlan	Swede	UK
s	a	d	l	a	a	a	d	n	UK
2001	0.0002	0.0003	-0.0001	-0.0017	-0.0001	0.0008	0.0012	0.0007	0.0024
2002	-	-	0.0008	-0.0013	-0.0001	0.0008	0.0014	0.0010	0.0000
2003	0.0001	0.0003	-0.0005	-0.0001	-0.0003	0.0002	0.0030	0.0015	0.0005
2004	0.0003	-	0.0004	-0.0002	-0.0008	-0.0001	0.0017	0.0010	0.0009
2005	-	-	-0.0002	-0.0008	-0.0003	-0.0001	0.0017	0.0010	0.0009
2006	0.0002	0.0025	-	-	-	-	-	0.0005	-
2007	-	-	0.0003	-0.0014	-0.0005	-0.0007	-	0.0005	-
2008	0.0009	0.0007	-	-	-	-	0.0001	-	0.0012
2009	-	-	-0.0006	-0.0014	-0.0005	-0.0009	0.0015	0.0004	-
2010	0.0013	0.0002	-	-	-	-	-	-	0.0021
	-	-	-0.0010	-0.0012	-0.0005	-0.0010	0.0013	0.0000	-
	0.0022	0.0014	-	-	-	-	-	-	0.0039
	-	-	-0.0013	-0.0024	-0.0003	-0.0010	-	-	-
	0.0021	0.0039	-	-	-	-	0.0002	0.0001	0.0049
	-	-	-0.0012	-0.0052	-0.0005	-0.0016	0.0008	-	-
	0.0028	0.0051	-	-	-	-	-	0.0001	0.0072
	-	-	-0.0031	-0.0074	-0.0004	-0.0018	0.0015	0.0002	-
	0.0024	0.0068	-	-	-	-	-	-	0.0049

(a) The sum of columns (1-27) gives the corresponding estimated cumulative per unit change in emission coefficient index ( $C_{emf} \sim 1$ ).

This analysis indicates the leading influence of Germany in EU emission coefficient trend, but it shows also an increasing attribution of ex-communist countries. Besides, it is striking that some Western Member States like Netherlands, Sweden and Finland do not seem to contribute to emission coefficient reduction.

#### 4. Conclusions

On Earth, human activities are changing the natural greenhouse. The burning of fossil fuels like coal and oil has increased the concentration of atmospheric carbon dioxide. This paper aims at analyzing changes in CO<sub>2</sub> emissions trend in the EU in the last decade, identifying and quantifying its relevant driving forces. Furthermore, we also pursue a detail analysis of emission coefficient factor, determining contribution of each economic sector to its percent changes. For these purposes, we first review the refined LMDI-II method and then we derive and adapt an attribution analysis of IDA.

Results suggests that energy efficiency and carbonization improvements become the largest important drivers in European emission reductions, being particularly significant contributions from big Western economies like Germany, the United Kingdom, Italy and Spain, and some ex-communist countries like Poland and Romania. Therefore, in order to achieve CO<sub>2</sub> emission reductions, to combat global warming and to fulfil international agreements, our findings recommend: R&D, modernization and adaptation to more efficient technologies, research for better quality fuels, support for lower carbon fuels use and installation of abatement technologies (e.g., CCS), particularly when these actions are implemented in the countries mentioned above.



## References

- Ang BW and Choi KH. Decomposition of aggregate energy and gas emission intensities for industry: a refined Divisia index method. *The Energy Journal* 1997;18(3):59-73.
- Ang BW and Liu FL. A new energy decomposition method: perfect in decomposition and consistent in aggregation. *Energy* 2001;26(6):537-548.
- Ang BW, Zhang FQ and Choi KH. Factorizing changes in energy and environmental indicators through decomposition. *The Energy Journal* 1998;23(6):489-495.
- Balk BM. Decomposition of Fisher indices. *Economics Letters* 2004;82:107-113.
- Choi KH and Ang BW. Attribution of changes in Divisia real energy intensity index - An extension to index decomposition analysis. *Energy Economics* 2012;34:171-176.
- Diewert WE. Recent developments in de economic theory of index numbers: capital and the theory of productivity. *American Economic Review* 1980;70(2):260-267.
- European Commission, 2014. European Economic Statistics. Publications Office of the European Union: Luxembourg; 2014. [Online at: <http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/themes>].
- Fernández González P, Landajo M and Presno MJ. The Divisia real energy intensity indices: Evolution and attribution of percent changes in 20 European countries from 1995 to 2010. *Energy* 2013;58(1):340-349.
- Fisher I. *The making of index numbers*. 3<sup>rd</sup> ed. London: Houghton Mifflin; 1927.
- Hammond GP and Norman JB. Decomposition analysis of energy-related carbon emissions from UK manufacturing. *Energy* 2012;41(1):220-227.
- Guo S, Shao L, Chen H, Li Z, Liu JB, Xu FX, Li JS, Han MY, Meng J, Chen Z-M and Li SC. Inventory and input–output analysis of CO<sub>2</sub> emissions by fossil fuel consumption in Beijing 2007. *Ecological Informatics* 2012;12:93-100.
- Hatzigeorgiou E, Polatidis H, Haralambopoulos D. CO<sub>2</sub> emissions in Greece for 1990-2002: a decomposition analysis and comparison of results using the arithmetic mean Divisia index and logarithmic mean Divisia index techniques. *Energy* 2008;33(3):492-499.
- International Energy Agency (IEA). *World Energy Outlook 2004*. [Online at: <http://www.worldenergyoutlook.org/publications/>].
- Liao H and Wei YM., China's energy consumption: a perspective from Divisia aggregation approach. *Energy* 2010;35(1):28-34.

Liu XQ, Ang BW and Ong HL. The application of the Divisia index to the decomposition of changes in industrial energy consumption. *The Energy Journal* 1992;13(4):161-177.

Ma C and Stern DI. China's changing energy intensity trend: a decomposition analysis. *Energy Economics* 2008;30(3):1037-1053.

Nag B and Parikh J. Indicators of carbon emission intensity from commercial energy use in India. *Energy Economics* 2000;22(4):441-461.

Ozawa L, Sheinbaum C, Martin N, Worrell E and Price, L. Energy use and CO<sub>2</sub> emissions in Mexico's iron and steel industry. *Energy* 2002;27(3):225-239.

Paul S and Bhattacharya RN. CO<sub>2</sub> emissions from energy use in India: a decomposition analysis. *Energy Policy* 2004;32:585-593.

Ramírez CA, Patel M and Blok K. The non-energy intensive manufacturing sector: an energy analysis relating to the Netherlands. *Energy* 2005;30:749-767.

Reinsdorf MB. Log-change indexes in fixed basket form Working paper 278. U.S. Bureau of Labor Statistics, Washington, D.C.; 1996.

Sahu SK and Narayanan, K. Decomposition of industrial energy consumption in Indian manufacturing: the energy intensity approach. *Journal of Environmental Management and Tourism, Association for Sustainable Education. Research and Science* 2010;0(1):22-38.

Sato K. The ideal log-change index number. *The Review of Economics and Statistics* 1976;58: 223-228.

Shahiduzzaman Md and Alam K. Changes in energy efficiency in Australia: a decomposition of aggregate energy intensity using Logarithmic Mean Divisia approach. *Munich Personal Repec Archive* 2012; Paper No. 36250. (Online at <http://mpa.ub.uni-muenchen.de/36250>).

Sun JW. Decomposition of aggregate CO<sub>2</sub> emissions in the OECD: 1960-1994. *The Energy Journal* 1999;20:147-155.

United Nations Framework Convention on Climate Change, 1997. Kyoto Protocol. [Online at: [http://unfccc.int/essential\\_background/kyoto\\_protocol/items/1678.php](http://unfccc.int/essential_background/kyoto_protocol/items/1678.php)].  
United Nations Framework Convention on Climate Change, 2012. Doha Amendment to the Kyoto Protocol. [Online at: [http://unfccc.int/files/kyoto\\_protocol/application/pdf/kp\\_doha\\_amendment\\_english.pdf](http://unfccc.int/files/kyoto_protocol/application/pdf/kp_doha_amendment_english.pdf)].

Vartia YO. Ideal-log change index numbers. *Scandinavian Journal of Statistics* 1976;3:121-126.

Zafrilla JE, López LA, Cadarso MA and Dejuán Ó. Fulfilling the Kyoto protocol in Spain: a matter of economic crisis or environmental policies? *Energy Policy* 2012;51:708-719.

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***Comparative Studies of Renewable Energy Development  
between China and the United States of America***

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**Abstract:** Current status of renewable energy development in China and US is analyzed via comparative studies. Past trend for each country is analyzed based on available data. The trajectory for the renewable energy development is different. In order to meet the demand of renewable energy and protect environment, a mathematical model is established to forecast the renewable energy consumption. This model exhibits characteristics of essential physical concept and provides predictions for rapid growth in renewable energy consumption in the future. Furthermore, if China and the US can jointly develop the renewable energy, there will be mutual benefits. Areas of co-development are explored in terms of technologies, markets and investments. This study may provide insightful information on renewable energy consumption in the future.

**Keywords:** Renewable energy consumption; Forecast; China; US

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## 1. Introduction

To achieve sustainability, renewable energy should be a part of energy profile in China and US [1-2]. Currently, these two countries are top two energy consumers in the world, and heavily depend on imported oil. For the future energy security and economy growth, it is desirable to correctly predict dynamic characteristics of renewable energy demand in both countries.

Previous studies addressed different aspects of energy consumption forecasting. Messner [3] utilized growth factor, economics and technology as variables to analyze energy, Zachariadis [4] explored dynamic evolutions of transport modes, and Sari [5] developed error variance decomposition techniques to determine the rate of growth. Various models were considered in different countries and regions. Kaboudan predicted Zimbabwe's electricity consumption via a non-linear dynamic econometric forecasting model [6], Tamimi predicted Jordan's energy consumption via an exponential forecasting model [7], Chavez predicted Spain's energy production and consumption via univariate Box–Jenkins time series analyses [8], and Ediger predicted Turkey's energy demand via semi-statistical techniques [9].

For energy consumption problems in China, there are limited studies [10]. In Crompton's work [11], Bayesian vector autoregressive methodologies were used to forecast China's energy consumption. In Adams' work [12], an econometric model was established to forecast Chinese energy consumption and imports to 2020. Due to rapid growth in economy, the need for oil and gas imports will be very high to meet the energy consumption demand in China. Some of the Chinese development stages may be similar to those experienced in US.

For US, Winebrake [13] applied an error decomposition technique to forecast energy consumption in major sectors such as commercial, industrial, residential, and transportation sectors. O'Neill [14] found that futuristic energy consumption projection is usually lower than the actual value. Saunoris [15] examined the dynamics of electricity demand in terms of growth and conservation.

Among all models for predictions, Logistic models seem to be appropriate to initiate studies due to their simplicity [16, 17]. For example, Bodger [18] used such models to forecast electricity consumption in New Zealand. Since renewable energy consumption is at its early stage in China and US, it is reasonable to consider a Logistic model as a prediction tool.

## 2. Method

In economy, biology and ecology, a logistic curve is often used to describe a growth process [19-24]. Such curve usually has three sections: slow growth at the beginning, rapidly increasing in the middle and reaching a steady state towards the end.

Because the curve has an “S” shape, it is also known as “S-curve.”

A Logistic model is utilized to forecast renewable energy consumption. The basic assumption is that the renewable energy development process will follow an S curve in China and US. The growth may be slow at the begging due to difficulty in technology development and capital acquisition, fast in the middle due to available technology and monetary funds, and slow at the end due to saturation in technology deployment and market penetration. The logistic growth rate equation of renewable energy consumption is as follows.

$$\frac{dx}{dt} = rx \left( 1 - \frac{x}{K} \right) \quad (1)$$

where  $x$  is the renewable energy consumption at any given time  $t$ ,  $r$  is inherent growth rate for renewable energy consumption, and  $K$  is the maximum renewable energy consumption at the end when the growth reaches saturation point. At  $t = 0$ , the energy consumption is  $x_0$ ; or  $x_0 = x|_{t=0}$ . After solving Equation (1), an answer can be obtained as follows.

$$x = \frac{K}{1 + \left( \frac{K}{x_0} - 1 \right) \exp(-rt)} \quad (2)$$

Assuming  $y = \ln \frac{K-x}{x}$  and  $\frac{K}{x_0} - 1 = e^a$ , Equation (2) can be rewritten as follows.

$$y = a - rt \quad (3)$$

### 3. Results

#### 3.1 Existing renewable energy consumptions in China and US

Renewable energy is an energy source which can be regenerated and sustained. In this paper, solar, wind, biomass, geothermal and tidal energy are considered. Between 2005 and 2012, the annual renewable energy consumptions for China and US are tabulated in Table 1 with the data from BP energy system yearbooks. All values are given in MTOE (Million Tons of Oil Equivalent). Each country had a different  $x_0$  value for  $t_0$  (year 2005), i.e., 1.06 MTOE for China and 20.62 MTOE for US. Seven years later, the Chinese annual renewable energy consumption was 31.90 MTOE, less than that of US (50.72 MTOE). Notice that the rate of change for China was larger than that for US.

Table1. Renewable Energy Consumption (MTOE)

Year	China	US
2005	1.06	20.62
2006	1.46	22.73
2007	1.86	24.73
2008	3.61	29.49
2009	6.94	33.65
2010	14.11	38.9
2011	25.43	45.03
2012	31.9	50.72

### 3.2 Estimation of K parameter in Logistic model

In order to establish a Logistic model for renewable energy consumption, one needs to estimate the ranges of the K parameter. Before running logistic iterations, the initial K value should be placed between two limits:  $K_{low}$  and  $K_{high}$ , with  $K_{low} > x_0$  and  $10x_0 > K_{high} > 2x_0$ . After iterations, different K values are obtained with different determination coefficients  $R^2$  as tabulated in Table 2 for US. For US, the largest coefficient is  $R^2 = 0.9939$  and the corresponding K value is 500 MTOE.

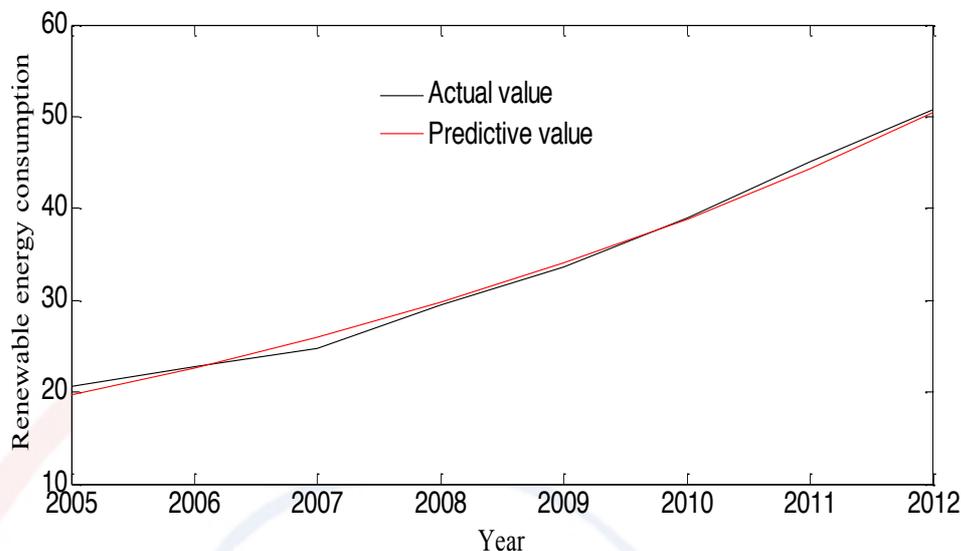
**Table 2**  
Statistical examination of renewable energy consumption in US

K (MTOE)	$R^2$	a	r
100	0.9869	1.639	-0.2016
150	0.9912	2.072	-0.1717
200	0.9924	2.378	-0.1600
250	0.9928	2.613	-0.1538
300	0.9933	2.804	-0.1500
350	0.9936	2.964	-0.1474
400	0.9937	3.102	-0.1455
450	0.9938	3.224	-0.1440
500	0.9939	3.332	-0.1429
550	0.9937	3.430	-0.1419
600	0.9934	3.519	-0.1412

In Table 2, corresponding to the largest  $R^2$  value,  $a = 3.332$  and  $r = -0.1429$ ; or  $y = 3.332 - 0.1429t$ . Therefore, Logistic prediction model of renewable energy consumption for US is as follow.

$$X = \frac{500}{1 + e^{3.332 - 0.1429t}} \quad (4)$$

In Figure 1, Equation (4) is plotted as a theoretically predicted curve, which is close to that based on the actual data.



**Figure1:** Actual and predictive value of renewable energy consumption in the US

The Chinese renewable energy development is rather fast. After iterations, different K values are obtained with different determination coefficients  $R^2$  as tabulated in Table 3. The largest coefficient  $R^2$  is 0.9759, and the corresponding K value is 300 MTOE.

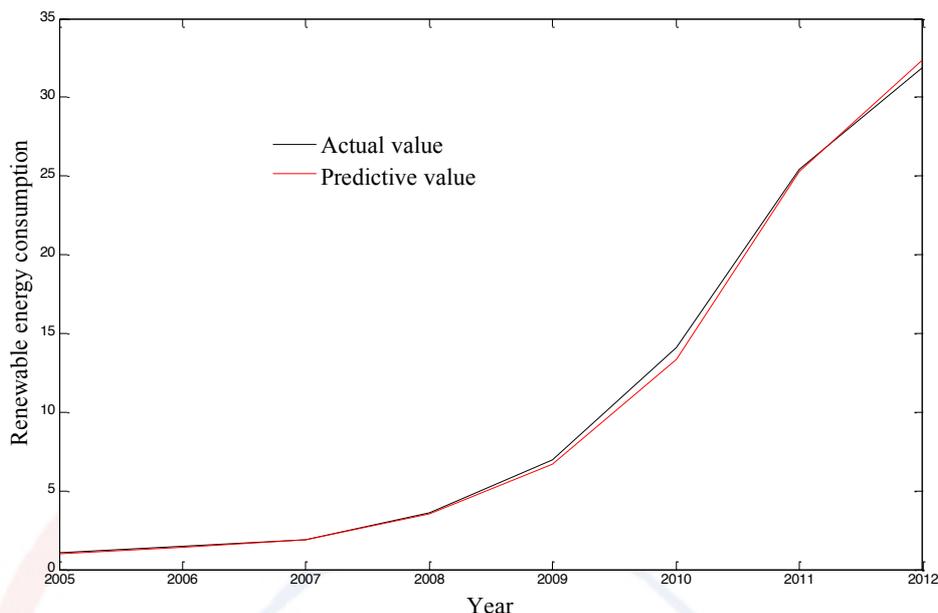
**Table 3**  
Statistical examination of renewable energy consumption in China

K (MTOE)	$R^2$	a	r
100	0.9717	5.523	-0.4837
150	0.9739	5.915	-0.4766
200	0.9749	6.197	-0.4731
250	0.9755	6.416	-0.4711
300	0.9759	6.596	-0.4698
350	0.9756	6.749	-0.4688
400	0.9753	6.881	-0.4681

As illustrated in Table 3,  $a = 6.596$  and  $r = -0.4698$ ; or  $y = 6.596 - 0.4698 t$ . Therefore, Logistic prediction model of renewable energy consumption for China is as follow.

$$X = \frac{300}{1 + e^{6.596 - 0.4698t}} \quad (5)$$

In Figure 2, Equation (5) is plotted as a theoretically predicted curve, which is close to that based on the actual data.



**Figure2:** Actual and predictive value of renewable energy consumption in China

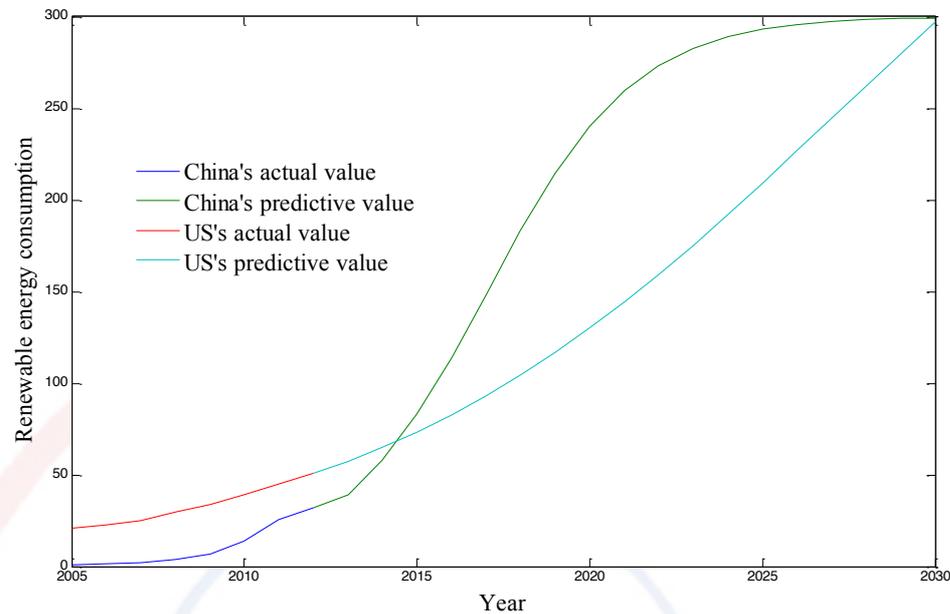
#### 4. Renewable Energy Consumption Predictions

Using models obtained above, one can then predict the renewable energy consumptions in the future. In Figure 3, the consumption for US is plotted as a function of duration. The predicted values (up to year 2030) and actual values (Year 2005 - 2012) can be viewed along one smooth curve without any apparent discrepancies. Additionally, for China, the predicted values (up to year 2030) and actual values (2005-2012) may be fitted to a curve with some kinks due to recent rapid development.

Between 2015 and 2020, the growth trend for China is much faster than that for US. By year 2030, the total amount of renewable energy consumption for each country will be very close. Such predictions can be related to the realistic situations in both countries. For China, rapid economic growth requires more energy resources, and leads to environmental pollutions. To solve both problems simultaneously, Chinese government places emphasis on renewable energy deployment. As a result, there will be accelerated development. For US, the economy is relatively stable, and the pace of renewable energy development will be increased slowly and gradually.

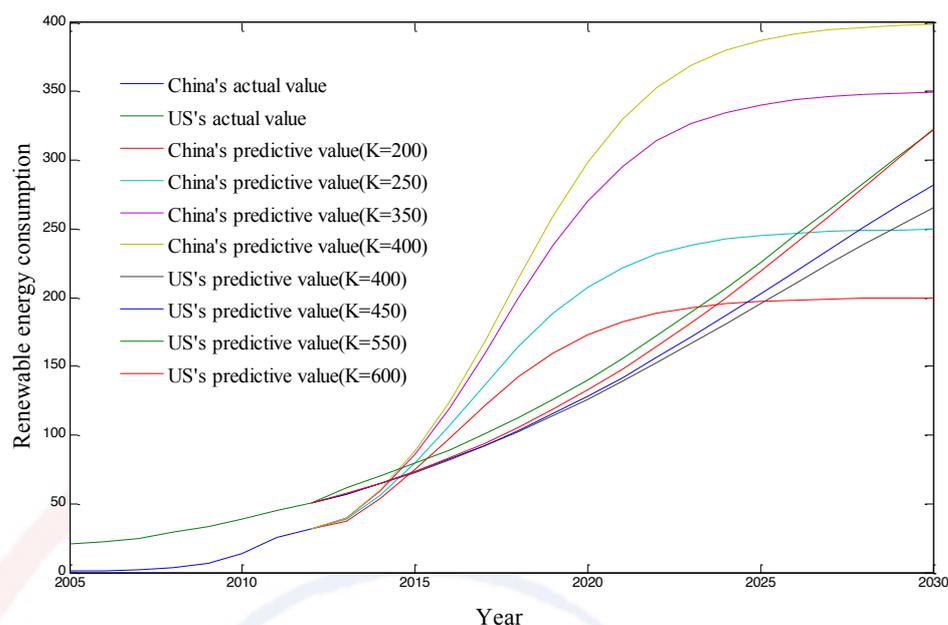
In Figure 3, the most important predictions are the trends, rather than the precise numerical values provided by the simulations. The maximum consumption value for China may be larger than that of US in the future because Chinese energy resources are less than that in US. Furthermore, it may take longer time for US to reach its maximum value than it is for China because US business emphasizes on longer term

investments for energy than that in China.



**Figure3:** Renewable energy consumptions in US and China

At this moment, the curves in Figure 3 are regarded as most probable trends based on available energy resources and relative costs of renewable energy deployment in these two countries. Other deviations from Figure 3 may exist as illustrated in Figure 4. The Chinese K parameter is between 200 and 400 MTOE, and the US parameter is between 400 and 600 MTOE. Around year 2015, the consumptions of both countries will be close regardless the K parameters. However, after 2015, the trajectories will depend on K parameters. With the same K parameter of 400 MTOE, Chinese consumption will always exceed that of US. With Chinese K parameter being 350 MTOE, Chinese consumption will still exceed US. At year 2030, with Chinese K parameter of 250 MTOE or less, the predicted Chinese consumption will be less than that of US. In the near future, such predictions may be modified with new breakthrough in technologies for renewable energy harvesting and deployment.



**Figure 4:** Renewable energy consumptions with different K parameters

## 5. Conclusions and Discussions

Based on the above analysis, renewable energy consumptions in China and US will increase with different trajectories. Around 2015, the consumptions in both countries will be close. Between 2015 and 2030, the growth rate in China may exceed that in US. For renewable energy development, experiences gained in one country may be useful in the other country. It would be beneficial if these two countries can cooperate in policies and technologies as they have the common interests in economy and environment. China gradually realizes that renewable energy may help its economy and environment. US may find a vast market for its renewable energy technologies. The fast growth in China is mainly due to the stimulus from its government. To sustain the growth, China should consider cooperation with US in technologies and investment. The steady growth in US is due to government policies and industrial needs. To increase the growth rate, US should consider cooperation with China in technology transfers and market development. Furthermore, if China and the US can jointly develop the renewable energy, there will be mutual benefits. Because two countries are similar in geological and geographical characteristics, cooperation between a Chinese province and a US state would be possible. Testing and measurement standards should be unified between China and US in order to promote the cooperation in renewable energy. Currently, we are exploring other modeling tools to compare development of hydroelectricity and smart grids. This study may provide insightful information on renewable energy consumption in the future.

