A Framework for the Governance of Socio-Technical Transitions in Urban Energy Infrastructures

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Abstract
In this paper, a conceptual framework is proposed to analyze the dynamics of techno-institutional lock-in preventing urban energy infrastructures to change and the way a governance approach can affect these dynamics and direct urban energy transitions. In this respect, the framework hypothesizes that the relative power of different rationalities in urban energy infrastructure as a complex socio-technical system shapes its system inertia against transition effort. It is composed of the feedback dynamics between social, technological, economic and political dimensions of existing institutions, as well as the way a systemic governance approach can affect these dynamics of system inertia and shape transition pathways. Based on the current practices in urban energy transition projects, affecting part of this power structure is not sufficient for a successful transition, and may even have counterintuitive effects in long term. Based on the insights from this conceptualization, methodological guidelines are presented for modeling these power rationalities in the form of feedback structures causing system level inertia. This framework is the starting point for further research towards modeling techno-institutional lock-in, designing governance scenarios as well as evaluating the impact of these scenarios in energy transition in general, and urban energy transition in particular. Conceptualization of system inertia and the governance of energy transitions in urban energy infrastructures has practical applications to evaluate current low-carbon and energy transition efforts as well as different energy and climate change policies by urban authorities and other relevant actors aiming to contribute to urban energy transitions.

Keywords: urban energy transition, Socio-technical system perspective, lock-in, techno-institutional complex

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Introduction

Cities and their energy systems are at the center of the most fundamental sustainability issues in the 21st century, as urbanization, climate change and the security of energy supply (Keirstead and Shah, 2013). Rapid urbanization has dramatically increased urban population as well as the need to basic goods such as energy. Indeed urban areas are responsible for around two thirds of the world energy consumption contributing to about 80% of global greenhouse gas emissions and climate change (IEA 2009, World Bank 2009; OECD 2009; Allix 2009; Bulkeley et al., 2015). Spatial concentration of activities, especially economic activities and energy services in cities is the main driver of economic growth, increase in urban population and energy consumption (Shah and Keirstead, 2013), which changes the patterns and trend of energy demand in urban areas as well. Considering the growing importance of local solutions for global challenges, such as the emergence of distributed energy systems to deal with climate change and energy transitions, cities are becoming the primary innovation locations, which need local institutions to exploit their local capital, skills, technologies and markets (Mancarella, 2013).
Energy infrastructures cannot be separated from the functionality other urban issues, since they are the backbone of urban infrastructure and are fundamental for urban activities (Chappin, 2011). Energy infrastructures (systems that satisfy needs for energy, Ajah, 2009) include environmental, economic, and social sustainability. These points address the fact that while cities are the source of many energy issues and problems in terms of their contributions to global energy consumption and global CO2 emissions, at the same time they are part of the solution to these issues (Rutherford and Jaglin, 2015). Therefore, changing the energy infrastructure systems is crucial for dealing with issues such as climate change through the massive introduction of renewable energy technologies and by reduction of energy use (Chappin, 2011).

In this respect, the so called ‘energy transition’, broadly defined as a radical, systemic and managed change towards ‘more sustainable’ or ‘more effective’ patterns of provision and use of energy (Rutherford and Coutard, 2015), is one of the major global challenges facing contemporary societies (see AGECC, 2010; Rifkin, 2011; WWF International, 2011). Cities as the main sites of energy consumption, are also a target as well as an instrument for energy transition (Rutherford and Coutard, 2014). Literature has already shown the role of cities in contributing to the transition of energy systems (International Energy Agency,2009; Bose,2010; WorldBank,2010 ;Commission for Environmental Cooperation, 2010; GDF Suez, 2010; Skanska, 2010; Greenpeace, 2005; Covenant of Mayors, n.d.; Harvey,2014; Droege, 2008; Newman et al., 2009; Troy,2012), but a systemic understanding of the relationship between cities and change in energy infrastructures is quite limited in literature. In order to understand the nature of this relationship and the potential for more elaboration, we need to consider three important issues: first, the conceptualization of the relationship between urban systems and energy transition; second, the systemic approach to analyze this relationship; and third, the best method to formulate and analyze specific problems such as system level inertia confronting change.

