Scientific Program “The Future of Energy”

Qualitative and Quantitative Assessment of New Paradigms and Challenges for Urban Energy Systems

Final report

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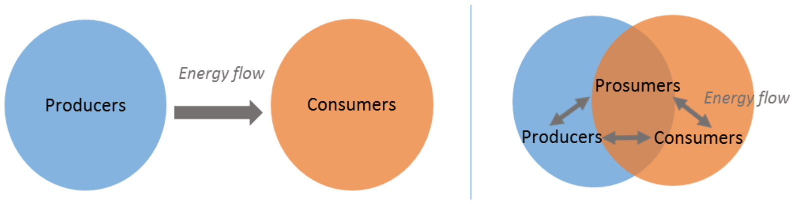
CONTENT

Executive Summary

With this study, the authors address the question of paradigm shifts and challenges which urban energy systems may face in the mid to long term. The role of cities and more broadly urban areas is increasingly gaining importance in the current context of sustainability. Most recent studies see cities as a major contributor to the efforts required to reduce global GHG emissions.

The question of the future of urban energy systems and how these may undergo new paradigms and challenges has been answered through a two-pillar qualitative and quantitative approach.

As a first step, the qualitative approach consisted in a thorough literature analysis to identify, understand and assess ongoing and future paradigms shifts likely to impact urban energy systems engaged in sustainability efforts. While this has allowed to track ongoing trends and possible future developments in terms of innovative solutions, technologies and expected impacts for the energy future of cities (including the increasing role of prosumers, i.e. consumers acting to some extent as self-producers), further lessons were learnt with regards to the prerequisites for a suitable assessment of urban energy systems and their sustainability. In particular, a crucial aspect is to perform such analyses with a fine granularity, i.e. considering specificities of districts' and buildings' types, which enables a representation of possible synergy and optimisation effects, as well as the simultaneous consideration of multidisciplinary requirements, including technical, economic, environmental, social and political aspects. The identification of such key aspects is of utmost importance both to develop and assess adequately strategic plans of urban areas, and, as a logical corollary, to precise which system components need to be addressed in any modelling exercise aiming at providing prospective insights for the long-term planning of urban energy systems.



In the second pillar of this study, Enerdata's EnerCity model has been described and applied for the calculation of three scenarios, with the aim to understand the possible energy pathways of the urban area of Grenoble Alpes Métropole. The model, covering a time horizon of 20 years until 2035, already fulfils some of the prerequisites identified in the literature review, and is based on a three-scale approach: the buildings level, the districts scale and finally the observation of the city/agglomeration as a whole, with a focused consideration of potential synergies and linkages at each step of aggregation. This approach allows in particular to address specific challenges identified in the literature analysis, such as the development of innovative solutions (photovoltaics, combined heat and power, electricity storage), the consideration of "prosumption" flow patterns, energy efficiency potential at the buildings level, and synergy potentials for the energy system through solutions such as district heating and the integration of mobility through the development of electric vehicles.

The EnerCity model has been used to calculate and assess three contrasted scenarios to explore the possible future of Grenoble's energy system: a baseline scenario (BAU) with current policies implemented, an energy efficiency scenario (EE) and a scenario with increased expansion of decentralised energies (DER). The results show that in the BAU case, energy consumption of the agglomeration is expected to increase slightly

(+0.1%/year over 2015-2035), even if the energy mix evolves towards a slight development of district heating and solar thermal equipment in buildings. The implementation of additional energy efficiency measures (EE scenario) could lead to substantial cumulated savings, reaching about 9% over the period compared to the baseline scenario, where demand reduction would be primarily achieved in the residential and tertiary sectors. Setting the effort on decentralised energies (DER scenario) shows promising opportunities for the whole urban area, where specific solutions such as the coupling of photovoltaics with storage solutions, solar thermal as well as geothermal technologies and heat pumps could meet together up to 16% of total energy needs of the metropole by 2035. Such an increase in decentralised means would be ideally coupled with flexibility management tools, leading to a shifting ad smoothing of the consumption load curve in the different districts.

The analysis performed in this study shows both limitations and promising perspectives. The main limitation of such a model-based assessment is the important requirements in terms of data collection and quality. Indeed, running such models requires an extensive amount of very disaggregated input data, e.g. at buildings scale. One of the main recommendations of this work is to further promote the openness of historical energy market data at districts' and buildings' level (e.g. energy consumption per building type, drivers of energy demand in the various sectors, use of district heat in the various quarters, emissions levels, etc.), and ideally at households' level in order to integrate a further socio-economic dimension in the city's assessment.

The work shows great perspectives in terms of further model developments likely to be performed in the future. Although the model already allows to consider urban energy systems as integrated entities and is very descriptive and granular up to the buildings scale, further research can be envisaged to increase its scope and reliability. Such developments include e.g. the consideration of the future potential role of gas and biogas technologies, the development of social indicators (e.g. to better track and tackle energy poverty) in a context of progress towards more sustainability, and more largely, the development of enhanced multi-dimensional indicators, including a systemic-technological dimension to depict how smart solutions can help stabilise the system. Last but not least, an emissions and climate module would capture the underlying dynamics between economic growth, energy consumption and GHG emissions. This could provide a promising model upgrade to help local authorities in their decision-making processes and urban strategies related to energy and climate policies.

List of Figures

List of Tables

1. Introduction

1.1. Context

The role of urban areas in the transition towards a sustainable energy future, i.e. as a contributor to meet global energy and climate targets, represents a complex and interdisciplinary field of research. Given their proximity with inhabitants, workers and infrastructures, local territories and in particular cities have a key role to play and can offer innovative energy management solutions and initiatives through many ways. Indeed, the evolution of urban areas is based on strong interlinkages between infrastructure planning and organisation, technological development and integration, development of new businesses or services, mobility, implication of all stakeholders through consumer/end-users participation and city governance.

According to [IEA, 2016], "*Urban areas dominate global primary energy use and CO_2 emissions. In 2013, the world's urban areas accounted for about 365 exajoules (EJ) of primary energy use (64% of global primary energy use) and about 24 Gt of CO_2 emissions (70% of the global total).*" In addition, IEA's forecasts show that urban areas will most likely play a considerable role in global decarbonisation efforts: the "*world's economic activity and population will be increasingly concentrated in urban areas. Global GDP will triple from US$ 111 trillion in 2015 to USD 337 trillion in 2050, when 84% of GDP will be generated by urban areas. Over the same period, the world's urban population will grow by 62% from 3.9 billion to 6.3 billion, with most growth occurring in developing and emerging economies.*"

These challenges will most likely be accompanied by a significant increase of energy consumption in the residential sector, but also other sectors like tertiary buildings and industry, given the strong correlation between economic growth and energy consumption.

In this context, local territories and urban areas in particular become a key element which energy and climate policies should focus on. This is illustrated in Figure 1, showing the effort required by the various sectors and the share of urban areas to reach global climate commitments.

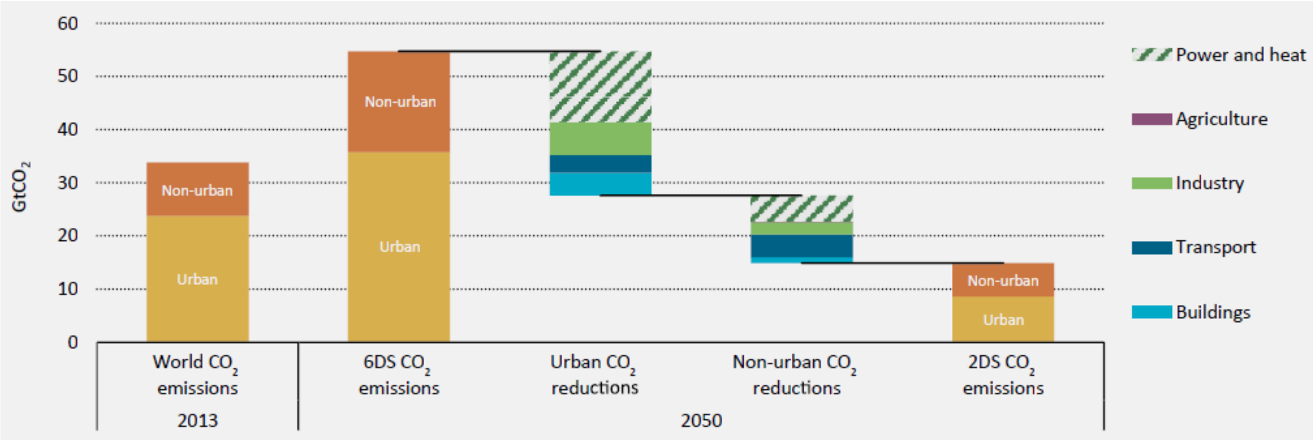


Figure 1: Role of cities in the reduction of world CO_2 emissions 2013-2050

1.2. Objectives of the project

The present report details the work performed by Enerdata within the Fondation Tuck's scientific program "the Future of Energy: Leading the Change".

In the context of the growing role of territories, especially cities, in the contribution to global energy consumption and fight against climate change, Enerdata addresses the topic of "local energy integration of urban areas" through a transversal analysis based on a qualitative and quantitative assessment of new paradigms and challenges for urban energy systems.

With respect to the cross-sectoral and interdisciplinary nature of urban energy systems, the study addresses simultaneously the following topics:

- the study provides an integrated analysis of energy demand in urban areas, including energy needs of the different activity sectors, with a focus on residential and tertiary buildings as well as transport (especially the role of electric vehicles), their drivers and evolution. The analysis emphasises on the existing integration schemes at the local scale;
- a special attention is paid to the topic of linkage to end-users, with an assessment of technological solutions and innovative options for an increased efficiency and integration at the city level.

Extensive work has already been carried out to provide an in-depth analysis of specific aspects of urban energy systems, and researchers have developed different modelling approaches to simulate urban energy demand and supply in a holistic way. Nonetheless, so far limited research activity has focused on assessing and quantifying the impacts of energy integration options at the local scale and evaluating the progress made towards more sustainability.

The purpose of this study is on the one hand to better understand the impact of energy integration – including the role of electric vehicles – at the urban scale, and on the other hand to assess quantitatively these effects in order to answer the following questions:

- which infrastructure and technologies are likely to develop and impact local energy demand? What will be the quantified effect of this future evolution on demand?
- to which extent can the deployment of flexibility instruments, including electric vehicles, support a more efficient energy supply and demand at the local level?

To answer these questions, the study provides, in a first step, detailed insights into the current paradigm shifts and associated challenges that urban energy systems are facing and may have to cope with in the future. The aim is to better capture the current dynamics impacting urban energy systems, along with its drivers; and to synthesise which main trends or parameters prove to be considered to assess properly urban energy systems and their sustainability. In a second step, the study provides a model-based quantitative analysis of the key topics previously identified, through the construction and assessment of three scenarios. Finally, key outcomes and conclusions are discussed, including on potential innovative solutions in the way towards more sustainable cities.

Deliverables of this study included:

- this final project report, detailing for each task the methodology used, the assumptions made, the results achieved and the key learnings;
- a detailed presentation of the project held at the premises of the Fondation Tuck in Rueil-Malmaison on January 17, 2017. The accompanying PowerPoint presentation support is provided to the Fondation Tuck.

1.3. Scope and structure of the study

1.3.1. Scope of the study

The study focuses on the impact of energy integration within urban areas. Today, no unique and common definition of “urban” exists; we based our approach on the widespread understanding of an urban area as an “agglomeration”, i.e. within given administrative or political boundaries.

Due to time restriction and a limited availability of publically available data aggregated at the local level, Enerdata made the choice to focus the literature study on mid-size cities in developed countries, and more precisely in Europe. The topic of energy planning and sustainability in cities is indeed relatively new: European cities have been among the first ones to initiate local sustainable strategies and to document accordingly their approach, and city-data as well as feedbacks, “best practices”, although scarce, are (partially) available.

The model developed by Enerdata, named “EnerCity”, however aims at covering all possible cities configurations, whatever their size, location or role in the global economy. In this study however, the model has been applied to the agglomeration of Grenoble Alpes Métropole, i.e. the city of Grenoble together with 48 suburban cities.

The study is based on a cross-sectoral and holistic approach, and therefore covers all relevant economic activities with the urban energy system. A particular attention is paid to residential and tertiary buildings due to their central role in energy use; an additional focus is made on the potential of electric vehicles and their possible future impact on the demand-supply power balance.

1.3.2. Structure of the study

The work is based on the following tasks, which are presented in detail in the various chapters of this document:

- Task 1 (Chapter 2): **Identification of current paradigms and future key challenges** based on a detailed literature review;
- Task 2 (Chapter 3): **Possible future evolution pathways based on a quantitative analysis** of the key topics identified in Task 1, through the implementation of scenarios built on the key results from the learnings and conclusions of the literature review;
- Task 3 (Chapter 4): **Conclusions and perspectives** of the study.

2. Literature review on current paradigms and future key challenges

2.1. Objectives of the literature review

The literature review aims at identifying the paradigm shifts currently impacting urban energy systems and the challenges they are likely to cope with in the future towards more sustainability; and at better understanding the main drivers of the ongoing or required changes.

On this basis, the review will enable to understand the key components to be considered when assessing energy systems in cities, and to capture the dimensions relevant for tracking the transition of cities and their energy systems towards more sustainability. Further, it will help assess the most promising solutions to be encouraged by cities to evolve in this direction.

In addition to these outcomes, the review will allow to check on the one hand which aspects are taken into account in the local energy model "EnerCity" developed by Enerdata, and which aspects should be focused on in future development efforts.

2.2. Methodology

This section describes the approach used for selecting the documents reviewed and presents the analysis framework used.

As a necessary preliminary step before undertaking the review, we conducted a brief keyword internet academic research on the definition, features and specificities of urban energy systems. It is indeed necessary to identify clearly the constituents of urban energy systems to define clearly the scope of the topic, to break it down by component so as to identify existing or possible interactions within the system, and thirdly, to analyse specificities of urban energy systems compared to other systems, or to identify differences between energy systems in different cities.

Once "urban energy systems" are better delimited, the next step includes a review of publications dealing with the new paradigms for and transformations of urban energy systems, as well as the main associated challenges, existing solutions or recommendations. Over the last years, cities and their energy systems have gained more and more attention from research as they were progressively identified as a central catalyser for a switch towards more sustainable ways of living, especially as regards their role in the reduction of energy consumption and in mitigation actions – a topic for which countries have committed themselves to strong efforts during the COP21. The question of "urban" and "energy systems" has been studied through a myriad of specialised articles and papers, and covered by experts from various disciplinary fields. The topic is indeed complex and covers many disciplines, from urbanism to sociology, economics, econometrics to energy expertise. However, much fewer publications explicitly deal with the issue of transitions and ongoing or future changes in urban energy systems.

Our review targets internationally recognised publications, based on the underlying idea that changes described and identified should reflect general trends or concepts that can be applied for and replicated by the majority of cities (however, it has to be kept in mind that each city, according to its history and specificities, can of course face specific changes and challenges). The selected publications offer a focus on changes, their impact on the traditional key features of urban energy systems which need to be considered to model and assess urban energy systems and their performances in terms of energy consumption and sustainability.

Moreover, our literature review focuses primarily on publications based on a cross-sectoral approach of urban energy systems and offer a complete and transversal insight, integrating possibly synergy effects.

The criteria used for selecting publications in our literature review are summarised in the table below:

Criteria	Targets
Theme	Urban Energy systems: focus on definition, features, changes and challenges
Scope	General and systemic approach, no focus on a specific issue or type of city
Type	International publication
Authors	Internationally recognized experts, organisations or institutions, from all backgrounds (academics, business, political, …)
Date	As recent as possible

Table 1: Scoping the literature review: selection criteria

The publications selected at this stage of the literature review are presented below. The detailed analysis framework used for the documents' selection is summarised in the Appendix I of this report.

Title	Author(s)	Date of publication
Energy Technology Perspectives 2016	International Energy Agency (IEA)	2016
Renewable Energy in cities	International Renewable Energy Agency (IRENA)	2016
Advancing Toward a more Sustainable Urban Energy System- Policy and Technology Considerations	International Energy Agency (IEA) and World Resources Institute Ross Center for sustainable cities	2015
Strategic Energy Technology Plan (SET)- Towards an Integrated roadmap: Research and Innovation Challenges and Needs of the EU Energy System	European Commission	2014
Energizing sustainable cities: assessing urban energy	A. Grubler and D. Fisk (IIASA)	2013
Energy Vision 2013- Energy transitions: Past and Future	World Economic Forum in Partnership with IHS CERA	2013
Urban Energy Systems- An integrated approach	J. Keirstead, N. Shah	2013
Challenges and ways forward in the urban sector	United Nations Department of Economic and Social Affairs (UNDESA)	2012
Global Energy Assessment- Toward a Sustainable Future	International Institute for Applied Systems Analysis (IIASA)	2012
Cities of tomorrow - Challenges, visions, ways forward	European Commission	2011

Table 2: Scoping the literature review: list of selected articles

In a further step, the literature review has been focused on reports from non-academic authors (strategy plans or case studies from policy makers, city councils, etc.); in particular, a special attention has been paid on a best practices and experiences from European cities in order to check whether their fields of action cover the shifts and drivers of change identified in the first step of the literature review. This benchmark allows to understand the potential gap between theoretical concepts and the actions/projects implemented by cities. Finally, this provides an indication on which topics are of particular relevance for developed cities, and therefore help understand which parameters should be carefully analysed and represented in the EnerCity model used in the quantitative assessment of this study.

The selection of reviewed cities was made among European cities recognised for their strong commitment in sustainability and local energy management. Within the European Union, about 120 cities are involved in energy and climate programs such as Sinfonia and Concerto, or have been rewarded for their urban energy policies through "labelling" (European Green Capital award from the European Commission, "Gold" cities of the European Energy Awards). A complete overview and analysis of all European labelled cities is out of scope of this project, so the review was restricted to a panel of 10 cities, however with the objective to cover a high diversity of countries, contexts, sizes and densities.

The list of selected cities is presented below. The selection of the published documents for each city was principally based on two criteria: information newness (i.e. most recent reports) and the level of detail of the strategy and actions described.

Name	Country	Label	Strategy and Action report/document used
Bolzano	Italy	Sinfonia	"Aktionsplan der Stadt Bozen für nachhaltige Energie" (APNE) (2010-2020)
Bristol	UK	European Green Capital	"The 20:20 plan: Bristol's Sustainable City Strategy" (2009)/ "Bristol Climate Change Strategy" (2015)
Brussels	Belgium	European Green Capital	"Regional Air-Climate-Energy Plan" (2016)
Copenhagen	Denmark	European Green Capital	"CH 2025 Climate Plan" (2012)
Freiburg-im-Breisgau	Germany	European Green Capital	"Environmental Policy in Freiburg" (2011)/ "Klimaschutz-Strategie der Stadt Freiburg" (2007-2020)
Geneva	Switzerland	Concerto	"Politique énergétique et climatique de la ville de genève - Objectifs Politiques et Stratégiques- Plan d'actions 2014-2018"(2014)
Grenoble	France	Concerto	"Plan d'Action Air Energie Climat de la Ville de grenoble étape 2016-2020" (2016)
Hambourg	Germany	European Green Capital	"Master Klimatschutz – Zielsetzung, Inhalt und Umsetzung" (2013)
Ljubljana	Slovenia	European Green Capital	"Energy for the City of the Future- Presentation of the Sustainable Energy Action Plan of the City of Ljubljana" (2012)
Stockholm	Sweden	European Green Capital	"Stockholm action plan for climate and energy 2010–2020" (2009)

Table 3: Cities selected for the literature review

A summary of the actions and programs implemented by these cities, sorted by type of challenges addressed, is available in the Annex.

2.3. Results

2.3.1. Definition of urban energy system, specific features and consumption drivers

Definition of urban energy system

Before starting an in-depth review of urban energy systems and the key changes and challenges they are facing on their way to more sustainability, it is first necessary to define "urban energy systems" more precisely. The goal here is to identify the main features and specifics of urban energy systems: what are their constituents, and how these are interwoven. This preliminary work is essential to subsequently analyse how current changing trends impact all or some of these constituents, and which characteristics may prove to be key drivers in coping with these changes.

Very few publications explicitly attempt to define clearly urban energy systems or to identify their specific features. Defining urban energy systems – the most commonly terminology found in the literature rather refers to "energy systems in cities" – requires to answer a complex issue: what is a "city", or a "urban area"? Which boundaries should be considered: administrative, functional, territorial? A "city" can indeed refer to a merely administrative unit – the *de jure* city –, also defined as the "city proper" by the United Nations, which represents “the single political jurisdiction which contains the historical city centre” [UN Habitat, 2009]. It refers to a certain population density (e.g. population threshold above 100,000 inhabitants for IRENA in its 2016 study, whereas the United Nations definition of city includes cities with less than 100,000 inhabitants). More largely, a “city” can also refer to physical or socio-economic realities, which have been approached through either a morphological or a functional definition: in this case, the city is not restricted to the administrative borders of the legal entity, but includes “the perceptions of an urban way of life and specific cultural or social features, as well as functional places of economic activity and exchange” [European Union, 2011]. A definition of cities based on such a functional approach has been developed jointly by the European Commission and the OECD: it is based on building blocks which are seen as “the functional urban areas’ smallest administrative units for which national commuting data are available” [OECD, 2013]. There is no clear and commonly accepted definition so far, although this can lead to different representations and results in terms of energy consumption. Any assessment of urban energy systems should therefore clearly explain the scope of the “urban area” covered, for example an administrative agglomeration including several communes.

Whatever the definition applied to the “city” or “urban area”, and the type of city considered (small, medium or large city), the literature converges towards a representation of the city as intricate and connected socio-economic, technical systems. Urban energy systems, corresponding to the way city produces and uses energy sources, represent one of its core component: “The vital urban infrastructures all depend on energy: water supply, treatment and waste water disposal, transport and communication systems, complex webs of food and material supplies, the resulting disposal of wastes, and, of course, energy supply itself” [IIASA,2012]. In the same way as cities, urban energy systems should not be restricted to energy infrastructure, but also include all social, political and technical processes which structure energy production and use.

This aspect is emphasised in the definition proposed by Keirstead: urban energy systems can be seen as “the combined processes of acquiring and using energy to satisfy the energy service demands of a given urban area” [Keirstead and Shah, 2013]. The term of “combined processes” emphasises the fact that the delivery of energy and energy services is the result of successive steps, including resource extraction, refining, transport, conversion, storage (e.g. a mobility need, the consumption of gasoline, does not only require the fuel to be made available at the tank station, but first oil to be extracted from an oil field, processed in a refinery, transported and then distributed in the considered city). Urban energy systems do not only refer to energy infrastructure within the city, but to the entire value chain of processes needed to deliver a final energy service to different end-use sectors (transport, industry, residential and services, etc.). Existing interactions between the different processes and the various sectors in place are a key attribute of urban energy systems. For this reason, a systemic approach for analysing urban energy systems is essential: the analysis of energy consumption of an isolated activity sector will only provide an incomplete and most likely misleading picture if there is no understanding of how this sector is linked to others. For instance, it can be interesting for a city to retrofit and develop an old quarter where buildings have a poor energy efficiency. However, if this quarter is remote from activity areas, good public transport solutions should also be provided: otherwise at the city level, energy savings made thanks to retrofit could be counterbalanced by the necessity for residents to commute by car.

Moreover, delivering an energy service includes both “acquiring” (production) and “using” (consumption) processes, i.e. it is essential to consider supply as well as consumption patterns for analysing urban energy systems. In the past, strong attention has been paid to supply issues such as energy security, or resources scarcity, but much less on demand: consumer was – and to some extent is still – seen as a passive stakeholder in the urban energy system. The notion of “energy services demand” is all the more crucial in a context of targeted energy efficiency: the question is not only to quantify how much energy consumers use, but also to identify to which purposes consumers use energy sources, how they use them and if there is a potential for a more efficient way to deliver the demanded energy service.