## References

- [1] Buckman, G. (2011). The effectiveness of Renewable Portfolio Standard banding and carve-outs in supporting high-cost types of renewable electricity. *Energy Policy*, 39, 4105–4114.
- [2] Christoffersen, G. (2010). US–China Energy Relations and Energy Institution Building in the Asia–Pacific. *Journal of Contemporary China*, 67, 871–889.
- [3] Messner, S., Strubegger, M. (1987). A framework to analyse the consumption of energy. In: *Proceedings of the workshop of economics, modelling, planning and management of energy* (pp.315-328). Italy.
- [4] Zachariadis, T., Kouvaritakis, N. (2003). Long-term outlook of energy use and CO<sub>2</sub> emissions from transport in Central and Eastern Europe. *Energy Policy*, 31, 759–773.
- [5] Sari, R., Soytas, U. (2004). Disaggregate energy consumption, employment and income in Turkey. *Energy Economics*, 26, 335–344.
- [6] Kaboudan, M. (1989). An econometric model for Zimbabwe's future electricity consumption. *Energy*, 1, 75–85.
- [7] Tamimi A, Kodah Z. (1993) Modelling of energy consumption and projection in Jordan. *Energy Convers Manage*, 34, 427–32.
- [8] Chavez, G. S., Bernat, X. J., Coalla, L. H. (1999). Forecasting of energy production and consumption in Asturias (Northern Spain). *Energy*, 24, 183–98.
- [9] Ediger, V. S., Tatildil, H. (2002). Forecasting the primary energy demand in Turkey and analysis of cyclic patterns. *Energy Convers Manage*, 43, 473–87.
- [10] Chow, L. C-h. (2001). A study of sectoral energy consumption in Hong Kong (1984–97) with special emphasis on the household sector. *Energy Policy*, 29, 1099–110.
- [11] Crompton, P., Wu, Y. (2005). Energy consumption in China: past trends and future directions *Energy Economics*, 27, 195–208.
- [12] Adams, F. G., Shachmurove, Y. (2008). Modeling and forecasting energy consumption in China: Implications for Chinese energy demand and imports in 2020. *Energy Economics*, 30, 1263–1278.
- [13] O'Neill, B. C., Desai, M. (2005). Accuracy of past projections of US energy consumption. *Energy Policy*, 33, 979–993.

- [14] Winebrake, J. J., Sakva, D. (2006). An evaluation of errors in US energy forecasts: 1982–2003. *Energy Policy*, 34, 3475–3483.
- [15] Saunorisa, J. W., Sheridan, B. J. (2013). The dynamics of sectoral electricity demand for a panel of US states: New evidence on the consumption–growth nexus. *Energy Policy*, 61, 327–336.
- [16] Miranda, L.C.M., Lima, C.A.S. (2011). On the forecasting of the challenging world future scenarios. *Technological Forecasting and Social Change*, 78, 1445–1470.
- [17] Meng, M., Niu, D. (2011). Modeling CO<sub>2</sub> emissions from fossil fuel combustion using the logistic equation. *Energy*, 36, 3355–3359.
- [18] Bodger, P. S., Tay, H. S. (1987). Logistic and energy substitution models for electricity forecasting: a comparison using New Zealand consumption data. *Technol Forecast Social Change*, 31, 27–48.
- [19] Pearl, R., Reed, L. J. (1923). On the mathematical theory of population growth. *Metron*, 3, 1–15.
- [20] Tsoularis, A., Wallace, J. (2002). Analysis of logistic growth models. *Math. Biosci*, 179, 21–55.
- [21] Peleg, M. (1996). A model of microbial growth and decay in a closed habitat based on combined Fermi's and the logistic equation. *J. Sci. Fd. Agric*, 71, 225–230.
- [22] Hastings, H.M., Rumignani, D.J., Vassalotti, A.G., Weiss, M.T., Wu, Y.R. (1996). Lack of predictability in model ecosystems based on coupled logistic equations. *Ecol. Model*, 92, 209–214.
- [23] Parsons, A.J., Schwinning, S., Carrère, P. (2001). Plant growth functions and possible spatial and temporal scaling errors in models of herbivory. *Grass Forage Sci*, 56, 21–34.
- [24] Matis, J. H., Kiffe, T.T., Renshaw, E., Hassan, J. (2003). A simple saddle point approximation for the equilibrium distribution of the stochastic logistic model of population growth. *Ecol. Model*, 161, 239–248.

***Meshed HVDC Transmission in the Context of Sustainable Power  
Transmission for the Future and its Environmental Impact***

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**Abstract**

When talking about the future of power systems, power transmissions cannot be omitted. While it makes sense to generate renewable energy where the potential is highest, it often means that renewable plants will be far from industrial zones or load centers. Hence, volatile renewable energy has to be transmitted over long distances. Because direct current (DC) transmission has less line losses and the AC/DC grid couplings (converter terminals) are fully controllable, high voltage direct current (HVDC) transmission is favored for modern long distance power transmission to reinforce existing AC transmission. In America, Europe, and around the world, HVDC transmission is discussed and implemented in grid expansion studies and plans. These plans range from point-to-point HVDC links, multi-terminal radial HVDC systems towards meshed HVDC grids. Some studies even introduce a complete transition from AC to DC power systems. This paper, based on previous work, explores meshed HVDC grids, and their ability to transmit volatile renewable energy in bulk and over long distances. Using these grids is shown to prevent a massive AC grid expansion, and therefore can positively impact the environment. The ideas introduced in this paper are applied in a feasibility study of a pan-European-North African HVDC transmission grid.

Keywords: meshed HVDC grid, renewable energy, power transmission, smart transmission, grid operation, environmental impact, management of resources

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## Introduction

Due to the increasing in-feed of renewable energy (RE) and the reduction of conventional power plants, power grids must be reinforced. While RE is generated where the potential is highest, it often means that renewable plants will be far from industrial zones or load centers (Platzer, 2011),(DESERTEC Foundation, 2014),(Sahara Wind Energy Development Company, 2014). Hence, volatile renewable energy has to be transmitted over long distances and transmission grids will play an important role in the future.

Because DC transmission has less line losses and the AC/DC grid couplings (converter/terminals) are fully controllable, high voltage direct current (HVDC) transmission is favored for modern long distance power transmission to reinforce existing AC transmission (Meah & Ula, 2007). In America, Europe, and around the world, HVDC transmission is discussed and implemented in grid expansion plans and studies. These plans range from point-to-point HVDC links (Bundesnetzagentur, 2013), multi-terminal radial HVDC systems towards meshed HVDC grids (CIGRÉ WG B4-52, 2012),(Krontiris & Benz, 2013),(Bohn, Boie, Kost, Agsten, & Westerman, 2013). Some studies even introduce a complete transition from AC to DC power systems (R. W. De Donker, 2013).

This paper, based on previous work (Bohn, Agsten, et al., 2014),(Marten & Westermann, 2012), explores meshed HVDC grids, and their ability to transmit volatile renewable energy in bulk and over long distances. Using these grids it is shown to prevent a massive AC grid expansion, and therefore positively impact the environment. The ideas introduced in this paper are applied in a feasibility study of a pan-European-North African HVDC transmission grid.

## Power Transmission

Power grids are divided into the transmission grid and the distribution grid. While the transmission grid transmits bulk power over long distances, the distribution grid distributes power in local regions. Today's power transmission grids mainly consist of the alternating current (AC) transmission in tri-phase at high voltages (HVAC transmission). Voltages range between 220 kV and 765 kV, and above for ultrahigh voltage (UHV) transmission, e.g. 1000 kV UHVAC in China (Liu, 2013).

High voltage direct current (HVDC) transmission has several advantages over AC transmission (Meah & Ula, 2007), and is more efficient, particular for wide-area transmission. In (Paris et al., 1984) the longest cost-effective distances for HVAC and HVDC transmission was determined. For HVDC transmission 7,000 km (4,300 mi) was determined. For AC it was 4,000 km (2,500 mi), although transmission lines in use today are shorter than this. In the study on a pan-European-North African electricity infrastructure (Boie et al., 2013) the existing AC transmission grid and the developed HVDC grid was modeled. The histogram of line length was determined afterwards, as shown in Figure 1.

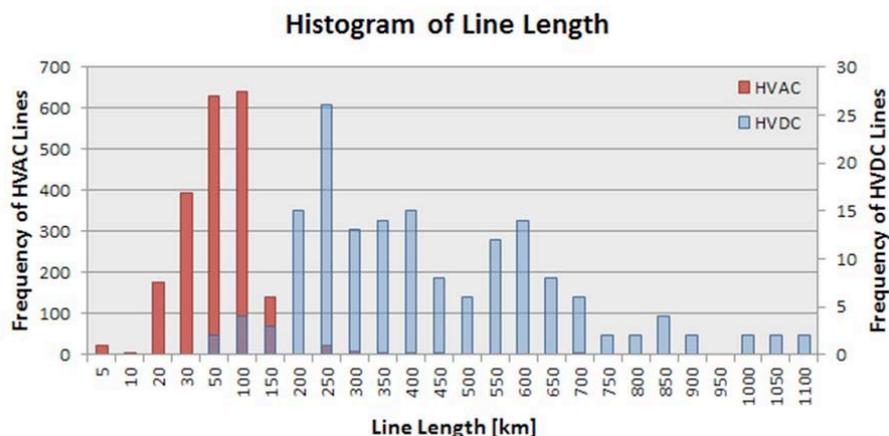


Figure 1. Frequency of transmission line length for HVAC and HVDC lines

It can be seen that the AC transmission system has more lines and the lines are shorter compared to the HVDC system. AC transmission lines range between 30 – 100 km while HVDC lines mainly range between 200 and 600 km, and above. This is because HVDC transmission is used when it comes to overlaying the AC transmission grid (DESERTEC Foundation, 2014), (CIGRÉ WG B4-52, 2012), (Krontiris & Benz, 2013), at higher voltages (e.g.  $\pm 800$  kV DC). An overlaying HVDC grid is supposed to relieve the underlying AC transmission grid from bulk energy transmission over long distances. Figure 2 shows the AC power transmission infrastructure and the overlaying HVDC grid in a meshed manner.

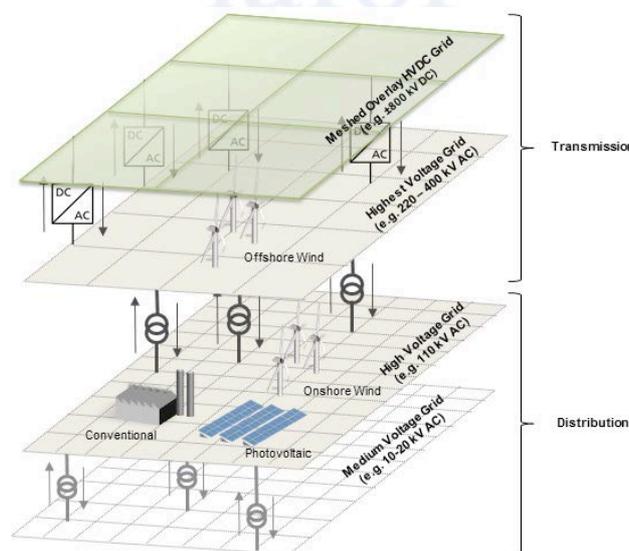


Figure 2. Power grid infrastructure

For the transmission of bulk power over long distances there are basically four technologies available; HVAC through overhead lines, HVAC through cable, HVDC through overhead lines and HVDC through cable. HVAC transmission through overhead lines exists already worldwide and is a mature technology. However, HVAC transmission has a disadvantage over HVDC due to the alternating current and its reactive power demand (Meah & Ula, 2007). This reactive power demand increases over distance. Also, HVAC transmission through overhead lines through water is not feasible. HVAC transmission through cable is doable but demands even more reactive

power due to the proximity of the AC current-carrying conductors. HVDC is the preferred method for transmitting bulk power over long distances, even, and particularly, when using cable technology. HVDC does not have a reactive power demand due to the absence of a system frequency.

### **RE Potential for a pan-European-North African Electricity Exchange**

In the project SUPERGRID (Platzer, 2011) three Fraunhofer institutes have evaluated the potential for RE deployment, strategic location planning for renewable energy plants in North Africa (NA) and the power transmission infrastructure for a European-North African electricity exchange (Boie et al., 2013). The study was done for the year 2050 and four possible scenarios with differences in CO<sub>2</sub> reduction goals, increases in local electricity consumption, energy efficiency and availability of a transmission grid infrastructure, were evaluated.

- (1) Moderate CO<sub>2</sub> reduction targets of 50% relative to 1990 levels for both EU and NA; high electricity demand in both regions, no integration of EU-NA transmission networks.
- (2) Ambitious CO<sub>2</sub> reduction targets of 95% relative to 1990 levels for the EU and 50% for NA; high electricity demand in both regions, no integration of EU-NA transmission networks.
- (3) Ambitious CO<sub>2</sub> reduction targets of 95% relative to 1990 levels for the EU and 50% for NA; high electricity demand in both regions; EU-NA transmission networks are interconnected.
- (4) Ambitious CO<sub>2</sub> reduction targets of 95% relative to 1990 levels for the EU and 50% for NA; low electricity demand in both regions; EU-NA transmission networks are interconnected.

Renewable energy potentials were determined using a geographic information system (GIS). Moreover, the power consumption of the five NA countries (Morocco, Algeria, Tunisia, Libya and Egypt) was estimated for the year 2050. Based on this data and assumptions for technology cost developments, cost-optimized generation mixes and power flows among the five NA countries, and between Europe and NA were determined by applying a linear optimization model (Boie et al., 2013). Results are shown in Table 1 and Table 2. For a European-NA electricity exchange eight cost-optimized interconnectors were determined between Portugal-Morocco, Spain-Morocco, Spain-Algeria, France-Algeria, Italy-Algeria, Italy-Tunisia, Italy-Libya, Greece-Libya. . It was found out that the potential for RE generation in NA exceeds the local demand by approx. 1/3. Hence, electricity export to Europe is possible and economically viable. The results for the RE generation mix and net energy flows are shown in Table 1 and Table 2. The RE generation is dominated by wind, followed by concentrated solar power (CSP) and photovoltaic (PV).

Table 1. Possible electricity generation portfolios in NA in 2050 (Boie et al., 2013)

	Generation per technology in 2050 [TWh/a]			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Wind	618	737	965	735
PV	97	86	118	94
CSP	199	303	416	222
Gas -GT	8	3	3	4
Gas-CCGT	125	68	21	38
Coal	47	0	1	3
Hydro	50	50	50	50
Total	1143	1247	1575	1146
RE-share	83%	93%	98%	96%

Table 2. Net electricity exchanges in 2050 (Boie et al., 2013)

	Net Electricity Exchanges [TWh]		Total
	Within NA	NA-EU	
Scenario 1	28	Per definition not possible	28
Scenario 2	37	Per definition not possible	37
Scenario 3	117	347	465
Scenario 4	68	191	259

These results were further used in a next modelling step for strategic location planning and short-term operation of individual RE generation plants (Kost, Schlegl, & Möst, 2013). In this modelling the five NA countries were further detailed into 23 regions. For each region a modelling for short-term operation was conducted. As results, further detailed generation mixes (c.f. Figure 3) and generation and consumption profiles (c.f. Figure 4) for each region were generated.

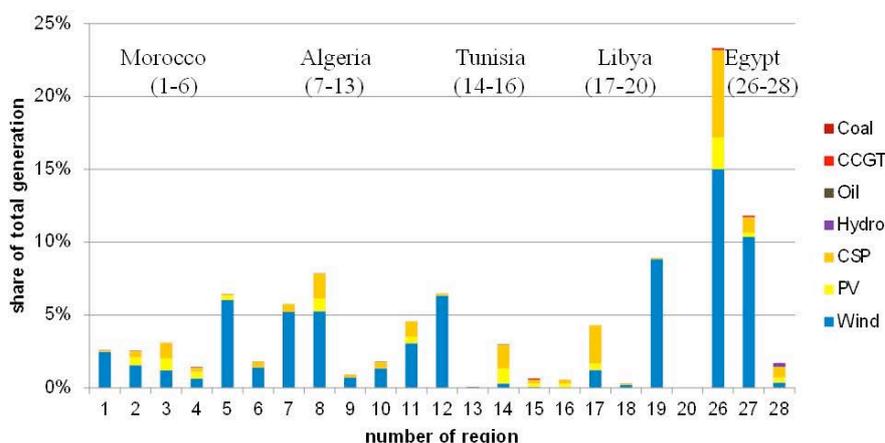


Figure 3. Generation mix per region in NA

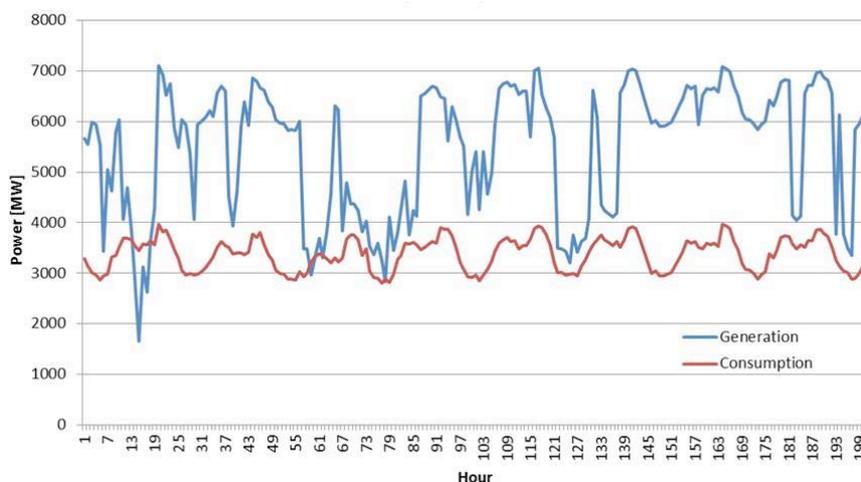


Figure 4. Excerpt of a generation (blue) and consumption (red) profile

### A pan-European-North African Electricity Infrastructure

The generation and consumption profiles from the previous modelling were used to evaluate the existing power transmission grid and to further develop the required power transmission infrastructure. To do so the existing AC transmission infrastructure was modelled and evaluated for the pan-European-North African electricity exchange. The currently existing transmission grid of the 220 kV voltage level and above was modelled as shown in Figure 5.

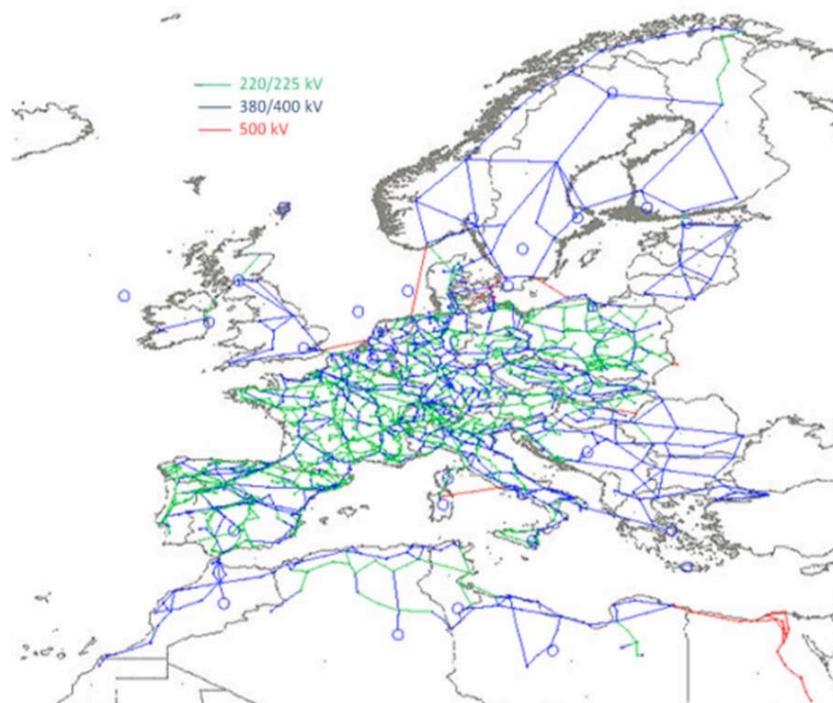


Figure 5. European and North African AC transmission grid infrastructure

In this power grid model the aforementioned generation and consumption profiles were applied to each power grid node of the model. Then power flows for each step (8760 steps in total, each for one hour of the year 2050) were observed in order to determine overloading of the power grid. The analysis of the existing AC

transmission grid revealed that the current transmission infrastructure is not able to transmit the predicted amounts of electricity. The transmission grid has to be expanded.

As mentioned before the HVDC transmission is the favored method for transmitting bulk power over long distances. Therefore, an HVDC grid from a feasibility study (CIGRÉ WG B4-52, 2012) was implemented first in the modelling. This HVDC grid enables the electricity transmission throughout the Mediterranean See and to the load centers in Europe. Based on this HVDC grid the AC grid expansion in NA was determined.

The total transfer capacity (TTC) is commonly used to quantify grid expansion needs. The TTC represents the maximum transmittable power through a power grid. It is the sum of the maximum transmittable power of each transmission line of the transmission infrastructure. The results are shown in Table 3.

Table 3. AC transmission grid expansion needs in NA until 2050

Scenario	TTC [MVA]	Expansion Needs	Total Length of Lines [km]	New Lines [km]
Base Grid (Status Quo)	390,184	-	24,320	-
Scenario 1	801,840	206 %	69,680	45,359
Scenario 2	919,690	236 %	87,589	63,269
Scenario 3	2,805,746	719 %	310,580	286,260
Scenario 4	2,696,822	691 %	290,886	266,566

An AC grid expansion of approx. two-times its actual capacity is required for the two scenarios that do not have a transmission infrastructure between Europe and NA. This grid expansion is required to cover the local demand in NA only. The scenarios that do allow electricity export to Europe require a grid expansion of approx. 7-times its actual grid capacity. This is an enormous grid expansion that has to be deled with by 2050. Assuming one km of new transmission line cost approx. 1 Mio. Euro this results in a massive investment.

On the other side, disadvantages of the AC transmission remain. The utilization of the transmission lines is low due to the demand of reactive power and the transmission of volatile renewable energy (caused by the Ferranti effect). Hence, transmission lines have to be installed to carry the total transmission power which is the sum of active (P) and reactive power (Q) but active power can be used only. It also means that transmission lines need to be financed fully while the return of investment can be calculated on the utilization of approx. 20-30% only. Also, the volatile power transmission generates a volatile reactive power demand which need to be compensated. Hence, controllable compensation devices have to be installed which increases the cost of transmission further.

Table 4. AC transmission grid utilization and reactive power demand

Scenario	Utilization [%]	Average Q/P Ratio	Max. Average Q/P Ratio
Scenario 1	21.4 %	4.47	69
Scenario 2	21.5 %	1.48	12
Scenario 3	27.7 %	2.07	37
Scenario 4	31.0 %	2.06	56

As HVDC transmission is the favored method the actual modelled HVDC grid was expanded in order to reduce AC transmission grid expansion. To expand the HVDC grid the results from the first modelling were used to place the identified cost-optimized interconnectors between Europe and NA, and the generation profiles for each region in NA were analyzed for the highest electricity export (c.f. Figure 6).

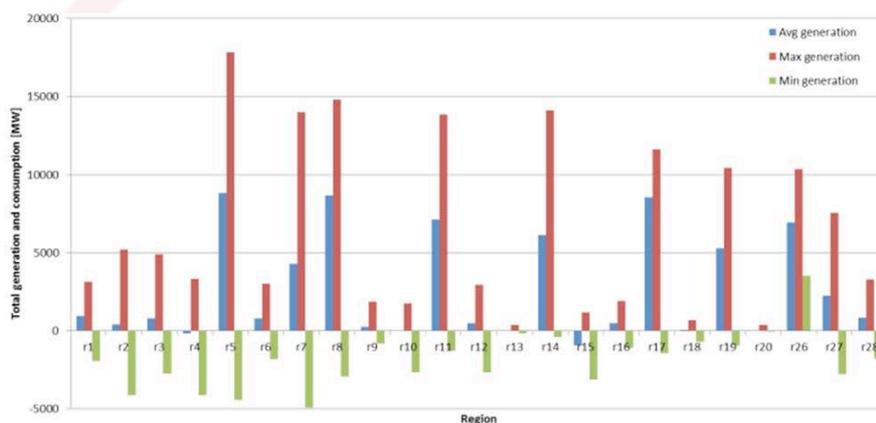


Figure 6. Total excess generation of each region (scenario 3)

Then the interconnectors between Europe and NA were placed in the regions with the highest electricity export. Additionally, AC/DC converter terminals were placed in these regions to connect the AC and HVDC grid. Also, based on the results of power flows among NA countries and the high reactive power demand of remote regions, some kind of collector grid was formed. The finally expanded HVDC grid is shown in

Figure 7.

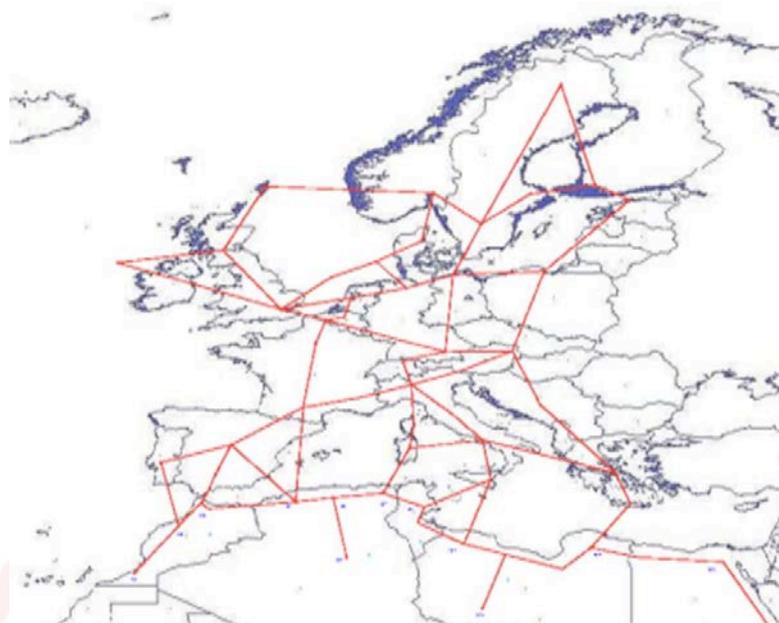


Figure 7. Pan-European-North African overlay HVDC transmission grid

The proposed HVDC grid enables the electricity export of RE from NA to Europe and is able to reduce AC grid expansion. The HVDC grid is designed in a meshed way, but meshed HVDC grids do not exist as of today. Hence, further investigation and development has to be undertaken in terms of grid operation of meshed HVDC grids, e.g. (Marten & Westermann, 2012),(Bohn, Fetisova, Agsten, Marten, & Westermann, 2014), which shall not be part of this contribution.

### **Environmental Impact**

The construction of new and the reinforcement of existing power transmission lines is usually refused by the relevant public and environment protection organizations. However, new and expanded transmission is required due to the increasing in-feed of RE (Energie-Forschungszentrum Niedersachsen, 2012). The expansion of transmission grids is foreseen in many power grid expansion plans worldwide. Hence, grid development and reinforcement plans have to respect ecological, environmental and territory considerations (Kühne, 2014).

In 2012 the German energy research center Niedersachsen did a study to evaluate the options for transmission grid expansion based on HVAC and HVDC from an environmental perspective. Special focus of the study was the comparison of overhead lines and underground cables and its environmental, ecological, and territorial impact. One result of the study is that it is difficult to compare HVAC and HVDC in general. There are technological, operational, and economic considerations that have to be taken into account and require a case-by-case comparison. HVAC using overhead lines is a well-established technology compared to the relatively new VSC HVDC technology with cables. Due to the underground work and more complex composition of cables the cable technology is more costly than overhead lines. HVAC transmission with cables requires compensation, already after a few 10 km, and is not feasible for the bulk power transmission over long distances. Advantages of VSC HVDC are the independent controllability of reactive power on the AC side, the

controllability of the (active) power flow and the low voltage drop across conductors. Also HVDC with cables is feasible for bulk power transmission over long distances. HVDC transmission using overhead lines even requires narrower power transmission routes which impacts the environment positively. The study, however, concludes that HVDC has an economic advantage over HVAC for transmission lines 130-280 km and above, even when using cable technology. (Energie-Forschungszentrum Niedersachsen, 2012)

The study further shows that electro-magnetic fields, which may impact humans and other creatures, are below the safety limits of the German 26. BImSchV provision if the appropriate geometrical alignment is chosen. HVDC using cables is the favored method in terms of electro-magnetic fields. They do not have an electric field outside the cable and have a static magnetic field due to the usage of DC current which does not exceed the magnetic flux of the earth magnetic field. Besides the note that HVDC in a meshed way is not useable today, and for the short distances in Germany, the study concludes that HVDC should be used where its advantages can be released – for the bulk power transmission over long distances, for interconnectors through a sea, to connect off-shore wind parks, and for a German or European-wide overlay grid. (Energie-Forschungszentrum Niedersachsen, 2012)

Besides these technical aspects, environmental aspects were looked at directly. The workgroup “environment” looked at aspects like

- Human health
- Animals, plants and biological diversity
- Ground
- Water
- Air and climate
- Landscape
- Cultural and other assets

## **Conclusions**

The study on a pan-European-North African electricity exchange revealed that there is enormous potential for the deployment of RE technologies in NA and the generation exceeds the local consumption by far. Hence, electricity export to Europe’s load centers is possible. Furthermore, the existing AC transmission infrastructure was evaluated, which is not able to support a pan-European-NA electricity exchange, and an overlaying transmission grid was developed using HVDC technology. The results and assumptions of the study were compared to the environmental impact of available transmission technologies, and it was found out that the technically preferred method – HVDC – is also the technology with the least environmental impact.

