Block 2 Reading

Management of Urban Electricity Systems

Authors: IGLUS, EPFL

In this, the third block of the MOOC, we first introduce the relationship between energy and cities and then explain urban electricity systems. Subsequently, we present the management of the urban electricity system, along with the challenges and opportunities that lie ahead. A concluding section illustrates all this by way of a case study of Copenhagen, where we identify the most relevant players involved in the urban electrical grid and discuss the challenges and opportunities derived from the city's current transformation.

Energy and cities

Energy is the lifeblood of cities. Without energy, cities simply do not work, as energy is essential for all infrastructures such as buildings, transportation, water, communications, and others. This generates an important imbalance between rural and urban energy consumption. Urban areas consume around 70 percent of the world's primary energy[1] (UN-Habitat 2012), while only a little more than 50 percent of the world's population live in cities (UN-Habitat 2013). Most of this energy is used in buildings (around 45%); less than a third is used in transport (around 30%); and a fourth is used for other purposes. Hence, if energy consumption is to be reduced, one should concentrate on urban areas and, in particular, on buildings and transportation (see Figure 1).

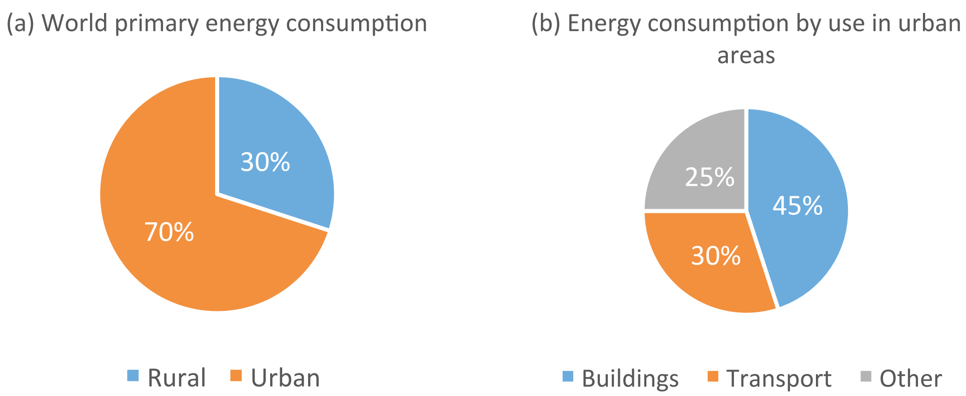

Figure 1: Relevance of urban energy consumption and main energy uses in urban areas. Author's elaboration, rough estimations based on UN-Habitat 2012.

The energy consumed in urban areas comes mostly from fossil fuels being directly delivered to vehicles and houses (such as oil and coal), while natural gas delivery is usually done through underground pipelines. Almost all the rest of the energy consumed in urban areas is in the form of electricity, which is the focus of this block.

[1] Primary energy refers to the energy in its first stage of conversion (such as natural gas consumed in power plants, not the electricity consumed at households), which is often substantially larger than the final consumption due to the inefficiencies in the multiple steps along the energy conversion chain.

Electricity is an energy vector, and not an energy source, which means that it has to be produced from a primary energy source (such as fossil fuels, nuclear sources, water, solar, wind, and others) and then transmitted to end consumers, where it will again be transformed into another form of energy, such as lighting, heating, or power. Typically, electricity is produced outside the city and then transported into the city by way of high- or medium-voltage transmission lines. It is then transformed to lower voltage levels and subsequently distributed to consumers (via a low-voltage electricity grid) (see Figure 2). Our focus in this block will be on the electricity-grid infrastructure in urban areas.

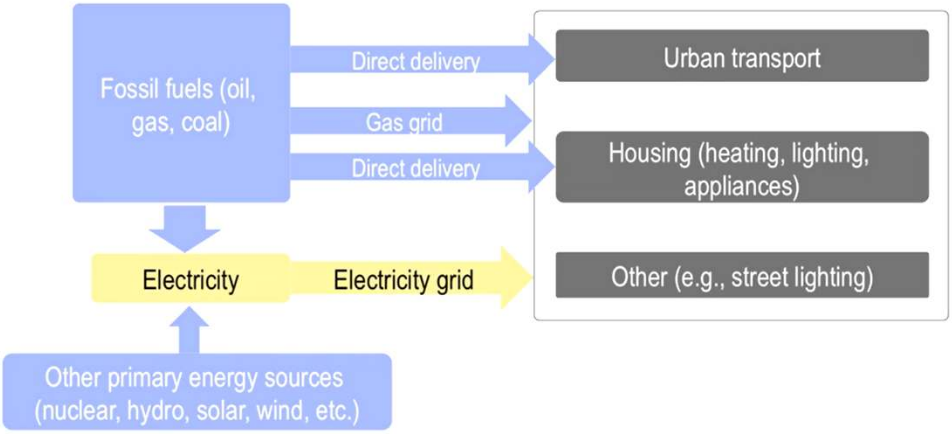

Figure 2: Schematic representation of energy inflows into an urban area.

Explaining urban electricity systems

Here are the main elements of the urban electricity system, and these terms and figures explain how the system is configured and how it operates. It is essential to understand these concepts as a way to identify the main management challenges.

- *Electricity infrastructures and operators*. Electricity is produced outside of the city where it is then transported to the city through above-ground cables (high and medium voltage) and/or underground cables (medium and low voltage). The voltage levels of the lines are then adjusted to the end consumers' needs through transformers, from which electricity is fed into distribution cables (above-ground and underground cables at low voltage) (see Figure 3). The final transformation and distribution are the tasks of the urban (electricity) utility company, acting here as the grid operator.

- *Electricity consumption and consumers.* Connected to the low-voltage end of the grid are the residential consumers (households), while industrial and commercial consumers (usually demanding much higher power) are connected to medium-voltage lines (say, for example, at malls and factories).

- *Electricity production and producers.* Traditionally, electricity is produced by major generation plants located outside the city (these might be coal-powered plants, nuclear power plants, and hydro-powered plants). Most of these plants cannot be located inside the city because they pollute their surroundings (they are fossil-fuel-burning power plants), or because this would not be socially acceptable (living near a nuclear facility), or because the resource is located outside of the city (where there is a water source such as a river for hydro-electrical power plants).

However, given the importance of a continuous flow of electricity to sustain services, there is often some backup generation inside the urban area. Particularly vulnerable consumers such as hospitals or IT centers usually have diesel or natural gas generators ready to step in in case of service interruptions. Backup generation is characterized by its exclusively internal use – that is, the owner uses it solely to feed its own appliances. In recent years, however, new trends in electricity generation are introducing previously unknown self-generation elements. Both residential and large consumers are starting to self-generate their own electricity, mostly through the use of rooftop solar photovoltaic systems, that can also feed electricity into the grid when generation exceeds domestic needs. This creates emerging opportunities and challenges for consumers, as well as for urban grid operators.