Characteristics of urban energy systems

If energy systems in cities do not fundamentally differ from other energy systems generally speaking, they show however some specific features [IIASA, 2012]. First, they are characterised by “a high density of population, activities, and the resulting energy use and pollution”; furthermore, they show a “high degree of openness in terms of exchanges of flows of information, people, and resources, including energy"; and "a high concentration of economic and human capital resources that can be mobilised to institute innovation and transitional change".

Density is generally defined as the number of people per square kilometre. We see clearly here that urban energy systems are in essence source of high spatial densities of energy use as they concentrate a large and growing population in a limited space, resulting in high population density compared to rural areas. In the same way, urban transport systems present a "high density of travel demand within limited space". On the one hand, high and concentrated levels of energy demand can allow significant economies of scale in supply and transport for example; the high diversity of activities settled in a city, and a sufficient mix of these activities can lead to significant economies of scope (e.g. use of heat from industries to supply residential consumers). On the other hand, in a context of sustainability, high population density and the resulting energy consumption often lead to negative externalities, such as environmental and health issues. This density attribute therefore leads to an inherent challenge for urban energy systems: how to supply energy for all while limiting the negative effects of a concentrated energy intensity?

The two further features of urban energy systems, i.e. openness and concentration of economic and human resources, are key assets as they can facilitate energy transition through a better acceptance of changes, a quicker evolution of behavioural patterns and a greater ability to implement and finance innovative solutions. Urban energy systems are "fertile ground for science and technology, for culture and innovation, for individual and collective creativity, and for mitigating the impact of climate change" [European Union, 2011].

Drivers of energy use in urban energy systems

Historically, population growth in urban areas and income increase have been the drivers of urban energy demand. Nevertheless, many parameters, whose combination define the uniqueness of each city, can impact its energy use [IIASA,2012].

Natural environment can play a significant role through the geographic location of the city, the climate, as well as its resource endowments (e.g. solar potential in a sunny city).

Urban spatial and organisational form is an important macro-determinant of urban energy systems and can have a strong impact on local energy consumption. The quality of the built urban environment (buildings stocks, energy, transport, water and waste infrastructure) and their spatial distribution are paramount. Last but not least, the function of the urban environment is crucial: diversity of activities coupled to significant mixed land-uses, in contrast to a city where different activities are located in separated zones, can enable energy optimisation, through minimised travel needs or the deployment of district heating for example. As mentioned above, density is also a key feature of urban energy systems. The literature review identifies a minimum density threshold of around 5,000 to 15,000 inhabitants per square kilometre below which urban energy use, especially for transport, increases substantially.

Socio-economic characteristics of the city are also important to consider, such as demography, households' characteristics (size, composition, etc.), the structure of the economy (e.g. value added by type of activities) and its dynamics. The local governance system, through its ability to control the organisation of energy markets and promote initiatives or investments, can influence urban energy consumption.

2.3.2. Identified paradigm shifts impacting urban energy systems

The international publications reviewed, mentioning several paradigms as key change trends currently impacting urban energy systems, are summarised in the paragraphs below.

From a cost-effective urban energy system to a « sustainable » urban energy system

Historically, the economic point of view has prevailed over other non-economic considerations when building urban energy systems. Thus, cities were settled near available resources in the past: a river for water, forests for biomass [Rutter, Keirstead, 2012]. With the growing industrialisation and from the 16th century, a transition towards a new organisation of the system took place: energy sources are exploited or produced at a large-scale and more cost-effective level, in fields (coal mines, more recently oil and gas plays) which are often far from inner cities and their suburbs. This change had a huge impact on the design of the still existing urban energy infrastructure, as it led among others to the development of long (but expansive to maintain) pipes networks, which enabled to transport energy from hinterlands to cities centres, or in other regions and even countries. It therefore resulted in a growing disconnection of consumers and supply location and patterns. The expansion of electricity at affordable costs in the late 19th century also deeply impacted the structure of urban energy systems, as cities became progressively dependent from a national network system. However, the recent increasing concerns about sustainability and the "external costs" of energy systems such as environmental and health issues significantly call today's urban energy systems into question.

With the concept of sustainability, development is not only assessed through economic progress, but also based on social and environmental pillars. In this context, today's challenges for urban energy systems can be summarised as followed: how to provide affordable and clean energy to all citizens of a city in the most efficient way in order to limit energy consumption and the impact on our living environment? This represents a radical change as previous energy transitions are characterised by an increasing per capita energy use [Rutter, Keirstead, 2012].

Taking into account the various dimensions of sustainability in the assessment of urban energy systems induces an additional difficulty as it requires to identify and analyse not only energy processes and infrastructure, but also their impact on and interlinkage with the environment and socio-economic context. It means that traditional energy indicators, such as energy use per capita or total GHG emissions, cannot capture alone the progress of a local energy system towards more sustainability.

From fossil fuels-based central energy systems to distributed renewables energies

Modern urban energy systems have been massively relying on fossil fuels: the first wave of industrialisation was based almost on coal alone, with the apparition of a disruptive technology, the steam engine. Coal replaced wood as the world's dominant fuel. The next major transitions took place with electricity and the internal combustion engine, and oil replaced coal in transport. Today, coal, oil and gas still represent about 80% of energy consumption for transport and buildings in cities [IEA, 2016]. However, the share of renewables in the energy mix has been skyrocketing over the last decade, boosted by falling costs and driven by a mix of technological innovation and enabling policies (subsidies, carbon tax): at the global level, solar installed capacities have been multiplied by 48 between 2005 and 2015, and wind installed capacities by 7 over the same period [Enerdata, 2016].

Low-carbon energies appear as a key option to reduce GHG emissions and reduce pollution, and many cities have already committed themselves to reach a 100% renewable energy system on the long-term, with zero net carbon emissions (such as Copenhagen, Bristol, Geneva). Some of the most promising technologies are in building-integrated PV, urban wind turbines, micro-CHP or solar cooling systems such as absorption or adsorption chillers.

Figure 2 lists renewable energy options available for cities in the transport and buildings sectors, as well as their potential according to different types of cities (low to high population density). Most of these technologies, which can be directly embedded in the local building environment, are redefining the structure of the energy system of the city: from fossil-fuels power plants connected to cities through a national transport and distribution network, urban energy systems are progressively moving to a local power generation pattern. In the future, a possibility could be that local distributed power generation becomes dominant, and the national distribution systems are only used as back-up [Patterson, 2009].

However, it is crucial to note that the supply potential of renewable energies within the spatial and functional boundaries of a city remains very limited; this can be seen through the analysis of power density, which corresponds to the rate of energy production per unit of land, measured in W/m^2 [Smil, 1991]. When comparing energy demand and power densities of different energy sources, it appears that the energy demand density of a city, which can range from 10 to 100 W/m^2 [Grubler and Fisk, 2013], significantly exceeds the low energy density of renewables (0.1 to 1 W/m^2). Due to this mismatch between (high) urban energy demand density and (low) renewable energy supply densities at the local level, it is estimated that renewable energies can, at best, provide 1% of the energy needs of a megacity and a few percentage points in smaller, low-density cities [IIASA, 2012]. Figure 3 provides an overview of the power density of a few renewable energies versus the average energy demand density of a city.

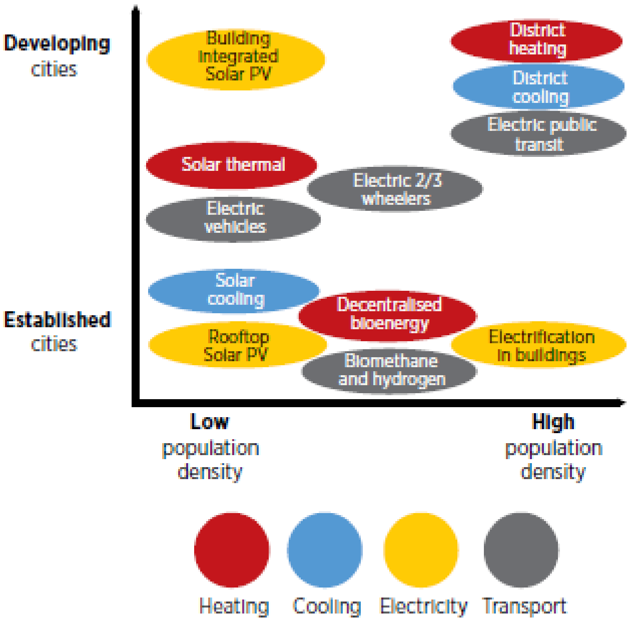


Figure 2: Renewable energy options and their potential in transport and buildings for different types of cities (source: IRENA, 2016)

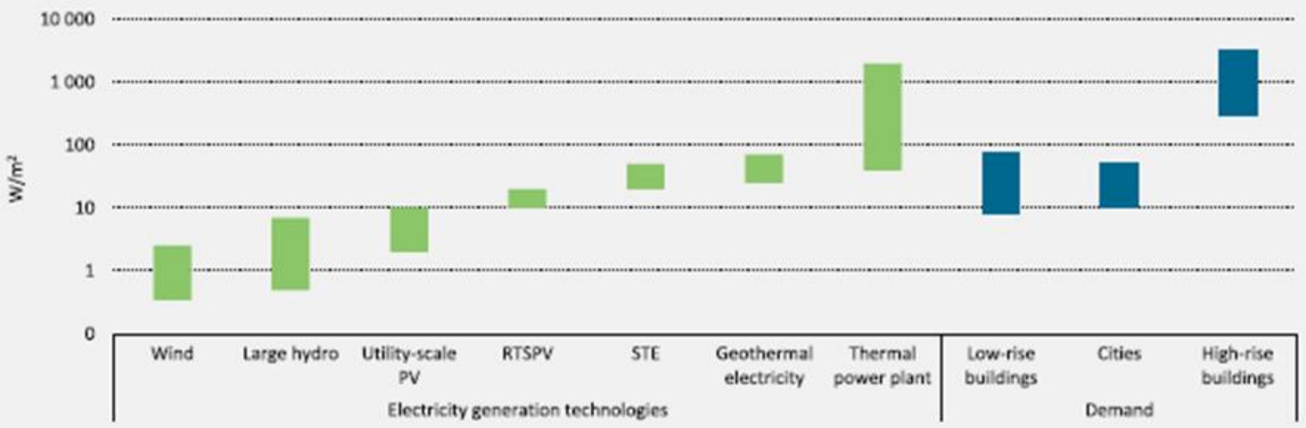


Figure 3: Energy supply densities by renewable energy type compared with typical energy demand densities (sources: (IEA, 2016) and (Smil, 1991))

On the other side, the high population and energy demand densities, typical of urban areas, can be an advantage for the deployment of renewable options: district heating networks, but also expansive transportation solutions such as metro systems, require a minimum population density to be cost-effective. The question for cities is therefore to assess to which extent densification of existing quarters should be promoted or limited in order to avoid negative impacts.

From one-way production-consumption approach to multidirectional urban energy system based on "prosumers"

Traditionally, the structure of energy systems was seen as polarised around two distinct poles: energy production on the one hand, and final energy consumption on the other hand. The two are historically linked thanks to transport and distribution networks, drawing a one-way energy flow from producers to more "passive" consumers.

As unanimously mentioned in the literature, the emergence of the consumer as an active player in the energy system at the local scale represents a significant transformation for urban energy systems. With the development of distributed renewable energies (rooftop solar PV, heat pumps, etc.), households are turning from end-users (consumers) into "prosumers" (simultaneously producers and consumers, see Figure 4). Commercial and residential buildings are amongst the largest energy consumers in cities, but in an urban energy system where local renewables are growing, they are also the most widely available urban resource. As mentioned by the United Nations in its Sustainable Development in the 21st century (SD21) Project, "In the new era, businesses, municipalities and homeowners become the producers as well as the consumers of their own energy; In the 21st century, individual access to energy also becomes a social and human right. Every human being should have the right and the opportunity to create their own energy locally and share it with others across regional, national and continental intergrids." [UNDESA, 2012].

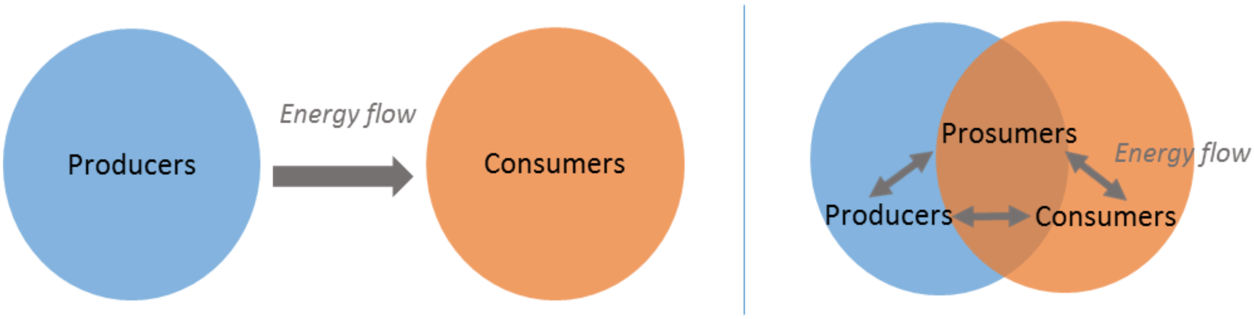


Figure 4: Shift from one-way production-consumption approach to "prosumers"-based urban energy system (own illustration)

The growing use of Information and Communication Technologies (ICT) such as the development of smart applications, enabling to connect and control "end-use" energy appliances in real-time, and the uptake of local solutions such as power storage technologies or electric vehicles, can help pushing the "prosuming" trend: consumers decide when to produce or consume, and have now the choice to use the produced energy (self-consumption), store it or sell it on the grid.

From a central and top-down governance system to local shared decisions involving stakeholders

Since decades, energy policies and issues have been focused on the supply-side of (urban) energy systems, with strong concerns regarding resources availability, energy security and self-sufficiency at the national level, or the diversification of the energy mix. Energy strategies and plans have been under the supervision of national ministries and central bodies. Nevertheless, with the rising awareness of sustainability, whose concept depends upon the participation and involvement of all citizens and stakeholders, a "re-municipalisation" of governance regarding energy matters at the urban scale can been observed. The launch of the U.N. Agenda 21 action plan in 1992 emphasises the importance of implementing energy initiatives at the local level.

Whereas some issues depend from national and centralised decisions, it appears that the local level can be more effective for specific matters; developing the urban transport network, or implementing coherent urban planning, requires a strong knowledge of the considered territory, its history and structure. The growing development of distributed energies which are directly embedded in the built environment (residential or commercial buildings) makes a local approach even more appropriate. Local governance structures have also a role to play in the deployment of more sustainable energy systems in cities, as they can better respond to challenges that are rooted in to the urban scale. According to cities' global umbrella organisation United Cities and Local Governments (UCLG), this decentralisation trend is based on two main arguments: first, local governments are considered "closer to the people than the central governments, and they have superior access to local information that allows them to better respond to the needs of citizens". Secondly, they "face stronger incentives to perform well on local matters than the central government, so that they are in a better position to derive the most from public resources at their disposal and are more likely to seek innovative means of doing so" [UCLG, 2010]. The way energy is used in cities is thus likely to be more and more influenced by local decisions.

To ensure democratic and transparent decisions, urban governance and cities should involve the different bodies of government, citizens and other stakeholders. New governance modes based on "innovative use of social capital" are needed [European Union, 2011].

Furthermore, winning over citizens' support is a prerequisite to make them actively participate in the transformation of the city's energy system and initiate behavioural change as regards energy consumption habits.

2.3.3. Underlying challenges and solutions

The previous section focused on the main paradigm shifts that are transforming cities' energy systems today. The energy transition brings many challenges for cities and their energy systems; the most important of them are analysed below. If these challenges can be seen as problematic issues, they can however turn to future opportunities thanks to technological innovations, but also to new socio-economic and governance schemes. The path to sustainability requires to re-think completely the organisation and structure of urban energy systems; key options and recommendations from the literature review are also detailed in the coming section.

Developing an affordable and socially inclusive urban energy system

As mentioned in part 2.3.2 of this document, the aspiration of cities to develop sustainable energy systems, which are compatible with high quality standards for all, have supplanted a merely cost-based vision regardless of the negative impacts on environment or society. Still, providing a universal access to energy and energy services at an affordable price remains a burning issue for all nations and cities. The issue of an affordable energy is often considered as a central topic for cities in developing countries, where an estimated 800 million low or middle income urban dwellers live in poor-quality and overcrowded housing with inadequate provision for basic services [UN Habitat, 2008]. But "energy poverty" is also a major challenge for developed countries; if the majority of households have access to all basic energy services, some of them however struggle to "pay the bill" for electricity and fuels as they typically spend more than 10% of the household incomes [Buzar, 2006] in energy. According to a study published by the European Union, nearly 11% of the European population is not able to adequately heat their homes at an affordable cost [Insight-E, 2015]. At the city level, "the developed and the developing world coexist in some form, creating the tensions of segregation and the challenge of inclusion" [UNDESA, 2012]. Inequity occurs, as the poorest households often live in old and low-efficient buildings, in quarters located far from the city centre, leading to higher transportation costs. In their ways towards a sustainable future, it is therefore essential for cities to come up with innovative solutions that do not depend on the most expensive technologies with high maintenance costs.

Over the last decade, the costs of power generation infrastructure from renewables has strongly decreased and further costs reduction can be reached through continuous learning and scale-up: between 2010 and 2015, "global average onshore wind generation costs for new plants fell by an estimated 30% on average, while costs for new utility-scale solar PV declined by two-thirds" [IEA,2016]. In the transport sector, Bus Rapid Transit (BRT) System for example is much cheaper that the expansion of a metro system and can represent an interesting option in terms of energy consumption and emissions.

Implementing affordable solutions for all would also help in avoiding a “lock-in” of infrastructure into systems that are dependent on heavy investment and maintenance expenses; adaptable systems, which can evolve and integrate easily adaptable new technologies, should be preferred.

Maintaining security, resilience and flexibility of urban energy systems

Supply side: towards a sustainable energy system with an increasing share of renewables

The progressive shift towards a lower-carbon energy supply based on a growing share of distributed renewable sources offers great opportunities for the future as regards the systems’ security and resilience. For the first time, the energy mix relies on a range of various energy sources including fossil energies, nuclear or renewables sources, whereas previous energy transitions were characterised by the emergence and predominance of one energy (from biomass to coal, then from coal to gas/electricity) [WEF, 2013]. Unlike fossil fuels whose scarcity is growing, renewables are also largely available.

The development of renewables is a key necessity for enabling a decoupling between energy related GHG emissions and economic growth. From a strategical point of view, it also appears as an interesting option: the development of distributed renewable technologies in urban energy systems means more local procurement, which in turn also means increased energy security (less dependence) and resilience to external shocks (such as oil price shocks). As mentioned by J. Rifkin, “the shift from elite fossil fuels and uranium based energies to distributed renewable energies, takes the world out of the ‘geopolitics’ that characterised the 20th century, and into the ‘biosphere politics’ of the 21st century" [Rifkin, 2009].

However, renewable energy sources, such as biomass, wind, and solar, vary greatly in intensity and availability, both seasonally, daily and even hourly. This intermittency is an important technological constraint for the stability of the energy system, and the integration of a significant share of renewables therefore requires an active renewable management to balance supply and demand, and a much greater operational flexibility on the grid. Due to the increasing share of variable renewables in the energy mix, “fossil fuel power plants will have to increasingly shift their role from providing base-load power to generating fluctuating back-up power to control and stabilise the electricity system” [European Commission, 2014].

This need for more flexibility as well as the complexity of balancing the system is exacerbated with the current development of distributed storage solutions in all sectors (electricity storage or thermal storage for air conditioning), and the expansion of plug-in electric and hybrid vehicles, which can also be used as local storage solutions. Yet, these solutions can also be of great advantage to reduce the energy consumption and smooth the power load if properly coordinated. In the near future, cities will therefore have to find ways to integrate new solutions and technologies for granting a proper energy management on the overall system.

In some of the papers reviewed, further advanced concepts based on the aggregation of local energy resources are also mentioned as key solutions for enhancing the reliability of the grid. The deployment of “micro-grid” system architecture, which is a small power grid segment that can works autonomously from the larger electric grid, can enable to aggregate distributed energy sources at lower costs; it can operate completely independently and therefore improves the resilience of the whole system. “Virtual power plants” (VPP) represent a new business model particularly suited to cities. The concept refers to the creation of a cluster of several types of individual power sources or loads (micro-CHP, photovoltaics or batteries from local residents and businesses, micro-grids); this energy aggregator manages both supply and demand sides of its portfolio, and has the ability to deliver peak-load power in a very short period. Thanks to their greater flexibility than conventional power plants, VPP can react better to fluctuations and therefore provide direct solutions allowing high shares of variable energy sources. Yet, they require complex and integrated systems which combine advanced control and forecasting systems with demand side management in order to propose an adequate balance. Thanks to a real-time optimisation of energy resources, VPP also enable to manage local energy by optimising costs. “By aggregating energy demand, cities can negotiate competitive rates with power suppliers and developers, between 3% and 10% lower than utility rates” [US LEAN, 2015].

In addition to technical measures, greater flexibility can be ensured by relevant policies and regulations schemes, for example through flexible pricing (e.g. solar power cheaper during the day).

Ensuring a better flexibility: smart grids and demand-side at the centre of the urban energy system

Given the strong need of an increased flexibility, the emergence of smart grids associated with the development of a proactive demand-side management are becoming major areas of focus as they represent innovative technical solutions to cope with this flexibility challenge.

Smart grid refers to an electricity transmission and distribution system based on "an increased use of digital information and control technology to improve reliability, security, and efficiency of the electric grid" (US Energy Independence and Security Act of 2007) thanks to the use of 'smart' technologies which enables a real-time and automated optimisation of the power network. Smart grids can "pave the way for efficient grids, intelligent power distribution and consumption" [UNDESA, 2012].

In this context, Information and communication technologies (ICT) play a central role for a better synchronisation of demand and supply: system optimisation can be supported by two-way digital communication devices connected to the grid such as smart power meters, fault detectors or voltage sensors. Smart grids will enable utilities to increase "their level of control [and action] over millions of connected devices, and to manage demand and power flows in real time" [IRENA, 2016] thanks to sophisticated metering equipment and enhanced real time information to both producers and consumers. Through more intelligent and interoperable systems, consumers and prosumers can become more active and energy efficient. Meanwhile, these innovative solutions using ICT can "contribute to the minimisation of the costs of expanding, upgrading, interconnecting, maintaining and operating the electricity grid" [European Commission, 2014].

The need for an increasing flexibility associated with the growing trend of "prosumption" have encouraged utilities to focus on consumers' energy consumption at a very granular level: the use of mobile devices indeed allows a real-time identification of energy needs per end-use and households. Demand-side management has therefore emerged as a key enabler to support controlling or reducing electricity consumption. Demand-side management refers to the ability of changing energy consumption at any given point of time for optimising available and planned power generation resources. Today, several tools allow to track and influence customers' energy use such as smart metering and appliances, load limiters, frequency regulation or the use of an effective time of use pricing. This can result on one hand to a significant load shift, i.e. customers are encouraged to reschedule their consumption when prices are lower (off peak times) or switch off temporarily unnecessary equipment; the effect is a decrease in peak demand (without changing total energy consumption), and the load curve becomes "flatter", as illustrated in Figure 5.