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## References

1. Bohn, S., Agsten, M., Marten, A.-K., Westermann, D., Boie, I., & Ragwitz, M. (2014). A Pan-European-North African HVDC Grid for Bulk Energy Transmission – A Model-based Analysis. In 2014 IEEE PES Transmission & Distribution Conference & Exposition. Chicago, USA. doi:10.1109/TDC.2014.6863272
2. Bohn, S., Boie, I., Kost, C., Agsten, M., & Westerman, D. (2013). „SuperGrid “ – Das europäisch-nordafrikanische HGÜ-Overlay-Netz der Zukunft. In Internationaler ETG-Kongress (pp. 1–8). Berlin, Germany.
3. Bohn, S., Fetisova, M., Agsten, M., Marten, A.-K., & Westermann, D. (2014). A continuous DC voltage control function for meshed HVDC grids, and the impact of the underlying future AC grid due to renewable in-feed. In 6th International Conference on Modelling, Identification and Control (ICMIC2014), (accepted). Melbourne, Australia.
4. Boie, I., Pudlik, M., Ragwitz, M., Sensfuß, F., Bohn, S., Agsten, M., ... Westermann, D. (2013). Scenarios for Renewable Energy Deployment in North African Countries and Electricity Exchange with Europe – A Model-based Analysis for 2050. International Journal of Smart Grid and Clean Energy (IJSGCE), 3, 299–306.
5. Bundesnetzagentur. (2013). Netzentwicklungsplan Strom 2013, Zweiter Entwurf.
6. CIGRÉ WG B4-52. (2012). HVDC Grid Feasibility Study.
7. DESERTEC Foundation. (2014). DESERTEC Concept. Retrieved July 07, 2014, from www.desertec.org
8. Energie-Forschungszentrum Niedersachsen. (2012). BMU Studie - Ökologische Auswirkungen von 380-kV-Erdleitungen und HGÜ-Erdleitungen.
9. Kost, C., Schlegl, T., & Möst, D. (2013). Integration of renewable energies in North Africa to supply European electricity markets. In 13th European IAEE Conference. Düsseldorf, Germany. Retrieved from <http://static.gee.de/cgi-bin/download.cgi?dl=1&id=1363257374>
10. Krontiris, A., & Benz, T. (2013). Vorteile einer Vernetzung von HGÜ-Verbindungen. In ETG-Kongress 2013. Berlin, Germany.
11. Kühne, O. (2014). Landschaftsbild und Akzeptanz beim Netzausbau. In Umwelt & Akzeptanz beim Netz- und Speicherausbau. Berlin, Germany.
12. Liu, Z. (2013). Electric Power and Energy in China (p. 400). John Wiley & Sons.
13. Marten, A.-K., & Westermann, D. (2012). A novel operation method for meshed HVDC overlay grids and corresponding steady state and dynamic power flow calculation principle. In The 10th International Conference on AC and DC Power Transmission (ACDC 2012). Birmingham, UK.
14. Meah, K., & Ula, S. (2007). Comparative Evaluation of HVDC and HVAC Transmission Systems. In IEEE Power Engineering Society General Meeting. Tampa, FL.
15. Paris, L., Zini, G., Valtorta, M., Manzoni, G., Invernizzi, A., De Franco, N., & Vian, A. (1984). Present Limits of Very Long Distance Transmission Systems. In International Conference on Large High Voltage Electric Systems. Paris.
16. Platzer, W. (2011). Supergrid: Efficient generation, storage and distribution of electricity. Fraunhofer Project Web Page. Retrieved from <http://www.fraunhofer.de/en/research-topics/energy-living/energy-efficiency/supergrid.html>
17. R. W. De Donker. (2013). Elektrische Netze der Zukunft. In VDE-Vortragsreihe. Ilmenau, Germany.

18. Sahara Wind Energy Development Company. (2014). Sahara Wind. Retrieved January 09, 2014, from [www.saharawind.com](http://www.saharawind.com)

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***Environmental Economic Benefit Assessment Research  
of Recycled Phosphor in Obsolete CRTs***

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**Abstract**

Lots of phosphors including rare earth elements (Y, Eu, Ce, Te, etc.) exists in the obsolete CRT TV sets and PC Monitor in recent years, on the other hand, the rare earth resources are scarce, and environmental pollution caused by primary rare earth ore mining is serious. To investigate the environmental benefits derived from recycling phosphors in CRT, the authors used treatment cost model for assessment from the viewing angle of environmental economic benefit. The environmental impacts of two rare earth elements flow modes: single flow mode and recycling flow mode have been evaluated respectively from both actual and virtual costs perspectives based on the treatment cost method. Considering the pollution and ecological destruction from the mining and the emission and mixing risks of pollutants from smelting, the treatment cost percentage of various stages and total treatment cost is estimated. It has been found that the virtual cost for the single flow mode is much higher than the actual cost. Moreover, the pollution control costs for two phosphor recycling processes have been studied as well. Compared with the single flow mode, the average actual and virtual savings for two recycling processes are estimated respectively, corresponding to the high cost of the single flow mode. Take 29 inch CRT as an example, the environmental benefits from the recycling flow mode save actual and virtual costs are estimated. Finally, the paper suggest the authorities support some fiscal subsidies to CRT recycle enterprise because their operating cost is higher than the economic benefits.

**Keywords:** Obsolete CRT; Phosphor Powder; Rare Earth; Recycling; Environmental Benefits; Treatment Cost Model

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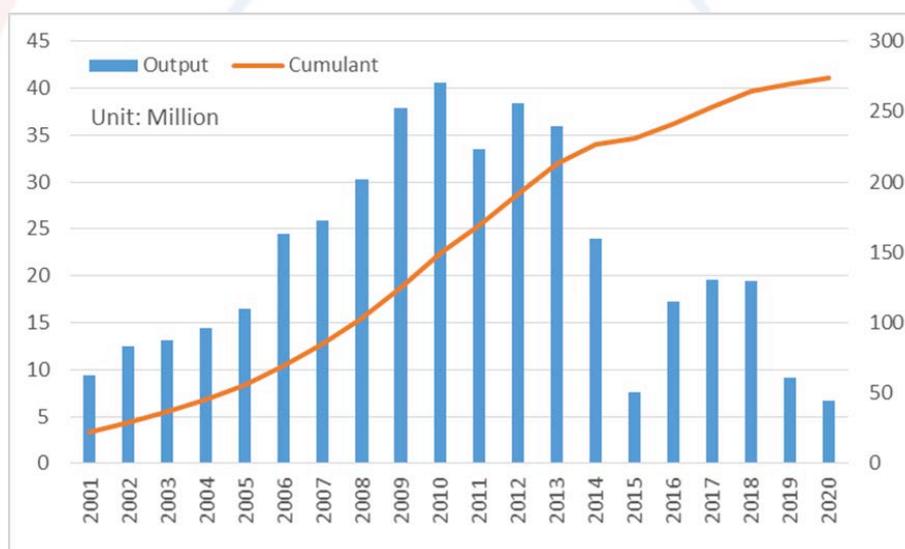
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## 1. Introduction

The amount of TV sets before 1980 in China are less than 10,000 units, and this number increased to 128 million units in 2012(Habuer, Nakatani, & Moriguchi, 2014). At present, China has become into the biggest production, consumption and export country of the TV(Kahhat & Williams, 2012). In the prior production stage, most of TV were manufactured with a cathode ray tube (Cathode Ray Tube), namely CRT monitors, according to their average life projections, taking into account the factors of economic development and technological progress, China has entered a peak period of retirement, It is estimated that three times the normal amount of solid waste when discarded household appliances in recent years, the amount of scrap CRT televisions nationwide in 2013 reached 35 million units. (Kuo, 2013)

From a global perspective, all scrapped CRT in only 26.75% was recycled, landfill accounted for 59%, accounting for 14.75 percent were burned(Li et al., 2013). Preliminary estimates (temporarily only consider starting in 2001), has not been effective recovery of CRT TV in 2013 has more than 200 million units, if not interfered, 2020 will reach 270 million units(Kahhat & Williams, 2012). The output and cumulate can be seen in Figure 1.



**Figure 1 the output and cumulate of scrap CRT in China**

A CRT contains 10-60g phosphor, which rare earth (RE) content accounted for more than 20% CRT phosphor quality, waste rare earth only produced in 2010 at least 80 tons(Mear, Yot, Cambon, & Ribes, 2006). RE as an important strategic non-renewable resources, because of its excellent optical, electrical, magnetic, and many other characteristics, are widely used in many fields of electronic information, national defense and so on. Although China is the most abundant rare earth resources in the country, but with the domestic rare earth consumption continues to increase, a large number of cheap exports and long-term predatory exploitation, resulting rare earth reserves plummeted(Song, Wang, Li, & Duan, 2012). According to the survey, China's rare earth resources have been from the 1970s accounted for 74% of the world total dropped to around 23% currently(Chung & Zhang, 2011). Therefore, the recovery of rare earths from discarded CRT phosphor, which can effectively improve

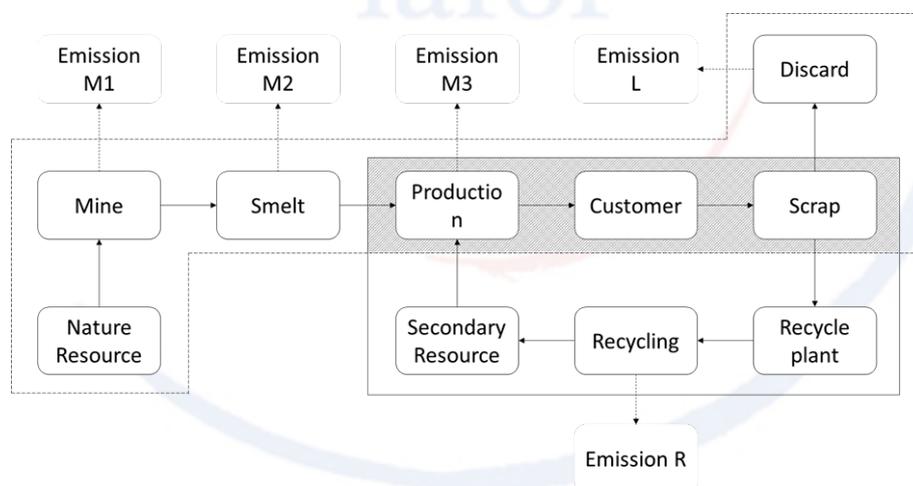
resource utilization and achieve sustainable development of rare earth resources, a move to save energy and protect the environment are equally important.

## 2. Research Method

This article uses the cost method of environmental governance, according to the disposal of the current situation in the main CRT phosphors, will be divided into single flow and recycling modes(Noon, Lee, & Cooper, 2011), for which emissions are calculated for each stage, come with their own environmental costs itemized total item value, after comparing the results produced using recycled environmental benefits.

A typical single flow of rare earth resources in CRT in the process is shown in the dashed box in the upper half of each unit as follows(Lim & Schoenung, 2010): natural rare earth mine through artificial mining, smelting, as the raw material entering the production enterprises, manufactured after CRT TV sales to consumers, reach retirement age discarded after use. In the rare earth mining, smelting and manufacturing sectors, mainly produce waste water, waste gas and solid waste, environmental protection enterprises in the investment part of the cost of treatment for most pollutants, will discharge a small amount of pollution. See

Figure 2.



**Figure 2 Emission of 2 types of flow-mode of phosphor in CRT**

The process flow of a typical recycled RE in CRT is shown in the lower right part of RE shown by the solid black frame units(Ahluwalia & Nema, 2007): the consumer product flow by the manufacturer, after using, the waste recycling after the hazardous waste collected, using various types of technology for its recovery, and then processed into renewable resources, to the use of production enterprises, eventually forming a loop.

## 3. Result and Discussion

According to each mode of governance and the generation of pollutants per ton of RE emissions of various pollutants combine real and virtual control unit cost(Li, Richardson, & Bricka, 2009;Niu, Wang, Song, & Li, 2012;Xu et al., 2013), calculated to bring treatment costs per ton of phosphor various pollutants, the unidirectional flow patterns in the actual and imputed treatment cost was 329.2 with a 322.56 yuan / t, which is four times the former; actual and imputed treatment cost recycling process were 37.80 and 3.73 yuan / t, compared with the one-way mode, the actual savings and imputed treatment cost was 242.75 and 1313.16 yuan / t of phosphor, a total savings of 94.2% of the total cost of the environment.

**Table 1 Total environmental costs of single-flow phosphor in CRT (cny/t)**

Item	actual costs	virtual costs	
M11:Mine stage waste	Waste water	12.19	22.96
	Waste gas	0.01	0.01
	Waste solid	240.20	540.83
	Sum up	252.40	563.79
M12:Mine stage ecology	Under mine	0.00	319.99
	Open mine	0.00	110.67
	Sum up	0.00	430.67
M2:Smelte stage	Waste water	63.75	10.05
	Waste gas	4.98	3.86
	Waste solid	8.07	4.75
	Sum up	76.81	18.67
L:Discard	Waste water	0.00	280.37
	Waste solid	0.00	29.07
	Sum up	0.00	309.44
Total	329.20	1322.56	

**Table 2 Total environmental costs of recycled phosphor in CRT (cny/t)**

Item	actual costs	virtual costs	
R: Recycle Mode	Waste water	12.75	2.01
	Waste solid	1.00	0.77
	Sum up	24.05	0.95
Total	86.54	9.4	

#### 4. Conclusion

To 29-inch CRT for example, the actual treatment cost savings phosphor after recovery was 0.49 yuan / set, imputed treatment cost savings of 2.63 yuan / set, this method of resource recovery and data for enterprise subsidies provided new ideas and method, the Government will be fully taken into account where there are price and other harmful elements to develop a scientific and reasonable subsidies.

#### 5. Acknowledgements

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## References:

- Ahluwalia, P. K., & Nema, A. K. (2007). A life cycle based multi-objective optimization model for the management of computer waste. *Resources, Conservation and Recycling*, 51(4), 792-826. doi: 10.1016/j.resconrec.2007.01.001
- Chung, S., & Zhang, C. (2011). An evaluation of legislative measures on electrical and electronic waste in the People's Republic of China. *Waste Management*, 31(12), 2638-2646. doi: 10.1016/j.wasman.2011.07.010
- Habuer, Nakatani, J., & Moriguchi, Y. (2014). Time-series product and substance flow analyses of end-of-life electrical and electronic equipment in China. *Waste Management*, 34(2), 489-497. doi: 10.1016/j.wasman.2013.11.004
- Kahhat, R., & Williams, E. (2012). Materials flow analysis of e-waste: Domestic flows and exports of used computers from the United States. *Resources, Conservation and Recycling*, 67(0), 67-74. doi: 10.1016/j.resconrec.2012.07.008
- Kuo, T. C. (2013). Waste electronics and electrical equipment disassembly and recycling using Petri net analysis: Considering the economic value and environmental impacts. *Computers & Industrial Engineering*, 65(1), 54-64. doi: 10.1016/j.cie.2011.12.029
- Li, J., Lopez N., B. N., Liu, L., Zhao, N., Yu, K.,... Zheng, L. (2013). Regional or global WEEE recycling. Where to go? *Waste Management*, 33(4), 923-934. doi: 10.1016/j.wasman.2012.11.011
- Li, Y., Richardson, J., & Bricka, R. (2009). Leaching of heavy metals from E-waste in simulated landfill columns. *Waste Management*, 29(21), 47-50
- Lim, S., & Schoenung, J. M. (2010). Human health and ecological toxicity potentials due to heavy metal content in waste electronic devices with flat panel displays. *Journal of Hazardous Materials*, 177(1-3), 251-259. doi: 10.1016/j.jhazmat.2009.12.025
- Mear, F., Yot, P., Cambon, M., & Ribes, M. (2006). The characterization of waste cathode-ray tube glass. *WASTE MANAGEMENT*, 26(12), 1468-1476
- Niu, R., Wang, Z., Song, Q., & Li, J. (2012). LCA of Scrap CRT Display at Various Scenarios of Treatment. *Procedia Environmental Sciences*, 16, 576-584. doi: 10.1016/j.proenv.2012.10.079
- Noon, M. S., Lee, S., & Cooper, J. S. (2011). A life cycle assessment of end-of-life computer monitor management in the Seattle metropolitan region. *Resources, Conservation and Recycling*, 57(0), 22-29. doi: 10.1016/j.resconrec.2011.09.017

Song, Q., Wang, Z., Li, J., & Duan, H. (2012). Sustainability evaluation of an e-waste treatment enterprise based on emergy analysis in China. *Ecological Engineering*, 42(0), 223-231. doi: 10.1016/j.ecoleng.2012.02.016

Xu, Q., Yu, M., Kendall, A., He, W., Li, G.,... Schoenung, J. M. (2013). Environmental and economic evaluation of cathode ray tube (CRT) funnel glass waste management options in the United States. *Resources, Conservation and Recycling*, 78(0), 92-104. doi: 10.1016/j.resconrec.2013.07.001

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## **Municipal Solid Waste Management in Greater Jos, Nigeria**

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### **Abstract**

In Nigeria, municipal solid waste management is an integral part of the waste management system. The current status of municipal solid waste management in Jos, a rapidly growing urban city in Nigeria has been reviewed through literature and other relevant documents. In addition, information from in-depth interviews conducted on senior government officials, industry stakeholders, participant observation and questionnaire survey on residential neighbourhoods have been used in this review of municipal solid waste management problem in Greater Jos. The problem is the existing municipal solid waste management system which is affected by unfavourable economic, financial, institutional, legislative, technical, operational and socio-cultural constraints. Despite recent improvements in the operations of the existing system through engagement of task force on environmental sanitation, municipal solid wastes are still dumped along roads, in culverts, drainage channels, underneath bridges and any available open spaces. A reliable municipal solid waste collection service that will be appropriate to local conditions is needed. Cooperation among the formal and informal sectors, communities, various stakeholders, good public awareness, attitudes and education is important. Markets for waste recyclable materials need to be encouraged. Small-scale composting plants could promote employment, income generation and poverty alleviation. Finally, recommendations for improvement include among others, policy and planning framework for municipal solid waste management, enforcing relevant clauses in development guidelines, accurate population data and funding for proper planning of waste management systems and infrastructure is necessary.

**Key words:** Greater Jos, Municipal solid waste, Planning, Stakeholder, Resource recovery, Nigeria

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## Introduction

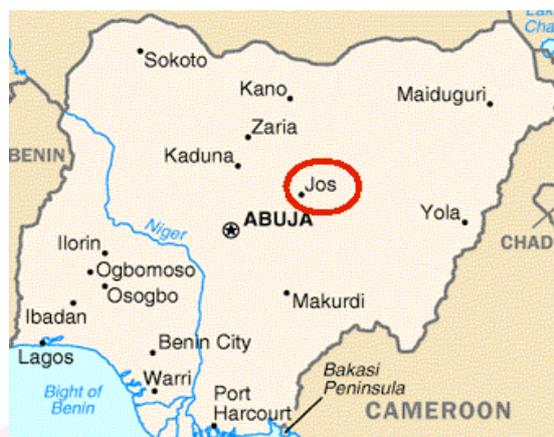
Municipal solid waste has become an important issue in Nigeria. Piles of wastes are often found by roads, rivers and many other open spaces in cities, and this is causing significant planning and environmental problems. The urban population is growing at an alarming rate. While the Nigerian population is increasing by about 2.8% per annum, the rate of urban growth is as high as 5.5% per annum (NPC, 2008). This is increasing the difficulties associated with providing an effective solid waste management system. As cities grow, land use becomes increasingly complex and the wastes generated increase in volume and variety (Ogwueleka, 2009).

The dimensions and forms of municipal solid and hazardous wastes as a result of constant economic growth, development and industrialization, is undergoing a rapid rise in the whole world. According to World Bank report on solid waste management released in March, 2012, it is estimated that the total amount of municipal solid waste generated by urban residents globally reached 1.3billion tonnes per year with 1.2kg per person per year (Hoorweg and Bhada-Tata, 2012). The report (World Bank) further estimated that between 2012 and 2025, global generation of municipal solid waste will increase to 2.2billion tonnes with 1.4 kg/capita/day. Poorly managed waste has an enormous impact on public health, local and global environment, and economy (Hoorweg and Bhada-Tata, 2012). Improperly managed waste is more expensive than what it would have cost to manage waste properly in the first place (Hoorweg and Bhada-Tata, 2012).

The total nature of municipal solid waste includes: its contribution to greenhouse gas emissions; increasingly global linkages of products; urban practices; and the reprocessing industry. The significance of the issues is maybe best revealed in the level of devotion set to the situation in the United Nations Millennium Declaration-September, 2000. Three out of the eight Millennium Development Goals (MDGs) drawn in the declaration ensure waste or resource efficiency implications (UNO, 2007).

Solid waste management systems (waste storage, collection and transport, resource recovery and recycling, waste treatment and disposal) in Jos (see figure 1) the capital city of Plateau State in Nigeria have been assessed. Information was obtained from a variety of relevant government/private officials and organisations including the Federal, State, and Local Ministries, the Plateau Environmental Protection and Sanitation Agency (PEPSA), National Environmental Standard Regulation Enforcement Agency (NESREA), private sector companies, local residents and the informal waste sector. Problems associated with existing waste management systems and facilities have been identified. The legal, administrative and institutional framework and the role of informal recycling/ scavenging has been analysed, and ways of achieving more efficient and effective management recommended. The work reported in this paper was therefore aimed at identifying the problems that are basically of planning constraints in the waste management sector in Nigeria using Greater Jos municipality as a case study.

Figure 1: Map of Nigeria showing the strategic position of Greater Jos



Source: Google images, June 2013

### Overview of Greater Jos municipality

Jos was created by the colonial administration having its growth tied to the history of tin mining activities on Jos-Plateau in Nigeria. The population grew in 1930 from not more than 10,000 to more than 600,000 in 1991 (Dung-Gwom, 2008). The current population of the municipality (see table 1) stands at over 1million people (NPC, 2008). Greater Jos is currently the capital and administrative/political headquarters of Plateau State. It covers Jos North, Jos South, and part of Jos East, Barkin-Ladi, Bassa and Riyom local government areas. These local governments were known to be one until in 1999 when they were separated as individuals' local government councils. Jos landscape is changing as a result of urban sprawl due to urbanization. The present and the past Master Plan development of Jos is merging with close rural areas surrounding the municipality.

Table 1: Greater Jos population

S/ N o	Local council	Population			
		Male	Female	Population	Population (percent)
1	Bassa	92,649	94,210	186,859	14.21
2	Jos North	217,160	212,160	429,300	32.64
3	Jos East	43,249	42,353	85,602	6.51
4	Jos South	155,262	151,454	306,716	23.32
5	Riyom	71,984	59,573	131,557	10.00
6	Barkin-Ladi	88,478	86,789	175,267	13.33
	<b>Total</b>	<b>668,782</b>	<b>646,619</b>	<b>1,315,301</b>	<b>100.00</b>

Source: National Population Commission (NPC) 2008, Nigeria

Greater Jos the capital of Plateau State in Nigeria was initially developed according to a Master Plan devised in 1976. This apportioned 2.0% of the Greater Jos area for government activity/usage, 49.0% for residential development, and 32.5% as open/green/recreational areas to add to the aesthetics of the city, with the remaining land (16.5%) being used for ancillary services, light industries, other infrastructure

and commercial activities. The Greater Jos master plan was designed to accommodate growth and provide an opportunity to avoid many of the problems associated with unplanned growth associated with other cities in Nigeria.

Plateau State Government establishments relocated to Greater Jos during the 1980s, and all federal and state government ministries and parastatals' headquarters with many national and multinational corporations and many national newspapers are now in Jos. This rapid expansion far exceeded what had been anticipated in the Master Plan of 1976 which expires in 2000. The population of Jos now exceeds the original design capacity. In 1991 the population of the Greater Jos was less than 1million, and this had increased to 1,315,301 by 2006. Projected population figures for the Greater Jos region predict massive growth with 2.6 million people expected by 2025 (Fola Konsult, 2008).

The planning implication of the estimated population figure indicated above is that even with the conservative growth rate of 5%, the population would have doubled itself within a period of 17 years between 2007 and 2025. The urban infrastructure will be stressed considerably in relation to the required waste management services and facilities, unless appropriate steps are taken to accommodate projected increase in population. Unfortunately, the opportunity to develop infrastructure (including that for waste management), in phase with city growth and in line with a pre-agreed Master Plan, was lost, and Jos now shares many of the same problems as other Nigerian cities.

The landmark Federal legislation on environmental protection in Nigeria was the decree Number 58 of 1988, which established the Federal Environmental Protection Agency (FEPA). The specific role of FEPA with respect to solid waste management is to (Onibokun, 1999): Study the most reliable systems that are appropriate for local, domestic and industrial wastes; Specify waste disposal and treatment methods that take into consideration the geological and environmental setting and encourage recycling; Specify waste disposal sites that guarantee the safety of surface and underground water systems; Set up and enforce standards for adequate sanitary facilities for the disposal of human and other solid wastes in dwellings, housing estates and public facilities in both urban and rural areas; Establish monitoring programmes including periodic surveillance of approved waste disposal sites and their surroundings and waste water systems; Establish monitoring stations for the control of the disposal of leachate from dumpsites into surface water and groundwater systems.

FEPA enacted a number of laws and regulations. These have included: The National Protection Management of Solid and Hazardous Wastes Regulations of 1991; The Pollution Abatement in Industries and Facilities Generating Waste Regulation of 1991; The General Guidelines for Pollution Abatement in Industries 1991.

The Plateau Environmental Protection and Sanitation Agency (PEPSA) is responsible for solid waste management in Plateau State. It has responsibility to: Remove, transport and dispose of domestic, commercial and industrial waste; Clear and maintain public drainage facilities, street cleaning and clearing of abandoned vehicles; Register private waste collection companies; Prepare and periodically up-date the master plan of waste collection and disposal in the city; Approve and monitor all disposal systems in the city; Assess recycling as a waste management option for

industries and government agencies; Establish and recommend the basic standard requirements for solid, liquid, gaseous or toxic waste management provided they do not conflict with, but complement the standards of the FEPA; Establish and recommend acceptable safe methods of collection and disposal of hazardous and toxic waste products in Plateau State; Educate the general public on the various disposal methods acceptable for domestic and industrial waste products; Initiate environmental protection legislation and keep existing legislations under constant review to reflect the latest discoveries and observations on the subject; Organise and mobilise the public to participate actively in regular clean-up exercises and beautification of their environments.