- *Electricity distributors, intermediaries, and other players.* Focusing on the financial flows, the traditional approach is that end consumers (both residential and large customers) buy their electricity from the same utility that manages the grid and the distribution network. In this case, the local (electricity) utility acts basically as a reseller, since it very rarely produces its own electricity, but buys it from (independent) power producers. Historically, the local power utility was in a monopoly position, where it was the only one allowed to sell electricity to households, as well as to commercial and industrial customers. Due to the progressive liberalization of electricity markets, customers – first industrial and commercial customers but now also households – have gained the opportunity to choose among different producers and resellers who compete among themselves. To be clear, such competition pertains to the electricity delivered, not to the distribution infrastructure, which remains a monopoly.

  Consequently, a final consumer's electricity bill is usually composed of three parts: the cost of distribution (use of the grid), which is monopolistic and therefore regulated; the cost of the electricity itself (where the consumer has a choice); and taxes. As liberalization progresses, a new type of player appears in the form of electricity traders. Traders do not directly affect the way the urban power grid operates, but play an important role in the electricity market, as distributors or resellers now also buy electricity from the traders. Finally, resellers known as Energy Services COmpanies (ESCOs) have appeared. ESCOs can act as resellers (selling electricity to households and large consumers), but also offer services to save electricity (such as smart systems), making a profit from the savings incurred by the customer due to their lower consumption.

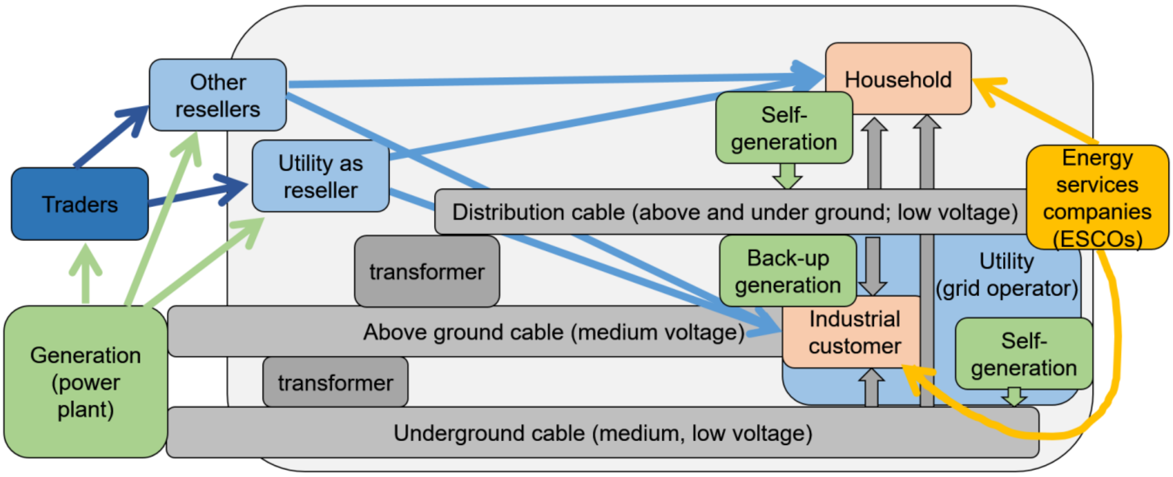

Figure 3: Schematic representation of actors and flows in liberalized urban electricity systems.

Managing the urban electricity system

The management of the integrated urban electricity system has traditionally been done by what is called the integrated (urban) utility. Despite our focus on the electricity system, we need to keep in mind that there might exist other local utility managers for services such as natural gas, water, cable, and others, which might or might not be part of the electricity system. In most countries, the urban electricity utility acts as the only managing entity. In some big cities, several electricity utilities may exist, each of which however has a monopoly on a given territory. This utility has generally been a public entity owned by the municipality. Recently, some tasks previously carried out by the utility are being outsourced to private operators, following the trend of liberalization and the spread of the market approach.

Let us systematically present the four main aspects of urban electricity infrastructure management:

- *Operations and maintenance of the grid* is fundamentally a *technical* task focused on balancing demand and consumption. The biggest challenge for the electricity infrastructure manager is thus maintaining the balance between demand and supply. This challenge derives from the very essence of electricity, which impedes its storage and requires the instantaneous match between demand and consumption, as well as the randomness of instantaneous electricity demand. There exist certain seasonal and daily consumption patterns, which create the peak and valley hours, but the exact amount consumed at each moment is a random variable. This challenge is made even more uncertain by the emergence of self-generation, as self-generation escapes the direct control of the utility. Besides, self-generation from renewable sources carries an important intermittency factor (it cannot be planned and depends on the immediate atmospheric conditions such as sun for solar or wind for turbines) that complicates the task even further. For this reason, it is sometimes necessary to reinforce the grid by increasing its transmission capacity and protection switchgear so it will be able to face consumers' excess generation.

- *Grid development* pertains to the construction of new connections and constitutes another challenge for urban utilities, particularly in rapidly growing cities. New electricity-grid areas have to be developed and corresponding electricity introduced without destabilizing the rest of the network. Proper planning is thus required to conduct grid development, as well as the allocation of sufficient financial resources, which might be difficult if taxes for grid usage are regulated and are not sufficient to develop the new connections. Overall, grid development combines the *technical* dimension of expanding the electricity network with the *economic* dimension for financing it. Additionally, the *jurisdictional* dimension can emerge as a challenge if the grid spreads across jurisdictions.

- *Customer relations*. The utility's relationship with its customers mainly takes the form of metering and billing of their electricity consumption. Metering and billing is also the source of the utility's regular income, thus the managers focus on servicing customers. Nonpaying customers must also be managed, and sometimes they must even be disconnected from the grid. The latter may not be allowed, or it may raise social and especially political issues. Either way, the utility is likely to incur additional costs, either for letting the nonpaying customers stay connected or for taking them off the grid. Another challenge in this context is electricity theft, which can be particularly problematic in emerging and developing countries. Again, electricity theft results in additional costs for the utility, but also in increased unpredictability when balancing the grid, since a part of the load remains unknown.

  Finally, in some urban areas, social taxes have been implemented to allow low-income inhabitants to access electricity. These taxes mean lower incomes for utilities and as such are always rooted in politics. The utility, forced to offer the social accommodations, will lose part of its revenue base and will have to pressure the political authorities to get compensated. In other words, we clearly see that customer relations for local electricity managers is not only a commercial but also a *social* and *political* activity.