Governance of Energy System and Transitions at the Urban Level

Apart from the theories of the governance of energy transitions in general, context affects the process of energy transition at different political levels especially at the urban level. Urban energy transitions in developed and developing countries are different, as transitions in developing countries have a greater focus on the provision of basic commercial energy services. Moreover, in the developed world, the efforts are toward visions of low carbon futures (DTI 2007), but whereas in the developing country context, the dominant cause of energy transitions are rising levels of income and urbanization (Keirstead, 2013).
The literature on the governance of climate change and energy transitions, has considered city's role and the role of municipalities as actors within a multilevel, global system (Bulkeley et al., 2015). In the global environment domain, three distinct ways the term are used are analytical, normative and critical (Biermann and Pattberh 2008). In addition, in the climate change literature, the analytical way is the most common to identify and explain the ways in which climate change is governed. In the analytical approach, three related phenomena are central (Biermann and Pattberh 2008):

- Considering new types of agency rather than the national government
- New mechanisms and institutions of global governance to deal with energy issues
- Segmentation of the governance system and the transition from government to governance

Based on some observations, municipal governments take action in the absence of initiatives at the national level and in some cases such as the USA and Australia in spite of it (Bulkeley and Betsill 2003, Gore and Robinson 2009, Warden 2011). Therefore, there are reasons for considering cities as places critical for addressing climate change:

- Institutional reasons: the need to address policy problems at institutional levels as close as to citizens or the subsidiary principle (Bulkeley et al., 2015)
- The potential to implement climate change action: it addresses the role of municipal government intervention both through formal competencies and by enabling action plan. (Bulkeley et al., 2015)
- Effectiveness of responses: the potential of municipal government to tailor responses to local needs and to use local knowledge to support decisions (Corfee-Morlet et al. 2011, Henstra 2012).

A substantial strand of research on urban energy system transitions considers the role of cities in wider energy transitions. For example, there are studies that analyze national multi-level systems and the translation of national policy goals into local politics (e.g. Gupta 2007). Most of the literature in this respect, considers the activities aim to contribute to climate change action (e.g. Bulkeley and Kern, 2006; Kern and Alber, 2008). In this way, cities are the proper unit of analysis because from one hand, climate change is related to local governments in different way and with different logics; for instance, in it argued that an increasing portion of GHG is generated in cities, global change has a direct impact on cities which arises the issue of adaptation in cities and steers cities to be more innovative. In addition, cities can cooperate apart from compete and serve as focal point for the development of best practices used in different contexts or levels.

Looking at cities in this ways leads to the conclusion that actual response of local governments may vary due to different factors such as the impact of global change and the perception of this impact, city's competences and authority, national programs to support local initiatives, the involvement of cities in national and transnational networks, etc. (Kern and Alber, 2008). Therefore, these studies address the solutions developed by the governments to direct the climate change actions, including the climate change policies as the most common form.

Context strongly affects the process of energy transition at the urban level (Keirstead, 2013). For example, urban energy transitions in developed and developing countries are different, as transitions in developing countries have a greater focus on the provision of basic commercial energy services, while in developed world there is more room for considering sustainable energy solutions. In other words, in the developed world the efforts are toward visions of low carbon futures (DTI 2007), but whereas in the developing country context, the dominant cause of energy transitions are rising levels of income and urbanization (Keirstead, 2013). In addition, energy system structures in secondary cities is different from the primary cities in terms of the technologies, fuels, and the impact of the system configurations on the local environment. in developed countries, retrofitting and upgrading existing energy infrastructures and ensuring robust affordable performance are the issues, while in the developing world, expanding access to modern energy services in order to support economic and social development goals are necessary. Apart from these differences, both contexts of developing and developed countries highlight similarities in terms of the effect of technological improvements on the transition, the effect of new business models and financial issues.

Apart from efforts to address climate change at the urban level focused on the mitigation activities, recently the debate on climate change has been shifted to adaptation to the risks of climate change as a complementary paradigm. Adaptation is necessary since the effects of climate change become obvious and the effects are different from region to region (CEC 2007). Again the local and regional levels are optimal levels for adaptation, but adaptation is out of the scope of this research and therefore, we don't go into analyzing different adaptation activities here.