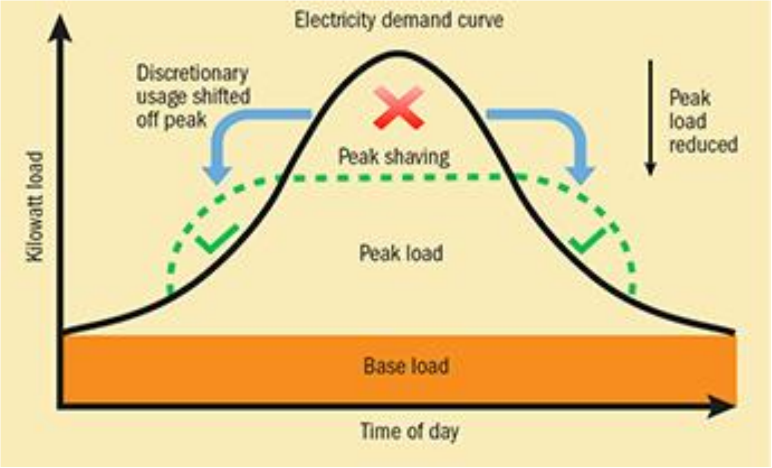


Figure 5: Demand-side management and the effect of load shifting (source: [IMF, 2016])

On the other hand, demand-side management can motivate end-users to use more energy efficient appliances thanks to the availability of transparent information about consumption and pricing. This can lead to a reduction both of peak-demand and total energy consumption. In the end, demand-side management can bring substantial benefits for both producers and customers.

In the future, the compilation of robust and real-time disaggregated data could allow to better predict individual's energy consumption patterns, even leading to a "situation in which load could 'determine' or 'chase' generation, rather than the other way around, as is the practice today" [WEF, 2013]. Demand-side management could therefore have a significant impact on the organisation of processes within the urban energy system.

Increasing energy efficiency across the urban energy system

The energy transition towards sustainable systems in cities is based on the central necessity to moderate energy use. Efforts made on the supply side to turn to a lower-carbon and optimised generation mix alone won't enable cities to cope with ongoing and future climate change objectives; meanwhile, it is essential for cities to strive to consume less and save finite resources, or to consume them in a more efficient way. Energy efficiency measures are generally estimated among the least-costly options for GHG abatement. Increasing energy efficiency therefore appears as a key challenge for reducing cities' impact on the environment and progress towards a more sustainable future.

Energy efficiency potentials can be tapped immediately at all levels of the urban energy system, both thanks to technical improvements and behavioural change of energy users. The literature unanimously identifies two sectors with the largest potentials for energy savings across the energy system: buildings and transport.

Efficiency in buildings

According to the IEA, urban buildings account for about 60% of the total global building floor area (2013) and therefore represent a huge source of energy consumption. Nearly 80% of the total building electricity and commercial heat consumption in 2013 is estimated to come from urban buildings, and more than 80% of the total global building electricity growth by 2050 is expected to come from urban buildings [IEA, 2016].

If energy consumption by end-use vary widely among cities, space heating and cooling together remain generally the largest urban building end-use (from 30% to 50% as for 2013) [IEA, 2016], followed by cooking and water heating uses, in developed countries. In the EU, improving heating and cooling energy efficiency is one of the focuses of the Energy Efficiency Directive (2012/27/EU).

Retrofits to improve the thermal efficiency of existing building stocks appear as a key option to reduce energy use and CO_2 emissions. According to the Global Energy Assessment, retrofitting buildings can reduce heating and cooling energy requirements by 50-90% [IIASA,2012]. This can be achieved through building insulation (envelope's performance), thermally efficient windows and doors, improved air cooling or heat equipment such as air heat pumps and heat exchangers. Retrofit of social-housing buildings also offer the opportunity to address the energy poverty issue. Many cities have launched retrofitting measures for their own public buildings to lead the change as good examples. Modernising the existing building stock of a city – especially in "old" European cities with a large architectural heritage – is a necessity to control urban energy consumption.

In new construction, the emergence of (net) zero-energy buildings (i.e. building's energy consumption not higher than the energy produced by this building) or passive buildings that can reduce energy use for heating and cooling up to 90%, shows that high performance levels are technically possible. However, the IEA notes that these performance levels are not always cost-effective, and research and development activities, as well as product promotion are needed to improve in this segment. The trend towards more efficient buildings should be further propelled by ambitious energy performance standards. The analysis of the IIASA shows that a 46% reduction of global final energy use for heating and cooling is possible over 2005- 2050 through use of existing state-of-the art practices in design, construction, and building operation technology, despite increasing amenities and comfort [IIASA, 2012]. As noted by the UNDESA, sustainable buildings do not necessary require high-tech solutions; as suggested by the "passive design" strategy, buildings can take advantage of ambient energy sources or urban fabric features to moderate their energy use: for example, the orientation of the building should facilitate natural cross ventilation, solar heat storage or – depending on the climate zone – try to take benefit from shade of adjacent buildings.

Besides retrofitting and solutions for new buildings, shifts to more efficient buildings will be driven by improved household's equipment efficiency. The adoption of more efficient lighting equipment (e.g. LEDs) or energy-consuming appliances (fridges, washing machines, computers, etc.) can significantly impact the energy consumption of the residential and tertiary sectors. Today, a large panel of renewables heating equipment is available, from solid biofuel-fired boilers (e.g. wood pellets) to solar thermal heaters for domestic water heating and heating purposes.

In addition to technological improvements, energy consumption of households can be strongly reduced thanks to deep inhabitants' behavioural changes (light switching in empty rooms, waste recycling, etc.); changes in consumption habits can also have a significant economic impact: for example, it is commonly admitted that increasing the indoor temperature of 1°C leads to a 7% surplus on consumers' energy bills. For this reason, programs for informing and raising awareness of citizens are essential; incentives through subsidies or financial support (tax reduction) can also be useful. In all cases, it is essential that local authorities or organisations define precise actions to the specific needs of the targeted public. Involving participation of citizens in this process appears as a prerequisite to achieve long-term sustainability objectives of the energy transition.

Efficiency in transport

Another major source of energy savings is the transport sector. Transport accounts for around one third of global energy use in cities today [IRENA, 2016], and IRENA's Roadmap for a Renewable Energy Future (REmap) suggests this could increase to 35% by 2030. In cities, the continuously growing population and activities afflux has led to a significant "urban sprawl" which in turn has increased transport and commute needs and congestion within the urban area.

In this context, three axes for action are essential: minimising travel needs, introduce an increased modal shift (transfer on another mode of transport to avoid congestion) and a transition to cleaner transportation equipment. This is the so called "'avoid-shift-improve" framework [IIASA,2012]. Modal shift and the development of cleaner technologies for all type of vehicles require a structural change in transport structure and design, whereas avoiding travels requires a change in passengers' or customers' behaviour.

Assuming an uptake of renewables in the power generation mix, the electrification of the transport sector, both in private and public transport, is a promising opportunity to reduce greenhouse gas emissions and the associated pollution which represents a major health concern for numerous cities. In private road transport, hybrid and electric vehicles are gaining shares and could represent up to 10% of the total vehicle stock at the global level by 2030 [IRENA, 2016]. Batteries of all-electric vehicles can achieve a very high efficiency (more than 90%, four times the efficiency of an internal combustion engine vehicle, excluding generation and transmission losses of the electricity). Moreover, there are still opportunities to improve the efficiency of conventional vehicle technologies. The use of biofuels in conventional vehicles is an alternative, and many countries have already implemented blending mandate at the national level.

In the public transport sector, many cities are developing electric transport with the deployment of further tramways or metro networks: nearly 160 cities worldwide had a metro system in 2014 [IRENA, 2016]. In 2014, 513 km of new metro infrastructure were added worldwide [IRENA, 2016]. Nevertheless, the high costs of the technologies require minimum density thresholds and are therefore not well suited to all cities. This should be taken into account when considering to develop transportation networks in the urban area. Other transport types can prove very efficient and cost-effective such as electrical buses, whose number has strongly increased, driven by improvements in battery performance, falling technology costs and the ease of charging in bus stations. Hydrogen represents another promising technology and several cities have introduced hydrogen busses in their fleet. The technology is however still in its infancy due to relatively high costs.

On the long-term, improving the efficiency of the transport sector will require not only technical innovation and fuel diversification, but also a deep quality and quantity improvement of public modes of transport in order to ensure affordable and optimal access to mobility for all urban citizens. Both the decision to travel and the choice of how to travel (type of transport) will affect fuel consumption, and citizens must be encouraged to use public transport or/and non-motorised transport instead of private cars. This can be achieved by reducing travel distances within cities through compact urban design that improves accessibility to jobs and services, and by facilitating the use of cheaper non-motorised modes such as cycling or walking (e.g. deployment of cycling lanes).

ICT will eventually be able to eliminate some urban mobility needs, through services such as teleconferencing, telecommuting or distant work, and virtual shopping for products like books and music.

Efficiency in industry

It is worth mentioning that energy savings potential from the industry sector is barely discussed in details in the reviewed publications, although energy savings can be significant: IIASA estimates that adopting the best achievable technology in different industrial sectors can result in savings of 10-30% compared to the current energy use levels [IIASA, 2012].

The recent ETP report of the IEA provides a detailed insight on the issue of quantifying “how much industrial energy use is urban?”. Industry is identified as a major contributor to energy consumption (about 40% of the final consumption at the global level in 2013); however, there is currently a strong lack of plant-specific data about the exact location of plants, their associated fuels inputs or their emissions. It is therefore extremely difficult to define precisely which industrial energy use is included within the urban-scale system.

Furthermore, the literature review underlines the efficiency potential derived from industry through the development of co-generation or district and cooling networks. Every year, huge amounts of heat are indeed lost from power generation or industrial processes. These technologies allow to reuse the heat produced and therefore contribute to a greater efficiency of the system as a whole, as detailed in the next section.

Further energy efficiency opportunities: the need for an integrated system

Energy systems of cities are facing various challenges to turn towards more sustainability in the future. Strong changes are occurring, impacting both the supply and demand sides as well all components and sectors of the local energy system. The previous sections show that innovative solutions exist to moderate the energy use in cities, especially on the demand-side thanks to great energy savings potential in the buildings and transport sectors. Considering these challenges and alternatives in an isolated way nevertheless does not enable to capture significant potentials of the overall system. As suggested by the definition of urban energy systems and their characteristics, interrelations between the different components of the urban energy system are a key feature to take into account, and a systemic approach (i.e. where changes in one element of the urban system may induce changes in others elements) seems more effective to adopt rather than single isolated actions. For example, the expansion of public transport networks should be highly dependent on the urban plan for the development of residential and commercial areas.

Vertical and horizontal integration as basis for optimisation of the system’s structure

One of the key assertion of the reviewed literature is the necessity of a system-based and integrated approach in order to identify all key drivers or opportunities when assessing urban energy systems. The optimisation of the urban system as a whole requires to develop new methodologies and solutions which ensure more efficient interactions between its different parts, and to better coordinate different and sometimes conflictual policies such as energy, climate or social measures.

The ongoing deployment of “smart grids”, together with the progressive development of storage technologies, can support a stronger vertical integration by facilitating the synchronisation of demand and production, which can interact in real-time in all sectors of the economy.

With the electrification of the transport sector and the growing penetration of electric vehicles, transport and power will become increasingly interconnected. Individual batteries, if vehicles are connected to the grid, can be used as local storage and as means to balance electricity loads: by shifting when vehicle batteries are charged (“smart charging”), or by discharging batteries when power delivery is needed on the grid (“vehicle-to-grid”). In the transport sector, railway systems can be used as energy storage facilities.

Thanks to the density and diversity of urban energy demand and to the concentration of multiple sources, urban areas also offer unique synergy opportunities between the various energy networks coexisting such as electricity, gas, heat, and transportation. At the individual level, heat pumps technologies for example provide a direct solution of using electricity to supply heat.

The reviewed documents underpin the prevalent role of cogeneration and trigeneration as a proven technology for integrating efficiently heat/cooling and power. Combined heat and power (CHP) allows to generate power while also capturing the usable heat that is produced in this process. The parallel development of district heating and cooling networks make it possible to reuse the locally produced heat by delivering it to residential or commercial end-users. They offer strong economic and environmental benefits: they enable economies of scale, avoid wasted heat and reduce energy losses due to transmissions. District heating and cooling networks contribute to the decongestion of electricity networks and can therefore enhance their stability. The potential of district and heating systems varies between cities: due to their high investments costs, they generally require a minimum level of energy demand density for district heating to be economically viable.

More generally, the development of multiple energy carriers’ solutions which enable to use local and surplus energy resources such as waste, biomass, or geothermal resources can strongly increase the efficiency of the whole urban energy system. For example, municipalities can coordinate district heating schemes with other municipal functions, such as waste management or sewage.

In a “distributed multi-generation” system, the simultaneous production of power, hot water or heating/cooling from different energy sources is made possible through the interaction of interconnected small-scale plants scattered over the local territory and linked to “centralised” energy transportation networks [Keirstead and Shah, 2013]. The development of efficient conversion technologies, enabling to switch from one energy carrier to another, will be essential. According to Smil, “the overall level of primary energy supply and its composition can be substantially modified by still considerable opportunities for more efficient use of energy: transitions toward universally adopted optimal conversion efficiencies could be as important as harnessing of new energy resources” (as cited in [WEF, 2013]).

One of the promising existing electricity conversion technologies is power-to-gas, with solutions based on hydrogen or methane. The adoption of distributed multi-generation systems may lead to significant benefits in terms of higher energy efficiency through high synergies at the local level, reduced CO_2 emissions, and enhanced economy through the optimisation of total investments in the system while increasing its safety and flexibility.

Figure 6 provides an overview of the technologies and concepts used as basis for an integrated urban energy system.

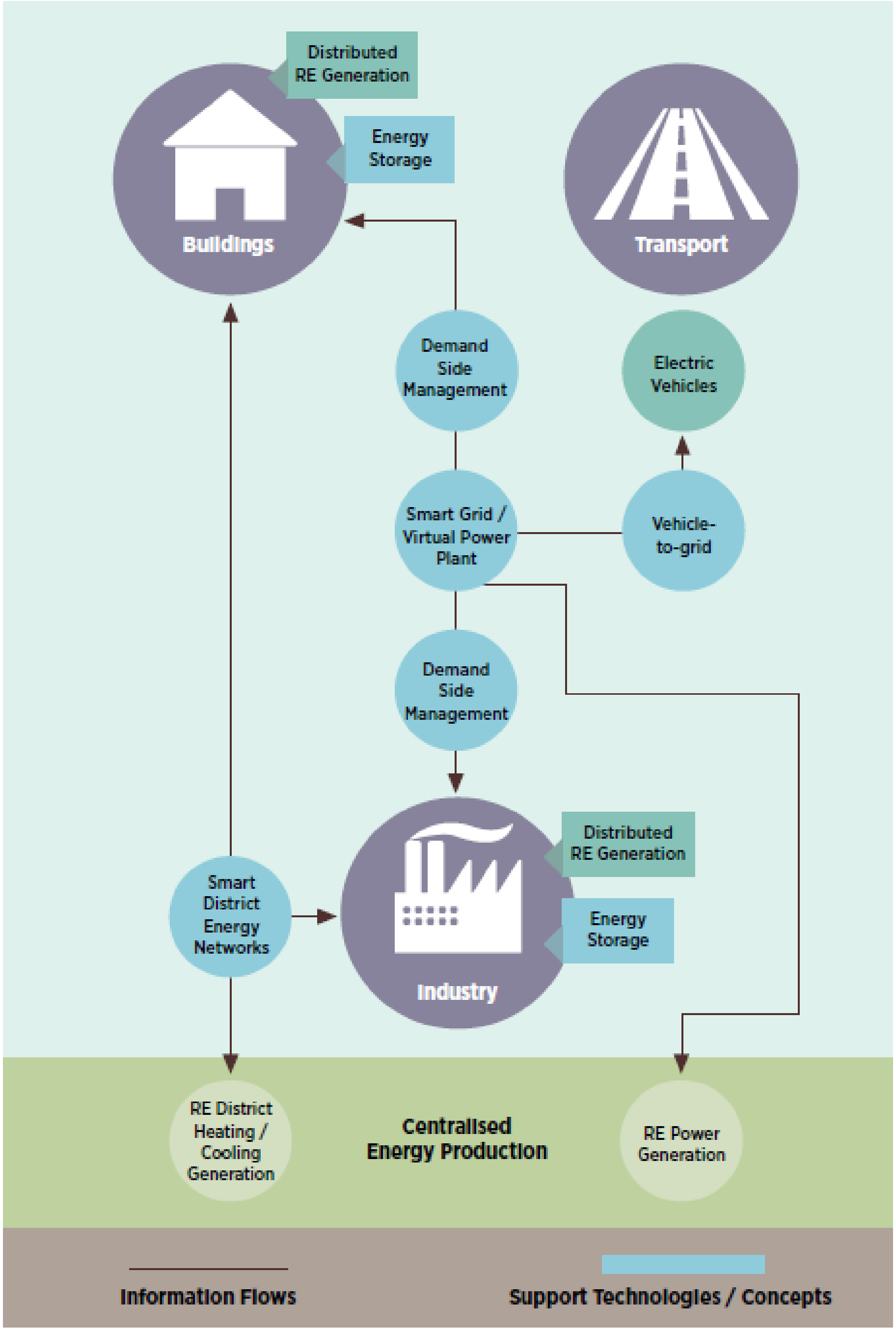


Figure 6: Technologies and concepts used as basis for an integrated urban energy system (source: IRENA, 2016)

The sustainable interconnected use of energies in cities however require a comprehensive and integrated understanding of the urban energy system as well as the associated technical, economic, social and political issues. In order to capture all energy reduction potentials, innovative methods and creative tools for an integrated vision and planning of the urban energy system should be promoted, based on the analysis of the whole energy system and of each of the energy networks with regards to the effects of substituting one type of energy supply by another.

The challenge of an integrated vision for policy and governance

Considering the urban energy system as an integrated framework, with its multiplicity of activities and services (buildings, industry, transport, transformation processes (power generation, heat, waste, etc.)) and interactions will lead institutions to address complex and various challenges or topics and to cover sectors and spatial scales that are traditionally outside their mandates. A sustainable answer to current issues should also integrate all dimensions of sustainability, including social, economic, environmental and spatial dimensions. It should "look beyond the energy sector to [integrate] urban planning, building design, waste management, and urban agriculture" [IRENA, 2016].

Depending on the challenges and topics that have to be addressed, the different territorial and governance levels will have more or less relevance. The literature identifies a strong need for flexible multi-scalar governance, which can combine both national and local competences according to the fields of action considered. Governance systems of the future must be able to reconcile national and cities' targets as well as to develop a shared vision reconciling all local and possibly conflictual objectives in the use of resources.

This represents a difficult task and to some extent a new kind of "governance paradox" [UNDESA, 2012]: most of the solutions and opportunities deriving from current challenges indeed require a system-based approach and policy integration, but meanwhile these policies should be rooted in the specific local context in order to be as effective as possible. This often leads to uncoordinated and dispersed actions. A flexible and multi-scale governance will avoid policy fragmentation but will encourage policy repartition between the relevant authorities and stakeholders.

If a new flexible and multi-scale governance scheme is needed to ensure a sustainable energy system in the city, it is also essential that local authorities can mobilise the necessary resources to implement their local energy strategy. Cities can of course benefit from national legislation which currently provides fair subsidies to support investments in renewables; but they should also evolve towards a role of "financers of renewable energy projects" [IRENA, 2016] by developing themselves innovative financing mechanisms for energy efficiency and energy supply, taking properly into account risk and rewards. A few existing innovative solutions are mentioned in the literature, most of which were initiated in US cities. One solution used by local governments is the Property-Assessed Clean Energy (PACE) model, in which low-interest loans are subsidised for homeowners who invest in renewable energy or energy efficiency; costs are progressively paid back by the property owners through an additional property tax. A second emerging alternative is the Sustainable Energy Utility (SEU) model: the SEU is a non-profit, community-based utility which is financed by low-interest municipal bonds; the gathered capital is then used to contract with private energy service companies to conduct energy efficiency or renewables programs. The bonds are repaid by the customers thanks to the energy costs savings realised. A third model developed in 2014 is the Integrated Utility Services (IUS) model, mentioned by [IEA, 2016]. The model is based on an on-bill financing mechanism: customers pay for a package of customised energy services (energy efficiency measures, renewables, demand-side responses, etc.) which are proposed by the municipal utility and its contractors. The IRENA also mentions the "Mankala" model, developed by Finnish municipalities, which is based on the cooperation of municipalities and operators through the creation of a joint-venture. Operators sell electricity and heat at non-profit to stakeholders, and in return municipalities pay a share of costs proportional to their share in the joint-venture, which allows to de-risk the financing of the structure.

These few examples show that innovative solutions to answer the financing challenge of sustainable energy systems require a strong participation of both local governments through enabling policies and industry players.

Empowering stakeholders and ensuring participation

One of the biggest challenges for ensuring the sustainability of urban energy systems is the ability to empower stakeholders in the different processes which form the energy system. This is only possible through a strong community engagement in the energy debate.

The participation of citizens and organisations is necessary for a democratic and participative governance and "innovative use of social capital are needed" [European Union, 2011] with the objective that "energy can be democratized" [UNDESA, 2012]. The implementation of the transition will require a greater social dialogue for an enhanced cooperation between public authorities, companies, research institutions and end-users, in order to ensure benefits to the whole society.

The participation of stakeholders, especially end-users, is all the more essential as urban energy systems of the future are evolving under the new paradigm of active consumers at the centre of the urban energy system. The shift towards “prosumers”, and the success of a smart system based on an enhanced demand-side management, can only be possible if customers actively take part in the system.

Consumers and various stakeholders should have the possibility to “become ‘active’ with a minimum learning curve [European Commission, 2014]: engaging consumers can be achieved through transparent communication and information programs which can drive a better understanding of the current issues and opportunities at stake. Increased social interaction and citizens’ participation in the local governance can be reached through the development of public consultations at the city or neighbourhood level. Trainings, but also more “responsive education systems” [European Commission, 2014], can further support the development of new skills to boost innovation and market transformation.

The necessity for a significant change in end-consumers’ behaviour is another major issue for moving towards a sustainable future in cities. The trend towards efficiency-aware behaviour patterns can be supported through the implementation of innovative but user-friendly technologies, products and services. Once again, communication campaigns have an essential role to play in raising awareness among citizens.

The development of innovative soft ICT solutions represents a key opportunity to give voice to citizens. Digitalisation can be helpful in opening access to information and to many services for customers, who, as a result, can adapt their energy consumption in real-time.

Availability and quality of urban data, a critical step as basis for a better assessment of urban energy systems

Fast urbanisation growth, spatial concentration of activities and the resulting increasing energy consumption of urban areas have put cities at the centre of attention when considering climate change and mitigation issues. But until now, most of the energy and emissions statistics or forecasts are based on national statistics. The issue of the availability and access to urban-specific data, which present a high robustness and quality level, is therefore critical.

As mentioned in section 2.3.1, there is currently no unique definition of what falls under the terms of “urban” or “city”, and the boundaries of urban energy systems can therefore differ accordingly.

Investment in long-term data capabilities is needed to provide detailed and robust energy statistics at the urban scale, i.e. including buildings’, districts’ and cities’ energy use and emissions data covering all major energy demand and supply sectors. Such data are crucial to identify major drivers of urban energy use and emissions, establish energy and emissions baselines, and monitor accurately the progress towards local and national targets.

Besides an enhanced availability of quality assured city-specific data, a further challenge is the ability to provide reliable and comparable data. Today, there is a big discrepancy among cities concerning the scope and quality of information. The development of platforms for information sharing could accelerate the adoption of best practices. Nevertheless, benchmarking cities between them proves to be a difficult task as they can use different accounting frameworks (e.g. production-based vs consumption-based accounts). Transparency about assumptions and methods used as well as data disclosure are key for both data quality and integrity, but also for well-informed policy choices [IIASA, 2012].