- *Energy purchasing.* Considering that the city, in general, does not produce its own electricity, utility managers have to buy it from generators, also called (independent) power producers. Rarely, in fact, do urban utilities own electricity-producing plants. Hence, electricity utility managers have to face important buying decisions, which are often framed in terms of long-term contracts (with a risk of not having made the optimal deal) and/or acquisitions on the power exchanges. The latter constitute an increasingly widespread way of buying electricity for a city, bringing traders in the picture and, with them, higher risks, but also the opportunity for getting better prices. Consequently, electricity purchasing has increasingly become a complex managerial task in which not only economic but also environmental considerations play a role.

These four main tasks of urban electricity managers will exist no matter what, but their challenges may be exacerbated because of some ongoing and new changes permeating the electricity sector, such as climate change and the ICTs (information and communication technologies). But these challenges also constitute opportunities.

Challenges and opportunities

Indeed, the four management tasks are becoming increasingly complex due to the combined effect of three growing trends: electricity market liberalization, environmental challenges, especially climate change, and the pervasive role of information and communication technologies (ICTs). In this section we look at each of them (figure 4).

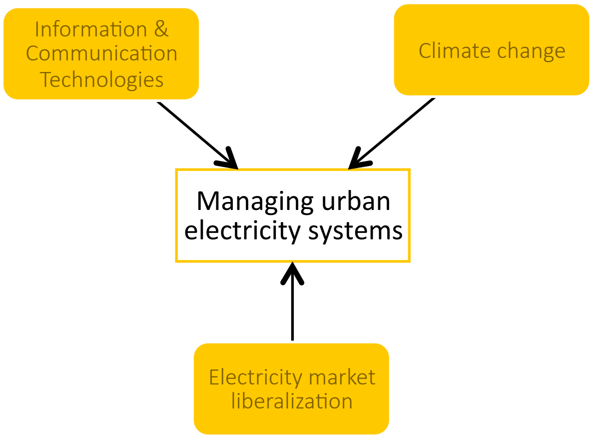

Figure 4: Principal trends creating challenges and opportunities in urban electricity systems management.

Electricity market liberalization. Currently, in many countries, the electricity market has been liberalized, or it is in the process of being liberalized. This means that the different functions within the electricity system are being unbundled: producers now compete for customers, who gain the right to choose. Customers, however, stay hooked to the electricity infrastructure (urban distribution network), since this remains monopolistic. This arrangement has profound consequences for the urban electricity system manager, which translates into challenges and opportunities concerning electricity purchasing, customer relations, and grid management.

- Regarding *electricity purchasing*, retail prices become competitive and customers can now switch among different companies. Competition thus requires professionalizing the electricity purchasing process in order to retain and/or gain customers, as well as expanding the energy services offered by the utility (including energy-saving services). Ultimately, the customer base determines the revenue stream of the utility and, therefore, its sustainability over time.

- As for *customer relations*, there is a risk of customer base shrinkage due to competition with other utilities, which is often particularly high among lucrative customers for which competition is harsher. As a consequence, managers will have to improve upon their services and/or expand their offer to retain their customers. Sometimes, metering and billing is also liberalized, which is usually a very lucrative technical activity the utility must also try not to lose to competitors. Overall, customers must now be treated differently and managed more actively; whereas, nonpaying customers must be disconnected, given that the possibility to cross-subsidize from paying customers disappears due to competitive pricing. The latter may create socially unacceptable situations that create political tensions between the utilities and the municipal government. They can be smoothed by the implementation of social tariffs which, however, have to be compensated by the local authorities.

- In terms of *grid management*, electricity market liberalization leads to increased complexity because of unbundling. Basically, since the system operator is no longer in control of all activities on the grid, it may lack information, thus making managing the grid more difficult.

Environmental challenges and especially *climate change* put pressure on urban electricity managers to reduce greenhouse gas emissions and to mitigate the effects of climate change. Overall, consumption of fossil fuels must be reduced, but overall electricity consumption must also be cut back. This creates several challenges but also opens up new opportunities for the urban electricity infrastructure manager especially in the areas of operations and maintenance, grid development, energy purchasing, and customer relations.

- The *operations and maintenance* of the electricity system becomes challenging due to intermittent production from renewable technologies. To maintain the system and keep it balanced at any moment, the intermittency introduced by renewable energy has to be compensated, which can be a particular challenge for an electricity utility that does not itself produce electricity.

- *Grid development* will become challenging because of grid reinforcement needs, caused in turn by self-production. Such grid reinforcement is above all a financial challenge, but also a regulatory issue (for example, with authorizations). In addition, the decrease in electricity consumption caused by the implementation of energy efficiency measures will erode the source of financial resources to carry out the grid development.

- In terms of *energy purchasing*, the urban electricity systems manager is pressured to buy more electricity from renewable sources. The shift in the electricity mix requires the identification of certified renewable producers who guarantee that the electricity the utility is delivering does not come from conventional sources (such as natural gas or coal).

- Concerning *customer relations*, the inclusion of self-production changes the traditional role of consumers who now also become prosumers, being simultaneously the utility's buyers (electricity consumers), but also the utility's suppliers (electricity producers). This new role challenges the current management of customer relations. Additionally, the demand for energy savings services requires the development of new business models and customer relations yet to be defined.

Role of the ICTs. The progressive inclusion of more ICTs can make the infrastructure usage more efficient, can involve the users more actively in the management of urban infrastructures, and can lead to new energy services. This transformation creates challenges and opportunities for the urban electricity system managers as related to operations and maintenance, grid development, energy purchasing, and customer relations.

- The *operations and maintenance* of the urban electricity system became easier thanks to the new possibility to commercialize balancing energy. Companies and customers can now sell their ability to balance the system by changing their consumption profile (in other words, turning off certain appliances such as refrigerators for a certain time period, for example). Overall, the inclusion of the ICTs makes the system more resilient, notably also by adding further measuring points and more rapid coordination.

- Concerning *grid development*, the ICTs are mainly a means to increase the network energy efficiency and thus reduce the need for grid development.

- As for *energy purchasing*, the use of the ICTs allows for the effective transformation of consumers into producers (at least for balancing energy).

- In terms of *customer relations*, the increasing role of the ICTs allows for much more flexible pricing (examples are hourly or even dynamic pricing thanks to smart meters) allowing for the transmission of price signals to consumers during peak and valley hours. The ICTs also open up the opportunity to develop new energy-related services, such as managing customers' own electricity consumption in real time.

All these three new trends affect the traditional management functions of urban electricity systems. They will be key determinants as to how the role of the urban electricity utility managers evolves in the coming years.