Urban Infrastructure, Complexity and a Systematic Approach to Un-Locking Techno-Institutional Complex

Changes in large technical systems, such as urban energy infrastructures, are the central topic of the scientific literature on transitions (Geels, 2002b) and transition management (Rotmans, 2003; Loorbach, 2007). An important premise for understanding and changing energy infrastructures is that these systems are complex. Indeed, infrastructure systems contain large number of elements that interact in a non-linear way (Simon, 1962). These systems are influenced by all sorts of actions taken and decisions made by multiple actors that are part of these systems. In other words, infrastructures are large, because they contain a whole hierarchy of systems which result in different feedback loops (Simon, 1973). This complexity of infrastructures has complications for both designing as well as intervening into the system by strategic decision makers. In their policy decisions, governments face deep uncertainty (Agusdinata, 2008).

Another facet of complexity in energy systems arises from their socio-technical nature. Indeed, transition in infrastructures is not only about technical aspects and technological transitions are much more than the technology alone (Keirstad, 2013; Chappin, 2011). Social and institutional aspects shape an important and including governance aspects are relevant in order to prevent the mal-functioning of markets and inefficient realization of long term public values (WRR, 2008)
Evans et al. (19999) analyzed the urban energy system for in the city of Newcastle-upon-Tyne for introducing combined heat and water and concluded that although the technology was ready, the necessary social networks couldn't be constructed to support the adoption of technology. In addition, by focusing on the price of new innovation, as the only determinant factor for adopting the technology, other important factors such as the partnership between universities and industry are neglected which limits the establishment of a coalition around the new technology.
In this respect, most of the research on energy and cities tend to divide between the social and the technical. It means that although they try to give importance to both dimensions, but in reality the research projects focuses on one of them (Rutherford and Coutard, 2014).
Each transition is emergent from a socio-technical system's perspective. A socio-technical approach to urban energy infrastructure transition considers both the institutional and technical dimensions of transition and their interactions. Socio-technical systems perspective points out to us that change in social elements and technological elements cannot be fully separated: in order to understand how infrastructure systems change, the relations between technical elements, between social elements and between social and technical elements need to be discussed (Chappin, 2011). Such an approach is necessary for analyzing and understanding the phenomenon because without understanding the social and institutional dimensions of any technological change, a sustainable and successful transition is not possible. For instance, in the case of combined heat and power in Newcastle-upon-Tyne, Evans et al. (1999) mentions that although the technology was ready, the necessary social networks could not be constructed to support the widespread adoption of the technology; or the well-known case of smart grid city in Boulder, Colorado was failed due to the lack of institutional capacity and facing social pressures.

In other words, rather than considering new technology and technical infrastructure, the entire relationship between consumers and produers might need to be redefined and modes of service provision adapted to meet new challenges (Keirstead, 2013). Transition requires a consistent policy framework and active market intervention to ensure the success of the network (Keirstead, 2013). In addition, our infrastructure systems are evolutionary, they show path-dependency and lock-in (Chappin, 2011). It means that options in the future are shaped by current behavior of the system and the return system is gaining by doing its current activities. As a result, the systems we observe today were not designed as such, they evolved to their present state (Nikolic et al., 2009; Herder et al., 2008).

The Theoretical Framework

In this paper, a theoretical framework is presented to analyze the process of urban energy transition to low carbon cities. By developing this framework, we try to answer the question that "How the assemblage of interventions in an urban energy system, leads to a transition to a low-carbon city?"

However, by analyzing this question in more details, three presumptions can be identified:

- An existing energy system
- An assemblage of interventions in the energy system
- Leading the system towards the final state of transition, namely a low carbon city

In fact, another approach is to consider the factors that prevent the system from a successful transition. In other words, a governance approach for a sustainable transition needs to investigate and overcome the barriers of transition in the existing system, as well as to promote the factors that facilitate the transition process.
In other words, these components can be classified as the following parts:

- Analyzing the underlying structure of a social system
- Capturing the operational environment in which the dynamics of interactions take place
- Observing the patterns of interaction and outcomes

In this respect, first we need to understand the dynamics of an urban energy system that shape the existing structure; then, the interventions take place in the operational environment and finally the outcomes of interventions and the resulting patterns of interactions should be identified and analyzed to evaluate the final state of the transition. Based on these parts, two main steps are proposed for understanding the governance of urban energy transitions:

1. System analysis for system-level inertia investigation
2. Governance by intervention in the urban energy system and evaluating outcomes

The main building blocks of this framework are depicted in Figure 1, briefly discussed in the following sections.