### Methods and Approach

This study exploits a mix of qualitative and quantitative investigation methodologies, in a three phase procedure, covering pre-fieldwork, fieldwork and post-fieldwork stages (see figure 2).

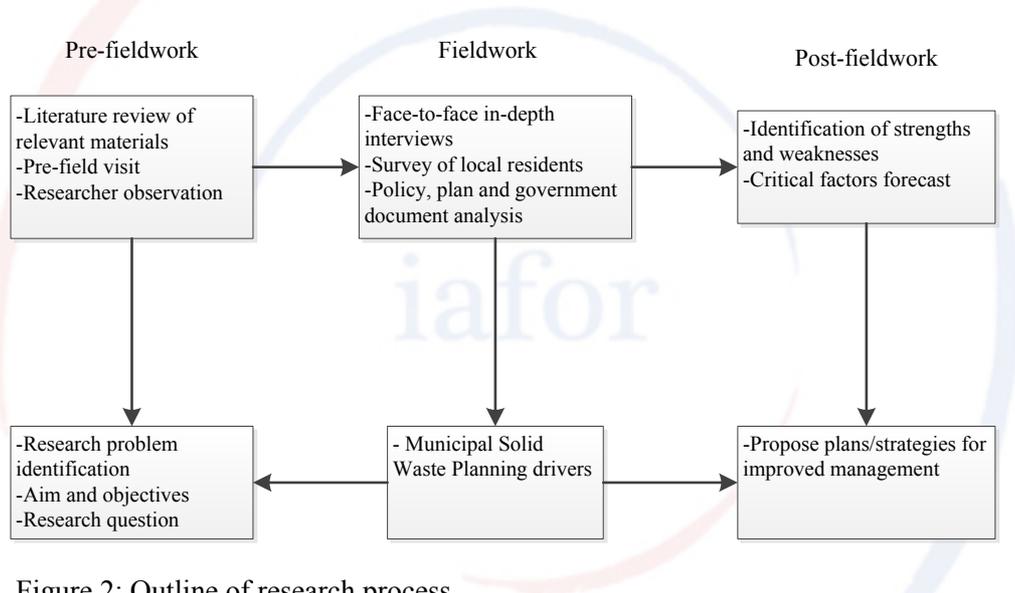


Figure 2: Outline of research process

Figure 1 is a summary of the three phase methodologies implemented for this study. The pre-fieldwork (primary) phase involved literature review on municipal solid waste management issues in developed and developing countries, and first hand pre-field visit to municipal solid waste planning and management authorities in the study area-Greater Jos (see figure 1). Following this, at the data collection stage, Jos North and Jos South local government areas were selected. Apart from being the former Benue and Plateau States capital city, both local government areas are main administrative and commercial foci respectively, especially for the middle-belt region of Nigeria. Using numerous strategic tools such as key informant interviews, researcher observation and household survey, primary data on municipal solid waste management in Greater Jos municipality was collected between 2011 and 2013.

### Municipal solid waste challenges in Greater Jos

Greater Jos (the study area), with a population of over one million people became the capital of Benue-Plateau State of Nigeria, a West African sub-region in 1976. Over

thirty-five years now, the city has been experiencing a rapid population growth; as a result, there is a continuous increase in residential, commercial, industrial, and institutional land uses leading to urban expansion. This has a direct effect on the increase in municipal solid waste generation leading to diverse and multiple environmental issues. As a result, it is becoming very difficult for municipal authorities to organize, manage effectively and efficiently municipal solid waste (Egbere et al., 2001; World Bank, 2004).

A cursory observation within the study area shows visible aspects of problem manifesting in accumulation of garbage, waste-clogged drains and water bodies, street litter and stinking gutters. In spite of the concerns frequently raised by concerned groups, institution and individuals, the municipal solid waste situation continues to worsen thereby posing serious threats to public health and environment. Besides, the planning issues associated with the worsening municipal solid waste situation appears to fall more heavily on the residents even though wastes management are supposed to be publicly funded and regulated. The problem in Greater Jos can be enumerated as follows: Problems caused by the urbanization process with irregular and unplanned urban growth is generating more wastes arising in Greater Jos without any framework for management in the Plateau State of Nigeria; The existence of a multiplicity of organizations, agencies and ministries responsible for environmental management with no or inadequate funding for municipal solid waste management development; Greater Jos’ master plans, past and the present lacked sustainable solid waste management strategies/ plans for implementation in line with best practices of sustainable development. The problems affecting municipal solid waste in Nigeria is summarized in figure 3.

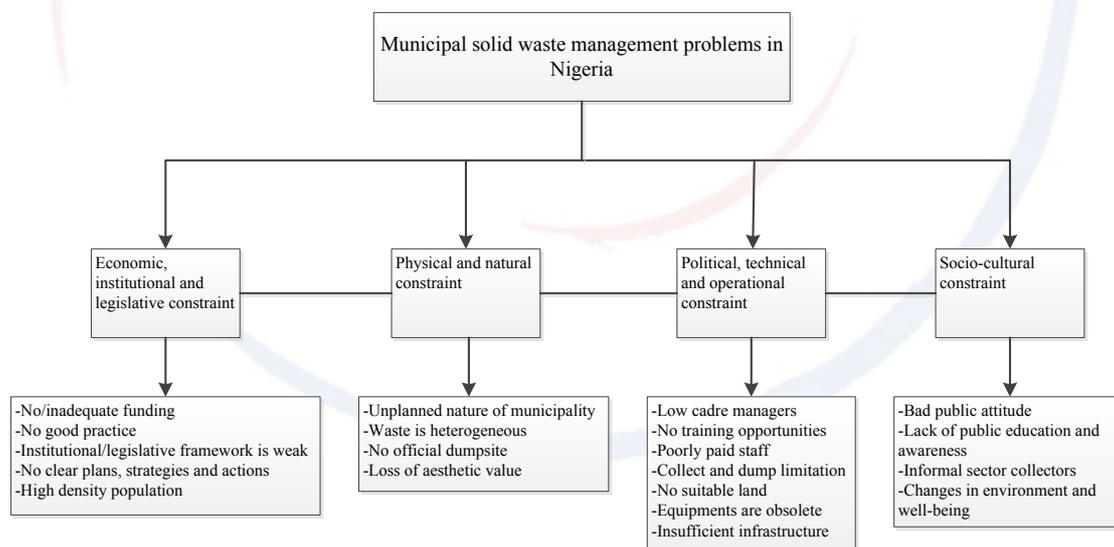


Figure 3: Problems affecting municipal solid waste management in Greater Jos, Nigeria.

### Quantity of municipal solid waste generated

The amount of waste generated has increased in both quantity and diversity without adequate investment in collection, transport, treatment and disposal facilities. These problems are further complicated by political, economic and social factors. The average waste generation rate in Jos is 0.55–0.58 kg per person per day (PEPSA,

2013). This is influenced by the time of year, local culture, traditions and personal income.

### **Municipal solid waste composition**

Table 2 provides composition data for municipal solid wastes produced in municipal councils of Greater Jos. The main components are food residues, plastics, paper, glass bottles and metals. The waste has a heterogeneous composition comprising of both degradable and non-degradable materials, and it is collected without sorting. The bulk of the non-degradable waste is potentially recyclable materials, while the degradable materials could be composted. Plastics mainly come from water and fruit juice bags and containers.

### **Municipal solid waste storage**

A key aspect of effective waste management is proper waste storage on the premises where the waste is generated (Oluwande, 1984). The PEPSA is responsible for collecting waste from municipalities, and they have made containers (120-L and 240-L plastic bins, and 1.1 m3 metal bins) available to very few household.

### **Municipal solid waste collection and transport**

Collection and transportation are a major cost in the waste management process. There are no private companies operating that collect waste. Collection of kerbside deposited waste tends to be quite irregular. Informal sector collection workers operate house-to-house collection services; they often separate out recyclable materials and dump unwanted degradable waste around the area. As a result, such informal collectors are officially banned from certain areas, and their carts are regularly impounded by the authorities. Collection and transportation of waste is both labour and capital intensive. It has been estimated that waste transportation, including labour and machinery, accounts for between 70% and 80% of the total cost of solid waste management in Nigeria (FME, 2004; Oluwande, 1984).

Table 2: Municipal waste generation data for different categories of settlement in Jos

WASTE COMPONENT	HIGH DENSITY (RESIDENTIAL) %	LOW DENSITY (RESIDENTIAL) %
Fabric	3.38	0.97
Plastic	3.14	0.97
Polythene	5.79	2.41
Organic	28.97	8.69
Metals/tin	1.45	0.97
Paper	3.14	1.21
Leather	1.26	0.72
Debris	19.56	13.76
Dead dry cells	0.97	0.24
Bottles/glasses	1.21	1.21

Source: PEPSA, June 2013

Traffic conditions often interfere with waste collection and transport in Jos. Collecting and transporting waste at night has been tested by the PEPSA, although this proved to be problematic because of security implications for householders. A shortage of waste collection vehicles in Greater Jos is due to lack of funding and inadequate maintenance. Efficient collection depends on proper selection of vehicles; this needs to take account of road conditions, traffic density, availability of spare parts, servicing requirements and haulage distances. A variety of motorised and manual vehicles are used for waste collection and transport in Greater Jos, as summarised in Table 3.

The waste composition in Greater Jos, as in many other cities in developing countries, has a high organic content, so that compaction vehicles offer little advantage in terms of increasing waste density. As shown in Table 3, about half of the PEPSA vehicles are compactors, but only 30% of these are operational. Manual collection equipment used by informal sector waste collectors includes push carts, wheel barrows and pedal tricycles. Other basic implements used by the informal sector (for waste sorting) include hand-rakes, shovels and iron sorting rods.

Table 3: Summary of municipal waste collection, transportation and disposal vehicles owned by government operating in Jos

S/N	TYPE	EXISTING UNIT	NUMBER FUNCTIONAL	%
1	Tippers	4	3	75%
2	Roll-On Roll-Off Skip Vehicles	4	3	75%
3	Tractors	2	1	50%
4	Automatic Compactor Trucks	4	1	25%
5	Side Loader Trucks	2	2	100%
6	Pail Loader	1	-	0%
7	Back Hoe/Bucket Loader	1	1	100%

Source: PEPSA, June 2013

### Resource recovery and recycling

The average recyclable content of waste in Nigeria is estimated at 28% (FME, 2004); the composition data for Greater Jos in Table 1 would suggest a rather higher figure, perhaps greater than 40%. The only recycling in Greater Jos is carried out by the informal sector. Limited amounts of cans, plastics, bottles and newspapers are stored in homes and sold to itinerant buyers, and house-to-house collection of these materials has significant potential for expansion.

Most recycling appears to be carried out by segregation from mixed waste. Such sorting is undertaken by the informal sector collectors from their carts; by the collection crew from waste vehicles; and by scavengers, both from street bins and at the dumpsite. Scavengers normally have no formal education, vocational training or access to appropriate equipment and do not normally have alternative employment opportunities in the formal sector. The scavengers and other informal sector recyclers

generally sell their recovered materials to middlemen, who in turn sell to small and large scale processing and manufacturing industries. For example, collected glass is processed and recycled locally as cullet for use in the glass industry; whole bottles are cleaned and reused as syrup, drinks and juice containers; the bases of broken bottles are sold to small scale industries that cut and polish the glass to manufacture items such as ash trays and candle holders.

A recent review has examined in detail the role of the informal sector in waste management in developing country cities (Wilson et al., 2006), although relatively little data are available on the effectiveness and overall contribution of informal sector recycling.

### **Municipal solid waste treatment and disposal**

Despite the good intentions of the Master Plan, there are no sanitary landfills in the Greater Jos for waste disposal. Solid waste from the formal collection system in the various settlements of Jos is transported to a single dumpsite at Dong, a suburb. Problems associated with odours and air pollution from burning wastes at the site have been significantly increased recently due to dumping of waste from almost all parts of Jos to this area.

Illegal disposal is also common in Jos. Piles of solid wastes are often found along roads, underneath bridges, in culverts and drainage channels and in other open spaces. One source is the informal collection workers, but there are many others involved in such 'fly-tipping'.

### **Public awareness and attitudes to waste**

Public awareness and attitudes to waste can affect all stages in the municipal solid waste management process. This has an impact on household waste storage, waste segregation, recycling, collection frequency, littering and fly-tipping, willingness to pay for waste management services, and the level and type of opposition to waste treatment and disposal facilities. In general, people in Jos have a poor attitude towards waste management (Agunwamba, 2003). People who handle waste are regarded as dirty, poor and inferior, and carrying household waste to bins is often regarded as a duty for children. Efforts have been made by both the government and the private sector in Greater Jos to increase public awareness of solid waste management issues, and there have been televised discussions on waste management. The side effects of improper waste disposal have been well publicised. However, most people still do not appreciate that environmental quality is not just the responsibility of the government and that the individual also has an important role.

### **Private sector participation**

There are now no private waste management collection companies operating in Greater Jos. An important factor in the success of the private sector is the ability of the state government to support, enforce and sustain written contracts. These describe the services required, and state penalties and other sanctions that will be applied in the case of failure to deliver. The award of contracts and the monitoring and enforcement of the contracts are the responsibility of the PEPSA, and a system is required that

ensures and encourages sustainable private sector participation (Cointreau and Coad, 2000; METAP, 2004; Coad, 2005).

### Economic constraint

The survey revealed that an average of about 54.56% of the sampled households earn less than or equal to about \$150, as monthly income (see table 4). Considering the economic requirement of the family, a monthly income of less than or equal to \$300 cannot meet the economic demand of the family hence as they can do without the service of a solid waste disposal agent they engage in crude open dumping of solid waste in drainages, around the streets and open market places, any peace of unused land, Open air burning without air pollution control. In addition economic constraints also make them to patronize cart pushers who are not able to get to the approved designated dump sites where the municipal solid waste are expected to be managed properly.

Table 4: Income range in Greater Jos

S/N	Range (Naira per month)	Frequency	Percentage (%)
1	18,000 – 20,000	4	22.2
2	20,000 – 30,000	1	5.6
3	30,000 – 60,000	5	27.8
4	60,000 above	3	16.7
5	Business	3	16.7
6	No indication	2	11.1
	Total	18	100

Source: Author's survey, 2013

### Financial constraint

Municipal solid waste management is given very low priority in the budget due to limited finances (PEPSA, 2013). As a result very limited funds are provided to the solid waste management sector by the governments, and the levels of services required for protection of public health and the environment are not attained (see table 5).

Table 5: Amount spent on waste disposal in Greater Jos

S/N	Range (Naira per month)	Frequency	Percentage (%)
1	< 500	4	22.2
2	500 – 1000	1	5.6
3	1000 – 5000	4	22.2
4	> 5000	0	0
5	Varies	9	50.0
	Total	18	100

Source: Author's survey, 2013

### **Technical constraint**

This study revealed that there is lack of human resources at both the state and local government level and the private sector with technical expertise necessary for municipal solid waste management planning and implementation. Many officers in charge of solid waste management, particularly at the State waste management agency and ministries handling the issues of municipal waste, have little or no technical background or training in planning or management. In fact all the problems that the municipal solid waste management system is faced with are exacerbated by the lack of trained personnel. This study also revealed that there is ineffective municipal solid waste collection and unreliable solid waste collection service. Aged vehicle fleet and poor road access were also observed.

### **Institutional constraint**

Several agencies have been created at the state level that is involved at least partially in solid waste management (Onibokun, 1999). Such agencies at the state level include – Plateau Environmental Protection and Sanitation Agency (PEPSA), special environmental task force etc. However, there are often no clear roles/functions of the various state and local government agencies defined in relation to municipal solid waste management and also no single agency or committee designated to coordinate their projects and activities. The local government environmental department has the responsibility of picking up and transportation of solid waste from public place to dumpsites (PEPSA, 2013). The PEPSA also has the mandate to pick up and transport solid waste to the dumpsite. However there is no body coordinating these activities. The lack of coordination among the relevant ministries and agencies often results in duplication of efforts, wastage of resources, and un-sustainability of overall municipal solid waste management programs. The lack of effective legislation for municipal solid waste management is partially responsible for the roles/functions of the relevant federal, state and local government agencies not being clearly defined and the lack of coordination among them.

### **Operational constraint**

This study revealed that the social status of solid municipal waste management workers is generally low (Agunwamba, 1998). This is due to the negative perception of the society regarding the work which involves the handling of solid waste. Such societal perception leads to low regards for the work, low self-esteem for the workers especially the garbage men and in turn produces low working ethics and poor quality of their work. Where the society allows only a certain social class or group to deal with solid waste, the availability of work force for solid waste collection and disposal becomes constrained by this rule.

### **Socio-cultural constraint**

In the course of this study, materials such as dead animals, food items and used clothes were observed at the road junctions and by the road side. The practice of dumping material for sacrifices such as animal parts or full dead bodies of animal at road junctions and by the road side is a cultural norm acceptable in some cultures.

Such norms affect designs and implementation of sustainable municipal solid waste management systems.

### **Conclusions and recommendations**

The new city of Greater Jos provided an opportunity to avoid some of the environmental problems associated with many other major cities in Africa. Unfortunately, accelerated population growth in the 1990s far outstripped the provisions made in the old Master Plan, and this is presenting the authorities with major problems concerned with the management of solid wastes. There is a general lack of public awareness or concern regarding waste issues, and wastes are currently taken to a single poorly engineered land disposal site. The existing system suffers from unfavourable economics, financial, institutional, legislative, technical operational and socio-cultural constraints.

A number of recommendations are made here, aimed at the development of an integrated and sustainable system for municipal solid waste management in Greater Jos.

To minimise costs, an improved waste storage and collection system is required. Each household should use standard 120-L or 240-L waste bins that are placed outside for ease of collection. In areas where this is not appropriate, centrally located waste collection points should be established that are shared by a number of households. The capacity of the private sector to provide reliable waste collection services and of the public sector to supervise them should be strengthened.

Vehicles need to be appropriate to the local conditions. Vehicles specifically designed for carrying wastes should be used wherever possible to avoid material being lost during transportation. A programme of regular vehicle maintenance is required and appropriate vehicles should be used (Wilson et al., 2001). Training needs to be provided, particularly for drivers operating waste tipping equipment, and more vehicles will be needed to cope with increasing waste generation.

There needs to be a continuing programme of public awareness concerning waste management that is particularly aimed at younger Jos residents. Wastes need to be increasingly sorted at the source, to separate materials that can be recycled and to reduce the amount of wastes requiring collection and disposal.

Co-operation is required among communities, the informal sector, the formal waste collectors and the authorities if recycling rates are going to increase (which would in turn reduce the quantities of residual waste for collection and disposal, and thus the costs of the formal waste management system). These include increased involvement and integration of the informal sector so the collectors can collect separated materials for recycling from households. Informal waste collectors could also provide an 'official' door-to-door collection service in areas that are inaccessible to larger vehicles. This would need to be integrated with formal collection services via waste transfer stations; the collectors should be provided with space at the transfer station to sort recyclable materials, to avoid the current problem of illegal dumping after separating the saleable items. Markets for recycled materials need to be encouraged both in Greater Jos and nationally.

A properly sited engineered landfill should be constructed as recommended in the 1976 Master Plan for developing countries (Rushbrook and Pugh, 1999). Unlike most developed and some developing countries, there is no clear policy in Nigeria on composting. Sorting would be required to exclude hazardous and non-degradable components like plastics, metals and glass from the waste and this is where co-operation from householders is needed to separate degradable waste at source. The removal of subsidies on fertilizers in Nigeria has created a demand for alternatives, and a market for compost exists. Small-scale composting plants could enhance the development of low-capital and labour intensive industries that promote employment, income generation and poverty alleviation in Greater Jos.

Enforcement of waste management legislation is required, as are a proper policy and planning framework for waste management. The government must control unauthorized use of land, and this should be achieved by enforcing relevant clauses in the development guidelines. There is also a need for accurate population data so that waste management systems and infrastructure can be properly planned. The Master Plan should be updated (or revived) in terms of its provisions for waste management infrastructure.

Funding and affordability remain among the major constraints and challenges. An element of specific user charging will be needed to supplement municipal and national taxes. A system for making micro-credit available to the informal sector would aid its development as part of an integrated and sustainable waste management system. Addressing the problems in an integrated way (as outlined above) would also increase the likelihood of multilateral donor funding for major investments, such as in the landfill site, transfer stations or new vehicles.

Effective involvement of the private sector and greater integration of the informal sector are recommended. Composting of biodegradable wastes and increased waste recycling and resource recovery are identified as areas for further development.

## References

- Agunwamba, J.C., (2003), *Analysis of scavengers' activities and recycling in some cities of Nigeria*. Environmental Management 32 (1), 116–127.
- Coad, A., (2005), *Private Sector Involvement in Solid Waste Management – Avoiding Problems and Building on Successes*. GTZ, Eschborn <http://www2.gtz.de/dokumente/bib/05-0412.pdf>.
- Cointreau, S., and Coad, A., (2000), *Guidance pack – private sector participation in municipal solid waste management*. Published by SKAT, distributed by Intermediate Technology Publications Limited, London.
- Dung-Gwom, J. Y., (2008), *The Nature of Peri-Urban Developments in Jos, Nigeria*. Paper Presented at the XXXVI World Congress on Housing Science, National Housing Programme- New Vision, Kolkata, India, November, 3-7.
- Egbere, O.J., Itelima, J.U., and Opiah, F. O., (2001), *Municipal Solid Waste Segregation and their Health Hazards Implications in Angwan-Rogo Ward of Jos, Plateau State, Nigeria*. Journal of Environmental Sciences, 4(1), pp.1-4.
- Federal Ministry of Environment, (2004), *Policy Guidelines on Solid Waste Management*, Federal Republic of Nigeria.
- Fola Konsult (2008), *Greater Jos Master Plan Report*, Jos, Nigeria.
- Hoornweg, D., & Bhada-Tata, P. (2012). *What a waste: a global review of solid waste management*. World Bank Report.
- METAP, (2004), *METAP Solid Waste Management Centre, Guidelines on Private Sector Participation, prepared for the World Bank by GTZ, ERM and GKW*. <<http://www.metap-solidwaste.org/index.php?id=5>>.
- National Population Commission (NPC), (2008), *2007 Population Census Figures. Abuja*. Accessed: 20th May, 2012. Available at: <http://www.population.gov.ng>
- Ogwueleka, T.C., (2009), *Municipal Solid Waste Characteristics and Management in Nigeria*, Journal of Environmental Health Science Engineering, 6(5).
- Oluwande, P.A., (1984), *Assessment of metropolitan solid waste management problems in China and Africa*. In: Holmes, J.R. (Ed.), *Managing Solid Waste in Developing Countries*. J. Wiley, Chichester, UK.
- Onibokun, A. G. (Ed.), (1999), *Managing the Monster: Urban Waste and Governance in Africa*. International Development Research Centre, Ottawa.
- Plateau Environmental Protection and Sanitation Agency (PEPSA), (2013), *Report on Solid Waste in Jos, Nigeria*. PEPSA, October.
- Rushbrook, P., Pugh, M., (1999), *Solid waste landfills in middle- and low income countries – a technical guide to planning, design and operation*. World Bank Technical Paper No 426. ISBN 0-8213-4457-9.

United Nations Organization (UNO), (2007), *Africa and the Millennium Development Goals*: Home Page. New York. Available at: <http://www.un.org/millenniumgoals/>

Wilson, D.C., Whiteman, A., Tormin, A., (2001), *Strategic planning guide for municipal solid waste management*. World Bank, SDC and DFID.  
<[http://www.worldbank.org/urban/solid\\_wm/erm/start\\_up.pdf](http://www.worldbank.org/urban/solid_wm/erm/start_up.pdf)>.

Wilson, D.C., Velis, K., Cheeseman, C., (2006), *Role of informal sector recycling in waste management in developing countries*. Habitat International 30, 797–808.

World Bank, (2004), *Regional Solid waste Management Project in Mashreq and Maghreb countries, country report – Palestine* (final version), World Bank Report

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***Environment Economy Assessment on Recycling of Rare Earths  
and Mercury from The Waste Fluorescent Lamps***

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**Abstract**

Rare earth elements and mercury in waste fluorescent lamps belong to the category of hazardous waste. In China, the scrap of waste fluorescent lamps produced each year is more than 5 billion. The improper disposal not only causes a waste of resources, but also pollutes environment seriously. People do not pay much attention to recycling the waste lamps (only 1% of the lamps have been recycled), and the vast majority of waste lamps are still disposed by the traditional landfill and incineration. However, the study of environmental economic of rare earth elements and mercury recycling has not been carried out yet. In this paper, we have considered the pollution and ecological destruction from the stage of mining and emission, and the risks of pollutants from smelting. The actual governance cost method and the virtual treatment cost method have been used to evaluate the environmental economic of rare earth elements and mercury recycling in the both unidirectional flow mode and the recycling mode. The treatment cost of various stages and total treatment cost is estimated. It has been found that the virtual treatment cost for the unidirectional flow mode is much higher than the actual treatment cost. Moreover, the environment economic for the unidirectional flow mode is much higher than the recycling mode. This provides a novel research idea for the evaluation of environment economic.

Keywords: waste fluorescent lamps; rare earths; mercury; environmental economy assessment

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## 1. Introduction

At present, China's fluorescent lamp production and usage is the highest in the world. As we all know, the average service life of a standard fluorescent lamp is 2~3 years, so the scrap of waste fluorescent lamps produced each year is more than 5 billion, in China. The waste fluorescent lamps contain highly toxic mercury. In terms of average 20 mg mercury filled in one lamp, the amount of mercury in waste fluorescent lamps could reach 100 tons every year. If these fluorescent lamps are not treated scientifically, it is easily to cause the leakage of mercury, pollute the environment and endanger human health. On the other hand, there are about 92% glass, 2% metal, and 2.4% phosphor in the waste fluorescent lamps. If 4 g phosphor contained in one waste fluorescent lamp, the value of the rare earths will exceed 10 billion yuan. Besides, it can be easily found that waste fluorescent phosphors contain much more rare earth metals and noble metals, which makes them rich resources of rare earth elements. Therefore, the improper disposal not only causes a waste of resources, but also pollutes environment seriously. However, people do not pay much attention to recycling the waste lamps (only 1% of the lamps have been recycled), and the vast majority of waste lamps are still disposed by the traditional landfill and incineration. The recycling of rare earths and mercury from the waste fluorescent lamps not only contributes to the environmental protection but also economically profitable. However, the study of environmental economic of rare earth elements and mercury recycling has not been carried out yet.

In this paper, we have considered the pollution and ecological destruction from the stage of mining and emission, and the risks of pollutants from smelting. The actual governance cost method and the virtual treatment cost method have been used to evaluate the environmental economic of rare earth elements and mercury recycling in the both unidirectional flow mode and the recycling mode.

## 2. Research Method

This article uses the cost method of environmental governance, according to the disposal of the current situation in the waste fluorescent lamps, will be divided into single flow and recycling modes, for which emissions are calculated for each stage, come with their own environmental costs itemized total item value, after comparing the results produced using recycled environmental benefits.

A typical unidirectional flow of rare earth resources and mercury in waste fluorescent lamps in the process (Fig.1a). The natural rare earth mine through artificial mining, smelting, as the raw material entering the production enterprises, manufactured after fluorescent lamps sale to consumers, reach retirement age discarded after use. Although the waste fluorescent lamp belongs to dangerous waste, the vast majority of waste lamps are still disposed by the traditional landfill and incineration. In the rare earth mining, smelting and manufacturing sectors, mainly produce waste water, waste gas and solid waste, environmental protection enterprises in the investment part of the cost of treatment for most pollutants, will discharge a small amount of pollution as shown in Fig.1.