Case study: Copenhagen, leading the way to sustainable cities

Achieving a sustainable energy system has become a global objective, where urban areas play a principal role. International efforts at national levels (for example, the Paris COP21 summit) cannot succeed without the active implication of cities, given that urban areas generate around 70 percent of greenhouse gas emissions (Spector 2015). To help curtail environmental pollution and promote sustainability measures, as many as 436 cities (representing 377.6 million people) joined the Compact of Mayors (COM 2014). This network (and others, such as Energy Cities in Europe (Energy Cities 2015)) promote local collaboration and learning from each other.

In this context, studying the successful case of Copenhagen will help us understand how urban infrastructure managers can carry out the transition toward sustainability.

Copenhagen is well known as a green city. Copenhagen was recognized in 2014 for being one of the European Green Capitals (European Commission 2014). It is often cited as a leading city in constructing a green economy to be followed (OECD 2015; Floater et al. 2014), and was named the world's greenest city for the second year in 2014 (Dual Citizen LLC & Tamanini 2014). Copenhagen is also on the way to converting its urban electricity infrastructure to carbon neutrality by 2025, and to become 100 percent based on renewable energy by 2050, together with the rest of the country (The City of Copenhagen 2015; Mathiesen et al. 2015). In this case study, we focus on how the urban electricity system of Copenhagen has changed, what the roles of the different agents in the city are, and the opportunities and challenges the city of Copenhagen faces.

Copenhagen, a green sprout in the North

Copenhagen, Denmark's capital, is home to roughly 580,000 people (Københavns Statistik 2014) and is located on the eastern coast of the island of Zealand. Copenhagen is the most populous city in Denmark with around 2.6 million people living in the Greater Copenhagen metropolitan area, which includes up to 46 independent municipalities (Frederiksberg Kommune 2015). The city was founded in the tenth century and gained importance as the capital of Denmark and Norway, becoming a major European urban and cultural hub in the twenty-first century. Copenhagen's economy is focused on high-tech, innovative services, manufacturing for export, and also a large public sector (Floater et al. 2014), which have made Denmark one of the world's top ten countries by GDP per capita (IMF 2015) and also most productive cities globally (Floater et al. 2014).

On the electricity system, despite having small, but not negligible fossil fuel reserves, Denmark is strongly committed to the introduction of renewable technologies in its electricity mix (City of Copenhagen 2012a). In 2013, the country had 13,550 Mega Watts (MW) of installed power, where 4,810 MW came from wind turbines (35.5%), 4,852 MW from large Combined Heat and Power (CHP) units (35.8%), and only 571 MW from solar photovoltaic[2] (Danish Energy Agency 2014). Renewable energies, such as wind energy, have been gaining momentum for decades (see Figure 5), and they are expected to keep growing with a stronger focus on offshore windfarms and replacing fossil fuels in CHP units (Energinet 2015; European Commission 2012).

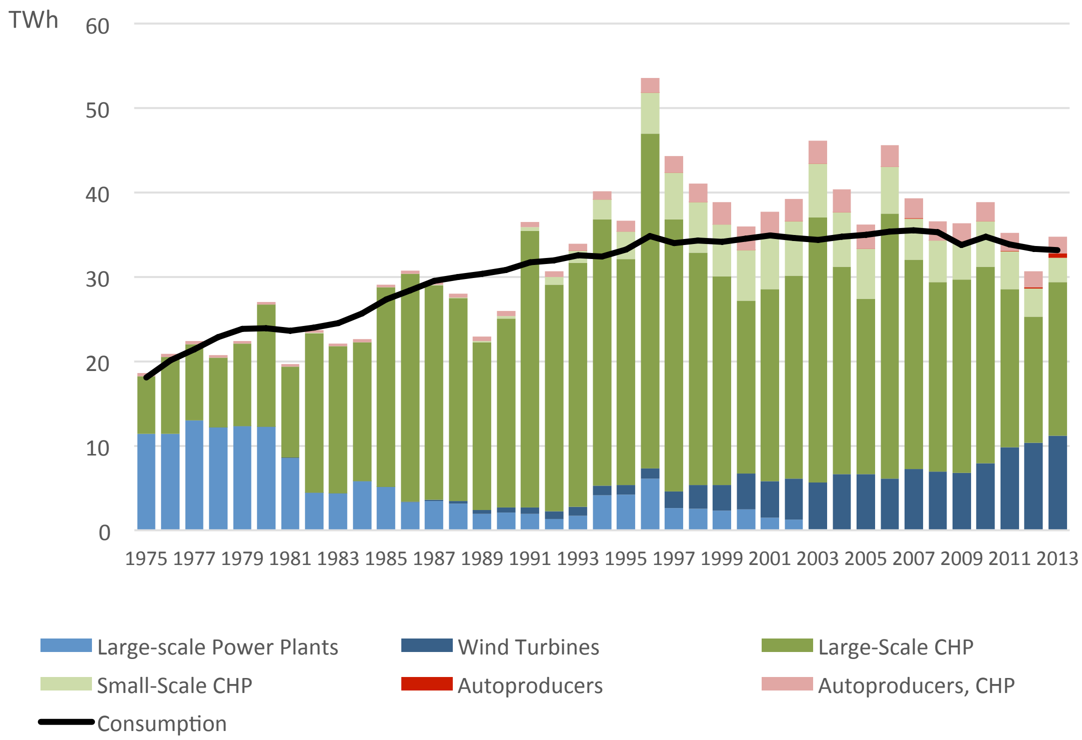

Figure 5: Denmark's electricity generation and consumption evolution 1975–2013. Author's elaboration. Data from Danish Energy Agency 2014.

The large role of combined heat and power production units partly comes from the intense effort to implement district heating (in Copenhagen, district heating reached full market penetration of 98.3 percent by 2008 (City of Copenhagen 2009)). Increasing the share of renewables in district heating, together with improving the buildings' energy efficiency, and prioritizing the use of renewable energy technologies, confirm some of the strategies pursued by the Copenhagen infrastructure managers to reach its ambitious goal of carbon neutrality for 2025 (European Commission 2012). Although heating and transportation infrastructure systems are not within the scope of this short case study, it is important to bear in mind that urban energy infrastructure managers need to address urban energy systems comprehensively since all sectors must contribute to the sustainable development of the city[3] (Mathiesen et al. 2015).

---

[2] Despite representing only the 4.2 percent of total installed capacity, solar PV has experienced an explosive growth rising from 7 MW in 2010 to 571 MW in 2013, an 80 times increase in three years (Danish Energy Agency 2014).

[3] To illustrate the importance of considering all energy uses when addressing urban sustainability, it suffices to look at the GHG emissions sources in Copenhagen for 2014: 40.7 percent electricity production, 30.5 percent traffic, 23.6 percent district heating, and 5.1 percent others (City of Copenhagen 2014b).