Step 1 - System Analysis for System-Level Inertia Investigation

In the first step, the current state of the energy system, its structure and the underlying dynamics should be investigated. The idea here is that the feedback processes and the underlying dynamics of interactions in the system are the sources of the obduracy and inertia of the system that are the barriers of transition towards a new system. This explanation has implications for the next steps of this framework. First, when the barriers to change are internal to the system, it means that the current structure cannot lead to the transition, and even the system might need a restructuring in order to define transition pathways. Second, the current actors are interacting in the existing structure and feedback processes of the system. Therefore, in order to have a transition, the current interactions between actors, incumbent technologies and governing institutions are not enough. In this respect, we need an intervention in the system aiming to change the structure and dynamics of the system and direct it toward the transition.
Indeed, the cities in different contexts show different dynamics, energy structures, objectives, and have different priorities based on their contextual factors. In other worlds, no one single solution fits all. In a city in the developed world, urban energy infrastructure can be analyzed as a complex socio-technical system. In this case, the objective of transition might be to mitigate the effect of energy system on climate

change by considering both technical and institutional factors. However, in a city in the emerging countries there might be a focus on the economic development and controlling rapid urbanization, which addresses the economic factors but again considers institutional changes as a required factor. The context of an underdeveloped infrastructure in an urban area however might be different, with the focus on the social objective such as accessibility and affordability of energy, as well as considering the urbanization process. Therefore, different contexts may share some characteristics but are different in terms of objectives, priorities and requirements.
Based on a socio-technical system perspective, in order to understand the underlying dynamics of the system, both the technical and institutional dimensions should be analyzed. The technical dimension constitutes the materiality of the system including its associated specifications. On the other hand, the institutional dimension addresses the rules of the game and the interactions in the human side of the system. This dimension can be decomposed further to economic, social/behavioral and political institutions, based on the different groups of stakeholders and their roles in shaping the system dynamics. Therefore, these four dimensions of the system dynamics are analyzed in the followings:

Technical Factors

Each urban energy system has a materiality manifested in the physical infrastructure and the flow of energy in the system. This physical infrastructure may have different degrees of maturity in different contexts as a mature or advanced infrastructure, a growing or developing infrastructure as well as an underdeveloping infrastructure, which needs to be developed to an advanced physical system. Based on the degree of maturity, the specifications and the complexity of the physical system might be different. The difference arises due to different standards, complexity in the physical network and its interdependencies.

Political Institutions

First set of the institutional factors, considers the rules of game as the formal and political institutions, which shape the relationship between all the actors involved in the system. These institutional factors have a multi-level and hierarchical nature, from international and national institutions that are external to the system dynamics, to the urban and local institutions that emerge based on the decision making process inside the juridical boundaries of the system . The primary assumption here is that the complex system of interactions between these institutions at different levels causes complex patterns that manifest themselves in terms of bureaucracies and legal complications. Based on the degree of formality, level of abstraction and their interdependency to the other factors in the system, political institutions have different weights in the obduracy of the system.

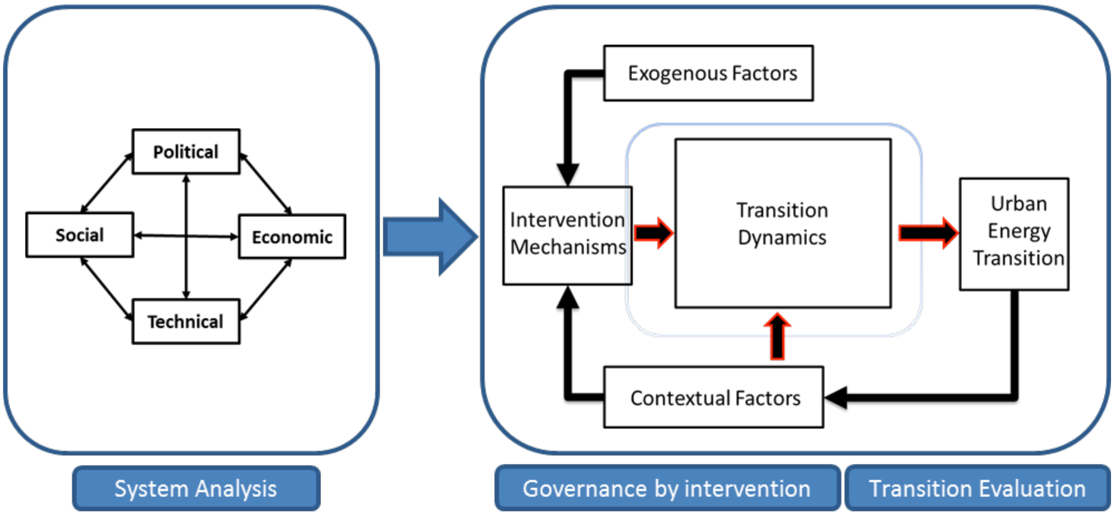

Figure 1: A framework for the governance of socio-technical transitions.