To properly assess their energy systems, cities need a solid knowledge base of their environmental, economic, human resources and social capital, and a better understanding of how these different activities are linked. Indicators are required to measure progress towards objectives on this range of various topics and to evaluate the effectiveness of sustainability strategies, thus ensuring a proper monitoring and reporting of the progress made.

Even with very comprehensive data sets (including for example socio-economic data), it is difficult to understand and analyse some issues such as e.g. behavioural patterns and social acceptance. Hence, cities also have to develop new tools able to deal with such more qualitative issues.

Last but not least, the growing role of information technology for balancing energy supply and demand and on how energy is used, puts an even greater emphasis on the need for disaggregated local data. The collaboration between the different stakeholder communities is essential to ensure the collection of the relevant energy data at the local level. The acceptance of disaggregated data collection about end-consumers and their habits will be of utmost relevance, and special attention shall be paid to data privacy and security.

2.3.4. Cities in action: an overview of current and planned actions

In the previous sections, the review of international and transversal studies on paradigm shifts and challenges impacting urban energy systems has enabled to identify general main issues to cope with for cities, as well as existing solutions to move into the desired direction of sustainability. In this section, we selected 10 European cities referred to as “early adopters” of sustainable energy practices in order to analyse if and how the general concepts and trends previously identified are taken into account by these cities. For this task, only primary local sources were used; the comparison is based on the analysis of the most recent sustainability or climate actions plans published by the cities (in original language when possible).

The list of the different topics, as identified in the literature review, covered by the portfolio of actions and measures of each city is summed up in Table 4.

The key common elements underlined in the different action plans analysed are in the paragraphs below.

Buildings retrofitting and development of public transport as core levers for an enhanced efficiency

In all cities analysed, implemented or planned measures are strongly focusing on buildings and transport.

In the buildings sector, cities target a better efficiency mainly through retrofitting of public and private buildings, associated with the implementation of high energy efficiency standards for new buildings.

A large panel of actions is proposed in the transport sector: reducing private transport by car appears as the key objective. A near-majority of cities describe measures to encourage modal shift from private cars to non-motorised transport or public transport, in particular through the expansion of cycle lanes and zones, especially for “home-work” or “education-work” travels (Brussels, Copenhagen). Additionally, cities aim at providing enhanced public transport networks (bus, tramways, metro) which rely on cleaner technologies (biofuel-powered busses in Stockholm, completely carbon-neutral public transport targeted in Copenhagen); they also target a better coordination and an optimised networking of the different transport modes.

It is interesting to note that a great number of measures are proposed to limit and reduce the negative impacts of private road transport: many cities intend to optimise and modernise their traffic lights through urban traffic control management or the deployment of intelligent traffic systems (Copenhagen). The development of car-sharing or low emissions zones where only efficient cars are allowed are also identified as options. Last but not least, several cities describe “dissuasive” measures to avoid car traffic, such as new parking planning including an increase of parking fees (Ljubljana) or the implementation of a congestion tax to deal with congestion and traffic disturbances (Stockholm, Ljubljana).

Development of local renewable energies: a key target

Most of the reviewed cities have set explicit targets as regards the share of renewables in their final consumption which often outreach the 2020 EU binding target (20% of renewables in final energy consumption). The objective to reach 100% renewables has been set for Copenhagen (CO_2 neutral energy supply by 2025), Freiburg-im-Breisgau (2035), Bristol (2050), Stockholm is aiming at a 100% renewable power supply by 2050, and Geneva targets 100% renewables for covering the energy needs of its municipal buildings by 2050.

The development of local renewable energy sources is therefore a prerequisite. All reviewed cities are promoting solar energy; depending on their location and the associated renewable resources potential, cities also plan to increase the use of various renewables such as geothermal power (Bolzano), wind (Copenhagen, Freiburg, Hamburg), marine energy (Bristol) or biogas (Freiburg).

Challenge and solutions	Bolzano	Bristol	Brussels	Copenhagen	Freiburg	Geneva	Grenoble	Hamburg	Stockholm	Ljubljana
Affordability and social inclusivity		x	x	x	x		x	x		
Security, resilience and flexibility										
Increasing share of renewables	x	x	x	x	x	x	x	x	x	x
Demand aggregation/mutualisation			x					x		
Smart systems, demand-side management	x	x	x	x			x	x		
Storage	x	x	x	x				x		
Other				x (hydrogen)				x (VPP, PTH,PTG)*		
Increasing Energy Efficiency										
Energy Efficiency in Buidings										
Retroffiting/ Eff. Standards for new buidings	x	x	x	x	x	x	x	x	x	x
More efficient Equipment/Appliances		x			x		x(public)	x	x	x
Behaviourial change					x			x		
Energy Efficiency in Transport										
Modal shift/ Develop public transport	x	x	x	x	x	x	x	x	x	x
Electrification and fuels diversification	x	x	x	x	x	x		x	x	x
Decrease transport needs		x	x	x	x			x		
Other (logistics, traffic optim., tax, …)	x	x	x	x	x	x	x	x	x	x
Efficiency in industry			x		x			x		x
Integrated system										
District heating/cooling (with renewables)	x	x	x	x	x		x	x	x	x
Cogeneration, multiple energy carriers	x		x	x	x			x	x	x
Integrated planning and policies	x	x		x	x		x	x		x
Multi-scale governance	x	x	x	x	x	x	x	x	x	x
Improved Monitoring + Report. inc. follow-up	x	x	x		x		x	x		x
Empowering stakeholders										
Improved communication and information	x	x	x	x	x		x	x	x	x
Enhanced participation in decision processes	x	x		x	x		x	x		x
Inovative Financing schemes		x	x	x	x	x		x		x
Other										
Water	x	x	x	x	x	x	x	x	x	
Waste	x	x	x	x	x	x	x	x	x	x
Sustainable Procurement	x	x	x	x	x	x	x	x	x	x

** VPP=Virtual Power plant, PTH= Power-to-heat, PTG=Power-to-gas*

Table 4: Key challenges and solutions, and coverage by action plans of the 10 cities selected

Integrated approach for a transition towards sustainability

There is a common awareness in all reviewed cities plans and strategies about the necessity to provide an integrated actions and policies framework when it comes to deal with climate change and energy.

Cities are making efforts to set a strategic energy planning, based on a transversal approach of the different sectors or energies covered; in particular, transport is identified as an integrated component of the urban energy system by all reviewed cities, and the proposed solutions integrate both energy and transport networks as well as the possible synergies trough an increasing electrification or the increase of renewables.

Moreover, cities have developed a broader vision of urban energy systems, and many of them integrate heat, air quality, water, waste in networks and transportation issues. Some cities even include a larger scope with actions and measures including city “logistics” (Bolzano, Hamburg) as a whole, such as goods or food distribution patterns. Reviewed cities have all defined targets to develop sustainable public procurement schemes, including the purchase of “green” energy but also of energy-related products with environmental certification.

The integration of energy carriers and the potential synergies from "the possible energy exchange between power, gas and heating networks" is also considered by a majority of cities. District heating/cooling systems as well as cogeneration are the most quoted technologies to develop further.

Many cities have identified the importance to establish a local utility rooted in the local environment and able to offer appropriate energy products and services (e.g. creation of the Bristol Energy Company).

Regarding governance, all cities are addressing the need for involving the various stakeholders – companies, organisations, citizens, etc. – for developing a sustainable energy strategy. Some cities underline the importance of a municipal governance able to act at multi-scale levels, e.g. at the regional level, through an enhanced cooperation with other municipalities as well as at the national and international level; Brussels for example set a goal to "participate in and impulse the creation of an inter-federal or international transport coordination".

The role of the city as initiator and enabler

The necessity to empower all shareholders in action and decision processes appears clearly in the reviewed local action plans. Especially, the role of municipalities as initiator of best practices is strongly underpinned. The sectoral measures targeted by cities are mainly declined for the public sector in priority, and municipalities aim at "leading by good example". Thus, the totality of reviewed cities has set up energy consumption and efficiency measures in public buildings, from retrofitting measures to the integration of renewable sources or to the supply of "green power" for administration buildings. Actions targeting public lighting are also implemented by the great majority of cities and are seen as a cost-effective measure with direct and significant impact on energy use. In the transport sector, most of the cities explicitly set up measures for reducing the environmental impact of the city administration vehicles fleet through the improvement of vehicles efficiency or the deployment of vehicles fuelled with either electricity, hydrogen or biofuels (Copenhagen, Geneva, Grenoble, Hamburg, Ljubljana).

Furthermore, cities wish to facilitate the emergence of a sustainable behaviour through enhanced information of customers and civil servants. Some actions target training for professionals (labels and standards processes in the building sector), and mostly for public administration. More largely, actions to ensure more sustainable behaviours and decisions within the public administration are proposed: all cities have set measures and pay a special attention to the sustainability of public procurement processes (goods and postal mailing, food in schools, IT products, etc.) by the consideration of "eco-responsible" criteria through guidelines or trainings.

Municipalities are also a key enabler to ensure financial support and investments at the local scale. Most of the cities are addressing the need for new, innovative financial schemes through the creation of energy cooperatives, municipal utilities or contracting services with local experts.

Primary focus on measures with direct impact, further savings and technology innovations still possible

The portfolio of measures implemented by cities is based on a selection of actions that can bring as many environmental, social and economic benefits for the society as possible, i.e. reducing the highest amount of CO_2 emissions or of energy consumed at an affordable cost and over a reasonable period of time. This can explain why most of the measures cited focussed on an adaptation of local infrastructure (buildings, energy, transport), while fewer measures directly target consumers' behaviour or "lifestyle", which are not directly under the "municipalities' right of disposition" (as mentioned by the city of Stockholm) and require in general a longer time to be durably changed. Almost all cities nevertheless mentioned the importance to change consumption patterns in order to ensure the sustainability of energy systems. For the moment, most of the actions implemented or planned to influence consumers' energy uses are based on enhanced information and communication, mostly through awareness campaigns about mobility or energy efficiency in homes. The development of information tools such as web exchange platforms, or the creation of energy centres with energy advisers is emerging as an active option for transforming consumption patterns.

In all sectors, the development of proven technologies is preferred. Innovation is mentioned as a key enabler but only a few cities address the development of less mature technologies or systems with concrete measures. Some actions for the development of technologies such as power-to-gas, power-to-heat based on renewable sources (wind, geothermal energy) are envisaged; more complex and innovative supply options such as energy aggregators are briefly mentioned, but rarely targeted through concrete actions; the city of Out of the cities reviewed, Hamburg is the only one which aims at developing a Virtual Power Plant.

2.3.5. Interdependencies and relations between urban energy drivers and key trends

As mentioned in the Global Energy Assessment of the IIASA, “no study so far has investigated the relative importance of all the factors known to influence urban energy use”. Positive correlations between income and final energy use which exist at the national level have also been shown at the households’ level in several countries. Similar results for GHG emissions have been obtained in Australian cities and CO_2 emissions in the United States [IIASA,2012]. In addition to income, demographic factors also impact urban energy use. For instance, studies suggest that households size plays a role in energy use: “above two people per household, economies of scale can reduce the energy used per capita” [IIASA,2012].

In terms of existing technological options or strategical orientation, it could be helpful for policy and decisions makers to quantify which panel of solutions can enable to minimise energy use and emissions levels at lower cost. For example, should public authorities rather invest in building retrofit or in the modernisation of the transport network? Should the district heating network be developed, or should the municipality rather promote retrofit and energy efficiency measures? Is energy efficiency correlated with a cleaner energy mix? To which extent can the shift towards more renewables impact the stability and affordability of the existing system? The interaction between all driving forces and trends may of course vary from city to city, and the IIASA underlines the role of the historical development of a given city in the relations between the different factors. Nevertheless, the IIASA estimates that “the quality of the built environment (buildings efficiency) and the urban form and density that, to a large degree, structure urban transport energy use, are roughly of equal importance. Also, energy systems integration (cogeneration, waste heat cascading) can give substantial efficiency gains, but ranks second after buildings efficiency, urban form and density, and associated transport efficiency measures” [IIASA, 2012].

So far very few conclusions can be drawn about quantified interactions within urban energy systems; this emphasises the current need for appropriate modelling and further quantitative analysis to complete the theoretical existing literature.

2.3.6. Key outcomes for the quantitative assessment

It is today generally recognised that local territories have a key role to play in the transition of energy systems; on the one hand, they are at the origin of most challenges and issues related to energy use and efficiency, given the spatial and functional concentration of activities that they carry. On the other hand, they are characterised by intense human, technological and economical flows which interact together, and can offer a unique favourable environment for innovative thinking to answer the challenge of a more sustainable future.

In the light of the changes, challenges and associated solutions presented in the previous sections, we identify the following outcomes as of significant importance for the assessment of urban energy systems.

Need for a strong granularity in the analysis of urban energy systems: representing buildings and districts

The definition and key features of urban energy systems as identified in the literature review underline several essential axes for analysing urban energy systems.

First, the spatial dimension is crucial to understand how the urban system is built and organised. Defining clearly the boundaries of the “urban” area is a pre-requisite for any assessment. The spatial development of the city (e.g. densification vs urban sprawl), the repartition of different activities (mixed land-use vs functional organisation) and urban density are key parameters. Modelling at the local scale should therefore enable to take into account the city composition at both buildings and quarters levels in order to simulate the features of each quarter (type of buildings, age, activities, etc.) and how the different quarters are linked (networks and transport infrastructure, but also economic role).

Disaggregation at the building level is all the most essential as the characteristics of the existing building stock (size, age, type of housing) have a strong impact on final energy use of the city. Main energy savings solutions, from the integration of distributed renewables to thermal renovation, are also directly depending on buildings' characteristics. Urban energy models should therefore integrate data on buildings as detailed as possible and offer the possibility to simulate different levels of retrofit (isolated measures vs package of several actions for example).

In the same way, urban models would ideally integrate individual data on households: socio-economic parameters, but also the access to individual loads and energy consumption patterns – which will be facilitated by the deployment of smart systems – can enable to better track and forecast energy consumption in the residential sector. The difficulty to compile and have access to such disaggregated data should here once again be underpinned as it represents a major challenge not only for energy modellers, but also for energy producers, distributors and municipal authorities themselves.

As identified in the literature review, urban energy systems however do not refer to isolated energy consumption entities but are made of cross-sectoral components such as the processes and infrastructure that connect them. Urban energy modelling ideally encompasses all activity sectors (industry, transport, residential and services, agriculture if relevant), and reflects the different processes and interrelations at stake, from production to transport and distribution, especially through the existence of and access to the various networks and energy carriers (transport, district heating, power, gas, water, waste, etc.).

Capturing synergy and optimisation potentials at all levels

The energy system of a city reflects "myriads of local optimisations" [Grubler and Fisk, 2013], i.e. synergies can be identified at several levels when considering urban energy systems with an integrated point of view: on the one hand in the interrelations between the various components, and on the other hand in the aggregation of entities at a "upper" level (buildings aggregated in quarters, quarters in agglomerations). Local energy models should focus on the potential optimisation and synergy levers at very disaggregated levels in order to capture adequately urban trends and possibilities.

The integration of distributed renewables at the buildings level is a new paradigm; substantial potential exists, especially for solar resources (water heating and electricity production). This offers the possibility for households to turn to "prosumers" and arbitrate, according to their needs and the tariffs on the grid, between self-consumption, storage, purchase from or injection and sale to the power network. These different options should be reflected in a local energy model.

In the residential and tertiary buildings sector, the central role of heating equipment and its dimensioning appears as an issue to cover: should the consumer rather invest in modern devices such as solar water heaters or geothermal heat pumps, or in thermal retrofit of the dwelling? We see clearly from concrete actions undertaken by the cities actions plans reviewed in the literature that system optimisation, whatever the step considered, does not only refer to energy but also to economic considerations. A similar arbitrage occurs at the district level: municipalities have the choice to either expand/upgrade district heat networks, which require large investments and a minimum density threshold, but can lead to substantial energy efficiency; or to invest in and promote deep energy retrofits in public and private buildings to minimise energy needs.

On the supply side, local models should be able to capture the impacts of an increased flexibility, which will lead to a higher mutualisation of energy, whatever the technologies or options deployed (distributed energies coupled to storage, smart systems through digitalisation and enhanced demand-side management, aggregators, etc.). The integration of several energy carriers through multi-energy networks or equipment also represents a core solution to take into account as it can lead to a huge efficiency potential, even though it has not been massively implemented by cities so far, with the exception of cogeneration.

At the city level, the role of industry and mobility as contributors to energy end-use is also to be considered. The ongoing electrification trend in the transport sector plays a particular role in the assessment of urban energy systems. Especially the development of private electric vehicles could lead to a dual role of the transport sector, both as driver of energy-use, but also as a flexibility option through the use of batteries as a mean of storage.

Integrated approach of urban energy systems: taking environmental, social and economic aspects into account

Reducing the analysis of urban energy systems to a merely quantification of energy flows and emissions cannot enable to assess the sustainability of these systems. Their assessment must capture the impact of the energy system's evolution on the local environment as well as on the economic and socio-political context. This task may prove particularly difficult as it requires expertise on cross-disciplinary fields, including environment, energy economics, macroeconomics, political sciences, etc. Such an assessment is all the more difficult as urban energy systems are intrinsically made of cross-sectoral components interlinked in a complex way.

Traditional macroeconomic and energy outputs or indicators are necessary but not sufficient to capture the progress of urban energy systems towards more sustainability. Energy poverty is a good example: the sole indication on how much energy is consumed by a household will not help quantify energy poverty, further data such as the share of income spent in the energy bill being required to cope with this topic. More generally, the percentage of households having good access to the networked infrastructure of the city (electricity, water, sewage, public transport) and at an affordable price can provide helpful information. Local energy modelling should therefore integrate specific indicators with diverse considerations, including energy flows, costs, but also political and social parameters. Ideally, local energy models can provide an integrated analysis of the retroactions between energy and climate policies, the energy system and the macro-economic context. In this regard, many cities have created their own Key Performance Indicators (KPIs) in order to better capture and link all aspects of sustainability and evaluate the impact of local policies implemented. At the international level, institutions such as the UN, or the World Bank (see e.g. [WB, 2000]) have created a set of urban indicators in order to provide a framework to track the sustainability of cities.

With respect to the socioeconomic dimension, two priority axes can be identified for the modelling. First, the importance of the affordability of the energy system for both end-consumers and the city as a whole requires to include detailed cost parameters in the model in order to assess the competitiveness of the various technologies. This includes investment estimates and operating costs for equipment, but also financial parameters such as subsidies, tax credits or actualisation rates for both private and public investors. Assessing energy affordability for end-consumers also requires to refine macroeconomic inputs by collecting revenue data at a very disaggregated level (e.g. households). Secondly and more largely, assessing the "social" sustainability of urban systems requires much more detailed households' data. The literature review has shown that households' features may indeed have an impact on energy consumption. Indeed, socioeconomic features are key constituents of urban energy systems, and ignoring them could lead to misinterpretation, as apparently similar quarters in terms of urban form and density may have a completely different social configuration. In some cities for example, the expansive city-centre is inhabited by high-income residents, close to amenities and leisure; but in many medium-sized cities, commercial activities have left for peri-urban quarters and high-income households rather move to less central houses with garden, leading to a pauperisation trend of the city-centre. Levers of actions and strategy will probably widely differ in these two configurations to address the special need of each population, albeit addressed to the same quarter type. Such a detailed representation requires a huge quantity of very granular data which are not included in the EnerCity model at this stage.

3. Model-based assessment of possible future evolution pathways

The key learnings from the literature review identified in the previous section serve as basis for the creation of contrasted scenarios in the EnerCity model. The objective is to quantify and forecast the possible effects of the identified paradigm shifts on local energy system in the considered urban area. This work complements the results of the literature review with a quantitative analysis, described in the following sections.

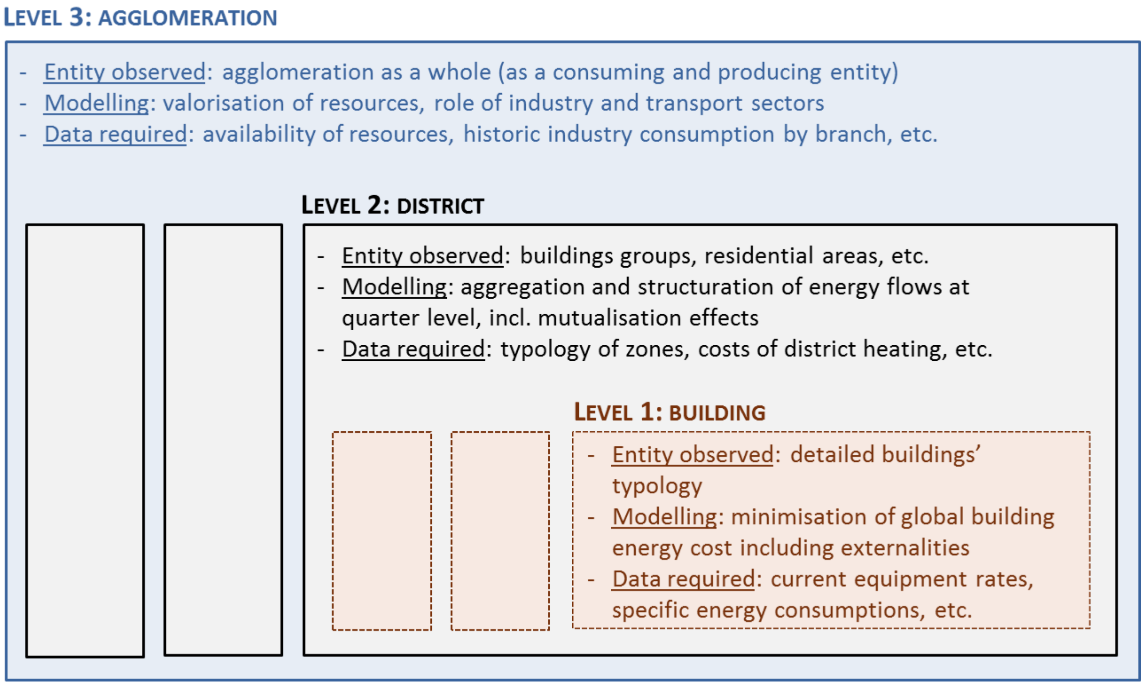
3.1. Model description

3.1.1. Overview

Overall approach

The model used for this project, named EnerCity, provides a representation of local energy systems at the city level over a 20-year horizon up to 2035. To account for local specificities, the model is based on a multi-scale approach based on three assessment levels (Figure 7): buildings, districts, and the city as a whole.

For each of the three scales, the following sections describe in detail the modelling logics, the main model variables and drivers used, as well as how the challenges identified in chapter 2 are tackled.



LEVEL 3: AGGLOMERATION

- Entity observed: agglomeration as a whole (as a consuming and producing entity)
- Modelling: valorisation of resources, role of industry and transport sectors
- Data required: availability of resources, historic industry consumption by branch, etc.

LEVEL 2: DISTRICT

- Entity observed: buildings groups, residential areas, etc.
- Modelling: aggregation and structuration of energy flows at quarter level, incl. mutualisation effects
- Data required: typology of zones, costs of district heating, etc.

LEVEL 1: BUILDING

- Entity observed: detailed buildings' typology
- Modelling: minimisation of global building energy cost including externalities
- Data required: current equipment rates, specific energy consumptions, etc.