In 2013, Danish citizens consumed an average of 5.56 MWh per capita[4] (Danish Energy Agency 2014), 1.8 MWh per capita in the residential sector, slightly above the EU-28 average of 1.6 MWh per capita, but well below neighbor countries of Norway at 7.3 MWh per capita or Sweden 4.0 MWh per capita (Eurostat 2015a). Electricity consumption reached its maximum in the late 2000s, and it has been declining since (see Figure 5). Total electricity consumption of around 31.23 TWh per year is mainly divided into households (around 33%), manufacturing industry and construction (around 27%), and services (around 22%)[5] (Danish Energy Agency 2014).

Electricity for industrial consumers, around 0.0894 EUR/kWh, is well aligned with the EU-28 average of 0.0894 EUR/kWh for the first semester of 2015 (Eurostat 2015c). However, household consumers have the most expensive electricity (0.3068 EUR/kWh) in the European Union (the EU-28 average is 0.2078 EUR/kWh) (Eurostat 2015b), mostly because of the taxes included in the final price, which amount to 0.1791 EUR/kWh or almost 60 percent of the price (Eurostat 2015b). The latter, the high tax load in electricity, allows the collection of funds for investing in the development of the grid and the promotion of renewable energies, plus incentivizing responsible electricity consumption and promoting the adoption of energy-efficiency measures (Rubin 2012).

Actors of Copenhagen's electricity system

The Danish electricity market has been liberalized since the late 1990s, although public presence and different forms of customer ownership (such as cooperatives) is notorious (Olsen & Skytte 2002; OECD 1999). The Danish energy market is regulated by the Danish Energy Regulatory Authority (2012), which establishes the rules of the national electricity system.

*Electricity infrastructures and operators***.** Copenhagen used to have its municipally owned utility for electricity supply, Københavns Energi, which operated the distribution system. However, in 2006, the largest energy company in the country, DONG Energy, merged with six other major energy companies, among them, the utilities from Copenhagen and neighboring municipality Frederiksberg (DONG Energy 2015a).

Despite the Danish government's owning a majority stake in DONG (58.8% of shares (DONG Energy 2015b)), the firm operates as a private company, independent from the Danish government and the local authorities. Denmark's electricity grid is divided into a number of different areas for which the different distribution system operation (DSO) companies are responsible. The DSO in Copenhagen, DONG Energy, must therefore make sure that the electricity grid is developed and properly operated. The municipal influence on this is relatively small (Hjøllund et al. 2014). The company is also responsible for purchasing the electricity required by the city consumers and effectively delivering it at the consumption point, making sure the grid is correctly operated and maintained.

The tasks of urban electricity system managers are operation and maintenance of the grid, grid development, customer relations, and energy purchasing, relying on the company, DONG Energy in Copenhagen (or other firms responsible for different parts of the

[4] Author's estimation based on the 2013 population of around 5.614 million people, according to the World Bank data, and the final electricity consumption data (Danish Energy Agency 2014).
[5] Percentages have been calculated over total electricity consumption net of distribution losses, based on data from the Danish Energy Agency, 2014.

distribution grid), and they are carried out by a professional management team. This scheme could be classified in the market-based approach studied in the previous block reading.

Part of the previous municipally owned utility (water, waste, and heat infrastructure) did not pass to DONG Energy, but became another private company HOFOR, the Greater Copenhagen Utility. The city of Copenhagen, however, remains the majority shareholder of HOFOR, with 73 percent of the shares (State of Green 2015). Despite not being involved in electricity distribution, HOFOR leads renewable energy and urban energy infrastructure development projects, partnering with DONG and the city of Copenhagen. In particular, HOFOR has been a main player in the development of the offshore wind turbines in the surroundings of Copenhagen that have allowed the city to jump forward in its goals toward carbon neutrality and full supply from renewables (City of Copenhagen 2014a).

Electricity production and producers. Besides these two utilities, and skipping the electricity customers in Copenhagen,[6] the other main players in the picture are electricity producers. The large presence of combined heat and power units adds relevance to the role played by HOFOR, but it is the distribution system operator, DONG Energy, who provides the most electricity to the city. DONG Energy, as one of the biggest energy companies in Denmark, is also the major electricity supplier to the city. Among other key energy producers in Copenhagen, the private company Vattenfall, owned by the Swedish government, emerges as one of the most prominent ones, who sold 8.1 TWh of electricity in Denmark in 2014 (almost 26% of the total consumption in the country) (Vattenfall 2014).

Self-producers are also on the rise in Copenhagen, although they are still a small chunk of the electricity system. These so-called auto-producers only amount to 7 percent of the electricity generated in 2013 (see Figure 6), but they are growing fast and posing their own challenges and uncovering new opportunities for the city (no-CHP auto-producers electricity production grew from 106 to 519 GWh between 2012 and 2013) (Danish Energy Agency 2014).

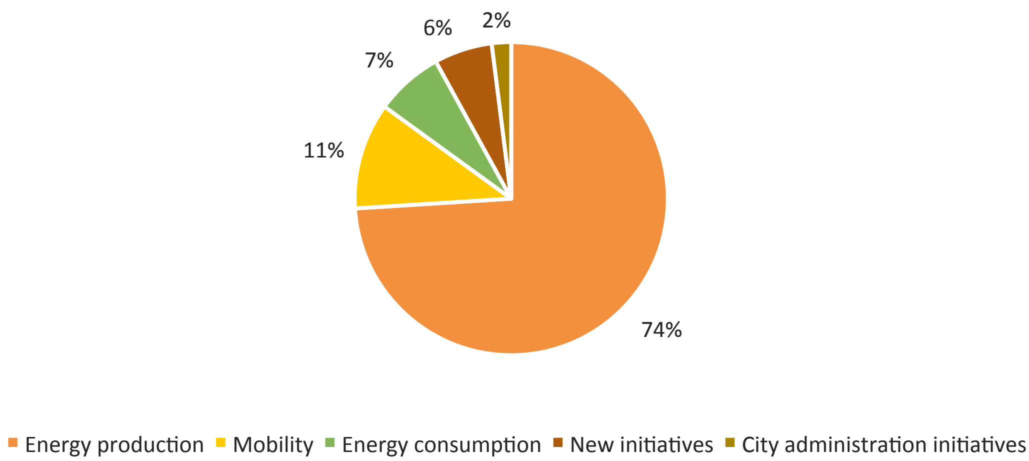

Figure 6: Total carbon emissions reductions distribution among initiatives.
Author's elaboration, adapted from City of Copenhagen 2012b.