Economic Institutions

The second set of institutional factors, addresses the market dynamics, the relationship between business actors and their influences on the energy sector. The economic factors are important to understand both the dynamics of interactions between actors in the system and the sources of obduracy. On one hand, monetary interactions and economic transactions in the energy market are an important part of overall interactions in the system closely related to the political factors. On the other hand, in a capital-intensive sector such as the energy sector, investments are huge which affect the future behavior of the actors such as businesses and utility companies and are a big issue in changing the behavior of the investors and beneficiaries. Apart from these factors, at the micro-level, the purchasing power of the households and income affect the social and behavioral dynamics in the system.

Social Factors

The third set of socio-institutional factors are associated with the behavior of the end users, informal institutions that govern their behavior and the patterns that arise from these behaviors. The social factors have different effects on the obduracy of the system. In terms of the social institutions, like the case of the political institutions, they shape a hierarchy from cultural norms to day-to-day interactions. The degree of obduracy of social behaviors increases when they are affected with the institutions at the higher levels of this hierarchy. Social factors also influence the structure of the system by their position in the decision-making process and political priorities on one hand, and as the micro-factors for understanding the dynamics of the energy sector on the other. Many governments and strategic decision makers place a high priority for the social factors such as availability and affordability of vital resources such as energy. In addition, consumption and behavioral patterns as well as the effects of urbanization and demographic factors are the important factors, which affect the decision-making and planning processes such as the well-known demand management programs.

System Interdependencies

Considering these underlying dynamics, the importance of these dimensions vary greatly based on the contextual factors. Therefore, system configuration may differ according to these different priorities, which leads to different objectives, structures and mechanisms. Here I argue that these dynamics and their interactions cause the system level inertia and resistance to transition in the energy infrastructure. In this respect, it is needed to investigate the interdependencies in different contexts to identify the primary sources of system obduracy. Therefore, by considering these four dimensions, six types of mutual interactions can be formulated as depicted in figure 2.