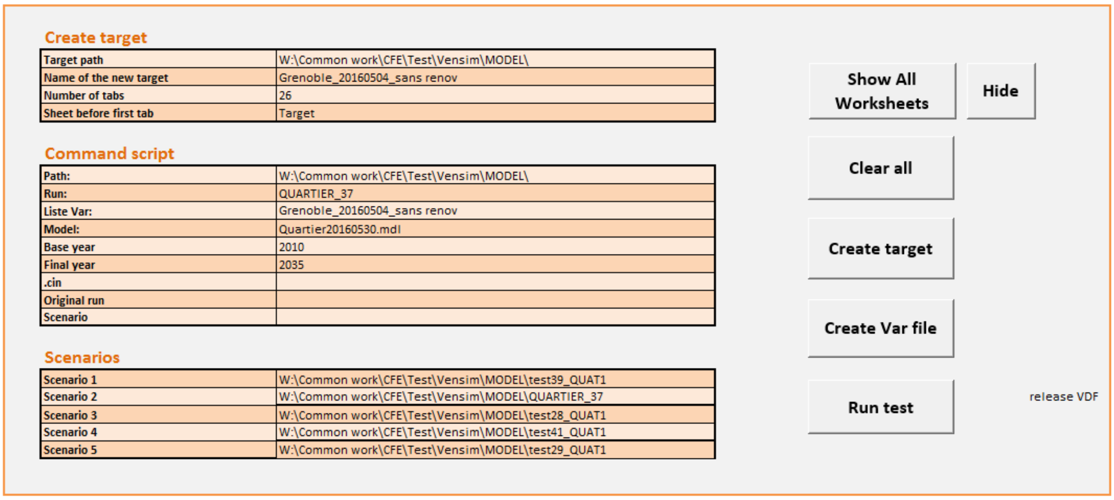
Figure 7: Methodological approach for the representation of urban energy systems

Implementation and interface

The model used for this project relies on the following elements:

- A program code of about 8,000 lines developed in Vensim (software commercialised by Ventana Systems);
- A set of MS-Excel sheets containing all model input data;

- An automatic user interface (Figure 8 and Figure 9), developed in VBA for MS-Excel, allowing both to start runs and visualise and assess model results.



Create target

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Name of the new target	Grenoble_20160504_sans renov
Number of tabs	26
Sheet before first tab	Target

Command script

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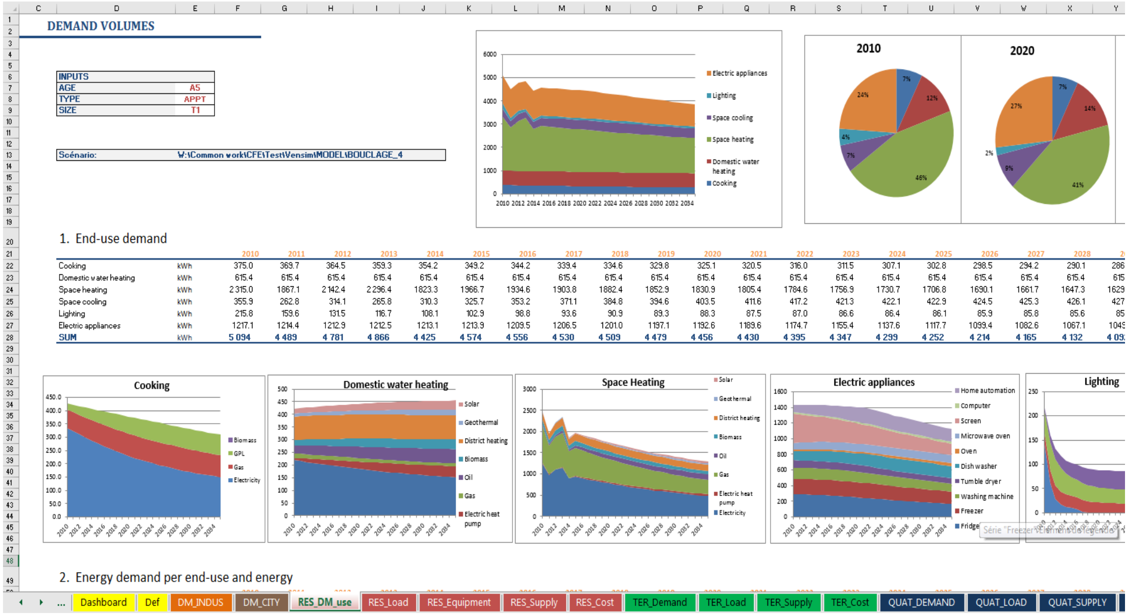
Liste Var:	Grenoble_20160504_sans renov
Model:	Quartier20160530.mdl
Base year	2010
Final year	2035
.cin	
Original run	
Scenario	

Scenarios

Scenario 1	W:\Common work\CFE\Test\Vensim\MODEL\test39_QUAT1
Scenario 2	W:\Common work\CFE\Test\Vensim\MODEL\QUARTIER_37
Scenario 3	W:\Common work\CFE\Test\Vensim\MODEL\test28_QUAT1
Scenario 4	W:\Common work\CFE\Test\Vensim\MODEL\test41_QUAT1
Scenario 5	W:\Common work\CFE\Test\Vensim\MODEL\test29_QUAT1

Figure 8: Model user interface – scenario management



DEMAND VOLUMES

INPUTS	
AGE	A5
TYPE	APPT
SIZE	T1

Scénario: W:\Common work\CFE\Test\Vensim\MODEL\BOUCLAGE_4

1. End-use demand

		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Cooking	kWh	375.0	369.7	364.5	359.3	354.2	349.2	344.2	339.4	334.6	329.8	325.1	320.5	316.0	311.5	307.1	302.8	298.5	294.2	290.1
Domestic water heating	kWh	615.4	615.4	615.4	615.4	615.4	615.4	615.4	615.4	615.4	615.4	615.4	615.4	615.4	615.4	615.4	615.4	615.4	615.4	615.4
Space heating	kWh	2 315.0	1867.1	2 142.4	2 296.4	1823.3	1966.7	1934.6	1903.8	1882.4	1852.9	1830.9	1805.4	1784.6	1756.9	1730.7	1706.8	1690.1	1661.7	1647.3
Space cooling	kWh	355.9	262.8	314.1	265.8	310.3	325.7	353.2	371.1	384.8	394.6	403.5	411.6	417.2	421.3	422.1	422.9	424.5	425.3	426.1
Lighting	kWh	215.8	159.6	131.5	116.7	108.1	102.9	98.8	93.6	90.9	89.3	88.3	87.5	87.0	86.6	86.4	86.1	85.9	85.8	85.6
Electric appliances	kWh	1217.1	1214.4	1212.9	1212.5	1213.1	1213.9	1209.5	1206.5	1201.0	1197.1	1192.6	1189.6	1174.7	1155.4	1137.6	1117.7	1099.4	1082.6	1067.1
SUM	kWh	5 094	4 489	4 781	4 866	4 425	4 574	4 556	4 530	4 509	4 479	4 456	4 430	4 395	4 347	4 299	4 252	4 214	4 165	4 132

2. Energy demand per end-use and energy

Figure 9: Model user interface – visualisation of results

3.1.2. Buildings modelling

In the buildings module, the approach allows to describe how supply and demand of energy are balanced under technical and economic considerations for any building type:

- Demand side: building types are defined according to their physical characteristics, construction year, size and equipment stock. Further, demand by end-use is calculated prior to calculating market shares of technologies able to satisfy the respective consumptions. This allows to calculate end-use consumption by energy and end-use for all types of buildings.

- Supply side: decentralised production is considered in the model, such as solar thermal and photovoltaics (PV), which are simulated based on heat production costs and feed-in tariffs for PV (defined exogenously). Storage solutions are also accounted for and sized based on demand levels and production capacities installed.

Buildings typology

The typology of buildings considers 45 representative types of buildings accounting for 3 structures (individual houses, adjoining houses and apartment blocks), 5 construction periods (accounting for specificities and improvements from various thermal regulations), and 3 building sizes (depending on the number of rooms).

For each of these 45 items, the typology specifies the average living space, the climate zone (unified degree-days approach), and further energy, technical and economic data (e.g. heat losses, equipment stock, etc.).

Final energy demand

An overview of energy end-uses covered by the model is provided in Table 5, along with the corresponding drivers, i.e. variables that have a direct impact on the future evolution of each end-use.

	Heating	Hot water	Cooking	Cooling	Lighting	Captive electricity
Construction date	X			X		
Building type	X			X		
Living space	X			X	X	
Size of household		X	X			X
Climate zone	X	X		X		

Table 5: Energy end-uses in residential buildings and driver parameters

For each end-use, a set of equations allows to calculate final energy demand, depending on the parameters provided in the table above. Two examples are given in the following:

- Heating: heat consumption is based on a thermal calculation involving unified degree days (DJU), the habitation's volume (VLM) as well as its heat loss coefficient (HTLOS), as shown in equation below. This latter is depending on the number of exterior walls (building type) and construction/rehabilitation date, but can also incorporate the solar contribution as well as regulation level in place. Heat consumption is calculated for each season.

DMSPH0[AGE,TYPE,SIZE,SEASON] = 24*DJU[SEASON] * HTLOS[AGE,TYPE] * VLM[AGE,TYPE,SIZE] / 1000

DMSPH[AGE,TYPE,SIZE]=SUM(DMSPH0[AGE,TYPE,SIZE,SEASON!]) (1)

with: DMSPH0 (kWh): heating end-use by season
DJU (°C): heating unified degree days
HTLOS (W/°C/m^3): heat loss coefficient
VLM (m^3): building's volume

- Cooking: cooking consumption is also calculated for each habitation type, based on the number of inhabitants. The calculation is based on a unitary consumption (NDMCOK) derived from country's average, which is exogenous and can be adjusted by the user to refine energy consumption for this end-use, for example if specific data is available at the city level.

DMCOK[TYPE,SIZE] = NDMCOK * NPH[SIZE] (2)

with: NDMCOK (kWh/cap/an): unitary consumption per capita
NPH[SIZE] (cap): number of inhabitants per household

Similar equations are used for other energy end-uses. Final demand of captive electricity is calculated for 10 equipment types (fridge, freezer, washing machine, dryer, dishwasher, oven, micro-wave oven, screens, computers, home automation).

Each equipment is characterised by its equipment rate, specific consumption and 6 labels – including 2 for new equipment from 2020 –, which aim at reflecting efficiency improvements over time. Progressive introduction of new labels is simulated through a logistic function (S-shaped curve). A seventh specific label is introduced for washing machines and dishwashers, corresponding to a new equipment generation allowing for a direct consumption of hot water through PV production, therefore reducing electricity consumption of those equipment.

Energy types, technologies and end-uses

For each end-use, several types of energy and/or technologies have been implemented to compete with each other to cover final demand. These are detailed in Table 6. Although the same set of energy types/technologies is assigned to both heating and hot water uses, their respective market shares are calculated separately.

Heating	Hot water	Cooking	Cooling	Lighting	Captive electricity
- Electricity		- Electricity	- Package / mobile	- Incandescent	- Fridge
- Heat pump		- Gas	- Heat pump	- CFL	- Freezer
- Gas		- LPG	- Cooling network	- Low energy halogen	- Washing machine
- Domestic fuel-oil		- Biomass	- Geothermal	- LED	- Dryer
- Biomass			- Solar		- Dishwasher
- Heat network					- Oven
- Geothermal					- Micro-wave oven
- Solar					- Screens
					- Computers
					- Home automation

Table 6: Competing energy types and technologies by end-use

Market shares

Core of the methodology relies in the calculation of market shares for energy types and technologies allowed to compete to fulfil each energy end-use. Market shares depend obviously on the respective exploitation costs of competing energy types and technologies, presented in the equation below. Exploitation costs cover the following cost components:

- Variable cost of consumption for installed equipment;
- Investment and variable cost related to demand-side energy efficiency measures (thermal rehabilitation) and to local production equipment;
- Fix cost: subscription, maintenance;
- Positive externalities, e.g. stream/tendency to energy autarky (more relevant for individual houses than collective buildings).

EXPCSTSPH[ENRHT,AGE,TYPE,SIZE] = (INVESTSPH[ENRHT,SIZE] / LIFSPH[ENRHT] + (MAINTSPH[ENRHT] + DMSPH[AGE,TYPE,SIZE] * PRCSPH[ENRHT] / EFFSPH[ENRHT]) - SUBSSPH[ENRHT])*NPV20 + SLDRENOV[ENRHT,AGE,TYPE,SIZE]

with: EXPCSTSPH[ENRHT,AGE,TYPE,SIZE] (€): yearly exploitation cost
INVESTSP[ENRHT,SIZE] (€): initial investment
LIFSPH[ENRHT] (years): equipment lifetime
PRCSPH[ENRHT] (€): energy price
EFFSPH[ENRHT] (%): technology/equipment efficiency
SUBSSPH[ENRHT] (€): subsidies
SLDRENOV[ENRHT,AGE,TYPE,SIZE] (€): net renovation cost

(3)

Electricity, gas and fuel-oil prices are exogenous and derived from Enerdata's prospective exercise EnerFuture[1].

Variable SUBSSPH is a driver variable allowing to account for financial incentives as well as tendency to energy autarky.

Variable SLDRENOV allows to consider explicitly the net renovation cost, which is depending both on costs engaged in refurbishment works and on cost savings realised through such actions. Enhanced retrofit measures considered in the model are assumed to reach new buildings' average performances. Net renovation cost is actualised over 20 years and accounts for a differentiation between public funding (4% actualisation rate) and private funding (20% actualisation rate).

After calculation of technologies' relative costs $C_i = EXPCSTSPH$ (example for heating), a logit function represented in the equation below allows to perform a pseudo-optimisation based on the distance to minimal cost, and calculates the corresponding market shares.

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[1] http://www.enerdata.net/enerdatauk/knowledge/subscriptions/forecast/enerfuture.php, last updated January 2017

$$\text{Market Share (i)} = \frac{\alpha_i * {C_i}^{\beta_i}}{\sum_i \alpha_i * {C_i}^{\beta_i}} \tag{4}$$

with: α: non-economic calibration coefficient[2]
β: price elasticity
C (€): yearly exploitation cost

Equipment stock renewal

Equipment rates are calculated at each model iteration on a yearly basis to account for replacement of equipment at the end of their lifetime:

Equipment Rate (i, t) = Existing Stock (i, t-1) – Scrapped Equipment (i, t) + Market Share (i, t) * Equipment To Replace (5)

with i: technology index
t: year

Temporality of final demand

The model approach integrates a detailed representation of load curves for electric equipment. Each year is split into 96 time blocks (8 typical days, 1 by season with a differentiation between week day and weekend day; and 12 2-hour time slots per day) to account for load variability in electric end-uses, which is necessary while considering decentralised energies' availability, strongly depending on meteorological conditions (wind speed, sunlight). Such approach enables to tackle effects related to consumption peak periods in the equilibrium between demand and supply, along with the potential role that smart grids systems may play in the future.

In addition to the temporality of electric uses, load curves for heating are further depending on the season considered, so that seasonal demand is considered along with potential electric inputs required for solar systems, heat pumps and geothermal equipment.

With the methodological approach developed it is possible to inform final consumers and decision-makers such as local authorities about a number of challenges and decisions they may have to take in the near future. Three of these challenges are further detailed in the following paragraphs.

Challenge 1 – Decision-making between thermal renovation and heat consumption

The competitive process applied to technical solutions at the building scale can help identify and quantify the economically most attractive configuration for end-consumers: for energy intensive end-uses such as heating at this scale, the model assesses in particular the economic viability of thermal refurbishment, depending on the level and the time structure of final heat demand. In particular, scenario calculations allow for comparing several cases with and without thermal renovation, hence allowing to observe and understand the

---

[2] α is a driver parameter allowing to account for non-economic factors impacting technologies' price formation such as e.g. specific regulatory contexts not explicitly related to pure economic competition.

consequences that refurbishment costs and savings may have on the long-term demand and supply equilibrium at the building scale. Exploitation costs can be compared across energy types as well as the resulting market shares up to 2035.

Challenge 2 – Sizing of solar water heaters under consideration of hot water needs for both sanitary and washing machine / dishwasher uses

The model allows to size precisely solar water heaters, while considering on the one hand solar energy for specific sanitary hot water (resulting from the competition process), but also specific consumption from equipment such as dishwashers and washing machines on the other hand. A further output of the model is the installed square meters of solar thermal equipment, depending on the efficiency of solar collectors and solar irradiation.

Challenge 3 – Photovoltaics systems: decision-making between storage, resale of solar power production and purchase from the electricity network

Solar PV production is calculated within the model, as well as storage capacities, which are sized in function of both PV production and final demand level. A model constraint requires them to fulfil the demand over a few days in case of limited sunlight. Further, to improve their lifetime, a fixed unload threshold is set as an upper limit (30-40%$_{SOC}$[3] in average). Levelised costs of storage are calculated; they depend on the installed capacity, initial investment and maintenance costs. The resulting challenge and decision to be made is illustrated in Figure 10, allowing to simulate how much solar production is fed-in to the electricity network, how much is self-consumed, depending on feed-in tariffs applied and storage costs. Three possible configurations are hence compared:

- Resale of total solar production (configuration 1),
- Self-consumption and resale of surplus (configuration 2),
- Self-consumption, storage and resale of surplus (configuration 3).

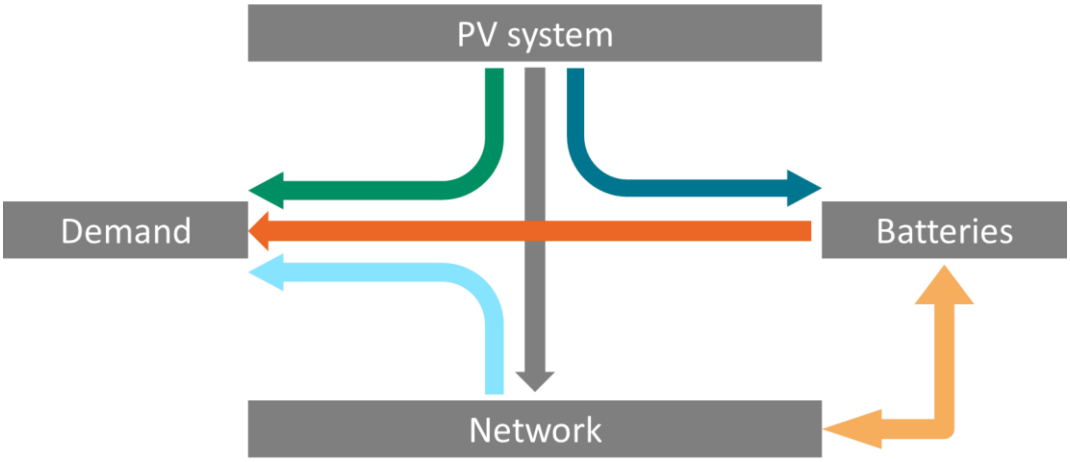

Figure 10: Decision-making challenge for PV systems: self-consumption, storage, purchase from /resale to network

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[3] %$_{SOC}$: % state of charge

3.1.3. Districts modelling

Another modelling layer is performed at the district level. A district is understood here as a grouping of (residential and tertiary) buildings, with the objective of aggregating their individual consumptions and decentralised supply patterns and hence answer further issues which are relevant at this scale: district heating networks, mutualisation of demand and of decentralised supply, impact on load curves.

The district module includes the creation of “typical quarter” homogeneous categories, given key features such as their size, density and nature (type of activities). The determined combination of these typical districts enables to model the composition of the final modelling level, i.e. the agglomeration.

Aggregating residential buildings (supply and demand)

The first step at this stage is to aggregate consumptions and decentralised supply of buildings from the residential sector. To this end, a general aggregation approach derived from the Balmorel model is used (see e.g. [Balmorel, 2005]), involving energy input flows from the distribution network, the flow produced locally, final demand of buildings, stored and unloaded flows and flows fed into the network. In this approach, illustrated in the equation below, additional parameters allow to account for network losses as well as an additional input flow for e.g. potential waste reuse or use of fatal heat from a surrounding industrial site.

$$\sum_{i=1}^{I}\left(\eta_{i,t} * F_{i,t}^{input}\right) + F_t^{fix} + \sum_{s=1}^{S} F_{s,t}^{unloaded} + \sum_{g=1}^{G} P_{g,t} = \sum_{j=1}^{J}\left(\eta_{j,t} * F_{j,t}^{output}\right) + \sum_{s=1}^{S} F_{s,t}^{stored} + \sum_{c=1}^{C} D_{c,t} \qquad (6)$$

$\eta_{i,t}$	network losses coefficient
$F_{i,t}^{input}$	node input flow
F_t^{fix}	constant input flow
$F_{s,t}^{unloaded}$	unloaded flow from storage
$P_{g,t}$	decentralised production
$F_{j,t}^{output}$	node output flow
$F_{s,t}^{stored}$	stored flow
$D_{c,t}$	node demand

Load curves from residential buildings are aggregated as well, as the total contribution from all buildings part of the district considered. In this calculation, a “natural[4]” mutualisation coefficient is introduced to account for offset effects on peak consumption across different buildings.

Tertiary buildings

The tertiary buildings sector is modelled in a similar way. To account for potentially differentiated consumption patterns, 9 classes of tertiary buildings are defined: big offices; small offices in residential buildings; large retail outlets; small shops; schools; sport and culture equipment; health equipment; hotels, restaurants and coffees; swimming-pools. For each of these classes, final energy demand by end-use is calculated using the drivers mentioned in Table 7.

The methodology used for heating, cooling and lighting end-uses is the same that the one adopted for residential buildings). Hot water, cooking and other thermal uses are derived from national statistics on

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[4] In the following, a « organised » mutualisation effect will be introduced to account for demand/supply flexibility efforts organised by potential ICT actors involved in last management and flexibility at district level.

tertiary buildings' consumption. Captive electricity is derived from the calculation of three energy use sub-categories, which are different according to the considered classes: cooling, Information and Communication Technologies (ICT) and portable electronics.

	Heating	Hot water	Cooking	Other thermal uses	Air cond.	Lighting	Captive electricity
Big and small offices	Sq. meters	-	-	Nb. employees	Sq. meters	Sq. meters	Nb. employees
Outlets and shops	Sq. meters	Nb. employees	Nb. employees	Sq. meters	Sq. meters	Sq. meters	Nb. employees
Schools	Sq. meters	-	-	Nb. students	Sq. meters	Sq. meters	Nb. employees
Sport and culture	Sq. meters	-	-	Sq. meters	Sq. meters	Sq. meters	Nb. employees
Health	Sq. meters	Nb. patients	Nb. patients	-	Sq. meters	Sq. meters	Nb. employees
Hotels and restaurants	Sq. meters	Nb. clients	Nb. clients	-	Sq. meters	Sq. meters	Nb. employees
Swimming pools	Sq. meters	Sq. meters	-	-	-	Sq. meters	Nb. employees

Table 7: Energy end-uses in tertiary buildings and driver parameters

Market shares for tertiary buildings are, like for the residential sector, calculated with the logit function described in the previous section.

Load curves are simulated through the apportionment of consumption across operating hours of the respective equipment. Cooling and ICT end-uses are simulated so as to provide a constant load over the year.

Definition of district types

So as to define homogenous districts' structures, four types of districts are modelled: city centre, inner suburbs, outer suburbs, peri-urban area. Unitary district types are defined with a size of 1 km² allowing to describe the whole territory as a linear combination of these:

$$\mathrm{AGGLO} = \sum_{\mathrm{i}} \mathrm{a_i} * \mathrm{QUAT_i} \tag{7}$$

Each of these unitary districts is characterised by its main housing types (e.g. dense and old collective buildings in city centre districts, low-rise residential areas in outer suburbs, an appropriate density for tertiary activities, etc.).