***Electricity intermediaries and other players*.** On a final note on other relevant players, it is important to note that Copenhagen employs a hybrid public-private business model for the district heating generation, with the merger of a large heat company based on a cooperative model. The company "purchases heat from the municipally owned transmission company, which itself buys heat from privately owned power stations in the surrounding areas" (United

[6] The role of customers in Copenhagen is addressed in the challenges and opportunities section that follows, where the effect of new loads (such as electric vehicles) and consumers' roles (self-generation, for example) is mentioned.

Nations et al. 2015, p. 98). The 5,260 customers, including residential, industrial, and commercial, become member-owners of the cooperative when they arrange the contract for heat. Copenhagen's municipality also provides the firm with a guarantee that largely reduces its risk and allows it to obtain low-cost financing (United Nations et al. 2015). These features make Copenhagen's case unique. The development model should be carefully studied before trying to extend it somewhere else.

Challenges and opportunities

All the actors are involved in contributing to the achievement of the carbon neutrality and fully renewable energy supply goals. However, all three partners – the city of Copenhagen, as guarantor of the services provision to the citizens, and the utility companies, DONG as the company responsible for the electricity network in the city, and HOFOR as the heat utility and principal renewable energy developer – confront the challenges and opportunities posed by the transformation of the urban region from a protagonist position.

The key challenges faced by Copenhagen relate to environmental challenges and climate change, but also to the inclusion of ICTs in the electricity system, as well as the accommodation of new partners, technologies, and demands.

Environmental challenges. Given the ambitious goals the city has imposed on itself, most efforts are now concentrated on fulfilling the goal of carbon neutrality by 2025. This challenging objective requires the offsetting of 84,000 tons of carbon dioxide per year, in which energy production and consumption in its many forms, including the urban electricity system, will play a critical role (see Figure 6).

To reach carbon neutrality, most reduction is expected to come from energy production initiatives, and the reduction in consumption from commercial buildings (see Figure 6) (City of Copenhagen 2012a). However, the different alternatives to achieve these reductions have distinctive weights. In energy generation, wind turbines are expected to prevent more than 250,000 tons of CO_2, while new biomass-fired CHP units are hoped to cover a similar amount (see Figure 7). On the energy consumption side, commercial customers (using energy-efficiency measures) are expected to play a major role with the 67 percent of emissions reduction in energy consumption coming from them (but this only represents less than 40,000 tons of CO_2, six times lower than the role the deployment of wind energy is supposed to play) (see Figure 7). It is also remarkable to note the ambitious goal for the diffusion of photovoltaics and the role they are hoped to play in reducing emissions from energy consumption (see Figure 7).

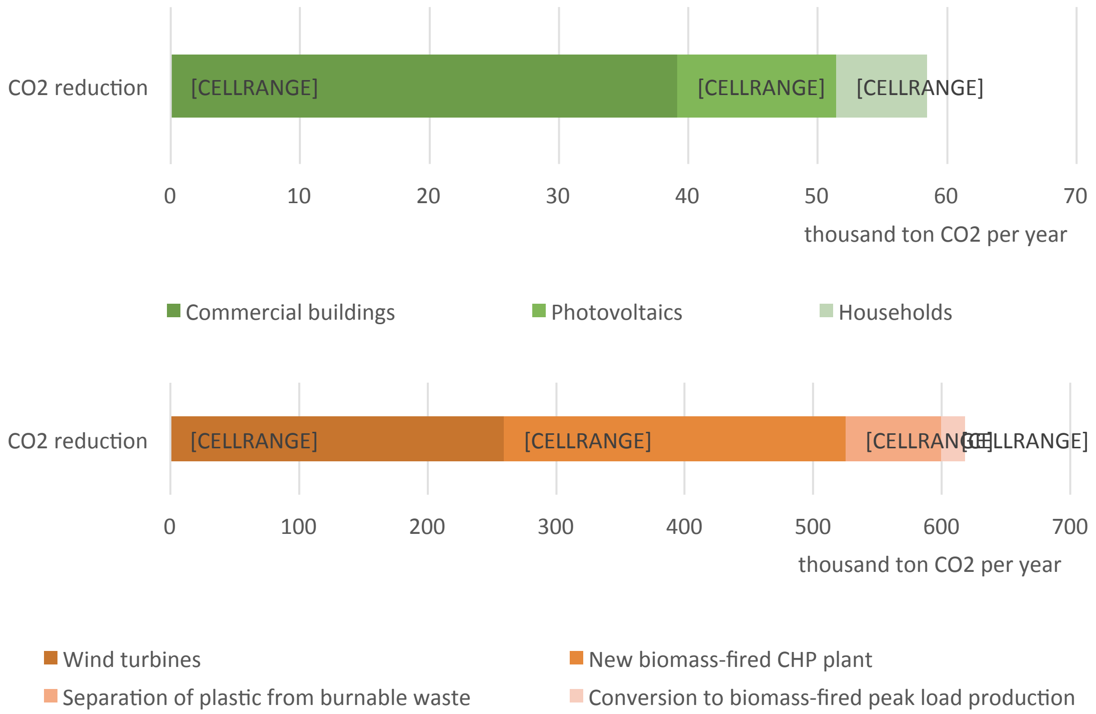

Figure 7: CO_2 emissions reduction allocation in (top) energy production, and (bottom) energy consumption.
Author's elaboration, data from City of Copenhagen 2012b; City of Copenhagen 2012a.

Role of ICTs. Copenhagen is deeply committed to the inclusion of information and communication technologies in its urban electricity system. This brings up opportunities to improve the energy efficiency of the grid and reduce the needs of its development, as well as transform the process of power purchasing due to intelligent loads, putting pressure on DONG Energy.

Electricity market liberalization. Copenhagen has a strong position in favoring market-based solutions complemented by extensive regulation to ensure social responsibility of the players in the urban electricity system. An example of such solutions is the cap on the revenues made by utilities operating in the Danish electricity system (Robles et al. 2011). One of the main challenges the city faces is how to include auto-producers in the current market regulation and formalize the role of prosumers.

To realize the necessary changes in the urban electricity system to confront these challenges (particularly the environmental ones, which currently constitute the main focus), the city of Copenhagen has prepared a battery of actions and strategies, each one containing its own challenges and opportunities.

Increase share of renewable energies. This strategy is mostly based on two trends: converting current and future CHP units to renewable fuels (that is, biomass and waste) and developing new renewable capacity (from wind energy or the sun).

Conversion of CHP from fossil fuels to biomass and waste. The conversion of the city's combined heat and power units from coal to biomass poses the challenge of supplying biomass in an appropriate scale, and from surrounding suppliers so as to limit emissions from its transportation. The city of Copenhagen and HOFOR have been working together and leading this strategy through the transformation of Amager Power plant unit 1 since 2010 (City of Copenhagen 2014b; European Commission 2012). Indeed, by 2010, biomass incineration in CHPs was already the largest renewable electricity producer in the city (European Commission 2012). Seasonality in the biomass supply may also pose a threat for this change, but the increased demand for biomass can be seen as an opportunity for agriculture and forestry companies.