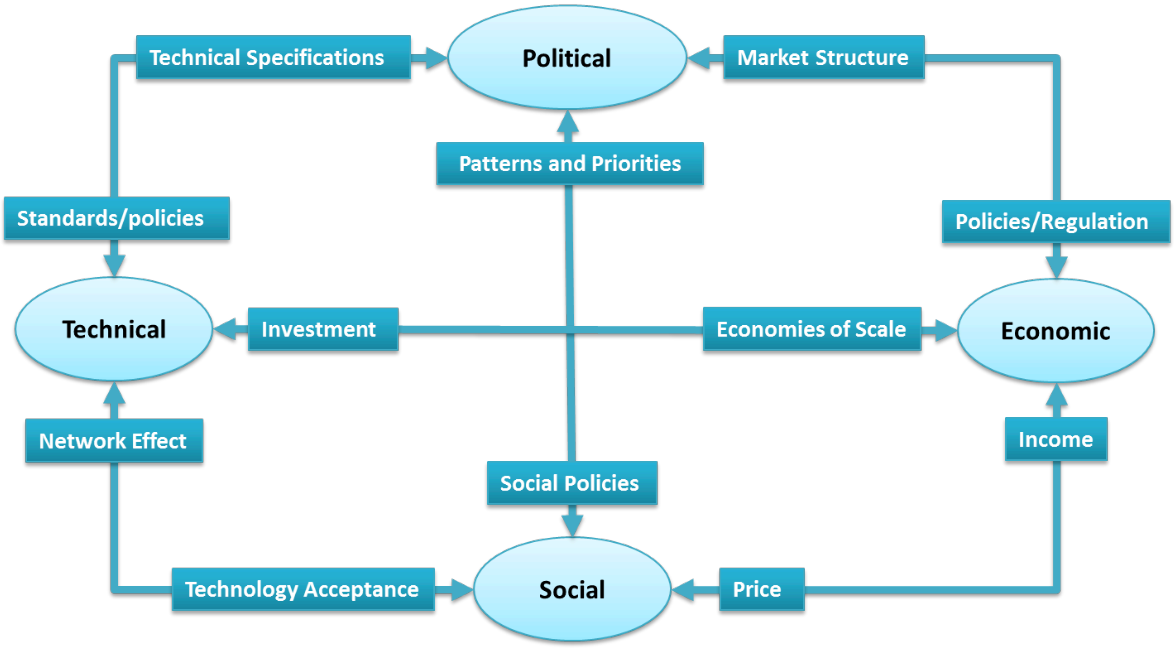

Figure 2 – System analysis to investigate system level inertia

Social-Technical

The interdependencies between social and technical factors can be explained by the dynamics of technology adoption. Technologies shape the social factors based on their level of acceptance, such as their ease of use and perceived usefulness. On the other hand, when the numbers of users increases, the benefit for potential users to use the same technology increases too; something commonly called as the network effect.

Economic-Political

The economic restructurings such as privatization, liberalization or re-regulation of markets are the primary effects of political institutions on the economy. At the urban level, these institutional effects manifest themselves in terms of new economic policies (such as urban energy policies and Feed-in Tariffs) and regulations. In the long run, these effects manifest themselves in the form of new market structure that shape a new institutional environment affecting the political decisions.

Social-Economic

Social and economic interdependencies arise from the purchasing power of actors in the system. The primary effect of economy on the end users emerges as the price of goods and services; while the level of income of the users and households explains the consumption behavior of the actors and its effect on the market economy.

Technical-Political

Technologies cannot function efficiently in a social system without well-established institutions. Standards and technical policies shape the development and diffusion of technologies in different societies. As a response, technical specifications are developed to satisfy these standards and constitute part of the broader institutional environment.

Social-Political

Actors' behaviors explain the relationship between social and political factors. On one hand, social policies affect the norms that shape the actors' behavior as the part of the institutional environment. On the other hand, actors' behavior in aggregate, shape the behavioral patterns such as the patterns of consumption that provide input for the emergence of new political institutions in future. The second mechanism for the influence of social factors on the political dimension is through the social priorities in the political agenda. These factors are important especially in the developing world and affect the political objectives in the transition process.

Economic - Technical

Finally, the interdependencies between technology and economy play a big role in the dynamics of inertia in urban energy system. The cost and benefit of technologies are the primary criteria for the businesses to evaluate the feasibility of investing in these technologies. Based on such analysis, investments on technologies by the economic actors, new dynamics of inertia emerge in the form of sunk costs and economies of scale.

Based on the four underlying dynamics of urban energy systems and their interdependencies, we can analyze the system level inertia and existing dynamics of different urban energy systems in various contexts. For this purpose, three steps are necessary in order to identify the prominent underlying factors and identifying the implications for the governance of urban energy systems:

- Analyzing the strengths of every pair of relationships between the four underlying dynamics
- Identifying the priorities of strategic decision makers involved in the governance of urban energy systems in terms of social, economic, technical and institutional objectives
- Formulating the potential opportunities for lock-out or leapfrogging in the system

Step 2 - Governance by Intervention in Urban Energy Systems

In the second part of the framework, a conceptual model is proposed for understanding the relationship between different interventions and the dynamics of urban energy transitions for low carbon cities. The primary idea here is that the governance manifests itself as a set of interventions in the dynamics identified in the first step.

The logic of this argument is that if we assume all the dynamics of energy systems in terms of social, political, technical and economic dimensions come from outside the urban boundaries, then there is no room for the urban governance to shape the transition and the future state of the energy system. However, in the real world there are factors at the urban level that influence the dynamics of transitions independent from the national and international forces or even in the absence of such forces.

Therefore, we hypothesize that governance at the urban level is meaningful and takes place in the form of interventions in the dynamics of the system.

Socio-Technical System Components

For formulating these interventions, in this part we propose a conceptual model for the governance of urban energy system transition as a set of interventions. For a system level analysis in a socio-technical system, we need to identify five different sets of factors as objectives, transition dynamics, intervention mechanisms, contextual factors and exogenous factors. Based on the underlying dynamics of system level inertia described in the first step, the contextual and exogenous factors can be decomposed to these four underlying dynamics; but the objectives, transition dynamics and intervention mechanisms are aggregate factors cause by nonlinear interactions between these underlying dynamics.