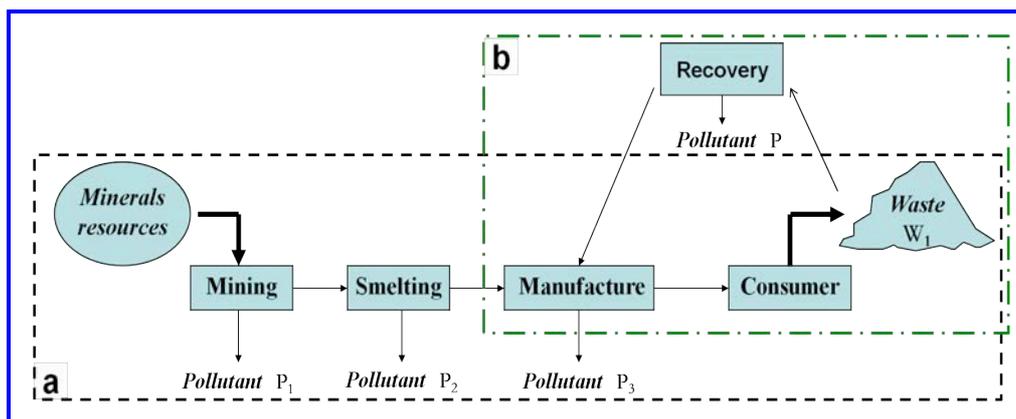


Fig.1 a Unidirectional flow mode, b Recycling mode of rare earth resources and mercury in waste fluorescent lamps

The process flow of a typical recycled rare earths and mercury in waste fluorescent lamps (Fig.1b).The consumer product flow by the manufacturer, after using, the waste recycling after the hazardous waste collected, using various types of technology for its recovery, and then processed into renewable resources, to the use of production enterprises, eventually forming a loop as shown in Fig.1.

Furthermore, analyzing the entire experiment process, and establishing the input and output equilibrium diagram of rare earth ions from waste phosphor powder as shown in Fig.2. The following relationship between material flow:

$$P_0 = (1 + \sum_{i=1}^{n=3} \beta_i) \times P_n \tag{1}$$

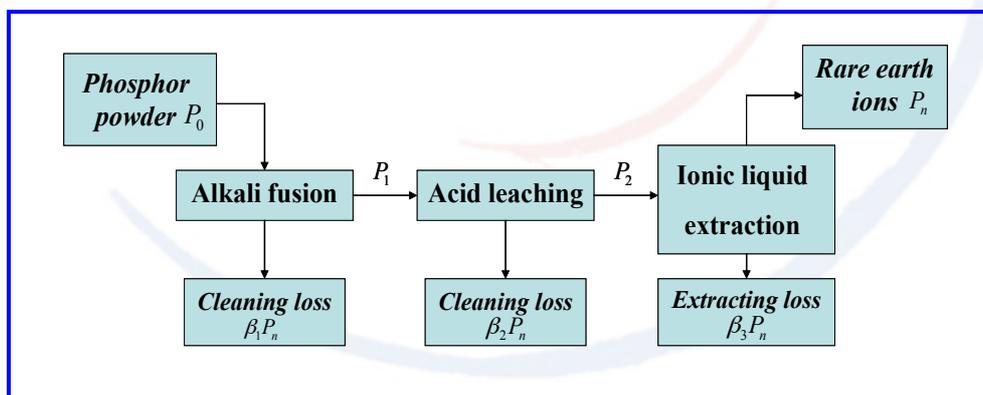


Fig.2 The input and output equilibrium diagram of rare earth ions

### 3. Result and Discussion

According to the amount of pollutants generated in each mode of the unidirectional and recycling flow, calculated to bring the actual and virtual treatment cost in the rare earth production process (Table 1). We can found that the actual and virtual treatment cost in the unidirectional flow patterns was 370.15 with a 1514.06 cny/t; the recycling flow patterns in the actual and virtual treatment cost was 135.10 and 15.06 cny/t. Contrast the costs of these two modes, the recycling mode will save 235.05 and 1499.00 cny/t in the actual and virtual treatment cost, respectively. compared with the

unidirectional flow mode, 92.03% of the total environment cost can be saved in the recycling mode.

Table 1 Total environmental costs of recycled phosphor in fluorescent lamps (cny/t)

	Item	actual costs	virtual costs
unidirectional flow mode	Waste water	78.83	312.05
	Waste gas	5.04	217.26
	Waste solid	286.28	984.75
	Total	370.15	1514.06
recycling mode	Waste water	8.83	10.05
	Waste gas	0.00	0.26
	Waste solid	126.28	4.75
	Total	135.10	15.06

Fig. shows that the material flow model of the entire recycling process of rare earth metals from waste phosphor power. According to the law of conservation of matter, in any period of time, each of the above material flow balance relation between the quality of the following:

$$PIN = \sum_{i=1}^{n=2} POT_i + PFN \tag{2}$$

The recovery rate of rare earth metals was calculated from:

$$R = \frac{PFN}{PIN} \times 100\% \tag{3}$$

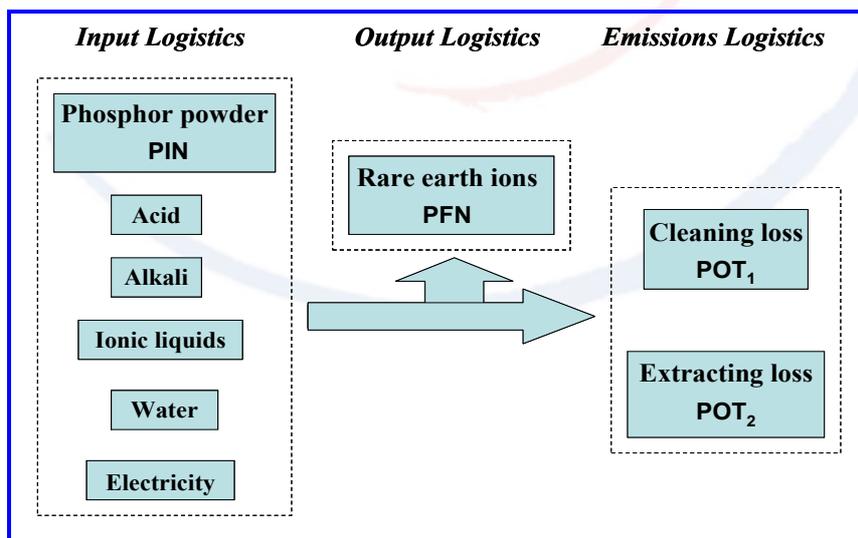


Fig.3. The material flow model of the entire recycling process of rare earth metals

Therefore, to reduce the loss of experimental process is the key to improving the recycling rate of rare earth metals.

#### **4. Conclusion**

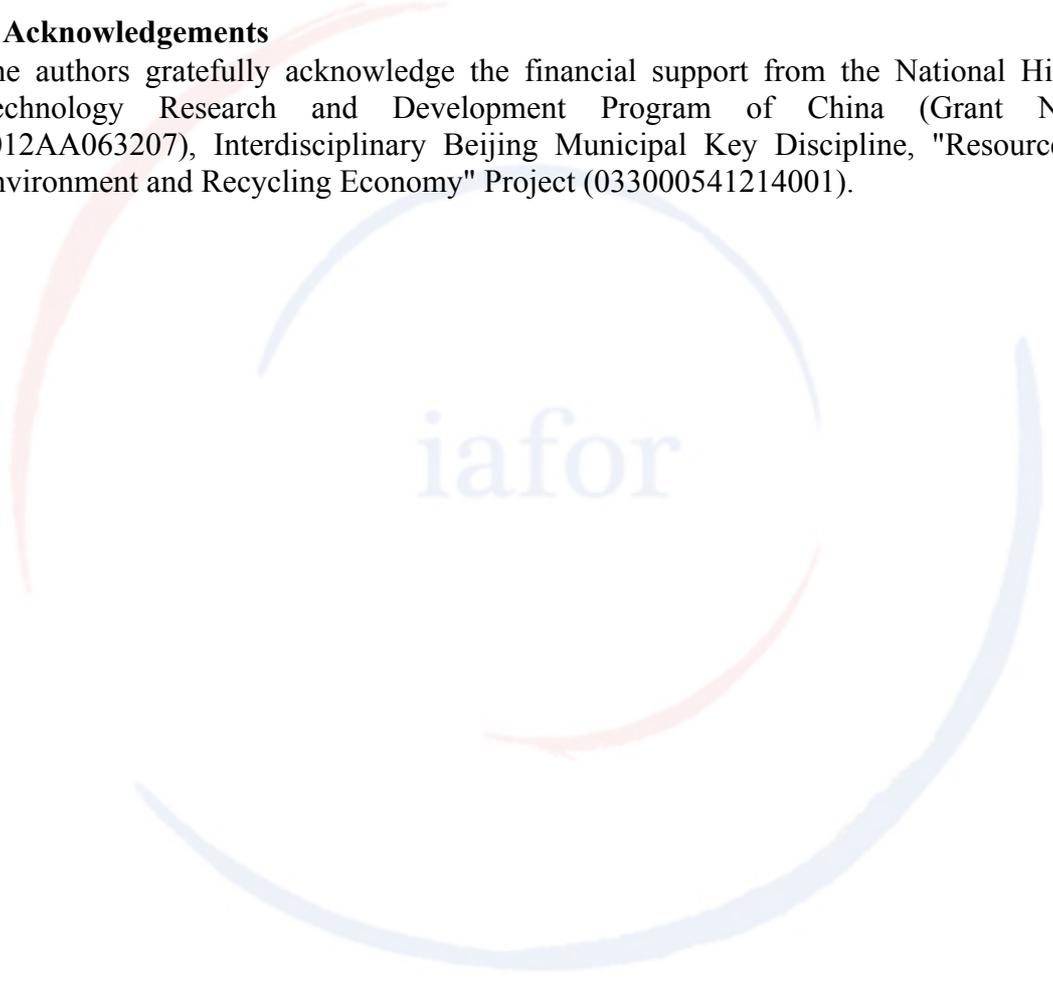
(1) After analysis of fluorescent lamps-way flow patterns, found that virtual treatment costs about four times the actual cost of treatment, indicating that the majority of pollutants in production has not been effective governance.

(2) The environment economic for the unidirectional flow mode is much higher than the recycling mode.

(3) The recycling of rare earths and mercury from the waste fluorescent lamps not only contributes to the environmental protection but also economically profitable. Government departments should increase the investment subsidies, to promote the recycling flow mode more widely promoted.

#### **5. Acknowledgements**

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## References

- Chung, S., & Zhang, C. (2011). An evaluation of legislative measures on electrical and electronic waste in the People's Republic of China. *Waste Management*, 31(12), 2638-2646.
- Habuer, Nakatani, J., & Moriguchi, Y. (2014). Time-series product and substance flow analyses of end-of-life electrical and electronic equipment in China. *Waste Management*, 34(2), 489-497.
- Kuo, T. C. (2013). Waste electronics and electrical equipment disassembly and recycling using Petri net analysis: Considering the economic value and environmental impacts. *Computers & Industrial Engineering*, 65(1), 54-64.
- Wu YF., Yin XF., Zhang QJ., Wang W., Mu XZ. (2014). The recycling of rare earths from waste tricolor phosphors in fluorescent lamps: A review of processes and technologies. *Resources, Conservation and Recycling*, 88, 21-31.
- Li, J., Lopez N., B. N., Liu, L., Zhao, N., Yu, K., Zheng, L. (2013). Regional or global WEEE recycling. Where to go? *Waste Management*, 33(4), 923-934.
- Fulvio A., Fabrice M., Marco R. (2014). Recycling of electronic displays: Analysis of pre-processing and potential ecodesign improvements. *Resources, Conservation and Recycling*, 92, 158-171.
- Wu YF., Wang BL., Zhang QJ., Li RQ., Yu JM. (2014). A novel process for high efficiency recovery of rare earth metals from waste phosphors using a sodium peroxide system. *RSC Advances*. 4, 7927-7932.
- Guo XF., Wang CZ., Du R., Zhang ZH. (2013). The prevention of mercury pollution in the production of fluorescent lamps. *GANSU METALLURGY*. 35(3), 52-54.
- Lim, S., & Schoenung, J. M. (2010). Human health and ecological toxicity potentials due to heavy metal content in waste electronic devices with flat panel displays. *Journal of Hazardous Materials*, 177(1-3), 251-259.
- Wu YF., Wang BL., Zhang QJ., Li RQ., Sun CH., Wang W. (2014). Recovery of rare earth elements from waste fluorescent phosphors: Na<sub>2</sub>O<sub>2</sub> molten salt decomposition. *Journal of Material Cycles and Waste Management*. 8, 635-641.
- Yin SQ., Tang N. (2009). The environmental risks of waste fluorescent lamps. *Technology Innovation Herald*. 9, 104-106.

Zhang HZ., Chen DH. (2011). The investigate of recycling the waste fluorescent lamps. *CHINA LIGHT & LIGHTING*. 4, 18-23.

Zhuang J., Li MJ., Wang XH. (2013). Recycling and secondary use of the waste fluorescent lamps. *China Resources Comprehensive Utilization*. 31(9), 44-46.

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***Aerobic Wastewater Treatment Packages:  
An Environmental and Energy-Saving Option***

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**Abstract**

The water management systems throughout the world employ and depend heavily on water supply management approach to cater the demand. This approach is unsustainable in the long run as water demand will eventually overtake water supply. It requires an effective approach like building water retaining structures; dams, canals etc., along with an effective management plan to sustain future needs. A more proper management of water is needed to sustain any adverse conflicts of water supply.

The objective of this work is the development of an aeration wastewater treatment package which includes a well-equipped system that enables a sustainable management in the field of wastewater treatment, low energy consumption, and last but not least low investment and operation costs. The treatment package works by Extended Aeration Method. Performance of these packages is based on the continuous aeration including injection of oxygen gas or air into the aeration chamber via tube aeration diffuser through very small apertures for providing the required oxygen for aerobic bacteria.

Keywords: wastewater treatment, Extended Aeration Method, aerobic bacteria.

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## Introduction

Water is essential for life and plays a vital role in the proper functioning of the earth's ecosystems. Water pollution has a serious impact on all living creatures, and can have undesired effects to human lives, their activities and also to their environment. Pollution in whole is caused by pollutants which is basically drawn into two types.

Type one pollutants are apparently acute and have short-term damages, while the other are latent, persistent, and carry long-term damages. The first type which includes air, sound pollution and..., are obviously clear and is one of the main concerns of scholars, experts, governmental and NGO bodies around the world as well as the whole community itself. The concern even runs into human daily lives and become part of people's demands and some may even use it as main their main issue for gaining election votes.

The second type of pollutants which are latent, persistent and actually carry long-term damages are recognized to be largely ignored by the international community. The threat is seen in the changing growth rate of human, animal and plant species together with human amenities, comfort, and health and property values. The unseen project done by these pollutants brings the world and the ecosystem to a catastrophe in a slow motion. As a consequence, people have been worriless about the danger it can cause to the future of their lives and therefore, exclude it from their country's development and health agenda budget. However, in some countries, the topic may be part of their political and economical budget agenda but in the end, no serious actions are taken to cure the critical on-going situation. These pollutants persist in the environment in the long term that even the particular sources of the pollution is blur and undefined and the line of affects and effects is also unknown. The examples of this second type of pollutants are industrial, municipal and agriculture wastewater.

According to FAO (Food and Agriculture Organization), the wastewater generated in developing countries is about 600 million cubic meters, which 95% of those without treatment enters the seas, oceans, rivers and underground waters. Another recent report done by World Water Development shows that 2 million tons of human waste are disposed in watercourses, and in developing countries 70% of industrial, sanitary and agricultural waste are dumped untreated into water where they pollute the usable water supply (WWD, 2012). Hence, there is a need to adopt measures which can significantly reduce water pollution and at the same time, increase water quality. This also leads to an improvement of wastewater treatment and water efficiency which reduces the water loss. One highlighted valuable option that is known to be environmental and energy-saving is the usage of wastewater treatment packages. Another reason is that the cost difference between septic tank usages in water management varies from the cost of wastewater treatment usage for such purpose. The first, demands for the average of 160 dollar for every 1 cubic meter while the second, only requires an average of 6 dollars for the same amount of water usage.

In the near future, water shortage crisis will paralyze humans and at that time there would be no time for political struggles, expanding geographical borders and ideological challenges. That time is pretty close even closer than finishing fossil fuels. We want 85.5 percent of generated wastewater to return to life cycle and be reused,

while in Asian countries only 2.4% of the generated wastewater returns to life cycle and is being reused. This problem needs your guidance and supervision. However our children will not be patient toward environmental pollution and it is our responsibility. This environment with all its beauty and divine bounty not only belongs to us, but also all animals and plants are parts of this nature.

### 1) Design of SHAR Wastewater Treatment Package

A new wastewater treatment package has been invented by Hady Hamidyan (CEO, SHAR WWTP Sdn. Bhd. Malaysia), holder of 8 international awards and 6 GOLD medal, using aeration wastewater treatment package which includes a well-equipped system that enables a sustainable management, low energy consumption, and last but not least low investment and operation costs.

The treatment package works by Extended Aeration Method with depth injection. Performance of these packages is based on the continuous aeration including injection of oxygen gas or air into the aeration chamber via tube aeration diffuser through very small apertures for providing the required oxygen for aerobic bacteria. It is also designed to be back sludge airlift pump-free.

The table below indicates the models of the packages with the details of the power, weight and volume:

1	Models		P1	P2	P3	P4	P5	P6
2	Capacity	m <sup>3</sup> /d	1	3	5	7	10	15
3	Power	kw	0/19	0/24	0/37	0/55	0/75	1.2
4	Weight	kg	37	58	90	160	280	340

Table 1: Models and Details of SHAR Packages



Picture 1: A Model 3 m<sup>3</sup>/d SHAR Package

### 2) Development of SHAR Wastewater Treatment Packages

#### 2.1: Project Site

SHAR WWTP Sdn. Bhd. has chosen Iran to be the site for longitudo developmental project in four years time; 2011-2014. Primarily the site was selected and make available by the regional administration, considering its geographical and climatic features to the targeted project.

Iran is covered by a remarkable salt swamp and partly by areas of loose sand of surrounding mountains. The climate is one of great extremes due to its geographic location and varied topography. The average annual rainfall is 230 mm, while rate of evaporation exceed 2000mm annually. Approximately, 90% of the country is arid or semi-arid and located in the interior and far-south which is characterized by long, warm and dry spells, lasting sometimes over seven months. About 23% of the rain falls in spring, 4% in summer, 23% in autumn and 50% in winter as snow fall.

## **2.2: Method of Project**

The development approach consist of three phase which is collection of data, analyze of data, implementation of invention.

### **Phase One**

Collection of baseline data such as soil and wastewater data, metrological and hydrogeological data. Scientific information that was gathered on the biophysical and socio-economic conditions which came from concerned such as Minister of Energy (MOE), Water Affairs Department (WAD), Water Resources Management Company (WRMC), Provincial Water Authorities (PWA) Irrigation and Drainage Operation and Maintenance Companies (O&M), Water and Wastewater Engineering Companies (WVEC) and National Water and Wastewater Engineering Company (NWWEC) were also collected.

### **Phase Two**

Analyze data using both qualitative and quantitative techniques.

### **Phase Three**

Implementation of designed models namely SHAR packages, according to geographical location as well as being based on available standards and legal requirements.

## **3) Results of Project: Impact to the Environment and Energy-Saving**

During operation phase, access to urban water supply has increased from 75% to 99%. Yet, a number of challenges remain in rural areas.

Out of 3,547.8 MCM sewage was produced and only 328.2MCM was used for mainly irrigation while it is estimated over 90% of the country's wastewater is treated by wastewater treatment by both dams and packages.

The package is known to have necessary adaption measures that deal with climate variability and is built upon existing land and water management practices, thus creates resilience to climate change and able to enhance water security and directly contribute to the development itself.

The feedbacks were mostly positive. Below is the list of feedbacks gained through interviews and surveys:

- Portable and light.
- Easy maintenance.
- Stainless and anti-corrosion.
- Low power consumption.
- Without the back sludge airlift, dislodging works become easier and saving (no dislodging trucks needed).
- Least required space for installation.
- No need of permanent operator due to its automatic application.
- Able to evacuate in surface water, agriculture lands and lawns.

Demands for installation of the package has increased throughout the years from 5 to 63 to 180 and 233 packages in the last year, respectively.

In whole, the percentage of population served by drinking water systems and wastewater treatment is, 75% and 45%, respectively. The figures is estimated to dramatically improve in the becoming years as the result of these installments.

Row	Parameter	Unit	Range	Method
1	Temperature	O C	29	St. M. 2550
2	EC	us/cm	1910	St. M. 2510
3	pH	-	7.8	St. M. pH Value-B
4	DO	mg/l	0.4	O-G-4500 .St. M
5	COD	mg/l	709	St. M. 5220-D
6	BOD5	mg/l	346	St. M. 5210-B
7	NO3	mg/l	51	St. M. 4500-NO3
8	PO4	mg/l	9.5	St. M. 4500-P
9	TDS	mg/l	1240	St. M. 2540-C
10	TSS	mg/l	242	St. M. 2540-D
11	Focal coliforms	No./100cc	>1100	MPN/100ml
12	Total Coliforms	No./100cc	>1100	MPN/100ml

Table 2: Result of Inlet Analysis from SHAR Package, Hotel Restaurant Nour City

Row	Parameter	Unit	Range	Method
1	Temperature	O C	25	St. M. 2550
2	EC	us/cm	591	St. M. 2510
3	pH	-	7.2	St. M. pH Value-B
4	DO	mg/l	2.7	O-G-4500 .St. M
5	COD	mg/l	62	St. M. 5220-D
6	BOD5	mg/l	31	St. M. 5210-B
7	NO3	mg/l	18	St. M. 4500-NO3
8	PO4	mg/l	2.9	St. M. 4500-P
9	TDS	mg/l	102	St. M. 2540-C
10	TSS	mg/l	45	St. M. 2540-D
11	Focal coliforms	No./100cc	0	MPN/100ml
12	Total Coliforms	No./100cc	1	MPN/100ml

Analysis Correspond To the Requested Test

Typing Results Correspond To the Analysis Results

Table 2: Result of Outlet Analysis from SHAR Package, Hotel Restaurant Nour City

#### 4) Conclusion and Recommendations

Nowadays, the wastewater treatment in developing countries are commonly using septic tanks rather than wastewater packages. People are not aware that septic tanks only treats 30% of the sludge and wastewater. Furthermore, high additional cost is also undertaken for the building and maintenance of absorber wells which in actual gives negative impacts to the environment silently. The inefficient ways of treatment leads the unwell-digested water to pollute the underground water as well as seas, oceans and the ecology system.

The management of water is not merely a technical issue. It requires a mix of measures including changes in policies, prices and other incentives, as well as infrastructure and physical installations. The current situation is that only 2.4% of the disputed wastewater is reused in human activities as well as to not create damage to the environment. The truth is that we can actually recycle 90% of them to be recycled back to the environment.

As the subsequence of the longitude developmental research, we have come out with some suggestions and recommendations for future applications, those are;

- A framework and educational model is needed to build up the environmental education and ecological culture in the global community; starting from early age to adolescents.
- An effective and proper wastewater management along with prevention of water-related pollution is needed. However, the management control of other waste disposal; air, agricultural fertilizers and pesticides, soil, sound, radioactive wave etc. should also be included.
- Measures to be adopted which addresses on recycling for productive purposes and reusing the waste that has been significantly improved in quality and structure.
- Efforts to be made for encouraging industries, constructors and all concerned bodies to implement centralized system and management treatment.
- A global investment should be made on new innovative inventions that benefits the sustainability of the environment and the development.
- A development of international agenda or framework should be built in preserving the environment which refers to global action and cooperation as well as having rules and legislations to be followed properly by every country.
- A treaty organization should be signed by countries all over the world to defend and preserve the sustainability of the environment.
- Established international conservation organization: environmental NATO called: **ETO** ( Environmental Treaty Organization)

### References

- FAO Aqua stat: Water and Water land Report, 2009.
- World Water Development Report, 2012.
- Joint Monitoring Program on water Supply and Sanitation, 2013.
- National Water and Wastewater Engineering Company publications and internal Reports, 2012.
- UNESCO-IHE Institute for Water Education: Training and Capacity Building for the Water and Wastewater Sector in Iran, accessed on May 2014.
- World Bank: Northern Cities Water Supply and Sanitation Project.
- Tajrishy, Massoud. Wastewater Treatment and Usage in Iran: Situation Analysis, 2011.

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The logo for the International Association of Agricultural and Fisheries Economists (IAFOR) is centered on the page. It features the word "iafor" in a light blue, lowercase, sans-serif font. The text is enclosed within a circular graphic composed of two overlapping, semi-transparent arcs: a larger, light blue outer arc and a smaller, light red inner arc, both of which are slightly offset from each other to create a sense of depth or rotation.



## **Removal of selenium from wastewater by using magnesite-bentonite clay composite: Kinetics and Equilibrium studies**

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### **Abstract**

In this paper, the adsorption of oxyanions of selenium from wastewater by magnesite-bentonite clay composite has been investigated. The removal of selenium by using Magnesite-bentonite clay composite was studied in batch experiments. The effects of equilibration time, composite dosage, selenium concentration and pH on removal of selenium from wastewater were investigated. The experiments demonstrated that selenium removal is optimum at 30 minutes of agitation, 2g of composite dosage, 20 mg L<sup>-1</sup> of selenium concentration. The adsorption data fitted well to Freundlich adsorption isotherm than Langmuir adsorption isotherm hence proving multilayer adsorption. The kinetic studies reported that the data favours pseudo second order reaction than first order hence proving chemisorption. Under optimized conditions, the composite was able to remove selenium to below World Health Organization (WHO) water quality guidelines. Henceforth, it was concluded that this fundamental study will be helpful for further application in the treatment of selenium contaminated water.