Increasing renewable energy capacity. On the renewable technologies side, over 100 wind turbines need to be installed by 2025, onshore and offshore (City of Copenhagen 2012b). The city council approved a loan guarantee of EUR 738 million to support the investment on this technology by the city's utility company HOFOR, contributing to reducing the challenging financing of the project and grid reinforcement requirements (European Commission 2012). The city is also trying to engage citizens through innovative initiatives, such as becoming co-owners of the projects through shares and helping reduce social acceptance issues, which are a major problem in some countries (such as the United Kingdom or Switzerland) (City of Copenhagen 2012b).

Photovoltaic implementation is also encouraged, and the municipality tried to set the example by installing 1000 square meters of solar in their rooftops (European Commission 2012). Self-generation is often the main product from solar PV diffusion, which poses the challenge of intermittency and dealing with new customer relations, problems the city tries to address by promoting smart energy systems and metering that smooth them out (Mathiesen et al. 2015).

Energy conservation and energy efficiency measures. Reducing consumption by improving energy efficiency, and reducing consumption by changing consumption habits, form the second pillar to reach the carbon neutrality goal.

Reducing consumption through improved energy efficiency. Buildings, which amount to a very large share of electricity and heat consumption, are at the center of this strategy. New buildings will have to comply with tight building codes for energy efficiency, and funds will be made available for retrofits (including EUR 38 million to municipally owned buildings) (European Commission 2012). This will not only lower the electricity consumption, but become an opportunity for distributed renewable production development without grid reinforcements, thanks to the lower power demanded by buildings.

Among the many other actions foreseen to improve energy efficiency, the city of Copenhagen will change all its street lighting for high-efficiency lighting (using LED lamps) (European Commission 2012).

Reducing consumption through changing habits. These measures range from cooperation with Danish energy companies to enforcing an energy-saving obligation based on a market for electricity savings (addressing the challenge of dealing with new energy services based on electricity savings), or to the transformation of modes of transportation.

The latter point is too long to be developed in this case, but the strong support of the city to alternative forms of mobility to oil-fueled vehicles has driven down energy consumption and pollution. Copenhagen has been named the best city for cycling, where people ride nearly 5 km per day, and it is also affecting the urban electricity system given the dispersion of electric bicycles, but also of electric vehicles (private ones and shared) (City of Copenhagen 2014b).

Flexible energy production and smart energy systems. Copenhagen aims to develop a smart grid including smart electricity producers, smart consumers, and prosumers, capable of integrating different forms of renewable sources (such as intermittent wind energy and stable CHP units) and loads (for example, intelligent buildings, self-generating customers), mainly by making use of the most recent information and communication technologies available.

Emerging new electricity loads. New load profiles and more dynamic loads are expected in the urban electricity system as some technologies become mainstream: electric vehicles (either in public transit as seen with the progressive electrification of trains in Denmark (Danish Energy Agency 2014), privately owned, or through sharing schemes), self-adjusting buildings, and others (Mathiesen et al. 2015; Hjøllund et al. 2014).

Smart energy system. Small steps are already on the way, such as the obligation of having smart metering online for all electricity consumers by 2020 (Hjøllund et al. 2014) and building a smart energy system (Mathiesen et al. 2015). However, the city is still far from these goals on many levels. For example, in Copenhagen, the city gets a bundled electricity bill from DONG and only by trying to unbundle the bill is it possible to get an idea of how much electricity is used for traffic lights in the city, because it's extremely difficult to get hourly consumption figures (Hjøllund et al. 2014).

Thus, the challenges, but also the opportunities, to reach a flexible production and smart energy system are large. A comprehensive understanding of the whole urban energy system is required, which is especially important for urban energy infrastructure managers. Integration of the different energy infrastructures (already well on the way with the dominant role of CHP units) will allow cities and their managers to exploit synergies among the energy systems (such as heat pumps to supply heating from low-temperature heat sources by using electricity), but also to create challenges in how to operate and maintain such an intricate system (Mathiesen et al. 2015).

The city is aware of these difficulties and has put forward examples of how to create innovative partnerships to incorporate the different players and stakeholders (for example, the North Harbor Energy Partnership among the city of Copenhagen, City and Port Development, DONG Energy, Copenhagen Energy, and the Ministry of Climate and Energy (European Commission 2012)), in order to enhance cooperation and integral planning.

Conclusion

Making a European capital city carbon neutral and fully supplied by renewable sources is a daunting task for any urban infrastructure manager. In the Copenhagen example, we have had the opportunity to take a look at the role of the urban electricity infrastructure as a key part in achieving sustainable development. By reviewing the current status of the city, the players involved, and the challenges and opportunities they face, it becomes clear the importance of urban energy infrastructure managers and of cooperation among stakeholders across the city infrastructure systems. Thanks to the combined efforts of the multiple players involved, starting from the citizens to the managers of the utilities, and their engagement in the changes (through ownership or inclusive public-private partnerships), Copenhagen can confront confidently such a wide-ranging transition successfully.

References

City of Copenhagen, 2009. *Application for the "Global District Energy Climate Award" - Copenhagen District Heating System*, Copenhagen, Denmark. Available at: https://stateofgreen.com/files/download/1512.

City of Copenhagen, 2014a. *Copenhagen Climate Projects - Annual Report 2014*, Copenhaguen, Denmark. Available at: http://kk.sites.itera.dk/apps/kk_pub2/pdf/1327_khT72sMrcI.pdf.

City of Copenhagen, 2014b. *COPENHAGEN GREEN ACCOUNTS 2014*, Copenhagen, Denmark. Available at: http://kk.sites.itera.dk/apps/kk_pub2/pdf/1393_x6fHiBE3UX.pdf.

City of Copenhagen, 2012a. CPH carbon neutral 2025 - Energy consumption. , pp.10–11. Available at: https://subsite.kk.dk/sitecore/content/Subsites/CityOfCopenhagen/SubsiteFrontpage/LivingInCopenhagen/~/media/F5440DB0C5A64B62A6AED68E51950F43.ashx.

City of Copenhagen, 2012b. CPH carbon neutral 2025 - Energy production. , pp.12–13. Available at: http://usa.um.dk/en/~/media/USA/Documents/News/Copenhagen2025 ernergy production.pdf.

COM, 2014. Compact of Mayors. Available at: http://www.compactofmayors.org/ [Accessed January 2, 2016].