Objectives

Transition to a low carbon city is an emergent property of an energy system as a complex socio-technical system. Therefore, predicting the future state of the system is impossible and the role of governance is to steer the transition pathways towards a satisfactory state in future. In this respect, concrete objectives are needed in order to satisfied and direct the system toward them. In general, the objectives of transition can be classified into two broad categories as objectives to reduce the dependency of the system to unsustainable energy infrastructure; and promoting the new and sustainable system and energy sources.

Exogenous Factors

There are factors beyond the urban level that cannot be influenced by the dynamics of urban energy transition but affect these dynamics. Therefore they are classified as the environment and the landscape pressures which should be taken into account for formulating the intervention mechanism. Aligned with the dynamics of system inertia, we can classify these factors in the form of the four underlying dynamics. Technological changes beyond the urban boundaries are the primary technological factors which affect the urban energy system. Considering the social and political dimensions, national and international institutions as well as cultures and cultural norms are institutions that shape the behavior of actors at the urban level, but should be regarded as external forces. Economically, investments from outside the urban boundaries and external funding are another set of external factors, which affect the dynamics of transitions.

Contextual Factors

Another set of important factors affecting the transition dynamics are contextual factors. The underlying dynamics of energy system and its obduracy greatly affect the contextual factors and are important concepts for selecting intervention mechanisms. In terms of the underlying dynamics, contextual factors can be classified as the technological base and local resources, institutional and financial capacity of the city as well as the consumption patterns of the urban residents. These contextual factors affect the transition dynamics and intervention mechanisms, and take effect from the consequences of interventions in the system.

Intervention Mechanism
From the viewpoint of a strategic decision maker, intervention mechanisms are the only place that changing the system is possible. These mechanisms are tools to affect the dynamics of transition and steering the whole system towards transition. Therefore, at the center of this step is the selection or design of these mechanisms by combining different governance tactics and techniques (or government technologies in Foucault's terms) which address the dimensions of system inertia. In this respect, cultural learning programs are the primary mechanisms for changing the social dimension of the system. The institutional changes in the forms of designing new policies affect the political dimension of transition. For changing the technical dimension and its associated institutions, the is the need to either developing new technologies, which hardly takes place at the urban level, or transferring new knowledge and technology from outside the urban boundaries. Finally, investment in the form of direct investment or creating incentives for the private sector by mechanisms such as economic policies is the primary source of changing the economic dimension.

Transition Dynamics
Dynamics of the system transition are the results of interactions between all the actors involved in the system based on the effects of exogenous and contextual factors as well as the effect of intervention mechanisms. These dynamics are the pathways for the system to reach to the transition objectives and can be classified as three following dynamics:

Energy Efficiency
By assuming a constant amount of energy consumption in the system, the system efficiency can reduce the dependency to unsustainable energy sources through reducing the amount of energy supplied. Efficiency can be gained for instance by more efficient consumption at off-peak times, improving efficiency in the distribution and even more efficient types of energy production, inside the urban boundaries.

Energy Conservation
If we assume a constant efficiency of the energy system, then another dynamic is to reduce the level of energy demanded and consumed in the system. Behavioral changes, cultural learnings and demand side management programs address this part of the transition dynamics.

Renewable Energy Production
Finally, replacing the incumbent energy system with a sustainable and carbon-neutral energy system completes the transition process. Producing energy from renewable sources and diffusion of distributed energy technologies are the primary factors in this dynamic.
Based on these factors, the following conceptual model is proposed for analyzing the governance of urban energy transitions as the set of intervention mechanisms (Figure 3).