Keyword: Selenium, Magnesite, Bentonite clay, Batch experiment, adsorption kinetics and adsorption isotherms

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## Introduction

Availability of selenium in drinking water has recently raised public concern due to hazardous impacts that it can impose to living organisms on exposure (Dubey and Gopal, 2007, Dönmez and Aksu, 2002, Fahim et al., 2006). Selenium is a natural trace element that exists as a metalloid in the aqueous environment (Kalidhasan et al., 2012). It is an essential nutrient that has very narrow margin between nutritionally optimal and potentially toxic dietary exposures for terrestrial and aquatic organisms (Ahsan et al., 2014, Chang et al., 2010, Correa et al., 2014, Chammui et al., 2014, Sasaki et al., Inukai et al., 2004). Accumulation of selenium in soils, surface, subsurface water and drinking water poses threats to plants, wildlife and humans (Singha et al., 2012, Kalidhasan et al., 2012, Bick and Oron, 2013, Elangovan et al., 2008, Fabbicino et al., 2013). The essential or toxic character of Se in living beings depends not only on its concentration in the circumstances, but also on the chemical form, which directly affects absorption and bioavailability (Ahsan et al., 2014, Mandal et al., Lescano et al., 2012, Choong et al., 2007, Zerze et al., 2013, Yamani et al., 2014, Yu et al., 2014, Randhawa et al., 2012, Yang et al., 2014, Zhang et al., Olgun and Atar, 2011). Selenium can emanate from human activities and geological weathering. Excessive amounts of selenium released into freshwater from mining, agricultural and petrochemical activities result in concentrations that are hazardous to aquatic environments (Dubey and Gopal, 2007, Bick and Oron, 2013, Dönmez and Aksu, 2002). In aqueous environment and depending on pH, selenium can portray various oxidation states such as elemental selenium (Se<sup>0</sup>), selenite (SeO<sub>3</sub><sup>2-</sup>), selenide (Se<sup>2-</sup>), selenate (SeO<sub>4</sub><sup>2-</sup>) and organic selenium. Selenite and selenate are the predominant chemical forms of selenium and are thermodynamically stable. Although selenium demonstrates different forms in aqueous environment, depending on its oxidation state, the predominant water soluble anionic species include selenite (HSeO<sub>3</sub><sup>3-</sup> or SeO<sub>2</sub><sup>3-</sup>) and selenate (SeO<sub>2</sub><sup>3-</sup>). Selenite mainly predominate oxidising and neutral pH environments. In addition, the selenite ion is more toxic and mobile in water than the selenate ion, which only exists at high pH and in oxidising condition (Dubey and Gopal, 2007, Bick and Oron, 2013, Dönmez and Aksu, 2002, Bansal et al., 2009, Fahim et al., 2006, Ahsan et al., 2014, Mercado-Borrayo et al., 2014, Almondes et al., 2014, Lacasa et al., 2011, Ciceo-Lucacel et al., 2014, Correa et al., 2014, Qiu et al., 2014, El-Shahawi and El-Sonbati, 2005, Sasaki et al., Inukai et al., 2004, Geillinger et al., Çelik et al., 2008, Streat et al., 2008, Hodlur and Rabinal, 2014, Ashournia and Aliakbar, 2009, Klas and Kirk, 2013, Criscuoli et al., 2013, Kyle et al., 2012, Güler et al., 2011, Awual et al., 2011, Tabelin et al., 2014, Oishi and Maehata, 2013, Su and Wang, 2011, Tresintsi et al., 2012, Zhang and Frankenberger, 2003, Kabay et al., 2007, Sheha and El-Shazly, 2010, Lizama Allende et al., 2014, Lizama Allende et al., 2012, Jain and Singh, 2012, Khosa and Ullah, 2014, Liu et al., 2009, Zhang et al., Olgun and Atar, 2011).

Exposure to excess concentrations of selenium can result to the development of genotoxicity (breaks DNA structure, oxidative DNA damage, and impairment of genomic stability), cytotoxicity (Arrest cell cycle, inhibit cell growth and proliferation) and epidemiology (prostate cancer, hepato-carcinogenesis, cardiovascular disease, amyotrophic lateral sclerosis and diabetes) (Ahsan et al., 2014, Chang et al., 2010, Das et al., 2013, Chammui et al., 2014, Inukai et al., 2004). To reckon that, the introduction of this chemical species to drinking water need to be monitored and control prior pollution. Several water decontamination methods have

been developed to for removal of selenium and they include Adsorption, ion exchange, precipitation, coagulation, flocculation, reverse osmosis (RO), electroplating, bio sorption, filtration, distillation and membrane technology (Almondes et al., 2014, Lacasa et al., 2011, Sasaki et al., 2014, Ciceo-Lucacel et al., 2014, Das et al., 2013, Wang et al., 2014, Sasaki et al., Çelik et al., 2008, Han et al., 2011, Yamamura and Amachi, 2014, Ashournia and Aliakbar, 2009, Bulut et al., Awual et al., 2011, Theiss et al., 2013, Pal et al., 2014, Tresintsi et al., 2012, Wu, 2004, Andrianisa et al., 2008, Sheha and El-Shazly, 2010, Jain and Singh, 2012). However, adsorption has recently received great attention to its effectiveness, efficiency and economic viability (Yamani et al., 2014). This study was developed to evaluate the feasibility of integrating magnesite and bentonite clay for removal of selenium from wastewater.

Combination of magnesite and bentonite clay (Composite) will increase the concentration of base cations which are suitable for selenium adsorption especially at basic conditions. Recent studies reported that the Yellow Star Quarries in the Kroonstad district, Cape Town, RSA contains 750 000 m<sup>3</sup> deposit of bentonite that can be projected to 67 years if it is mined at a rate of 4000 m<sup>3</sup>/ month. The magnesite mine in folovhodwe, Limpopo province, RSA showed that the magnesite deposit is close to 18 mega tons of amorphous magnesite which can be mined for the coming 50 years. In terms of economic viability, the technology will be feasible since it is relying on natural and locally available materials.

## **Materials and methods**

### **Feedstock**

Raw magnesite rocks were collected prior any processing at the mine from the Folovhodwe Magnesite Mine in Limpopo Province, South Africa (22°35'47.0"S and 30°25'33"E). Magnesite samples were milled to a fine powder using a Retsch RS 200 miller and passed through a 32 µm particle size sieve. Raw AMD samples were collected from a disused mine shaft in Krugersdorp, Gauteng Province, South Africa. Bentonite clay samples were supplied by Bentonite PTY, LTD (Cape Town, South Africa). The raw bentonite samples were washed by soaking the samples in ultra-pure water and draining the water after 10 minutes. The ultrapure water used was such that it covered the entire sample in the beaker and allowed to overflow. The procedure was repeated four times. The washed bentonite was then dried in an oven for 24 hours at 105°C. The dried samples were crushed into a fine powder using a Retsch RS 200 miller and passed through a 32 µm particle size sieve. Thereafter, the composite (1 Kg) of powdered bentonite and magnesite was fabricated on 1:1 gram ratio. 500 grams of bentonite clay was mixed with 500 grams of magnesite. The mixtures were crushed and homogenised by pulverizing them together into fine powder using a Retsch RS 200 miller (USA) and passed through a 32 µm particle size sieve. After sieving, the samples were tightly kept in zip lock plastic bags until application for wastewater amelioration.

### **Physicochemical characteristics of the samples**

Elemental analysis of raw and processed water samples was done by Inductively Coupled Mass Spectrometry (ICP-MS) (ELAN 6000). The accuracy of the analysis

was monitored by analysis of National Institute of Standards and Technology (NIST) water standards. pH, Total Dissolved Solids (TDS) and Electrical Conductivity (EC) were monitored using CRISON MM40 portable pH/EC/TDS/Temperature multimeter. Sulphate analysis was done by analyzed by Spectroquad pharo, model 100 Merck spectrometer. Chemical characteristics of magnesite samples were ascertained using X-ray Fluorescence spectroscopy (XRF). Mineralogical characteristics of magnesite samples were ascertained using a Philips X-ray diffractometer with Cu-K $\alpha$  radiation. Phase identification was performed by searching and matching obtained spectra with the powder diffraction file data base with the help of JCPDS (Joint committee of powder diffraction standards) files for inorganic compounds (Both XRF and XRD analysis were done at the facility of Geology, University of Pretoria. morphology and elemental composition of magnesite by Energy dispersive X-ray spectrometry (EDX: FIB-SEM, Auriga from Carl Zeiss) attached to Scanning electron microscopy (SEM: JEOL JSM7500 microscope from Carl Zeiss) (SEM-EDX) and surface are by Brunauer-Emmett-Teller (BET: A Tristar II 3020, Micrometrics BET from Norcross, GA, USA). pH<sub>pzc</sub> was determined using solid addition method as described by Kumar et al.(2011). Cation Exchange Capacity (CEC) was determined using ammonium acetate method.

### Adsorption experiments

The adsorption experiments were carried out in a batch process and effect of different parameters such as effect of contact agitation time, composite dosage, selenium concentration and pH were studied. The known weight of the composite was added to 100 mL of selenium metal ion solution with an initial concentration of 0.3 - 40 mg/L. The contents were shaken thoroughly using a reciprocating shaker rotating with a speed of 250 rpm. Effect of time was evaluated by varying equilibration time between 1 – 360 minutes, effects of dosage was determined by varying the composite dosage between 0.5 – 5 grams, effects of adsorbate concentration was determined by varying the initial concentration between 0.3 to 40 mg/L and effects of pH were determined by varying the pH between 2 – 12. All experiments were conducted at room temperature. ICP-OES was used for analysis of water samples.

### Modelling of analytical results

#### Percentage removal

$$\% \text{ Removal} = \left( \frac{C_o - C_e}{C_o} \right) \times 100 \quad (1)$$

Where:  $C_o$  = initial concentration and  $C_e$  = equilibrium ion concentration respectively

#### Adsorption capacity

$$q = \frac{(C_i - C_e)V}{m} \quad (2)$$

Where:  $C_i$  = Initial selenium concentration (mg L<sup>-1</sup>),  $C_e$  =selenium concentration at equilibrium (mg L<sup>-1</sup>),  $V$  = Volume of selenium solution (L),  $m$  = Weight of the composite (adsorbent) in grams (g)

## Adsorption isotherms

The mechanisms and intensity of adsorption was described by use of two common adsorption models: Langmuir and Freundlich adsorption isotherms these models describe adsorption processes on a homogenous or heterogeneous surface respectively

### The Langmuir Isotherm

The Langmuir isotherm is valid for monolayer sorption due to a surface with finite number of identical sites and can be expressed in the following linear form

$$\frac{C_e}{Q_e} = \frac{1}{Q_m b} + \frac{C_e}{Q_m} \quad (3)$$

Where,  $C_e$  = Equilibrium concentration ( $\text{mg L}^{-1}$ ),  $Q_e$  = Amount adsorbed at equilibrium ( $\text{mg g}^{-1}$ ),  $Q_m$  = Langmuir constants related to adsorption capacity ( $\text{mg g}^{-1}$ ) and  $b$  = Langmuir constants related to energy of adsorption ( $\text{L mg}^{-1}$ )

A plot of  $C_e/Q_e$  versus  $C_e$  should be linear if the data is described by the Langmuir isotherm. The value of  $Q_m$  is determined from the slope and the intercept of the plot. It is used to derive the maximum adsorption capacity and  $b$  is determined from the original equation and it represents the intensity of adsorption.

### The Freundlich Isotherm

The Freundlich adsorption isotherm describes the heterogeneous surface energy by multilayer adsorption and can be expressed in linear form

$$\log Q_e = \frac{1}{n} \log C + \log K_f \quad (4)$$

Where  $C_e$  = Equilibrium concentration ( $\text{mg L}^{-1}$ ),  $Q_e$  = Amount adsorbed at equilibrium ( $\text{mg g}^{-1}$ ),  $K_f$  = Partition Coefficient ( $\text{mg g}^{-1}$ ) and  $n$  = Intensity of adsorption

The linear plot of  $\log Q_e$  versus  $\log C_e$  indicates if the data is described by Freundlich isotherm. The value of  $K_f$  implies that the energy of adsorption on a homogeneous surface is independent of surface coverage and  $n$  is an adsorption constant which reveals the rate at which adsorption is taking place. These two constants are determined from the slope

## Adsorption kinetics

### Pseudo-first-order model

The pseudo-first-order is a kinetic model described by the following equation:

$$\log(q_e - q_t) = \log q_e - \left(\frac{K}{2.303}\right)t \quad (5)$$

Where  $q_e$  ( $\text{mg g}^{-1}$ ) is adsorption capacity at equilibrium,  $q_t$  ( $\text{mg g}^{-1}$ ) is the adsorption capacity at time  $t$ , and  $K$  ( $\text{min}^{-1}$ ) is the rate constant of pseudo-first-order. The value of  $K_1$  can be obtained from the slope by plotting  $\text{Log}(q_e - q_t)$  vs.  $t$ .

### Pseudo-second-order model

Pseudo-second-order mode is applied when the applicability of the first-order kinetics becomes untenable. The equation of pseudo-second-order is given in the following equation

$$\frac{1}{q_t} = \frac{1}{k_2 q_e} + \left(\frac{1}{q_e}\right)t \quad (6)$$

This equation is applied to obtain  $K_2$ , the second order rate from the plots  $t/q_e$  vs.  $t$ .

## Results and discussion

### X-ray fluorescence (XRF) analysis

Elemental composition of bentonite clay, magnesite and composite is shown in Table 1

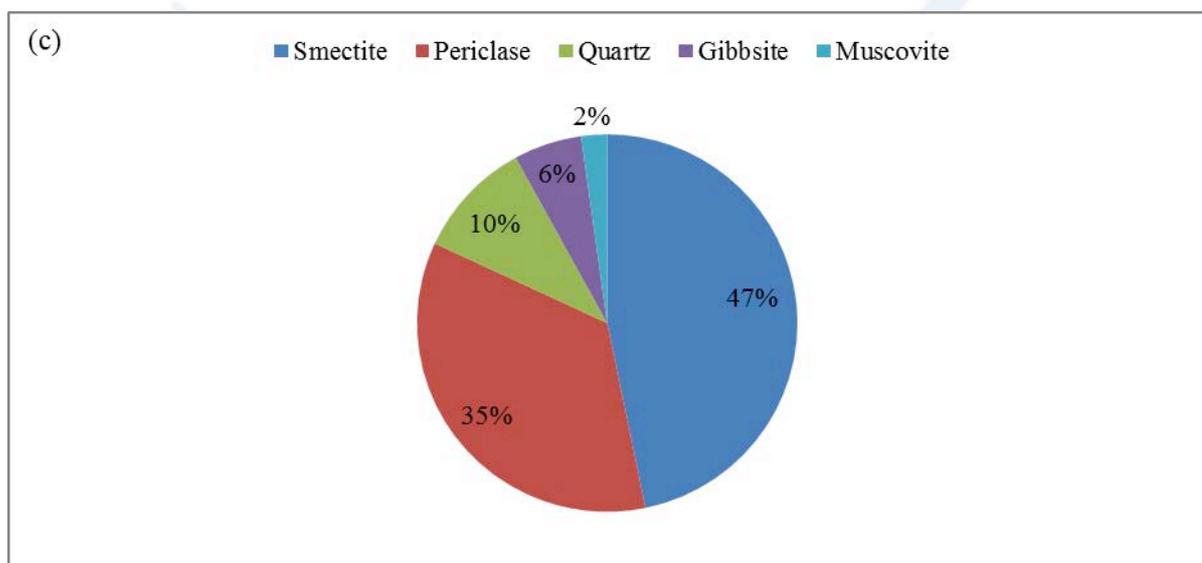
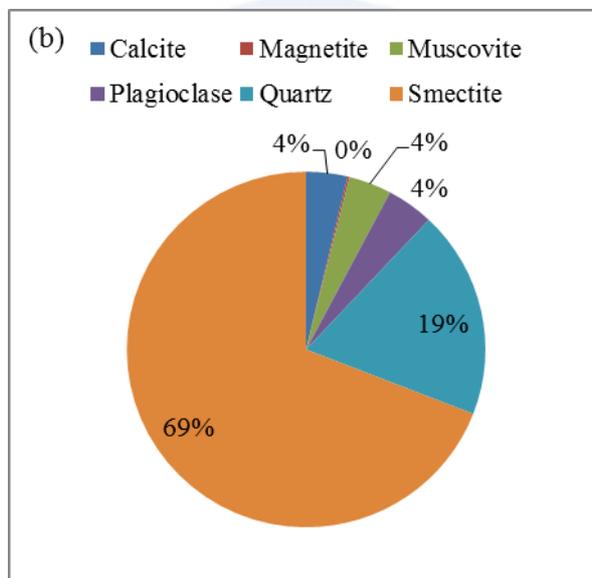
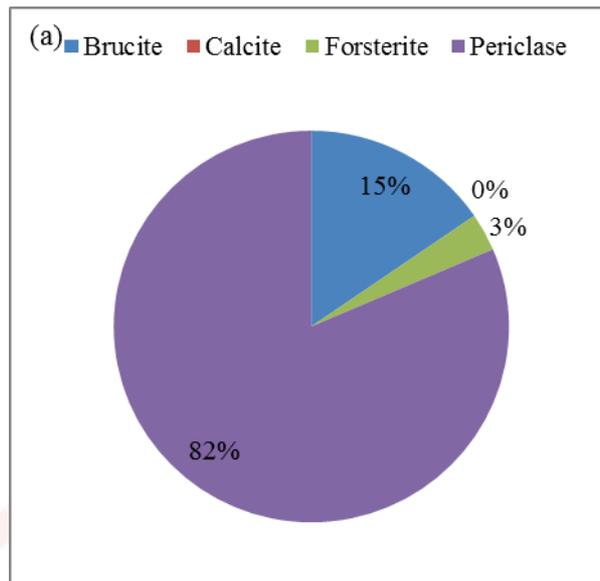
**Table 1:** Elemental composition of bentonite clay, magnesite and the composite

% Composition	Bentonite clay	Magnesite	Composite before
<b>SiO<sub>2</sub></b>	66.51	4.76	51.72
<b>Al<sub>2</sub>O<sub>3</sub></b>	16.81	0.14	10.37
<b>Fe<sub>2</sub>O<sub>3</sub></b>	3.26	0.25	4.44
<b>MnO</b>	0.13	0	0.1
<b>MgO</b>	3.12	91.80	29.43
<b>CaO</b>	1.43	5.59	2.29
<b>Na<sub>2</sub>O</b>	1.17	0	0.79
<b>K<sub>2</sub>O</b>	0.54	0.003	0.32

Bentonite clay is mainly comprised of Al and Si hence proving that the material understudy is an alumino-silicate. The presence of Fe indicates possible adsorption of Fe during deposition. MgO, CaO, NaO and K show that these are the main exchangeable cations in bentonite clay matrices. Magnesite is dominated by Mg as the major element hence validating that the material is magnesium based. The synthesized composite is dominated with Al, Mg and Si hence showing that the material is a combination of magnesite and clay mineral.

### X-ray diffraction (XRD) analysis

XRD revealed that the composite is enriched with Magnesite, Montmorillonite and Quartz (Figure 1). Figure 1 below shows the mineralogical composition of the fabricated composite.

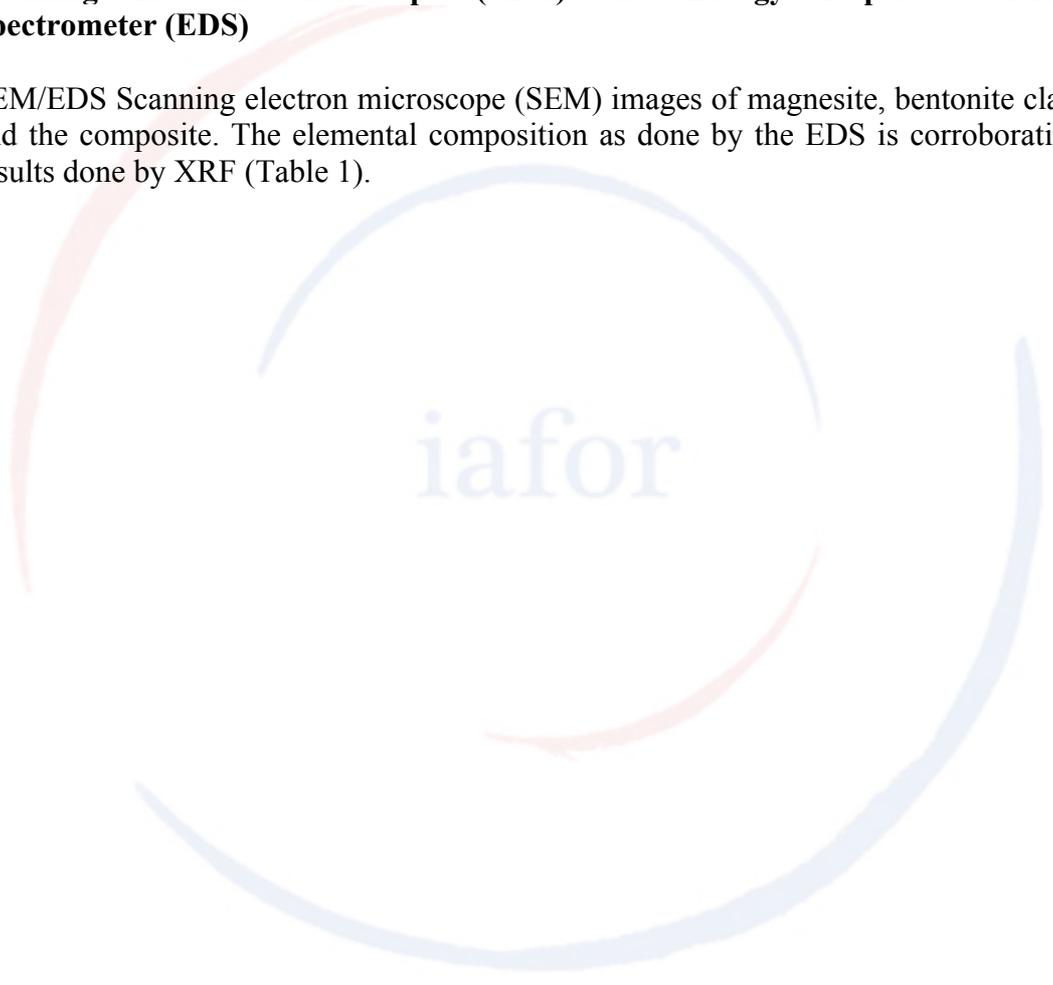


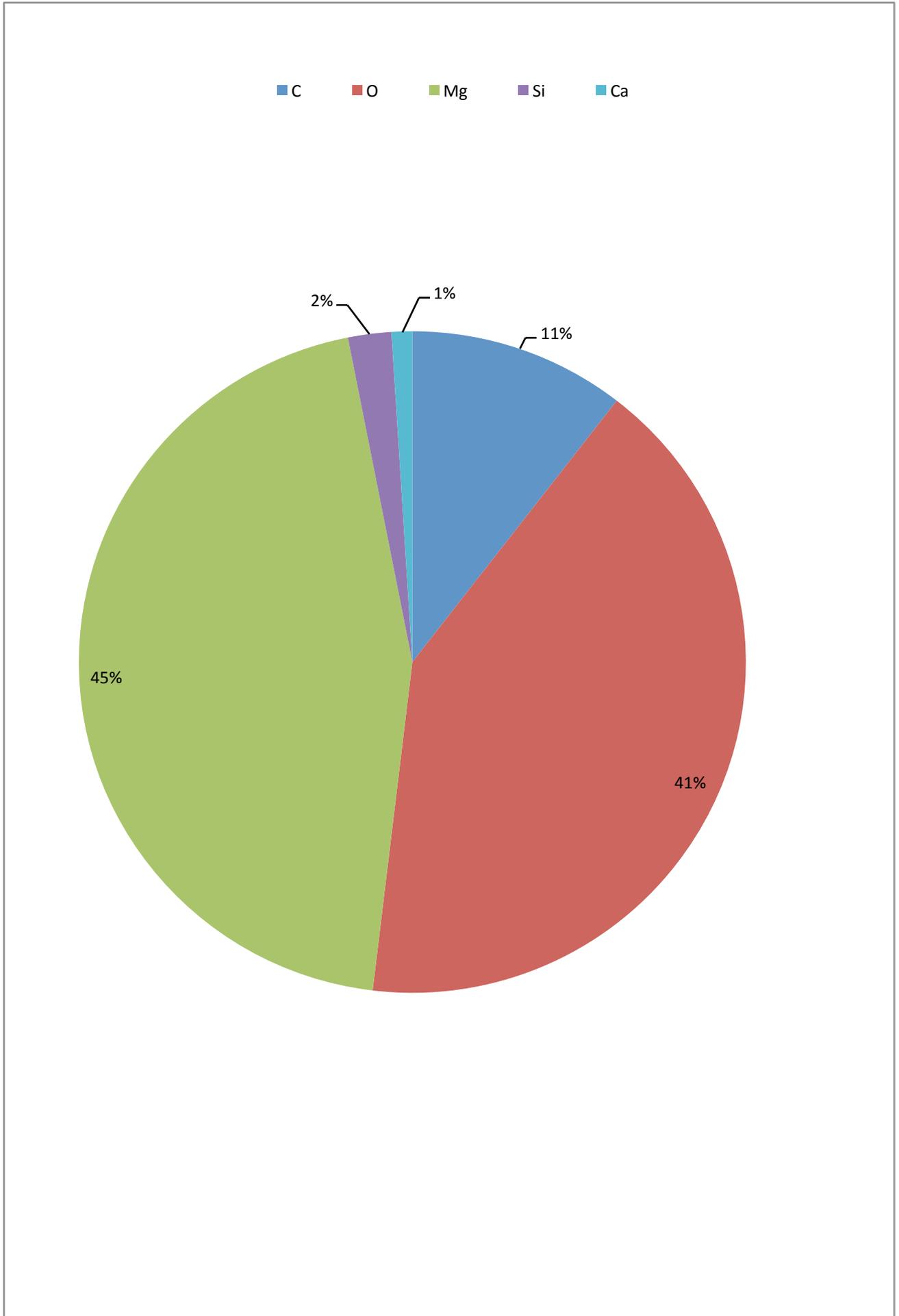
**Figure 1:** Mineralogical composition of (a) magnesite, (b) bentonite clay and (c) the composite

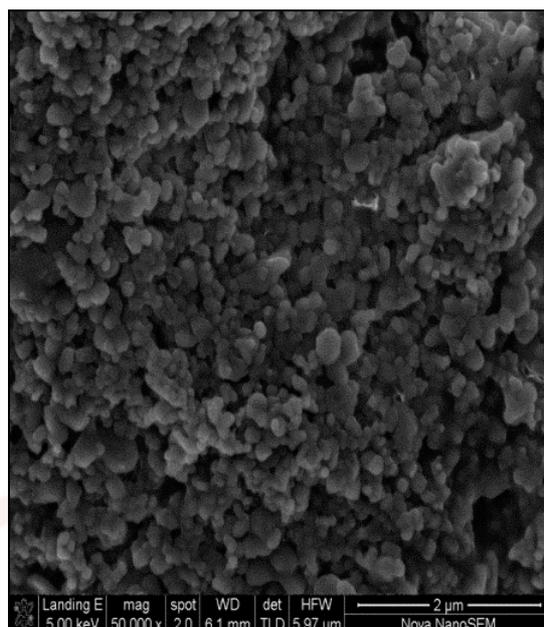
XRD analysis showed that magnesite consists of Periclase, brucite and forsterite as the main mineral phase (Figure 1.a). Bentonite clay was observed to contain smectite, quartz, plagioclase, calcite and muscovite (Figure 1. b). The composite was determined to contain smectite, periclase, quartz, gibbsite and muscovite which are the main components of magnesite and bentonite clay (Figure 1.c). The presence of periclase in the composite will aid in increasing the alkalinity of the solution hence promoting conditions which are suitable for Selenium adsorption.

### **Scanning Electron Microscope (SEM) and Energy Dispersive X-Ray Spectrometer (EDS)**

SEM/EDS Scanning electron microscope (SEM) images of magnesite, bentonite clay, and the composite. The elemental composition as done by the EDS is corroborating results done by XRF (Table 1).