Danish Energy Agency, 2014. *2013 Annual Energy Statistics*, Copenhagen, Denmark. Available at: http://www.ens.dk/en/info/facts-figures/energy-statistics-indicators-energy-efficiency/annual-energy-statistics.

Danish Energy Regulatory Authority, 2012. *2012 National Report Denmark*, Available at: http://www.energy-regulators.eu/portal/page/portal/EER_HOME/EER_PUBLICATIONS/NATIONAL_REPORTS/National Reporting 2012/NR_En/C12_NR_Denmark-EN_v2.pdf.

DONG energy, 2015a. *Dong energy at a glance*, Available at: https://assets.dongenergy.com/DONGEnergyDocuments/com/Investor/Fast_Facts/dong_energy_at_a_glance_en.pdf.

DONG energy, 2015b. Shareholder distribution. *Shareholders*. Available at: http://www.dongenergy.com/en/investors/shareholders [Accessed January 3, 2016].

Dual Citizen LLC & Tamanini, J., 2014. *The Global Green Economy Index - 2014. Measuring National Performance in the Green Economy*, Available at: http://dualcitizeninc.com/GGEI-Report2014.pdf.

Energinet, 2015. Electricity generation. *Climate and Environment, Environmental Reporting*. Available at: http://energinet.dk/EN/KLIMA-OG-MILJOE/Miljoerapportering/Elproduktion-i-Danmark/Sider/Elproduktion-i-Danmark.aspx [Accessed January 2, 2016].

Energy Cities, 2015. Energy Cities. Available at: http://www.energy-cities.eu/ [Accessed January 2, 2016].

European Commission, 2012. Overall goals and objectives in the most recent action plan; The Copenhagen Climate Plan. , pp.1–6. Available at: http://ec.europa.eu/environment/europeangreencapital/wp-content/uploads/2012/07/Section-12-Energy-performance_Copenhagen.pdf.

European Commission, 2014. Winning Cities: 2014 - Copenhaguen. *European Green Capital*. Available at: http://ec.europa.eu/environment/europeangreencapital/winning-cities/2014-copenhagen/index.html [Accessed January 2, 2016].

Eurostat, 2015a. Consumption of electricity per capita in the residential sector. *Electricity and heat statistics*. Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_and_heat_statistics#Consumption_of_electricity_per_unit_of_GDP [Accessed January 3, 2016].

Eurostat, 2015b. Electricity prices for domestic consumers - bi-annual data (from 2007 onwards). *Energy price statistics*. Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics#Electricity_prices_for_household_consumers [Accessed January 3, 2016].

Eurostat, 2015c. Electricity prices for industrial consumers - bi-annual data (from 2007 onwards). *Energy price statistics*. Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics#Electricity_prices_for_household_consumers [Accessed January 3, 2016].

Floater, G. et al., 2014. *Green Economy Leader Report*, London, UK. Available at: https://lsecities.net/publications/reports/copenhagen/.

Frederiksberg Kommune, 2015. Frederiksberg Kommune. *Greater Copenhagen*. Available at: http://www.frederiksberg.dk/da/Borger/Information-in-English.aspx [Accessed January 2, 2016].

Hjøllund, T. et al., 2014. *Copenhagen , Nordhavn*, Available at: http://urbantransform.eu/wp-content/uploads/sites/2/2015/07/D4.2-Copenhagen.pdf.

IMF, 2015. List of per capita nominal GDP for countries and dependencies. *IMF Database*. Available at: http://www.imf.org/external/pubs/ft/weo/2015/02/weodata/index.aspx [Accessed January 2, 2016].

Københavns Statistik, 2014. *Folkeregisteropgørelse primo oktober 2014, Københavns bydele*, Copenhagen, Denmark. Available at: http://www.kk.dk/artikel/folkeregisteropgørelse.

Mathiesen, B.V. et al., 2015. *Copenhagen Energy Vision 2050 - A sustainable vision for bringing a capital to 100% renewable energy*, Available at: http://vbn.aau.dk/en/publications/copenhagen-energy-vision(ccf7d834-06d0-4666-bd52-50c22c0ea96e).html.

OECD, 1999. *Denmark - Regulatory Reform in Electricity*, Paris. Available at: http://www.oecd.org/regreform/sectors/2497351.pdf.

OECD, 2015. *Monitoring the Transition to a Low-Carbon Economy, A strategic approach to local development*, Available at: http://www.oecd.org/cfe/leed/Monitoring-Green-Transition-Final2.pdf.

Olsen, O.J. & Skytte, K., 2002. Consumer Ownership in Liberalized Electricity Markets. The Case of Denmark. *Annals of Public and Cooperative Economics*, 73(1), pp.69–88. Available at: http://doi.wiley.com/10.1111/1467-8292.00186.

Robles, H.B. et al., 2011. Economic regulation of electricity grids in Nordic countries. , 7/2011(NEI-DK-5653), p.116. Available at: http://www.risoe.dtu.dk/rispubl/NEI/NEI-DK-5653.pdf.

Rubin, J., 2012. High energy prices make Copenhagen green. *The Globe and Mail*. Available at: http://www.theglobeandmail.com/report-on-business/rob-commentary/high-energy-prices-make-copenhagen-green/article4325962/.

Spector, J., 2015. The Paris Climate Deal Can't Succeed Without Cities. *City Lab, The Atlantic*. Available at: http://www.citylab.com/cityfixer/2015/12/cop21-paris-climate-treaty-cities-success/420288/.

State of Green, 2015. HOFOR - Greater Copenhagen Utility. Available at: https://stateofgreen.com/en/profiles/hofor [Accessed January 3, 2016].

The City of Copenhagen, 2015. Sustainable City Initiatives. *The City of Copenhagen Official Website*. Available at: http://international.kk.dk/artikel/sustainable-city-initiatives [Accessed January 2, 2016].

UN-Habitat, 2012. Energy. *Urban Themes*. Available at: http://unhabitat.org/urban-themes/energy/ [Accessed December 3, 2015].

UN-Habitat, 2013. *Prosperity of Cities: State of the world's cities 2012/2013*, Nairobi, Kenya: Routledge. Available at: http://unhabitat.org/books/prosperity-of-cities-state-of-the-worlds-cities-20122013/.

United Nations, Copenhagen Centre on Energy Efficiency & ICLEI, 2015. *District Energy in*

Cities: Unlocking the Potential of Energy Efficiency and Renewable Energy, Available at: http://www.unep.org/energy/districtenergyincities.
Vattenfall, 2014. Overview: Vattenfall at a glance. , (April), p.9. Available at: http://corporate.vattenfall.de/Global/Deutschland/vattenfall_at_a_glance.pdf#page=1&zoom=auto,0,579.