Aggregating flows at district level

Considering one node for each district, all flows are modelled as linear combinations of flows from the previous level. For example, final demand for heating in each district is simulated for both residential and tertiary sectors based on the number of typical buildings and their respective specific consumptions:

QDMSPH0 [QUAT, RES, SEASON] = SUM (COMPO RES [QUAT, AGE !, TYPE!, SIZE!] * DMSPH0 [AGE!, TYPE!, SIZE!,SEASON])

QDMSPH0 [QUAT, TER, SEASON] = SUM (COMPO TER [QUAT, AGE!, TERBAT] * TDMSPH0 [AGE!, TERBAT !, SEASON]) (8)

with: DMSPH0 and TDMSPH0 (kWh): seasonal heating energy demand for residential and tertiary sector, respectively

Market shares at district level are then calculated:

- Cooking, lighting and captive electricity: derived from residential and tertiary market shares, accounting for total exploitation costs which are not depending on specific districts;
- Heating, hot water, other thermal uses and air conditioning: recalculated with the logit function (see previous section) as heating costs depend on the existence, at district level, of a district heat network, of the district's density and of the mutualisation level of local resources.

Load curves are finally built as the aggregation of all load profiles over the typical days modelled. The load curve of a specific end-use therefore considers the contributions of all buildings in the district, also accounting for a "natural" mutualisation effect resulting from peak load offsets across buildings. Finally, contributions from all energy end-uses are summed up to derive the district's total load curve.

Solar photovoltaics electricity production capacity is derived at district's level from the sum of capacities of individual buildings in the district, allowing therefore to calculate total solar production by district as a function of each building type's equipment rate. The modelling approach uses two additional variables, *SLDSLR* and *TSLDSLR*, respectively for residential and tertiary buildings, to calculate the difference between yearly solar PV production and electricity consumption from PV, depending on self-consumption of solar PV production:

SLDSLR[AGE,TYPE,SIZE] = PRODPV[AGE,TYPE,SIZE] *(1 – SLFCSM[AGE,TYPE,SIZE])
TSLRSLD[AGE,TERBAT] = TPRODPV[AGE,TERBAT] * (1- TSLFCSM[AGE,TERBAT] (9)

Hence, these two variables correspond to solar PV production fed-in to the local electricity network, which is depending on the decision-making between self-consumption with storage and the resale to the grid.

Simulation and sizing of district heating networks

The last step of the district module consists in the sizing process for heat networks, district by district, depending on total buildings' consumption, themselves being dependent on fuel prices and on specific investments in networks' boilers and pipes (operating with wood and one back-up fossil fuel), as shown in Table 8 and defined exogenously. An intermittency variable is introduced in the modelling as the ratio between operating hours of heating equipment and the activity period of a building [IDEX, 2012] (see equation below). As illustrated in Figure 11, the number of sub-stations is calculated for each district based on its structure, and the network's size is estimated based on the district's density.

The share of residential and tertiary buildings connected to the district heat network is then calibrated over 2010-2014 for each district so as to derive the installed capacity at city level. From 2015 onwards, market shares of district heating evolve depending on its exploitation costs.

Installed capacity	Specific investment	
	Boilers (€/kW)	Pipes (€/m)
200 kW	954	302
750 kW	654	315
4,000 kW	501	484

Table 8: Specific investment for district heat networks as a function of installed capacity, based on [ADEME, 2009]

DHPOW[QUAT,SPH] = SUM(QSECSPH0[QUAT,SCTR !,NETHT,WINTER] / INTERM[SCTR !]) * (T_{int} – T_{ext})/DJU[WINTER]

DHPOW[QUAT,DWH] = SUM(QSECDWH0[QUAT,SCTR!,NETHT,WINTER]/(DHHOUR*365/4)

with: DHPOW[QUAT,SPH] and DHPOW[QUAT,DWH]: capacities of boilers for production of heat and hot water, respectively
QSECSPH0[QUAT,SCTR !,NETHT,WINTER]: winter heat consumption
QSECDWH0[QUAT,SCTR!,NETHT,WINTER]: winter hot water consumption
INTERM[SCTR]: consumption intermittency
DHHOUR: hot water production hours

(10)

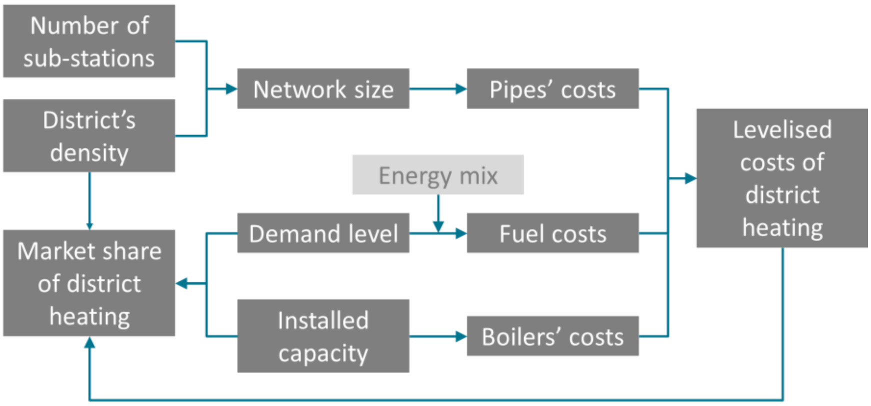

Figure 11: Sizing and simulation of heating networks at district level

Challenge 4 – Impacts of mutualisation of solar photovoltaics and storage towards an optimum at district scale

The approach is here different from the residential buildings, where electricity supply costs have been calculated while considering solar PV production, potential storage and feeding into the network. At the district level, the modelling accounts for potential mutualisation of decentralised PV, along with its management through the use of batteries to cover part of district's demand, thus having a potential impact on electricity volumes supplied from the centralised grid.

Mutualisation is simulated through a specific coefficient as a function of each building's self-consumption level, depending on penetration rates of solar PV and storage capacities installed at the building's scale.

Challenge 5 – Decision-making between thermal renovation and district heat consumption

To inform the decision-making process on the choice, at district level, between investing in thermal renovation or consuming district heat, the model considers the specific characteristics of the district observed and derives the consequences on the competitiveness of district heating, depending on the level and structure of energy needs as well as of the economic viability of buildings' thermal refurbishment.

The approach allows to simulate the scale effects related to the construction/extension of district heat networks, through the consideration of the number of buildings to be connected, along with the possibility of utilising local biomass resources available on the territory.

In this challenge, the economic viability of thermal refurbishment is simulated through enhanced performances of renovated buildings equalling those of new buildings in the definition of the district, before recalculating heat demand levels and the corresponding heat supply costs.

Challenge 6 – Aggregation effects of energy consumption and supply

Another interesting aspect of the model is to provide answers on the possible consequences that districts' characteristics (its size, density, number of habitations in each building type) can have on electric mutualisation both on the demand and on the decentralised supply side, as a function of local production from the district's buildings and storage capacities.

To this end, two types of mutualisation are distinguished: "natural" mutualisation is introduced in the aggregation of the district's load curves and results from peak load offsets across different buildings, whereas "organised" mutualisation is simulated as a result of management efforts from third parties in the balance of demand and supply at district level. Indeed, mutualising local production and involving storage capacities may help adjust and balance efficiently any district's energy supply and demand patterns.

3.1.4. City modelling

The final observation scale of the model is the city level, where the overall objective is to draw conclusions on the current and future levels of decentralised energy production and final energy demand, the related question being the quantification of energy supply to be delivered from the centralised network, along with the potential impact of decentralised production on the aggregated load curve to be handled by network operators outside the territory.

The overall scope considered for the city encompasses not only the aggregation of all districts, but also additional relevant sectors such as the industry in the near suburb and the transport sector (with a special focus on the potential role of electric vehicles). The city is seen in the model as a consuming and producing entity, with consideration at this scale of additional production means such as solar farms, wind turbines, geothermal energy, industrial heat and biomass. These, if available in the urban area considered, are subject to an economic assessment aimed at analysing whether such means can economically replace part of the conventional supply.

Overall, the model allows to determine the local energy balance at city level and therefore to derive the net energy balance seen from the centralised network, as well as the resulting electric load curve and the associated costs.

Definition of the city level and aggregation of district entities

In a first step, the city is characterised by its macroeconomic context: population, number of households and value added by economic sector are defined exogenously from historical figures and assumptions on their respective growth rates. Then, as described briefly in the previous section, the city is aggregated as a linear combination of the various unitary district types modelled. Real districts of the city analysed as well as the surrounding municipalities belonging to the urban area are characterised by their respective densities, structures and distance to city centre, before being associated to the four model district types with coefficient accounting for their respective surfaces.

From the base year 2010 onwards, district types evolve according to the demographic growth of the urban area. The population growth results in the reallocation of the number of new households over the various districts. This is accounted for by means of the matrix *SHDWLGRW[QUAT]* (share of dwellings growth by district), reflecting the city's policy in terms of urban development, e.g. allowing to consider specific urban densification or sprawl policies:

HH[QUAT] = SHDWLGRW[QUAT] * (TOTHH – TOTHH DLY)/COMPOCITY[QUAT] + HH DLY[QUAT] (11)

with: HH[QUAT]: number of households by district
SHDWLGRW[QUAT]: allocation factor for new households by district
TOTHH: total number of households in the urban area in year *t*
TOTHH DLY: total number of households in the urban area in year *t-1*
COMPOCITY[QUAT]: mix of the city in terms of district types

Aggregating supply and demand from districts

At the level of the urban area, the balancing between demand and supply occurs first through the aggregation of results from all building components, hence defined as a linear combination of unitary district types modelled. Energy demand by end-use, technologies' market shares, local production as well as load profiles are therefore calculated through the patterns derived from the district flows. The two equations below provide, with the example of space heating, how energy end-uses are aggregated first by sector and by season, then how energy end-use consumptions by energy type and by season are calculated.

CDMSPH0[SCTR] = SUM(COMPOCITY[QUAT!]*QDMSPH[QUAT!,SCTR])
CDMSPHSEASON[SEASON] = SUM(COMPOCITY[QUAT!] * QDMSPH0[QUAT!,SCTR!,SEASON])
CDMSPH = SUM(CDMSPHSEASON[SEASON!]) (12)

with: CDMSPH0[SCTR]: yearly space heating demand by sector
CDMSPHSEASON[SEASON]: space heating demand by season
CDMSPH: space heating demand in residential and tertiary sectors

CSECSPH[ENRHT,SEASON] = SUM(COMPOCITY[QUAT!] * QSECSPH[QUAT!,SCTR!,ENRHT]) (13)

with: CSECSPH[ENRHT,SEASON]: specific space heating consumption by energy type

Aggregation of load curves occurs as in the district module, i.e. load profiles are calculated through the addition of districts' load patterns.

Integration of industry

The role of industry is quantified thanks to its value added. Energy flows are defined and simulated for the following three main industry branches:

- Non-durable intermediate goods: agribusiness, paper, textiles, etc.;
- Intermediate goods: metals, non-metallic minerals, chemistry, etc.;
- Capital goods: mechanic and electric industry, automotive, aeronautics, marine industry, etc.

Energy demand is calculated for each of these branches based on their respective value added and energy intensity, the latter being estimated for the base year 2010 from historical energy consumption and value added, and its future evolution being calculated from assumptions made on both its historical growth trend and a technology progress factor. As for other end-uses in the model, energy types able to fulfil each final demand of industrial branches (electricity, fuel oil, gas, coal, biomass, steam) are subject to a competition process accounting for their respective costs:

SHIND[INDSCTR,ENRIND] = ALPHAIND[INDSCTR,ENRIND] * CSTIND[ENRIND] ^ BETAIND[INDSCTR,ENRIND]) / SUM(ALPHAIND[INDSCTR,ENRIND!] * CSTIND[ENRIND!] ^ BETAIND[INDSCTR,ENRIND!] (14)

with: ALPHAIND[INDSCTR,ENRIND] (-): infrastructure cost coefficient
CSTIND[ENRIND] (€/kWh): energy price
BETAIND[INDSCTR,ENRIND]: energy price elasticity

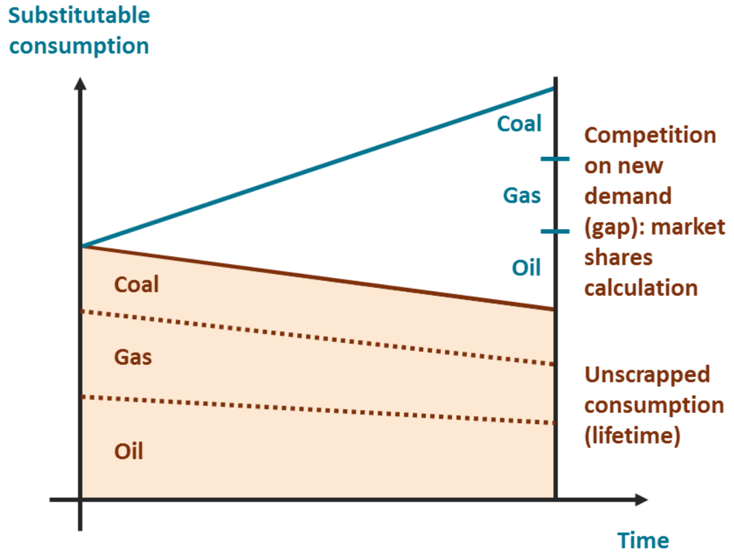

Figure 12: Equipment renewal process and competition on energy types in the industry

Lifetime of equipment along with the assumed growth of the industry sector lead, at each model iteration, to a new unsatisfied demand, as illustrated in Figure 12, on which the competition process described above is applied for the year *t+1*.

Integration of transport

Overarching objective of the transport module is to quantify the evolution of the electric vehicle fleet to derive the additional storage capacity likely to be operational at the city level. The modelling of the transport sector is split into three categories: transport of goods, private transport of passengers, and public transport of passengers. For each category, the model simulates energy consumption through the calculation of ton-kilometres (goods) and vehicle-kilometres (persons).

Individual private transport of passengers is simulated as a function of the existing historical fleet, the population growth rate and the urban area's motorisation growth rate. Vehicle types are split into four categories, namely internal combustion engines, electric vehicles, plug-in hybrid electric vehicles, and motorcycles. Fuel competition for vehicles occurs between oil-based fuels (gasoline, diesel), gas-based fuels (natural gas, LPG), biofuels and electricity. The vehicle stock renewal is simulated following the same approach as for residential equipment (detailed in section 3.1.2 and Figure 12). Vehicles-kilometres are calculated for all vehicle types on the basis of the remaining stock and new vehicles:

VKMPRVT[CAR]= (REMPRVT[CAR] + NEWPRVT[CAR]) * KMCAR

with: REMPRVT (vhcl): remaining private vehicle stock (15)
NEWPRVT[CAR] (vhcl): new private vehicles
KMCAR (km): average distance travelled by private vehicle

Furthermore, the average specific fleet consumption is simulated based on the specific consumption of new vehicles. For each vehicle type, the model calculates the corresponding energy mix, allowing to account in particular for plug-in hybrid electric vehicles and multi-fuel vehicles.

The integration of mobility aims at analysing the potential contribution of electric vehicles in terms of electricity storage capacity as well as the resulting interactions with the local grid. Electrical storage capacities of vehicles are simulated in function of the size of the electric and plug-in hybrid vehicles' fleet:

CAPSTOCAR = (NCAPSTOCAR[EV] * VKMPRVT[EV] + NCAPSTOCAR[HYB] * VKMPRVT[HYB]) / KMCAR

NCAPSTOCAR[CAR] = (NCAPSTOCAR DLY[CAR]*REMPRVT[CAR] + NCAPSTONEWCAR[CAR] * NEWPRVT[CAR]) / (REMPRVT[CAR] + NEWPRVT[CAR])

(16)

with: CAPSTOCAR (kW): total storage capacity of the vehicle fleet
NCAPSTOCAR DLY[CAR] (kW): average storage capacity by vehicle type in previous year
NCAPSTONEWCAR [CAR] (kW): average storage capacity by vehicle type (electric / plug-in)

An exogenous assumption is made on the storage capacity provided by car (*NCAPSTONEWCAR*), which amounts to 25 kW/vhcl in 2010 and reaches 30 kW/vhcl in 2035.

Public transport of passengers is aggregated with one variable covering the vehicle-kilometres travelled by the whole public transport fleet. An exogenous initial value is assumed, whereas its future evolution is driven by further assumptions made on the development of respective market shares for trams and buses. This allows to calculate the total vehicle-kilometres travelled by mode, along with the resulting energy consumption.

Transport of goods gathers all travels for goods and materials, including goods' exchanges between facilities (industries, distributors, wholesale and retail trade, supplies to craft and services), supply flows to private consumers and flows of non-commercial goods and products (supplies to building sites, flows related to maintenance and expansion of urban networks, postal services, etc.). Three vehicle categories are considered: heavy duty trucks, light duty trucks and freight trains. Although the market for electric light duty trucks is currently relatively small, energy competition for transport of goods occurs between the same energy types as in the private sector, so that the modelling is similar, with one exception: the activity variable driving this sector is the number of ton-kilometres, describing the weight of goods and the distance travelled.

Integration of local energy resources

As a last step of the modelling approach, local energy resources are integrated to the supply side. All decentralised production sources from residential and tertiary buildings are considered, along with thermal supplies from surrounding industry sites as well as local energy supplies available on the urban area (solar farms, wind turbines, small hydro) [Albergel et al., 2014].

Decentralised production from buildings is taken into account at the district level. For locally available large renewable energy sources, the model also accounts for their respective existing technical potential, hence easing potential studies on the assessment of additional commercially exploitable renewable sources.

After this step is achieved, the model allows to perform a full energy balance at the urban area's level to calculate the net energy supply and demand balance.

Challenge 7 – Role of electric mobility

The simulation of the electric vehicles fleet is based on the road passengers transport demand and on assumptions on yearly new registrations. Electric vehicles can account for a significant storage capacity, for a relatively moderate cost (incl. the cost for charging infrastructure and ICT systems).

The modelling enables to quantify the total storage capacity connected to the grid and to analyse its impact on the management of local intermittent sources (wind and solar production).

Given that average travel times are relatively moderate within an agglomeration, electric vehicles can play an important role in maintaining the demand-supply balance on the grid: batteries can discharge during on-peak times to inject power on the grid and avoid the use of additional thermal power plants; they will charge during off-peak times based on centralised production. For the different scenarios built, it is assumed that the existing tariff system as well as the required available storage capacities are adequate. The modelled tariff system takes into account compensation for the injected electricity from batteries and for the additional use of battery due to additional discharge/charge cycles.

The share of renewables in local production mix is then modelled depending on the simulated number of electric vehicles.

Challenge 8 – Role of industry

Energy flows in the industry sectors are modelled according to the existing types of industries implanted at the local scale and their added value in the economy. Energy demand of the industry sector is forecasted for each energy carrier and by sub-sector; industrial energy production is calculated by production technology according to the available surfaces.

Energy needs of the industry sector are significant, and improved processes can lead to large energy efficiency savings. The EnerCity model of Enerdata takes the specific energy consumption of different processes for each sub-sector (e.g. space heating, furnaces, thermal exchangers, separation processes…) into account and therefore enables to reflect improvements in efficiency performance.

Moreover, industrial sites – especially in energy intensive branches – have also developed intern energy production or recovery plants in order to reduce their energy bills, such as cogeneration. This technology offers many benefits as it provides an adequate solution to reuse the different waste and effluents produced, and meanwhile to cover a part of the site's energy needs (electricity, gas…).

The EnerCity model therefore provides a focus on decentralised renewables technologies, including cogeneration, but also solar or geothermal power and evaluate the possibility to combine them with flexibility mechanisms or demand curtailment in order to maximise auto-consumption. In this case, the model assumes that demand curtailments are sold at the same tariff as the purchase price on the grid.

3.2. Model application, scenarios and results

3.2.1. Urban area studied and scenario definition

As agreed with the Fondation Tuck, the EnerCity model was applied to the French agglomeration of Grenoble Alpes Métropole.

The scope of the studied territory is based on the administrative and legal boundaries of the agglomeration Grenoble-Alpes Métropole, which is sub-divided into 49 'communes' as followed (listed in alphabetical order): Bresson, Brié-et-Angonnes, Champagnier, Champ-sur-Drac, Claix, Corenc, Domène, Échirolles, Eybens, Fontaine, Fontanil-Cornillon, Gières, Grenoble, Herbeys, Jarrie, La Tronche, Le Gua, Le Pont-de-Claix, Le Sappey-en-Chartreuse, Meylan, Miribel-Lanchâtre, Montchaboud, Mont-Saint-Martin, Murianette, Notre-Dame-de-Commiers, Notre-Dame-de-Mésage, Noyarey, Poisat, Proveysieux, Quaix-en-Chartreuse, Saint-Barthélemy-de-Séchilienne, Saint-Égrève, Saint-Georges-de-Commiers, Saint-Martin-d'Hères, Saint-Martin-le-Vinoux, Saint-Paul-de-Varces, Saint-Pierre-de-Mésage, Sarcenas, Sassenage, Séchilienne, Seyssinet-Pariset, Seyssins, Varces-Allières-et-Risset, Vaulnaveys-le-Bas, Vaulnaveys-le-Haut, Venon, Veurey-Voroize, Vif, Vizille. In total, the agglomeration has a population of about 450,000 inhabitants (as of 2015) over a territory of 541.17 km^2.

The assumptions made to build the scenarios feeding the model are detailed and explained below.

For the modelling of the Grenoble-Alpes Métropole, four typical districts have been identified and built:

- inner-centre districts (QUAT1)
- first-ring suburbs (QUAT2)
- second-ring suburbs (QUAT3)
- peri-urban districts (QUAT4)

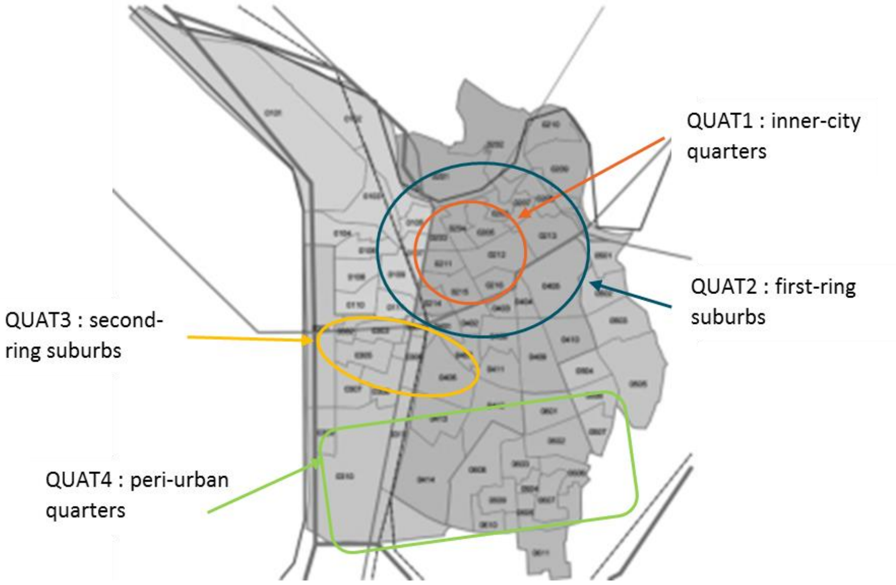

Figure 13: Segmentation by typcal district for Grenoble-Alpes Métropole

Three contrasted scenarios were built in order to provide a quantitative assessment of the impact of the main new paradigms and challenges on urban energy systems as identified in section 2 of this report.

The three scenarios are based on city's historical data publically available – mostly from the INSEE – or kindly provided by the local authorities. When not available, historical data have been estimated or completed with regional or national inputs.