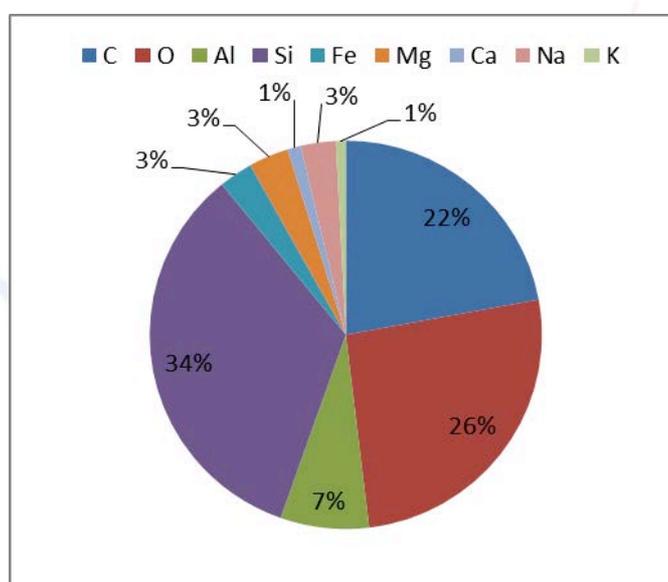
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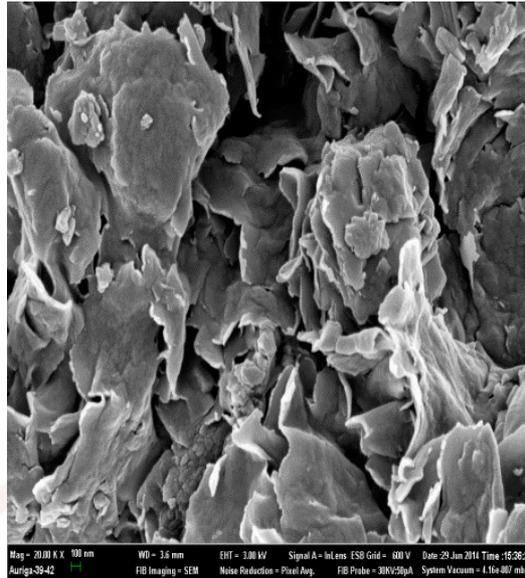




**Figure 2:** Elemental analysis and SEM image of magnesite

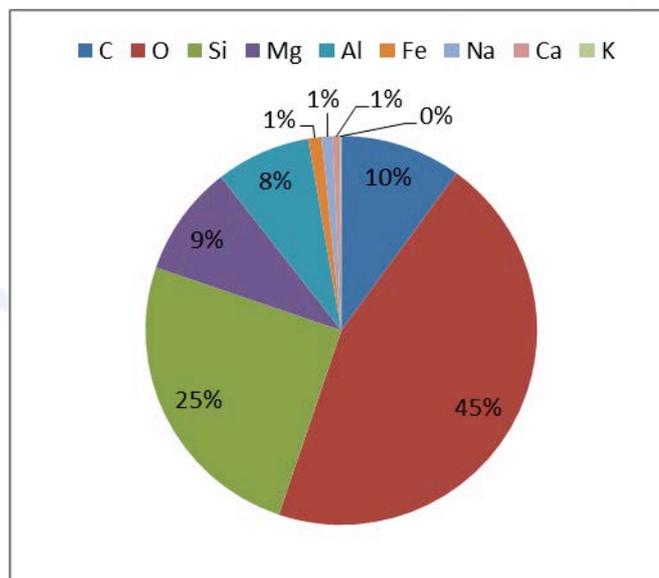
As shown in figure 2, EDS results showed the presence of Mg, C, O, Si and Ca. The morphology by SEM showed the presence of spherical structures. From Masindi et al. (2014), it was reported that magnesite contains a fraction of crystalline phases and a portion of amorphous phase. EDS is showing the presence of Mg, C, O, Si and Ca hence confirming that the material is magnesite. Mg and Ca will also aid in adsorption of Selenium from aqueous medium.

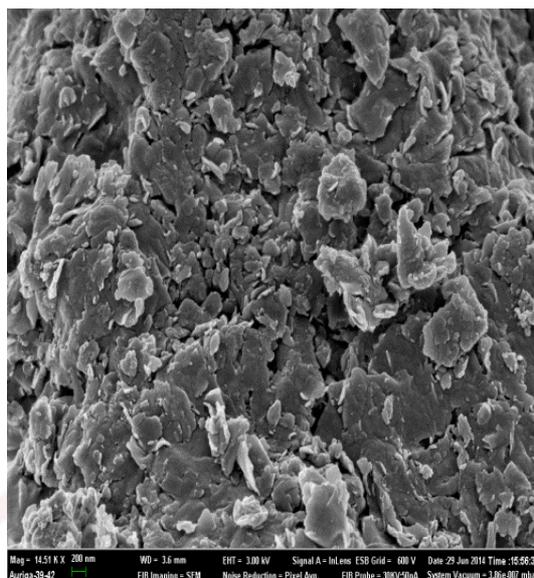




**Figure 3:** Elemental and SEM image of bentonite clay

As shown in figure 3, EDS results showed the presence of Al, Si and O as the main constituents hence the name Aluminosilicate. The presence of Mg, Ca, Na and K shows that these are the exchangeable cations on bentonite clay matrices (Spark, 1997). The morphology by SEM showed the presence of leafy structure. Impurities of Fe are also present. This might have been adsorbed during deposition and weathering processes. Base cations and Al, Si and Fe will aid in adsorption of Selenium from aqueous solution





**Figure 4:** Elemental and SEM image of unreacted composite

As shown in figure 4, EDS results showed the presence of Al, Si, Mg and O as the main constituents. This shows that the material under study is a mixture of magnesite and bentonite clay. After modification, the levels of exchangeable cations (particularly Mg) increased significantly hence indicating higher neutralization potential on the synthesized material. This will play a significant role in creating conditions that are conducive for adsorption of Selenium.

### Brunnet-Emmet-Teller (BET) analysis

Surface area of magnesite, bentonite clay and the composite is presented in Table 2.

**Table 2:** BET surface, micropore area, external surface area, micropore volume and total pore diameter of magnesite, bentonite clay and the composite

% Composition	Bentonite clay	Magnesite	Composite before
<b>SiO<sub>2</sub></b>	66.51	4.76	51.72
<b>Al<sub>2</sub>O<sub>3</sub></b>	16.81	0.14	10.37
<b>Fe<sub>2</sub>O<sub>3</sub></b>	3.26	0.25	4.44
<b>MnO</b>	0.13	0	0.1
<b>MgO</b>	3.12	91.80	29.43
<b>CaO</b>	1.43	5.59	2.29
<b>Na<sub>2</sub>O</b>	1.17	0	0.79
<b>K<sub>2</sub>O</b>	0.54	0.003	0.32

Surface area is one of the most important aspects of adsorption. If the surface area is high, the adsorption capacity will also be high (Spark, 1997; Masindi, 2013). Mixing of magnesite with bentonite clay increase the adsorption surfaces (Table 2) on the fabricated material and this has presented more adsorption sites for Selenium adsorption from Selenium rich effluents.

### Cation exchange capacity (CEC)

Table 3 below shows the cation exchange capacity of raw bentonite and the composite

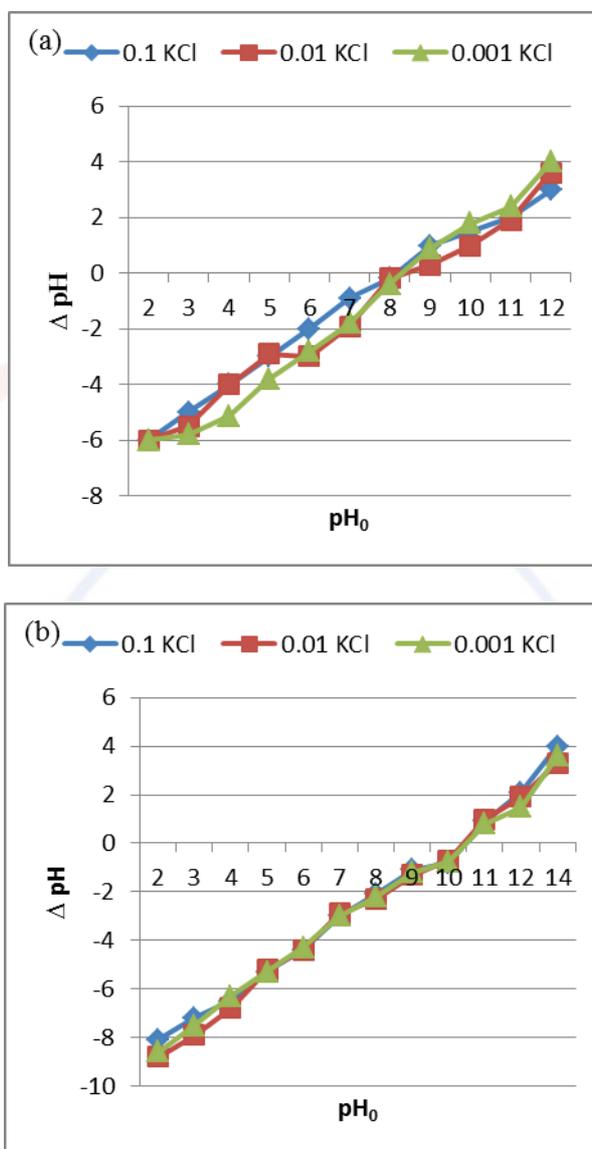
**Table 3:** Concentration of main exchangeable cations ( $\text{mg L}^{-1}$ ) and calculated cation exchange capacities at pH 5.4 and 7.4 for bentonite clay and the composite

% Composition	Bentonite clay	Magnesite	Composite before
<b>SiO<sub>2</sub></b>	66.51	4.76	51.72
<b>Al<sub>2</sub>O<sub>3</sub></b>	16.81	0.14	10.37
<b>Fe<sub>2</sub>O<sub>3</sub></b>	3.26	0.25	4.44
<b>MnO</b>	0.13	0	0.1
<b>MgO</b>	3.12	91.80	29.43
<b>CaO</b>	1.43	5.59	2.29
<b>Na<sub>2</sub>O</b>	1.17	0	0.79
<b>K<sub>2</sub>O</b>	0.54	0.003	0.32

Analysis of CEC by ammonium acetate method revealed that the main exchangeable cations in the supernatant include  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Na}^{+}$  and  $\text{K}^{+}$ . From the supernatant, it was also observed that  $\text{Na}^{+}$  is the dominant cation for raw bentonite clay hence confirming that the clay under study is Na-bentonite. After blending bentonite clay with magnesite the dominant cation was observed to be  $\text{Mg}^{+}$  hence showing that addition of magnesite increase the levels of  $\text{Mg}^{2+}$  on the composite matrices. Blending of bentonite clay with magnesite increase the CEC of the synthesized composite this may be attributed to addition of magnesium. Mixing bentonite clay with magnesite led to an increase in CEC from 262 to 437.1 meq  $100\text{g}^{-1}$  at pH 5.4 and 265.5 to 442.9 meq  $100\text{g}^{-1}$  at pH 7.4. This is a very important aspect of Selenium removal since those exchangeable cations will aid in adsorption of Selenium from Selenium rich effluents (Alloways, 1995; Langmuir, 1997; Spark, 1997).

### Point of zero charge (PZC)

Figure 5 (a) and (b) below shows the  $pH_{pzc}$  of bentonite clay and the composite



**Figure 5:** Initial pH ( $pH_0$ ) and  $\Delta pH$  of supernatant in  $pH_{pzc}$  determination for the bentonite clay and the composite

Figure 5 (a) and (b) shows the initial and change in pH ( $\Delta pH = pH_0 - pH_f$ ) profiles for  $pH_{pzc}$  determination. This helps to determine type of chemical species that will be removed from aqueous solution. When  $pH_{pzc}$  is greater than the supernatant pH the adsorbent will adsorb cations and when the pH of the supernatant is above the  $pH_{pzc}$  the adsorbent will adsorb anions from the solution. The study conducted by Spark (1997) which pointed out that aluminium and iron oxides have high PZC values (usually at pH 8). The high PZC in bentonite clay is an attribute of the presence of aluminium and iron oxide or hydroxides in the clay matrix (Masindi, 2013). The  $pH_{pzc}$  value of a material is a reflection of the individual  $pH_{pzc}$  values of the components present. Clay and oxide contents increase the  $pH_{pzc}$  of the material (Gitari et al., 2014). Mixing bentonite clay with magnesite increases  $Mg^{2+}$  hence leading to an

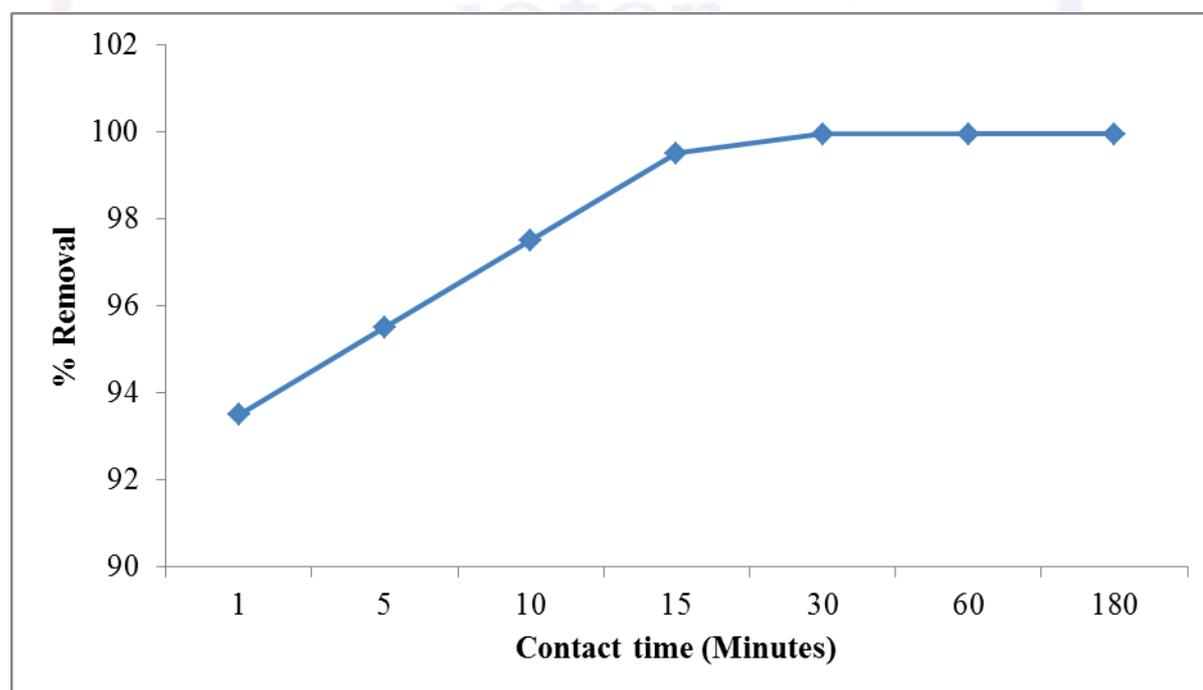
increase in  $\text{pH}_{\text{pzc}}$  for the composite. High PZC of the composite will enhance the efficiency of the material to scavenge anions of Selenium from aqueous media.

### Optimization experiments

Several operational parameters were evaluated to configure optimum condition for removal of selenium from the aqueous solution. Effects of agitation time, dosage, concentration and pH were investigated.

### Effect of equilibration time on removal of selenium

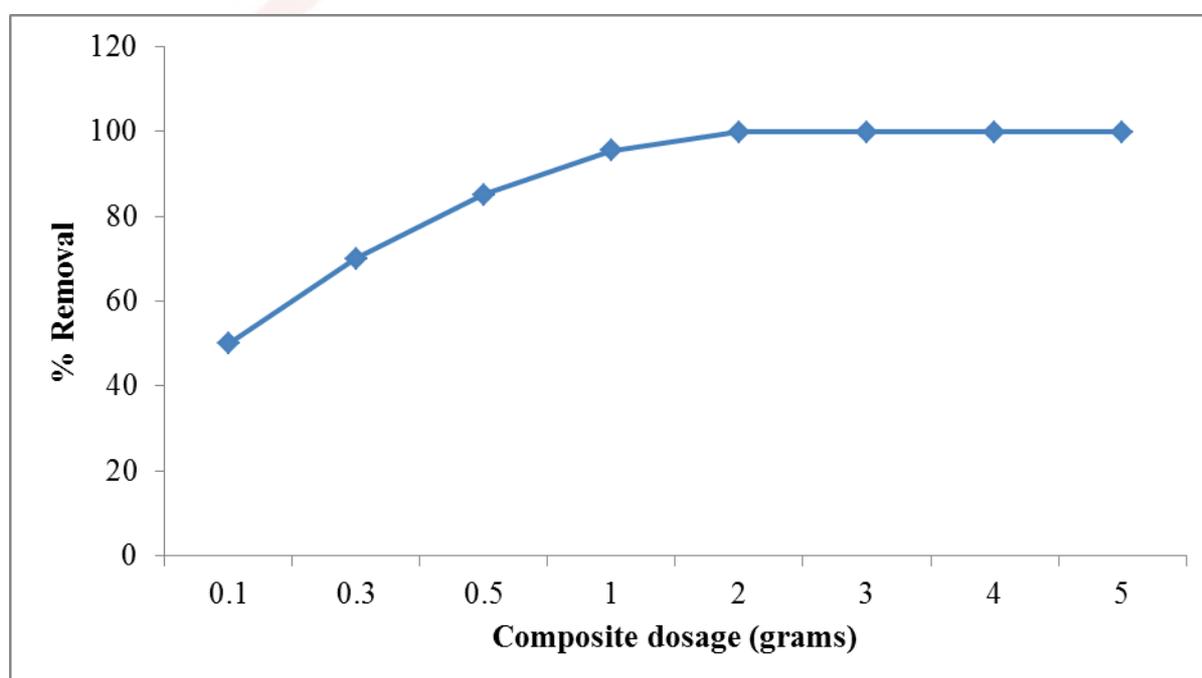
Figure 3 shows the effect of contact time on selenium adsorption onto the composite. The percentage removal of selenium was observed to increase with an increase in contact time in the first 20 minutes. At 30 minutes, no further change in adsorption was observed hence indication that the reaction has reached equilibrium, by then, almost 100% of selenium was removed from the solution. The adsorption affinity of the composite to selenium proved to be very high. This also provides evidence that the composite provided enough surfaces for sorption of selenium from aqueous solution. High percentage removal of selenium may also be attributed the presents of base cations of  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Na}^+$  and  $\text{K}^+$  on the composite matrices. Those elements play an exceptional role in the adsorption of anions. Henceforth, it was concluded that 30 minutes of equilibration will be the optimum time for removal of selenium from aqueous solution.



**Figure 3:** Removal of selenium with an increase in agitation time (1 gram of the composite,  $20 \text{ mg L}^{-1}$  of selenium, 250 rpm, 1:100 S/L ratios and at ambient temperature). Time was varied from 1 – 360 minutes.

### Effect of adsorbent dosage on removal of selenium

The effect of the amount of fabricated composite on selenium removal is presented as percentage removal (Figure 4). The percentage removal of selenium was observed to increase with an increase in the composite dosage (Figure 4). From 0.1 g to 1 g, thereafter, the adsorption efficiency approached a steady state at 2 grams. An increase in adsorption capacity of selenium with an increase in dosage was attributed to more adsorption site becoming available as dosage increase. 2 grams of composite dosage has provided enough surfaces for adsorption of selenium from aqueous solution. This was shown by stabilization in percentage removal hence showing that the composite scavenged all the chemical species that were in aqueous solution. As such, the composite showed optimum removal efficiency at 30 minutes of equilibration and 2 grams of composite dosage hence denoting that those conditions should be used in the subsequent experiments

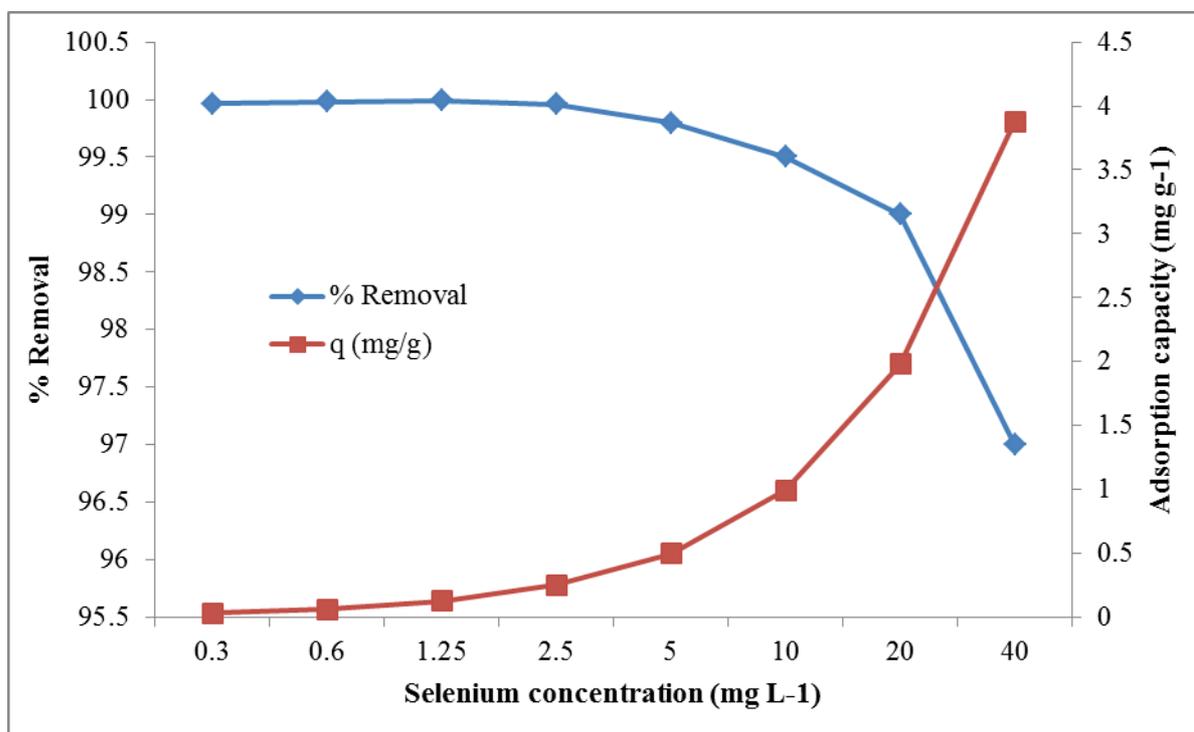


**Figure 4:** Variation of selenium removal with an increase in composite dosage (30 minutes of equilibration, 20 mg L<sup>-1</sup> selenium, 250 rpm and at ambient temperature). Composite dosages were varied from 0.1 – 5 grams.

### Effect of adsorbate concentration on removal of selenium

The effect of adsorbate concentration of selenium on percentage removal of selenium is presented as percentage removal and mg of selenium adsorbed per gram of the composite (figure 5). As depicted by Figure 5, when the concentration of selenium increases the sorption capacity of the composite was gradually decreasing. A decrease in adsorption percentage may be attributed to adsorption surfaces becoming finite as adsorbate concentration increases. More selenium species are introduced to aqueous solution and the adsorption surfaces are becoming depleted. This also shows that the composite is becoming saturated with selenium species on its surfaces. At low concentration, more surfaces are available for adsorption of selenium and at elevated concentration more surfaces are occupied with selenium. Post 20 mg L<sup>-1</sup> the

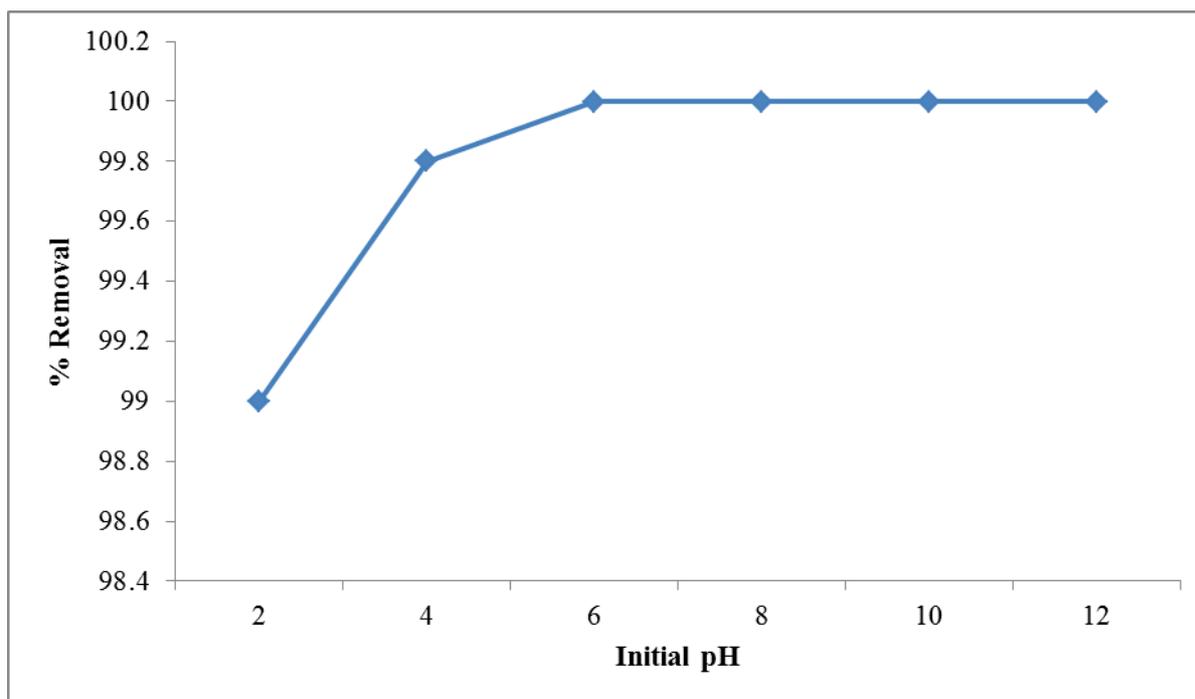
percentage removal of the composite was gradually going down. As such, it was concluded that 20 mg L<sup>-1</sup> will be the optimum concentration of selenium that can be removed by 2 grams of the composite.



**Figure 5:** Variation on percentage removal and adsorption capacities of selenium concentration with an increase in adsorbate concentration (30 minutes of equilibration, 1 gram of the composite, 250 rpm, 1:100 S/L ratios and at ambient temperature). Selenium concentrations were varied from 0.3 – 40 mg L<sup>-1</sup>.

### Effect of solution pH on removal of selenium

The amount of selenium adsorbed depends on the distribution of selenium species which are mainly controlled by the pH of the solution. During the interaction of selenium rich water and the composite, the feedstock material release base cations of Mg<sup>2+</sup>, Ca<sup>2+</sup>, Na<sup>+</sup> and K<sup>+</sup>. Those species raise the pH of the solution. High pH ranges promote the mobility of selenium species. Nevertheless, the point of zero charge (pH<sub>pzc</sub>) of the composite plays a notable part in adsorption of selenium species from aqueous solution. The pH<sub>pzc</sub> of the composite has been established to be 11. The value above pH<sub>pzc</sub>, the adsorber surfaces are negatively charged and they are conducive for cation adsorption. The value below pH<sub>pzc</sub>, the adsorber surfaces are negatively charged and they are conducive for anion adsorption. Selenium exists as anionic species at alkaline pH conditions. From Figure 6, it is shown that, there is a sharp increase of adsorption from pH 2 to pH 6 after that the adsorption is becomes steady. As pH increase, the composite adsorb more selenium onto its matrices since its rich in basic cations of earth alkali metals (Mg<sup>2+</sup>, Ca<sup>2+</sup>, Na<sup>+</sup> and K<sup>+</sup>). When the composite is introduced to aqueous solution, it rapidly increases the pH of the solution hence creating conditions which are conducive for adsorption of selenium. Moreover, it was concluded that from pH 6 -12 the composite will be capable to scavenge selenium from aqueous solution.