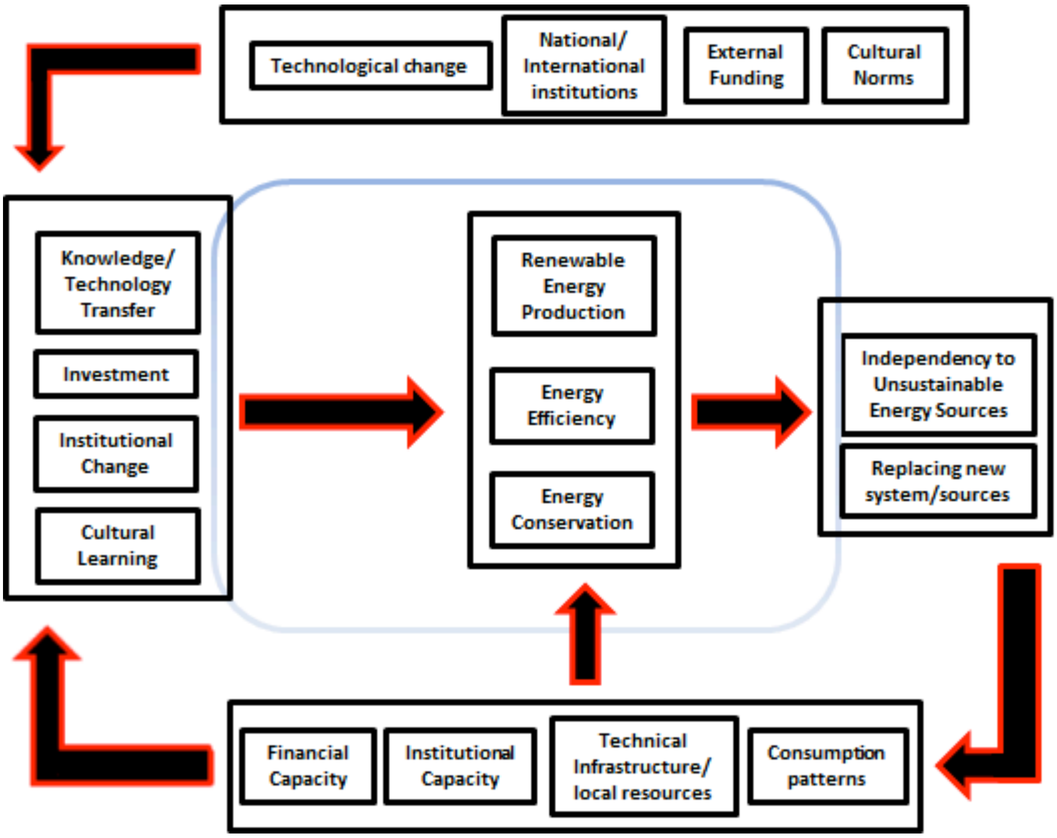

Figure 3 – The conceptual model of urban energy transition dynamics

System Intervention as the Governance Approach

Following this conceptual model and the dynamics of system inertia explained in the first part, the primary transition dynamics are formulated and intervention in the system can be designed by considering all the factors important in the governance of urban energy transition. The output of this step would be a combination of different intervention mechanisms as governance scenarios, which should be tested, in the third step. In this respect, three steps are necessary for designing different scenarios:

1. Identification of exogenous and contextual factors, setting transition objectives and formulating the possible transition dynamics
2. Formulating the effect of different intervention mechanisms on the transition dynamics
3. Selection and design of intervention mechanisms as the governance scenarios

The first step of this framework provides input for identifying the contextual factors involved in the energy system. In this step, a preliminary analysis is needed for the identification of the leverage points and designing the intervention mechanisms. This analysis provides input for understanding the effects of different scenarios in the system, which is the aim of the third step.

Conclusions

This paper proposed a conceptual framework for analyzing the dynamics of techno-institutional lock-in preventing urban energy infrastructures to change, and the way a governance approach is able to influence these dynamics and direct urban energy transitions. It formulated the relative power of different rationalities in urban energy infrastructure as a complex socio-technical system shapes its system inertia against transition effort. It is composed of the feedback dynamics between social, technological, economic and political dimensions of existing institutions, as well as the way a systemic governance approach can affect these dynamics of system inertia and shape transition pathways. Based on this framework, affecting part of this power structure is not sufficient for a successful transition, and may even have counterintuitive effects in long term. Based on the insights from this conceptualization, methodological guidelines were presented for modeling these power rationalities in the form of feedback structures causing system level inertia. Based on this framework, further research for modeling techno-institutional lock-in, designing governance scenarios as well as evaluating the impact of these scenarios are needed, especially using System Dynamics as a proper methodology for modeling feedback structures creating techno-institutional lock-in. Conceptualization of system inertia and the governance of energy transitions in urban energy infrastructures has practical applications to evaluate current low-carbon and energy transition efforts as well as different energy and climate change policies by urban authorities and other relevant actors aiming to contribute to urban energy transitions.

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