Underlying macro-economic assumptions are similar for the three scenarios: the economic growth of Grenoble-Alpes Métropole is expected to increase at an average rate of 2.0%/year, and the population is expected to increase at an average rate of 0.98 % (Enerdata own estimates based on [INSEE, 2016]). The prices of fossil fuels and electricity are set exogenously and are based on Enerdata national forecasts modelled in its prospective exercise EnerFuture[5].

It is assumed that the city structure, which is modelled through the definition of typical district categories, remains constant over the forecast period.

In the power sector, the Métropole has the specificity to rely on several micro-hydro power plants operated by EDF and the independent regional producer Gaz et Electricité de Grenoble. The assumption was made that local hydro electricity production is entirely consumed within the Métropole and remains constant over the period.

Business as Usual Scenario ("BAU"):

This scenario provides an outlook of the local energy system up to 2035, based on the present local thermal regulation and current subsidies levels on distributed energies (e.g. "Mur-Mur" thermal renovation campaign over 2011-2014 for buildings). Technological progress is assumed, so that the different equipment types become more efficient over the period, whereas the associated investment costs decrease.

Energy Efficiency Scenario ("EE"):

This scenario explores the implications of more ambitious energy policies and faster technological progress to reduce final energy demand and optimise energy distribution within district areas. In the residential and tertiary sectors, the number of renovation actions increases compared to the BAU.

Greater energy efficiency measures and campaigns lead to a growing public awareness, and consumption behaviours are evolving. E.g. in the residential and tertiary sectors, the required inner comfort temperature is lower for heating and higher for cooling. Enhanced demand-side management is simulated through an assumed load smoothing of 20% for each district and end-use.

In the transport sector, national targets for an improved efficiency of conventional cars are assumed to be reached: i.e. average emissions decrease to 95 g/km by 2020 and by around 50 g/km by 2035 (official objective of 2 l/100 km). Meanwhile, the share of hybrid and electric vehicles in the vehicles fleet is increasing compared to the BAU.

Improvements are also reached through more energy efficient processes in the industry sector.

Decentralised Energies Scenario ("DER"):

This scenario describes a local energy system with abundant distributed energy generation thanks to high subsidies and enabling policies, and assesses the impact on the local and the centralised energy system.

The context pictured in this scenario supports a significant increase of equipment such as solar water heaters and individual electric heat pumps, as well as solar PV panels (PV equipment rate multiplied by 4 over 2015-2035). At the district and city levels, strong investments are realised to expand the district heating and cooling networks.

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[5] http://www.enerdata.net/enerdatauk/knowledge/subscriptions/forecast/enerfuture.php, last updated January 2017

The development of a smarter and more flexible energy management system, in order to cope with the integration of a growing share of decentralised energy sources, leads to an enhanced mutualisation of energy; “prosumers” are encouraged to sale their production of electricity onto the grid according to flexible and attractive tariffs.

In the following, the main results of the scenarios are described: energy balances, trends and main outcomes, providing detailed insights on the evolution of key parameters and outputs as well as a comparison between the different scenarios.

3.2.2. Energy consumption by sector and by source at the city and quarter levels

Final energy consumption by scenario and sector at the city level

Over 2015-2035, the final energy consumption of “Grenoble-Alpes Métropole” slightly increases by 3.0% in the BAU, driven by the population and activity growth. It reaches nearly 950 ktoe in 2035.

In the EE scenario, the implementation of stronger energy efficiency and climate policies leads to a 11% reduction of the total final energy consumption by 2035 compared to 2015. This corresponds to a 14% reduction compared to the BAU in 2035: final consumption in that year amounts to 815 ktoe.

Final energy consumption increases progressively over the period in the DER scenario, with a 2.3% increase between 2015 and 2035, amounting to 940 ktoe at the end of the simulation.

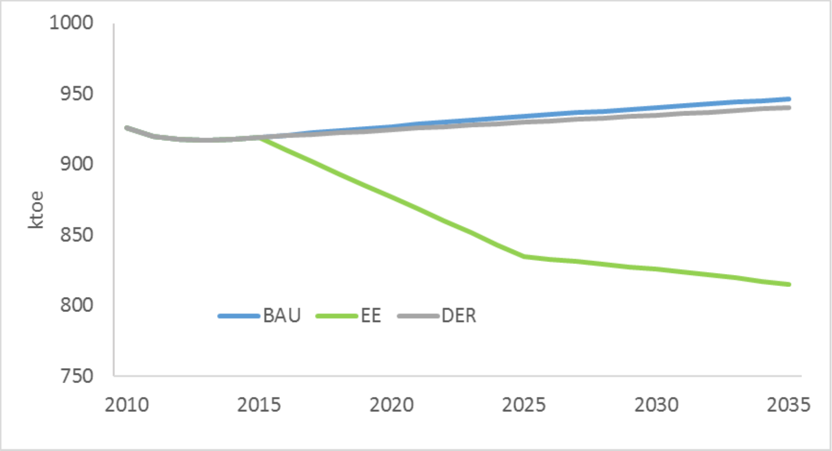

Figure 14: Evolution of final energy consumption for Grenoble-Alpes Métropole in the three scenarios

In all scenarios, the residential and industry sectors remain the main energy consuming sectors of the agglomeration over the period. However, energy consumptions from the industry and from transport raise significantly (both +8% over 2015-2035 in the BAU scenario) due to the growing activity in the agglomeration.

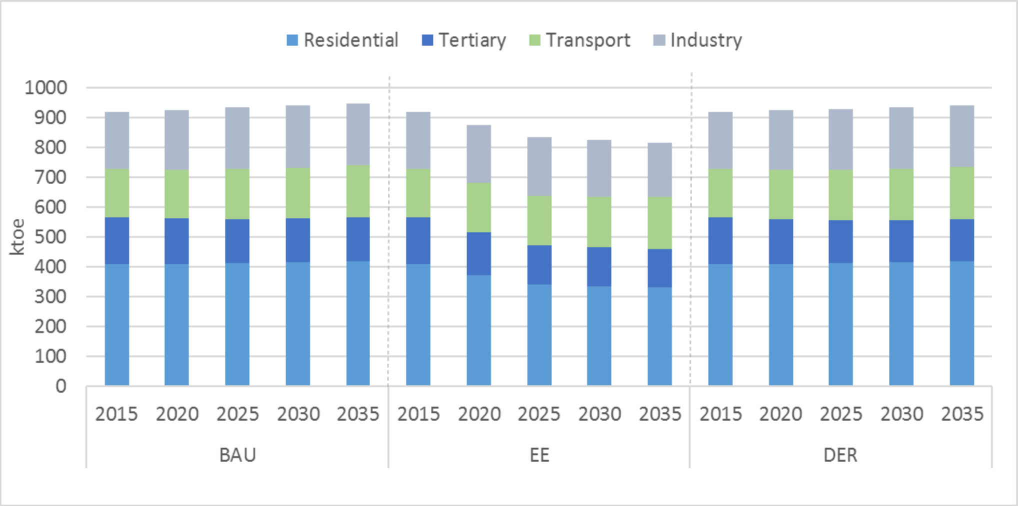

Figure 15: Final energy consumption by sector for Grenoble-Alpes Métropole in the three scenarios

Final energy consumption by end-use in buildings

In both the residential and tertiary sectors, space heating and cooling represents by far the largest energy end-use until 2035 with a share of the total reaching more than 70% in the residential sector and more than 50% in the tertiary sector. This confirms the relevance of policies and actions targeting either buildings refurbishment and efficiency standards or the promotion of more climate-friendly heating technologies (e.g. district heating, heat pumps).

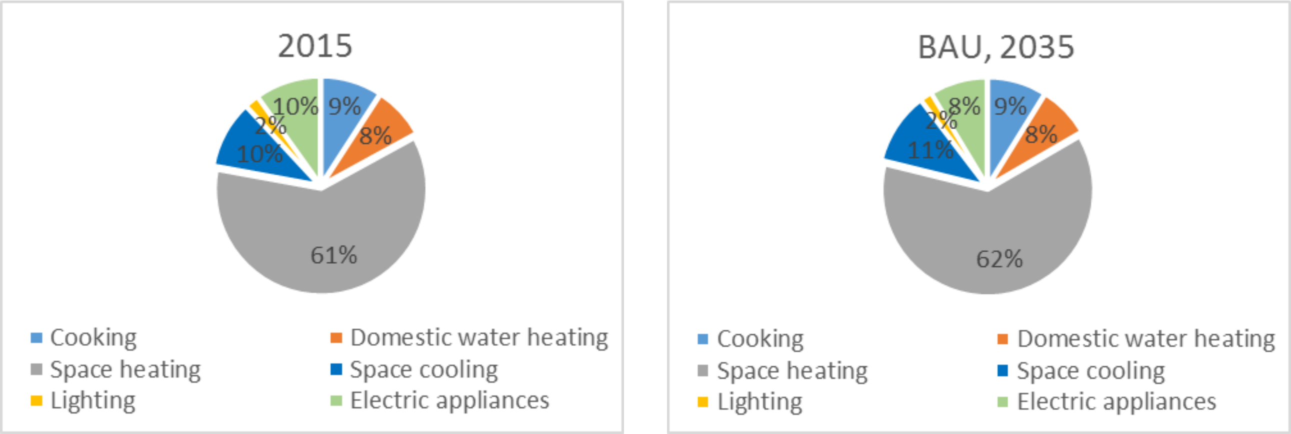

Figure 16: Final energy consumption by end-use in the residential sector in the three scenarios

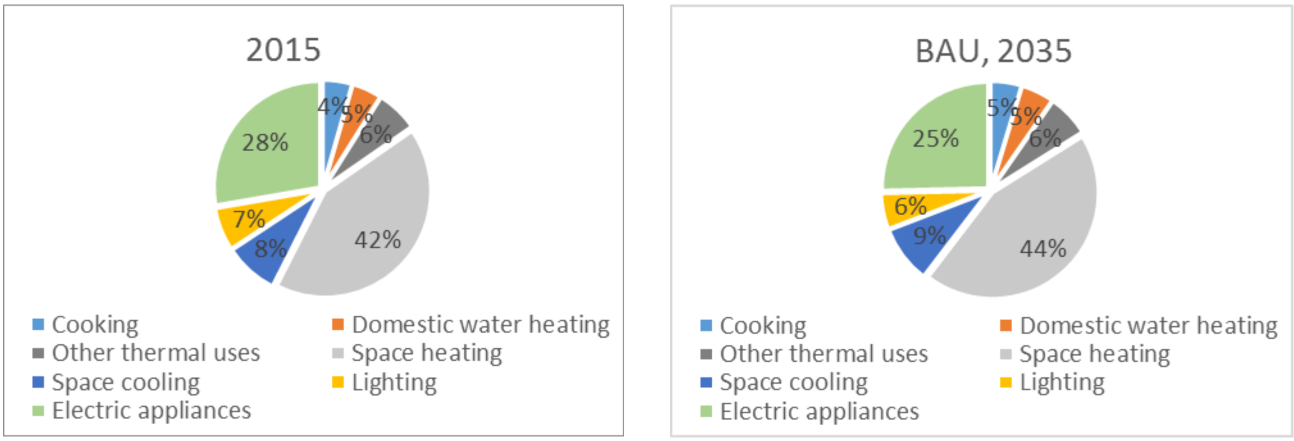

Figure 17: Final energy consumption by end-use in the tertiary sector in the three scenarios

Role of urban form and density in the final energy mix

As reviewed in the literature, the features of the urban built envionment (form and density) have a significant impact on both energy consumption and energy mix.

Figure 18 shows the 2030 energy mix of the four different typical districts built for modeling the Grenoble-Alpes Métropole in the BAU scenario. The development of biomass is more significant in districts where density is lower (QUAT3 et QUAT4): its share in the energy mix reaches respectively 10 to 12%, whereas it accounts for less than 5% in city centre quarters.

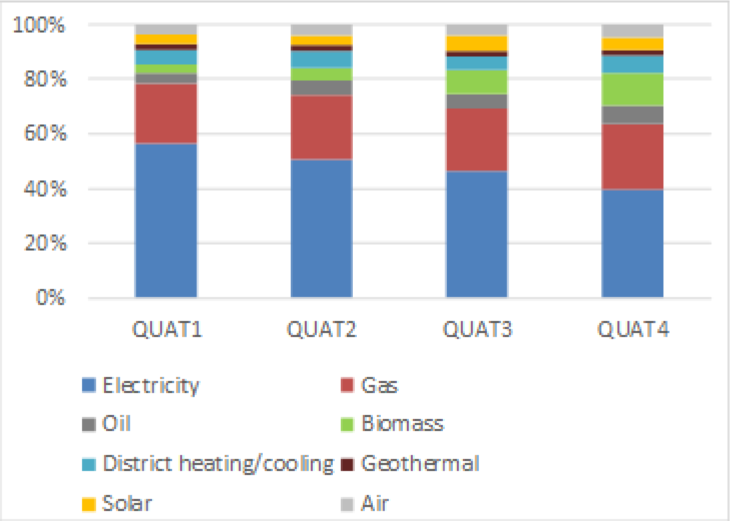

Figure 18: Final demand in residential and tertiary sectors, by district type and energy source in 2030, BAU scenario

At the building level, the energy mix and the integration of distributed renewable energy sources vary widely according to the type of housing considered (size and construction date).

Figure 19 illustrates, in the DER scenario, the different energy mixes in a small flat and in a large individual house (residential sector), both for the oldest and newest modelled age categories for buildings (i.e. built before 1946 and after 2008).

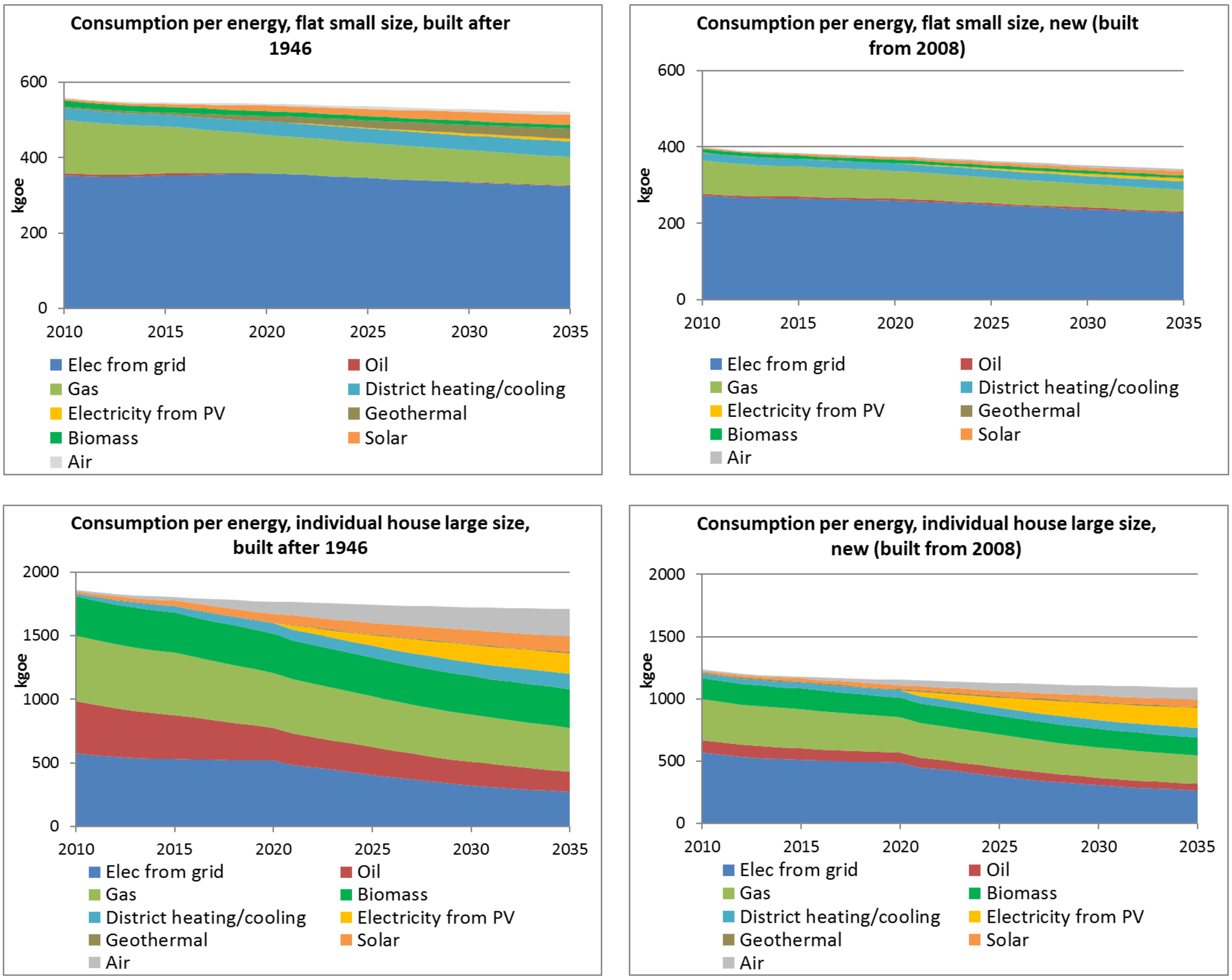

Figure 19: Comparison of final consumption in a small flat and in a large individual house, for two age categories, DER scenario

3.2.3. Integration of distributed renewable energies: the growing role of prosumers

Evolution of distributed renewable energy sources and impact on the energy mix

In all scenarios, the share of fossil energies decreases by 6 to 9 points, whereas renewables develop to reach around 23% in 2035 in both BAU and EE scenarios; in the DER scenario, this share increases to 30%, driven by distributed renewable energy sources, whose share is multiplied by 4 over 2015-2035. Hydropower remains a significant source of energy, with a share of 8-9% in the three scenarios considered.

The evolution of distributed renewable energy sources, which supports the growing role of "prosumers", is shown in Figure 20 for the three different scenarios considered.

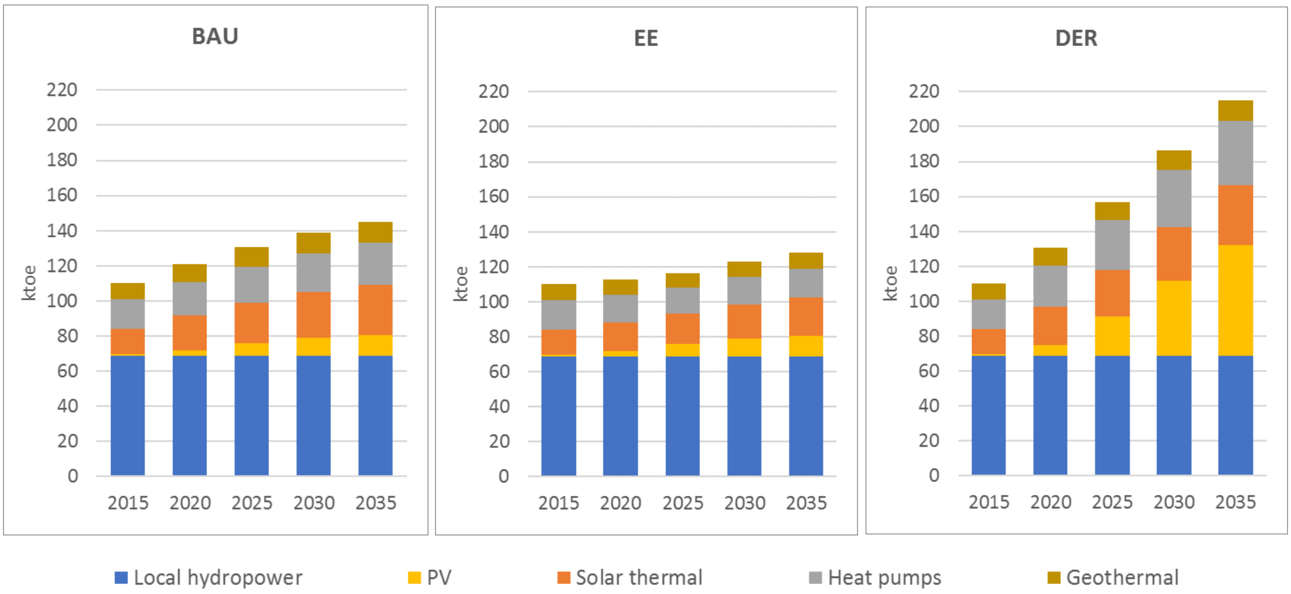

Figure 20: Evolution of consumption from distributed renewabes sources in the three scenarios

In the DER scenario, the increase of the share of distributed renewable resources is driven by solar energy (PV and solar thermal), which represents up to 10% of the total final energy consumption by 2035.

Energy efficiency actions modelled in the EE scenario (retrofit and incentives to replace equipment in buildings, more energy-efficient behaviours) lead to a decrease of energy consumption from all energy sources, i.e. including renewables. The share of distributed renewable sources in the energy mix of the EE scenario is not higher than in the BAU; this is due to the fact that energy efficiency measures encourage consumers to reduce their consumption, not particularly depending on the technology: end-users tend to replace their old equipment with the most affordable technologies and without significant subsidies, they turn to more efficient, but not necessarily climate-friendly technologies. It is therefore essential to accompany energy efficiency measures with an appropriate incentive scheme so that end-users turn to clean technologies.

PV and "prosumption": impact on the share of self-consumption, supply costs and load shifting

In the DER scenario, the modelled uptake of distributed energy sources results in a fivefold increase of PV installed capacities by 2035 compared to the installed capacities in the BAU at this horizon.

This development of PV increases the possibility for end-users to adjust their production and consumption patterns according to electricity tariffs on the grid and storage costs. The EnerCity model enables to analyse, according to these parameters, the structure of PV production, i.e. the share of PV electricity directly auto-produced (PV to load), stored (PV to storage) or injected into the grid (PV to grid for a given type of buildings).

Figure 21 shows the impact of growing PV capacities, in the DER scenario, on supply costs and the structure of electricity supply over the forecast period and compared to the BAU scenario for an individual large house built before 1946.