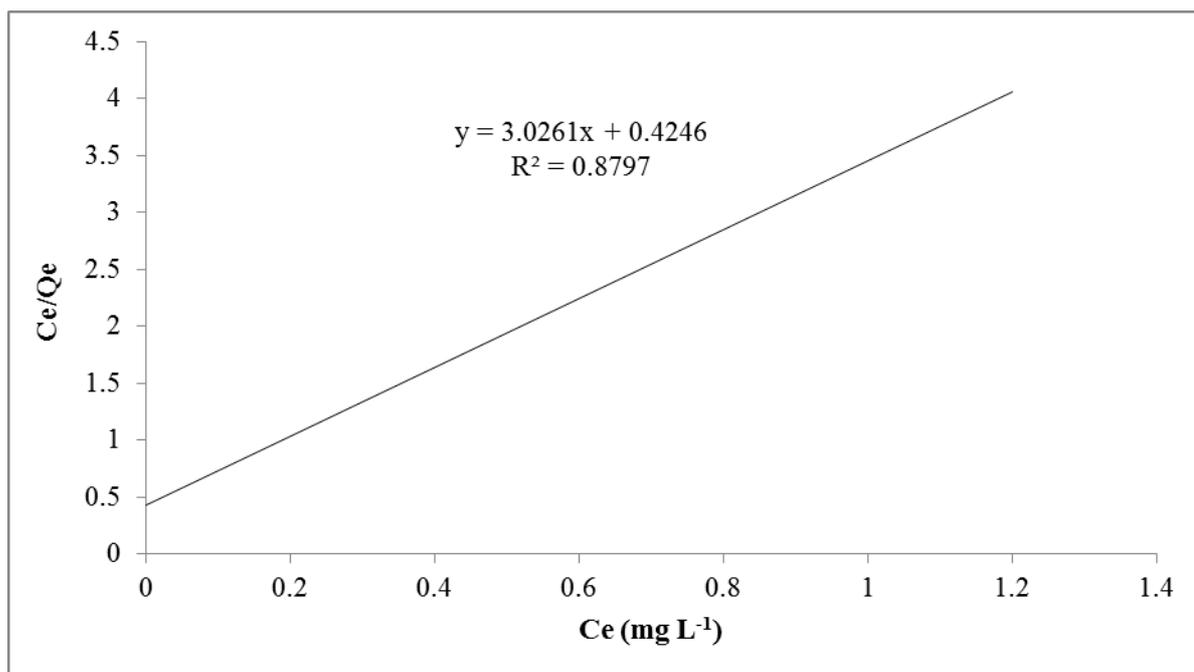
**Figure 6:** Variation in percentage removal of selenium with varying pH ranges (30 minutes of equilibration, 1 gram of the composite, 20 mg L<sup>-1</sup> of selenium, 250 rpm, 1:100 S/L ratios and at ambient temperature). pH was varied from 2 - 12.

### 3.3 Removal of selenium under optimized conditions

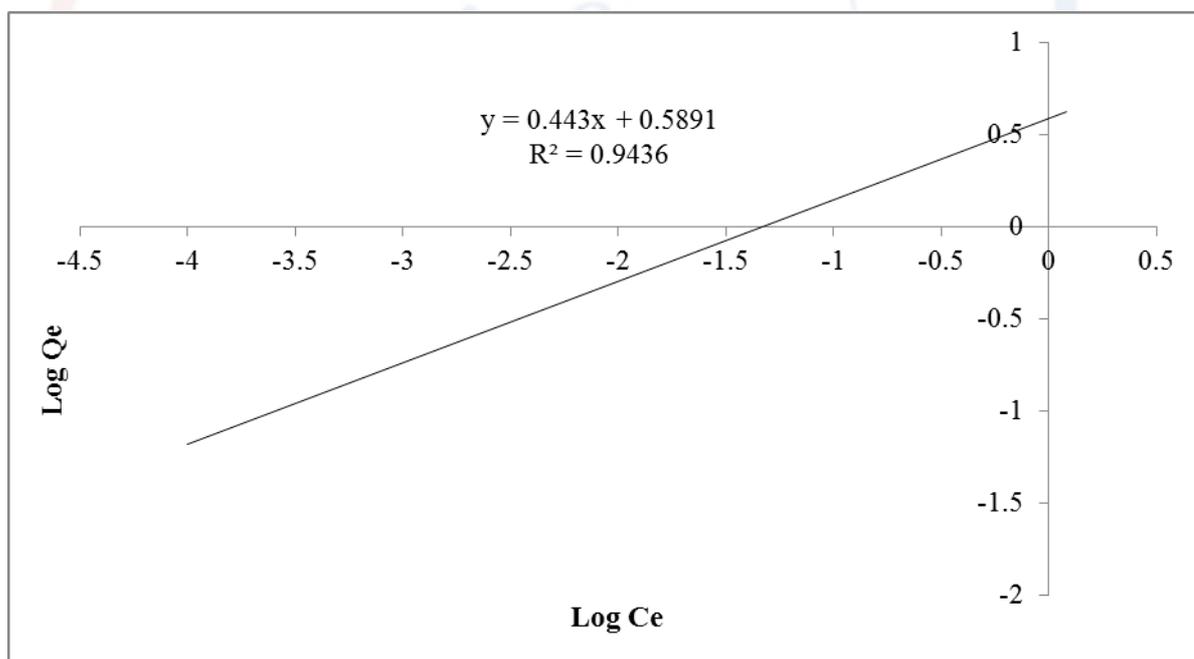
The removal of selenium was observed to be high and effective. The composite removed selenium to below World Health Organization (WHO) recommended water quality guidelines. Before the treatment process, the concentration of selenium was 20 mg L<sup>-1</sup> and after treatment it was 0.001 mg L<sup>-1</sup>. The composite removed selenium from contaminated water to below WHO guidelines of 0.01 mg L<sup>-1</sup>.

#### Adsorption isotherm

The results from isotherm modelling suggest that Freundlich model fits the data better as compared to Langmuir adsorption isotherm. This was indicated by the correlation coefficient of 0.8797 for Langmuir and correlation coefficient is 0.9436 for Freundlich. This result demonstrates adsorption on the composite surfaces is heterogeneous.



**Figure 7:** Langmuir isotherm model (30 minutes of equilibration, 2 grams of the composite, 250 rpm and at ambient temperature). Selenium concentrations were varied from 0.3 – 40 mg L<sup>-1</sup>.

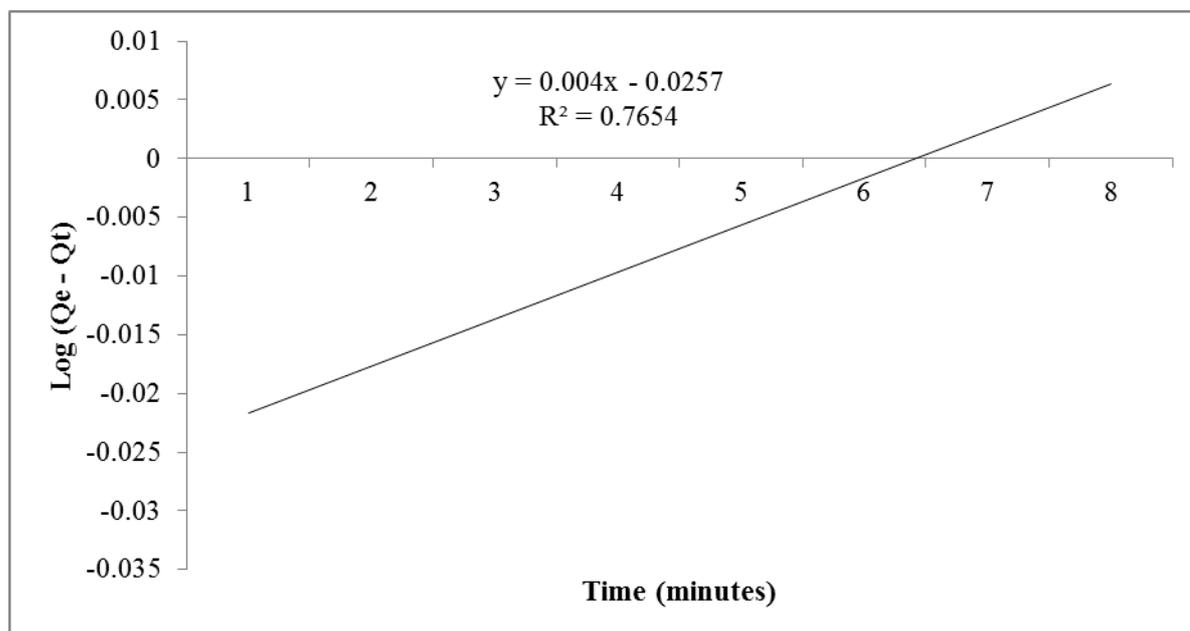


**Figure 8:** Freundlich isotherm model (30 minutes of equilibration, 2 grams of the composite, 250 rpm and at ambient temperature). Selenium concentrations were varied from 0.3 – 40 mg L<sup>-1</sup>.

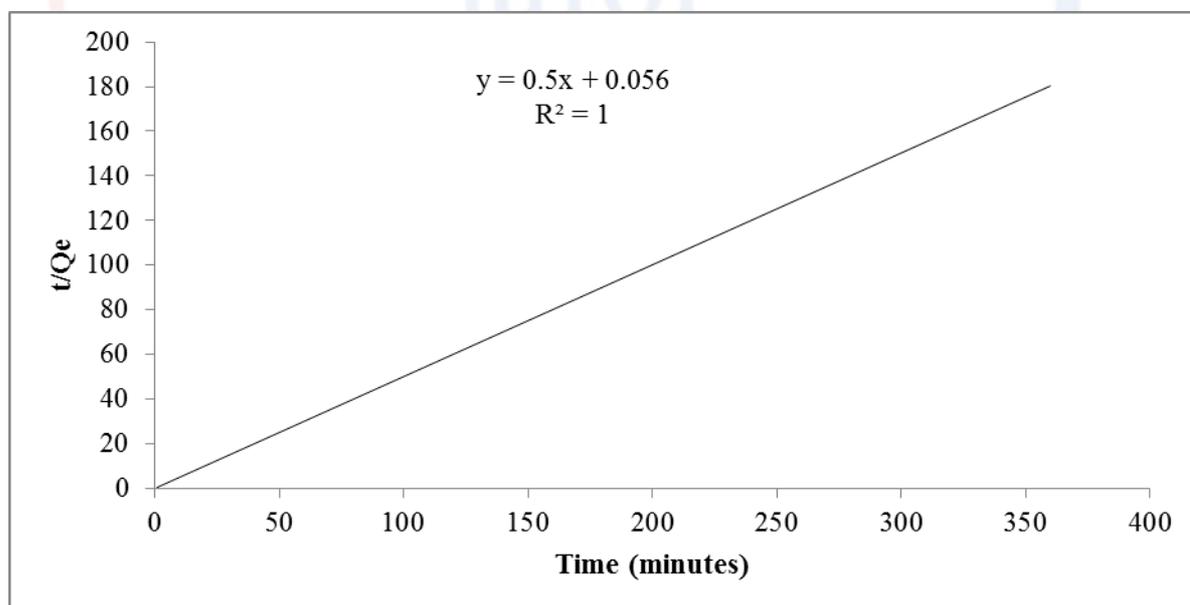
### Adsorption kinetics

The high correlation obtained by plotting the linearized form of pseudo-second-order model ( $R^2 = 1$ ) compared to that for the pseudo-first-order model ( $R^2 = 0.7013$ )

demonstrated that the former gives a better fit, implying that the adsorption occurs via a chemisorption process.



**Figure 9:** Pseudo-first order kinetic model (1 gram of the composite, 10 mg L<sup>-1</sup> of selenium, 250 rpm and at ambient temperature). Time was varied from 1 – 360 minutes.



**Figure 10:** pseudo-second-order model (1 gram of the composite, 10 mg L<sup>-1</sup> of selenium, 250 rpm and at ambient temperature). Time was varied from 1 – 360 minutes.

### Conclusion

This investigation shows that the composite can be used to remove selenium from aqueous medium. Optimization experiments revealed that 30 minutes of equilibration,

2 grams of dosage is enough for removing close to  $20 \text{ mg L}^{-1}$  of selenium from polluted water. Kinetic data agreed with pseudo-second-order model than pseudo-first-order. Adsorption isotherm fitted Freundlich adsorption isotherm than Langmuir adsorption isotherm hence confirming that adsorption is of heterogeneous nature.

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## Reference

- AHSAN, U., KAMRAN, Z., RAZA, I., AHMAD, S., BABAR, W., RIAZ, M. H. & IQBAL, Z. 2014. Role of selenium in male reproduction—A review. *Animal Reproduction Science*, 146, 55-62.
- ALMONDES, K. G. D. S., OLIVEIRA, T. F. D., SIVIERO-MIACHON, A. A., LEE, M. L. D. M., RONDÓ, P. H. D. C., LOUREIRO, A. P. D. M., SPINOLA-CASTRO, Â. M. & COZZOLINO, S. M. F. 2014. Selenium inadequacy is not associated with oxidative stress in child and adolescent acute lymphocytic leukemia survivors. *Nutrition*, 30, 563-568.
- ANDRIANISA, H. A., ITO, A., SASAKI, A., AIZAWA, J. & UMITA, T. 2008. Biotransformation of selenium species by activated sludge and removal of bio-oxidised arsenate from wastewater by coagulation with ferric chloride. *Water Research*, 42, 4809-4817.
- ASHOURNIA, M. & ALIAKBAR, A. 2009. Determination of selenium in natural waters by adsorptive differential pulse cathodic stripping voltammetry. *Journal of Hazardous Materials*, 168, 542-547.
- AWUAL, M. R., EL-SAFETY, S. A. & JYO, A. 2011. Removal of trace selenium(V) and phosphate from water by a highly selective ligand exchange adsorbent. *Journal of Environmental Sciences*, 23, 1947-1954.
- BANSAL, M., SINGH, D. & GARG, V. K. 2009. A comparative study for the removal of hexavalent chromium from aqueous solution by agriculture wastes' carbons. *Journal of Hazardous Materials*, 171, 83-92.
- BICK, A. & ORON, G. 2013. Boron removal from seawater reverse osmosis permeate: A Hasse diagram analysis of current technologies. *Desalination*, 310, 34-38.
- BULUT, G., YENIAL, Ü., EMIROĞLU, E. & SIRKECI, A. A. Selenium removal from aqueous solution using pyrite. *Journal of Cleaner Production*.
- ÇELIK, Z. C., CAN, B. Z. & KOCAKERIM, M. M. 2008. Boron removal from aqueous solutions by activated carbon impregnated with salicylic acid. *Journal of Hazardous Materials*, 152, 415-422.
- CHAMMUI, Y., SOOKSAMITI, P., NAKSATA, W., THIANSEM, S. & ARQUEROPANYO, O.-A. 2014. Removal of selenium from aqueous solution by adsorption on Leonardite. *Chemical Engineering Journal*, 240, 202-210.
- CHANG, Q., LIN, W. & YING, W.-C. 2010. Preparation of iron-impregnated granular activated carbon for selenium removal from drinking water. *Journal of Hazardous Materials*, 184, 515-522.
- CHOONG, T. S. Y., CHUAH, T. G., ROBIAH, Y., GREGORY KOAY, F. L. & AZNI, I. 2007. Selenium toxicity, health hazards and removal techniques from water: an overview. *Desalination*, 217, 139-166.
- CICEO-LUCACEL, R., RADU, T., PONTA, O. & SIMON, V. 2014. Novel selenium containing boro-phosphate glasses: Preparation and structural study. *Materials Science and Engineering: C*, 39, 61-66.
- CORREA, L., REA, L. D., BENTZEN, R. & O'HARA, T. M. 2014. Assessment of mercury and selenium tissular concentrations and total mercury body burden in 6 Steller sea lion pups from the Aleutian Islands. *Marine Pollution Bulletin*, 82, 175-182.
- CRISCUOLI, A., BAFARO, P. & DRIOLI, E. 2013. Vacuum membrane distillation for purifying waters containing selenium. *Desalination*, 323, 17-21.

- DAS, S., JIM HENDRY, M. & ESSILFIE-DUGHAN, J. 2013. Adsorption of selenate onto ferrihydrite, goethite, and lepidocrocite under neutral pH conditions. *Applied Geochemistry*, 28, 185-193.
- DÖNMEZ, G. & AKSU, Z. 2002. Removal of chromium(VI) from saline wastewaters by *Dunaliella* species. *Process Biochemistry*, 38, 751-762.
- DUBEY, S. P. & GOPAL, K. 2007. Adsorption of chromium(VI) on low cost adsorbents derived from agricultural waste material: A comparative study. *Journal of Hazardous Materials*, 145, 465-470.
- EL-SHAHAWI, M. S. & EL-SONBATI, M. A. 2005. Retention profile, kinetics and sequential determination of selenium(IV) and (VI) employing 4,4'-dichlorodithizone immobilized-polyurethane foams. *Talanta*, 67, 806-815.
- ELANGO VAN, R., PHILIP, L. & CHANDRARAJ, K. 2008. Biosorption of chromium species by aquatic weeds: Kinetics and mechanism studies. *Journal of Hazardous Materials*, 152, 100-112.
- FABBRICINO, M., NAVIGLIO, B., TORTORA, G. & D'ANTONIO, L. 2013. An environmental friendly cycle for Cr(III) removal and recovery from tannery wastewater. *Journal of Environmental Management*, 117, 1-6.
- FAHIM, N. F., BARSOUM, B. N., EID, A. E. & KHALIL, M. S. 2006. Removal of chromium(III) from tannery wastewater using activated carbon from sugar industrial waste. *Journal of Hazardous Materials*, 136, 303-309.
- GEILLINGER, K. E., RATHMANN, D., KÖHRLE, J., FIAMONCINI, J., DANIEL, H. & KIPP, A. P. Hepatic metabolite profiles in mice with a suboptimal selenium status. *The Journal of Nutritional Biochemistry*.
- GÜLER, E., KABAY, N., YÜKSEL, M., YIĞIT, N. Ö., KITIŞ, M. & BRYJAK, M. 2011. Integrated solution for boron removal from seawater using RO process and sorption-membrane filtration hybrid method. *Journal of Membrane Science*, 375, 249-257.
- HAN, D. S., BATCHELOR, B. & ABDEL-WAHAB, A. 2011. Sorption of selenium(IV) and selenium(VI) to mackinawite (FeS): Effect of contact time, extent of removal, sorption envelopes. *Journal of Hazardous Materials*, 186, 451-457.
- HODLUR, R. M. & RABINAL, M. K. 2014. A new selenium precursor for the aqueous synthesis of luminescent CdSe quantum dots. *Chemical Engineering Journal*, 244, 82-88.
- INUKAI, Y., TANAKA, Y., MATSUDA, T., MIHARA, N., YAMADA, K., NAMBU, N., ITOH, O., DOI, T., KAIDA, Y. & YASUDA, S. 2004. Removal of boron(III) by N-methylglucamine-type cellulose derivatives with higher adsorption rate. *Analytica Chimica Acta*, 511, 261-265.
- JAIN, C. K. & SINGH, R. D. 2012. Technological options for the removal of selenium with special reference to South East Asia. *Journal of Environmental Management*, 107, 1-18.
- KABAY, N., SARP, S., YUKSEL, M., ARAR, Ö. & BRYJAK, M. 2007. Removal of boron from seawater by selective ion exchange resins. *Reactive and Functional Polymers*, 67, 1643-1650.
- KALIDHASAN, S., SANTHANA KRISHNA KUMAR, A., VIDYA, R. & RAJESH, N. 2012. An efficient ultrasound assisted approach for the impregnation of room temperature ionic liquid onto Dowex 1 resin matrix and its application toward the enhanced adsorption of chromium (VI). *Journal of Hazardous Materials*, 213–214, 249-257.

- KHOSA, M. A. & ULLAH, A. 2014. In-situ modification, regeneration, and application of keratin biopolymer for selenium removal. *Journal of Hazardous Materials*, 278, 360-371.
- KLAS, S. & KIRK, D. W. 2013. Understanding the positive effects of low pH and limited aeration on selenate removal from water by elemental iron. *Separation and Purification Technology*, 116, 222-229.
- KYLE, J. H., BREUER, P. L., BUNNEY, K. G. & PLEYSIER, R. 2012. Review of trace toxic elements (Pb, Cd, Hg, As, Sb, Bi, Se, Te) and their deportment in gold processing: Part II: Deportment in gold ore processing by cyanidation. *Hydrometallurgy*, 111-112, 10-21.
- LACASA, E., CAÑIZARES, P., SÁEZ, C., FERNÁNDEZ, F. J. & RODRIGO, M. A. 2011. Removal of selenium by iron and aluminium electrochemically assisted coagulation. *Separation and Purification Technology*, 79, 15-19.
- LESCANO, M., ZALAZAR, C., CASSANO, A. & BRANDI, R. 2012. Kinetic modeling of selenium (III) oxidation in water employing the UV/H<sub>2</sub>O<sub>2</sub> process. *Chemical Engineering Journal*, 211-212, 360-368.
- LIU, H., QING, B., YE, X., LI, Q., LEE, K. & WU, Z. 2009. Boron adsorption by composite magnetic particles. *Chemical Engineering Journal*, 151, 235-240.
- LIZAMA ALLENDE, K., FLETCHER, T. D. & SUN, G. 2012. The effect of substrate media on the removal of selenium, boron and iron from an acidic wastewater in planted column reactors. *Chemical Engineering Journal*, 179, 119-130.
- LIZAMA ALLENDE, K., MCCARTHY, D. T. & FLETCHER, T. D. 2014. The influence of media type on removal of selenium, iron and boron from acidic wastewater in horizontal flow wetland microcosms planted with *Phragmites australis*. *Chemical Engineering Journal*, 246, 217-228.
- MANDAL, S., MAHAPATRA, S. S., SAHU, M. K. & PATEL, R. K. Artificial neural network modelling of As(III) removal from water by novel hybrid material. *Process Safety and Environmental Protection*.
- MERCADO-BORRAYO, B. M., SCHOUWENAARS, R., LITTER, M. I., MONTOYA-BAUTISTA, C. V. & RAMÍREZ-ZAMORA, R. M. 2014. 5 - Metallurgical Slag as an Efficient and Economical Adsorbent of Selenium. In: AHUJA, S. (ed.) *Water Reclamation and Sustainability*. Boston: Elsevier.
- OISHI, K. & MAEHATA, Y. 2013. Removal properties of dissolved boron by glucomannan gel. *Chemosphere*, 91, 302-306.
- OLGUN, A. & ATAR, N. 2011. Removal of copper and cobalt from aqueous solution onto waste containing boron impurity. *Chemical Engineering Journal*, 167, 140-147.
- PAL, P., CHAKRABORTTY, S. & LINNANEN, L. 2014. A nanofiltration-coagulation integrated system for separation and stabilization of selenium from groundwater. *Science of The Total Environment*, 476-477, 601-610.
- QIU, X., SASAKI, K., HIRAJIMA, T., IDETA, K. & MIYAWAKI, J. 2014. One-step synthesis of layered double hydroxide-intercalated gluconate for removal of borate. *Separation and Purification Technology*, 123, 114-123.
- RANDHAWA, N. S., DAS, N. N. & JANA, R. K. 2012. Selenite adsorption using leached residues generated by reduction roasting-ammonia leaching of manganese nodules. *Journal of Hazardous Materials*, 241-242, 486-492.
- SASAKI, K., QIU, X., MIYAWAKI, J., IDETA, K., TAKAMORI, H., MORIYAMA, S. & HIRAJIMA, T. 2014. Contribution of boron-specific resins containing N-methylglucamine groups to immobilization of borate/boric

- acid in a permeable reactive barrier comprising agglomerated MgO. *Desalination*, 337, 109-116.
- SASAKI, T., IIZUKA, A., WATANABE, M., HONGO, T. & YAMASAKI, A. Preparation and performance of arsenate (V) adsorbents derived from concrete wastes. *Waste Management*.
- SHEHA, R. R. & EL-SHAZLY, E. A. 2010. Kinetics and equilibrium modeling of Se(IV) removal from aqueous solutions using metal oxides. *Chemical Engineering Journal*, 160, 63-71.
- SINGHA, S., SARKAR, U., MONDAL, S. & SAHA, S. 2012. Transient behavior of a packed column of Eichhornia crassipes stem for the removal of hexavalent chromium. *Desalination*, 297, 48-58.
- STREAT, M., HELLGARDT, K. & NEWTON, N. L. R. 2008. Hydrous ferric oxide as an adsorbent in water treatment: Part 2. Adsorption studies. *Process Safety and Environmental Protection*, 86, 11-20.
- SU, T. & WANG, J. 2011. Modeling batch leaching behavior of selenium and selenium from bituminous coal fly ashes. *Chemosphere*, 85, 1368-1374.
- TABELIN, C. B., IGARASHI, T., ARIMA, T., SATO, D., TATSUHARA, T. & TAMOTO, S. 2014. Characterization and evaluation of selenium and boron adsorption onto natural geologic materials, and their application in the disposal of excavated altered rock. *Geoderma*, 213, 163-172.
- THEISS, F. L., AYOKO, G. A. & FROST, R. L. 2013. Removal of boron species by layered double hydroxides: A review. *Journal of Colloid and Interface Science*, 402, 114-121.
- TRESINTSI, S., SIMEONIDIS, K., VOURLIAS, G., STAVROPOULOS, G. & MITRAKAS, M. 2012. Kilogram-scale synthesis of iron oxy-hydroxides with improved selenium removal capacity: Study of Fe(II) oxidation-precipitation parameters. *Water Research*, 46, 5255-5267.
- WANG, J., XU, W., CHEN, L., HUANG, X. & LIU, J. 2014. Preparation and evaluation of magnetic nanoparticles impregnated chitosan beads for selenium removal from water. *Chemical Engineering Journal*, 251, 25-34.
- WU, L. 2004. Review of 15 years of research on ecotoxicology and remediation of land contaminated by agricultural drainage sediment rich in selenium. *Ecotoxicology and Environmental Safety*, 57, 257-269.
- YAMAMURA, S. & AMACHI, S. 2014. Microbiology of inorganic selenium: From metabolism to bioremediation. *Journal of Bioscience and Bioengineering*, 118, 1-9.
- YAMANI, J. S., LOUNSBURY, A. W. & ZIMMERMAN, J. B. 2014. Adsorption of selenite and selenate by nanocrystalline aluminum oxide, neat and impregnated in chitosan beads. *Water Research*, 50, 373-381.
- YANG, L., WEI, J., ZHANG, Y., WANG, J. & WANG, D. 2014. Reuse of acid coagulant-recovered drinking waterworks sludge residual to remove phosphorus from wastewater. *Applied Surface Science*, 305, 337-346.
- YU, T., YANG, Z., LV, Y., HOU, Q., XIA, X., FENG, H., ZHANG, M., JIN, L. & KAN, Z. 2014. The origin and geochemical cycle of soil selenium in a Se-rich area of China. *Journal of Geochemical Exploration*, 139, 97-108.
- ZERZE, H., OZBELGE, H. O., BICAK, N., AYDOGAN, N. & YILMAZ, L. 2013. Novel boron specific copolymers with quaternary amine segments for efficient boron removal via PEUF. *Desalination*, 310, 169-179.
- ZHANG, M., TANG, S., HUANG, X., ZHANG, F., PANG, Y., HUANG, Q. & YI, Q. Selenium uptake, dynamic changes in selenium content and its influence on

photosynthesis and chlorophyll fluorescence in rice (*Oryza sativa* L.).  
*Environmental and Experimental Botany*.

ZHANG, Y. & FRANKENBERGER, W. T. 2003. Factors affecting removal of  
selenate in agricultural drainage water utilizing rice straw. *Science of The  
Total Environment*, 305, 207-216.







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