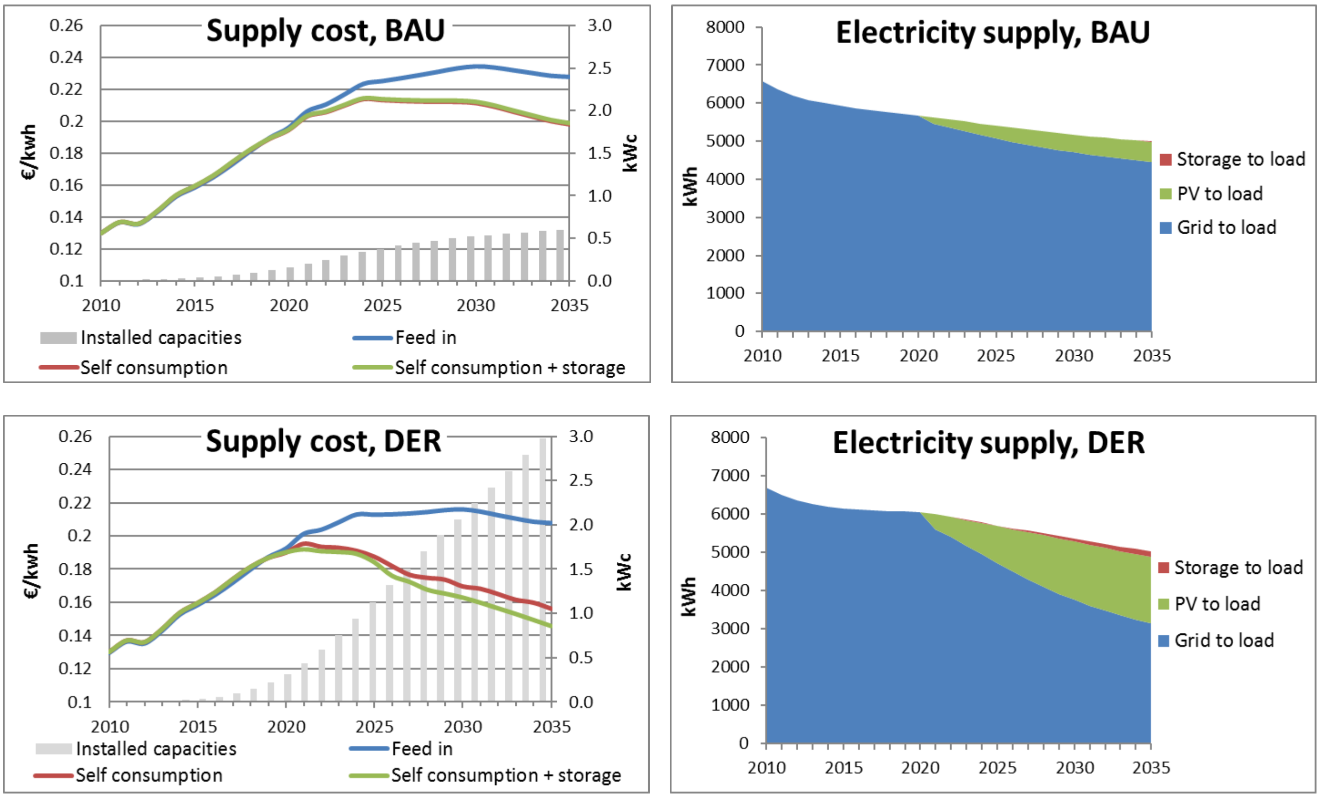

Figure 21: PV suppy costs (€/kwh), installed capacities (kWc) and strucure of PV electricty supply in the BAU and DER scenarios

Until 2020, in both BAU and DER scenarios, the development of PV and storage capacities is too limited to impact significantly the total supply costs, whatever the option chosen by the end-user (self-consumption with or without storage, or resale to the grid). From 2020, it becomes more profitable for end-users to self-consume their PV production (without storage or including storage in the DER scenario) rather than to sale electricity to the grid, as feed-in tariffs progressively decrease whereas power prices increase. In the DER scenario, an enhanced flexibility of the system is achieved through the development of distributed energies and storage capacities, leading to overall lower electricity supply costs and therefore tending to reduce energy bills of end-users.

Self-sufficiency of buildings (i.e. the share of buildings' consumption covered by own production) increases over 2015-2035 in both scenarios. For a large house built after 2008, it reaches 15% in the BAU by 2035, 46% in the DER scenario (without storage), and up to 58% when considering storage.

On the supply side, the integration of decentralised PV coupled with storage capacities (DER scenario) leads to a greater flexibility of the system through the possible growing mutualisation of energy at the district level: the share of energy production which is self-consumed decreases significantly over the period, as a greater amount of electricity produced is injected into the grid and therefore "shared" with other consumers. In 2035, about 30% of the electricity produced by the considered building type is injected into the grid (PV and storage options considered) compared to less than 2% in the BAU. Meanwhile, the use of storage options enables to optimise self-consumption of buildings (+15 points when PV is coupled with storage at horizon 2035).

At the quarter level, the greater integration of decentralised energy sources and storage capacities, as modelled in the DER scenario, has a significant impact on the load curve. Figure 22 represents the evolution of the load curve of an inner-quarter (QUAT1) in 2035 for a given week day in winter (BAU and DER scenarios). The implementation of distributed and flexibility options (DER scenario) enables to shift the load curve down: thanks to storage solutions, consumption can be temporarily modulated in order to minimise peak loads.

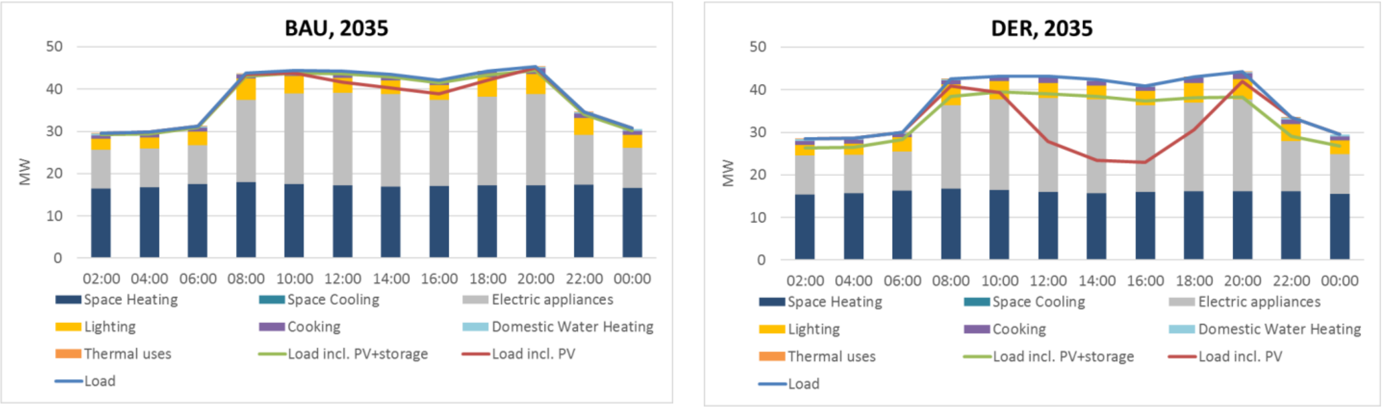

Figure 22: Aggregated load curve at the district level, city-centre, withouy and with PV and storage, BAU and DER scenarios

3.2.4. Impact and costs of energy efficiency in buildings

Energy efficiency is seen as a major pillar for increasing sustainability of energy systems. In the residential and tertiary sectors, numerous exemplary cities involved in sustainability actions have targeted significant retrofit of their existing building stock, coupled with high efficiency standards for new buildings (see section 2.3.4).

Energy efficiency measures for private and public housing have been simulated in the EE scenario; they lead to energy savings of nearly 105 ktoe in 2035 compared to the BAU, and to cumulated energy savings amounting to about 1,465 ktoe over 2015-2035.

Especially, buildings' consumption (residential and tertiary) for space heating and cooling decreases in total by 27% in 2035 in the EE scenario compared to the BAU.

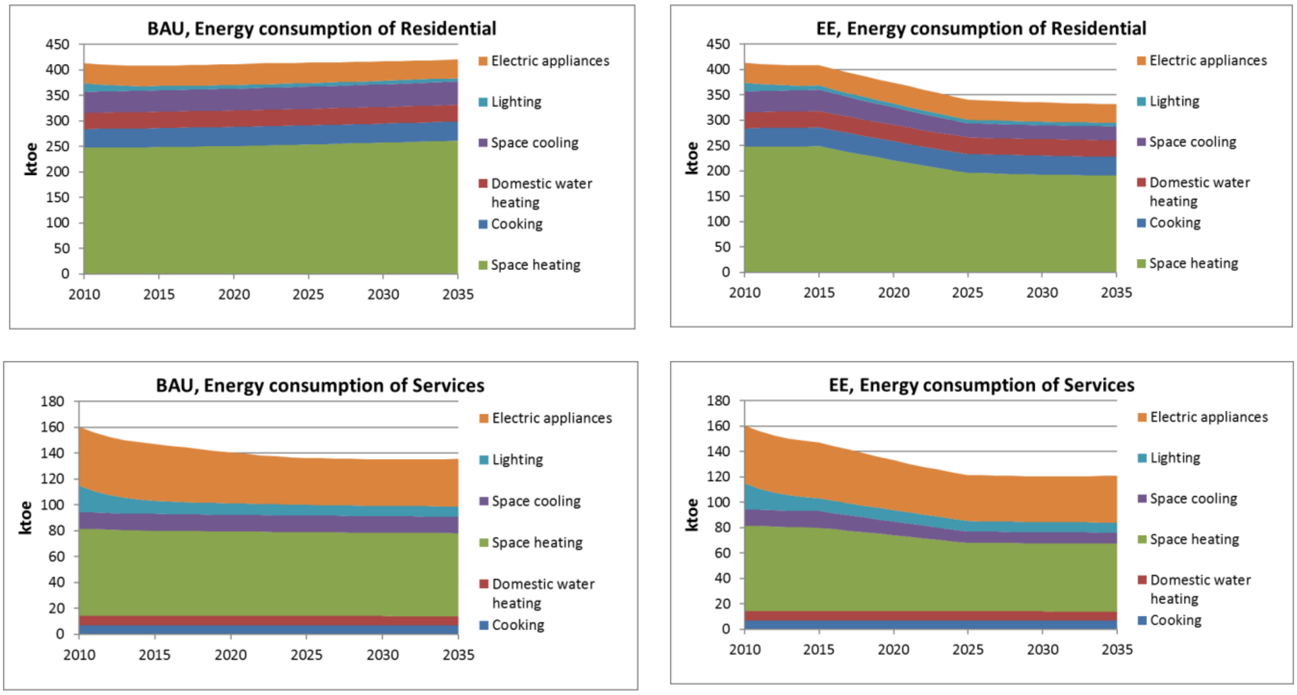

Figure 23: Final energy consumption by end-use in residential and tertiary buildings, BAU and EE scenarios

In order to reduce energy consumption for space heating/cooling, two options are modelled for end-consumers at the building level: either replace their equipment for more efficient ones, or implement building retrofit measures.

Figure 24 illustrates the competitiveness of each type of heating technology for space heating for a medium-sized house built before 1946. It represents the evolution of total annual costs (including initial investment and operating costs) for the different existing heating technologies, and takes into account the costs of refurbishment as well as the associated cost savings on the energy bill when relevant (configuration with retrofit). A sensitivity test has been conducted based on the EE scenario to compare the evolution of these costs in the case of enhanced retrofit measures; assumption is made that the energy consumption level of the retrofitted buildings is similar to this of new constructions.

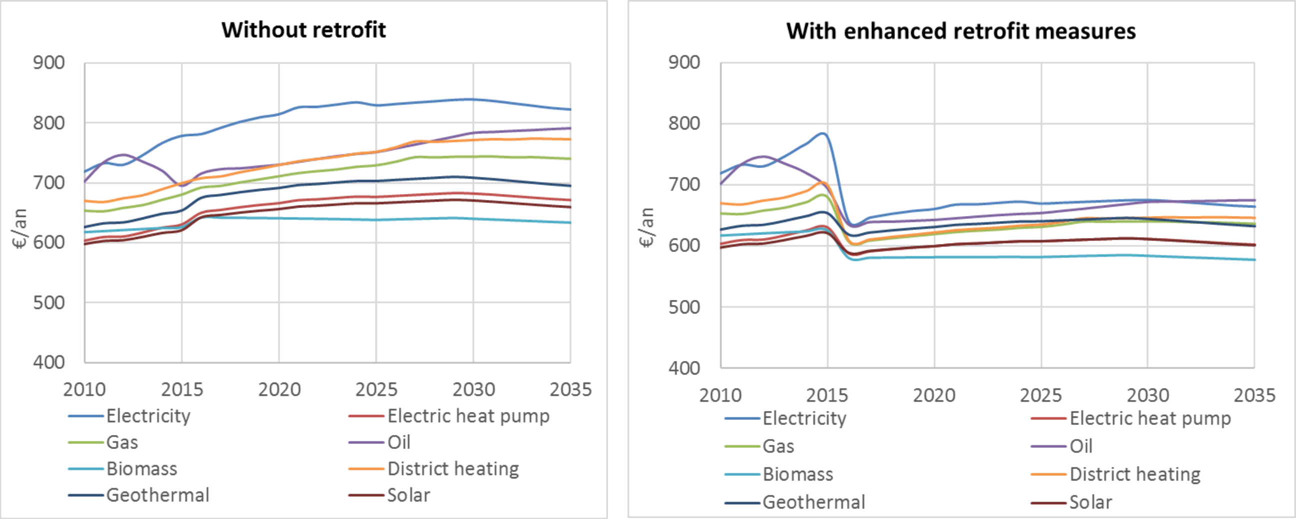

Figure 24: Exploitation costs by heat equipment technology, medium-sized house built before 1946, in configurations with and without refurbishment, EE scenario

In the configuration where no retrofit measure is implemented, it appears that it is economically more interesting to switch to equipment based on renewables, which are currently strongly subsidised through tax credits such as biomass, solar or electric heat pumps. The estimated exploitation costs of these technologies is expected to be 20-25% cheaper than electricity-based equipment by 2035, with an increasing cost gap over the period due to the growing prices of electricity. More generally, the higher investment required by new renewables-based heating equipment is compensated by avoided costs related to the increase of energy prices (evolution of energy prices is derived from Enerdata’s EnerFuture long-term energy scenarios, see section 3.1.2).

In retrofitted buildings, electricity and gas remain however competitive compared to renewable options; in particular, electricity becomes the most affordable energy for consumers. District heating also appears to be an economically viable option. Moreover, the gains arising from refurbishment and the resulting lower energy needs for heating contribute to lower the total annual costs for end-consumers, whatever the type of energy considered, compared to a configuration without retrofit: average annual costs in retrofitted buildings amount to 630 €/a by 2035, compared to average annual costs higher than 720 €/a in a configuration without refurbishment.

3.2.5. Energy consumption in the transport sector and deployment of electric vehicles

In all scenarios, the final consumption of the transport sector continues to increase progressively over 2015-2035 due to the growing traffic in passengers and freight. In the EE and DER scenarios, the enhanced efficiency of new vehicles and the further development of electric vehicles enable to reduce the energy consumption of the sector by 1.2% compared to the BAU at horizon 2035.

The share of passengers' public transport expands, especially supported by enabling policies in the EE and DER scenarios. Meanwhile, the development of electric and hybrid vehicle is encouraged. The resulting energy mix in passengers' private and public transport is shown below is shown in Figure 25.

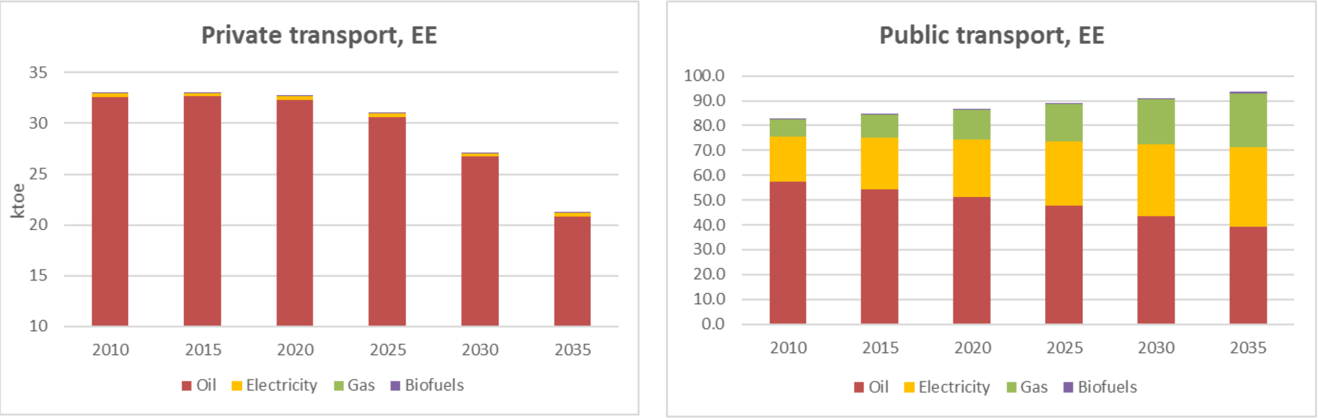

Figure 25: Final consumption by fuel in the passengers' private and public sectors, EE scenario

The number of electric vehicles in the private car fleet is multiplied by 15 over 2015-2035 in the BAU scenario, and by 22 in the EE and DER scenarios, as illustrated in Figure 26. The storage capacities provided by cars' batteries consequently increase to reach more than 20,000 Ah by 2035 in the EE and DER scenarios. Hence, the development of electric vehicles may have a considerable impact in terms of the expansion of power storage means and therefore can strongly contribute to more flexibility and optimisation potential of the urban energy system in the future.

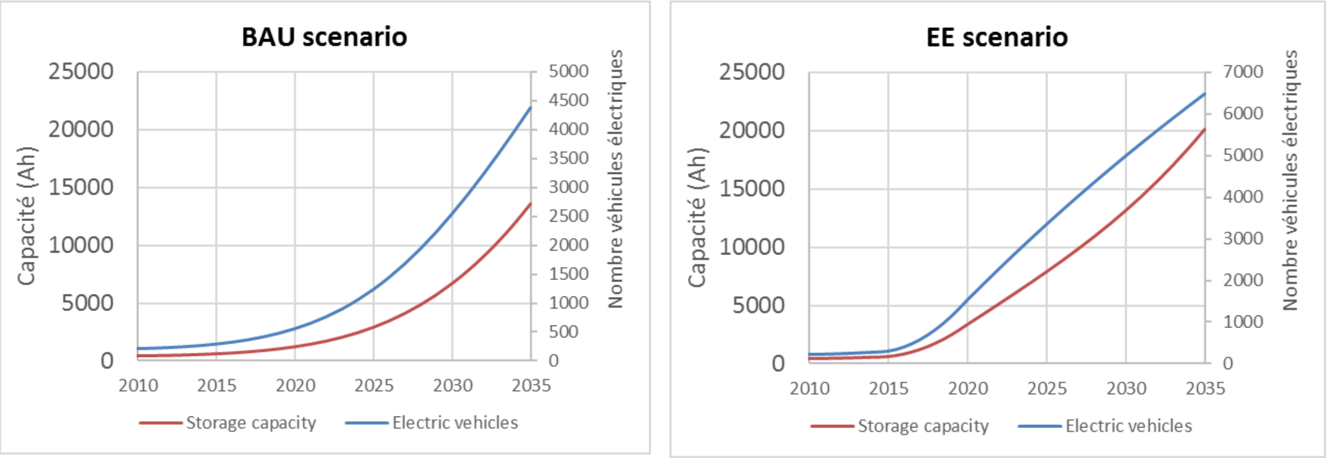

Figure 26: Development of electric vehicles and storage capacities, BAU and EE scenerios

3.2.6. Energy balance of the urban area

The resulting final energy balances of Grenoble Alpes Métropole is presented below for each scenario (Figure 27 to Figure 29), with a detailed view by sector and by type of energy. Here, the added value of the modelling approach is clearly shown in terms of the potential role of decentralised supply versus conventional centralised supply.

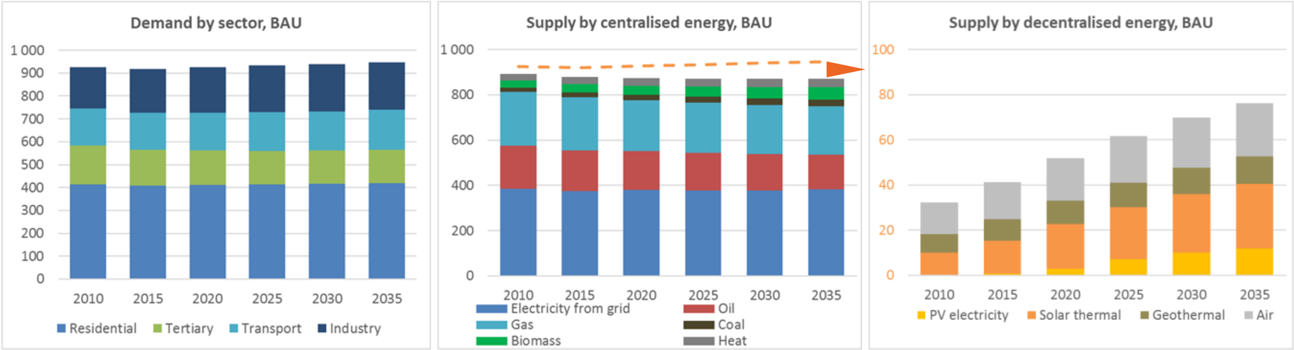

Figure 27: Energy balance of Grenoble Alpes Métropole, BAU scenario (ktoe)

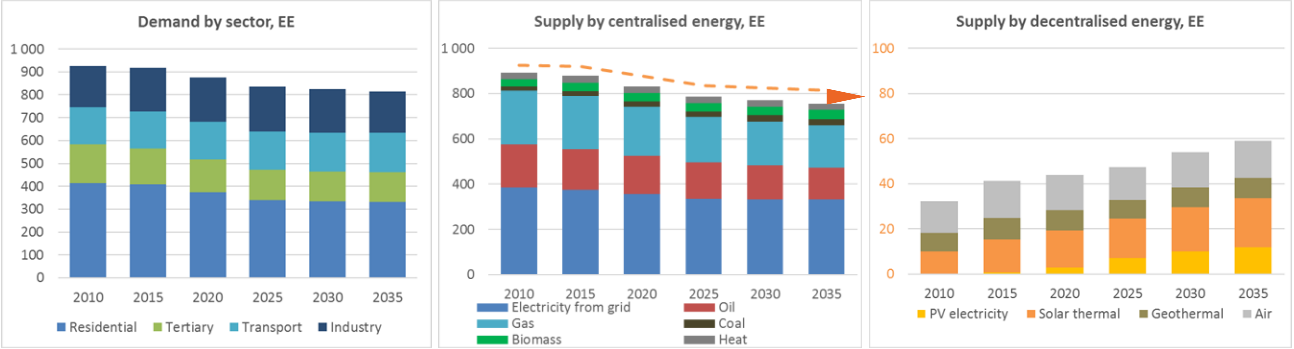

Figure 28: Energy balance of Grenoble Alpes Métropole, EE scenario (ktoe)

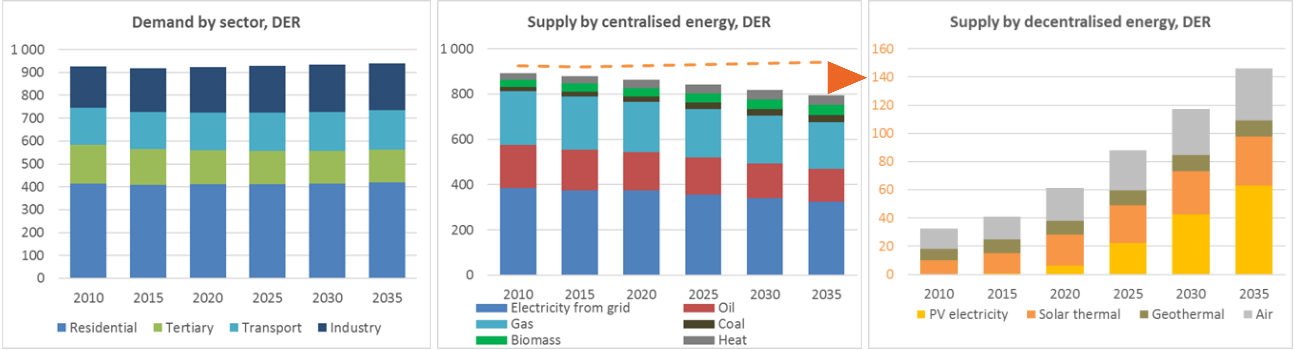

Figure 29: Energy balance of Grenoble Alpes Métropole, DER scenario (ktoe)

In the BAU scenario, the contribution of each sector in the city's demand remains stable over the period. The needs of the city remain mostly covered by fossil energies and electricity from the grid, which represent each 40% of the city's consumption by 2035. Over 2015-2035, the share of oil and gas share in final energy consumption decrease by 3 and 4 points to the benefit of district heating, heat pumps and solar thermal technologies.

Energy efficiency measures (EE scenario) greatly impact the final demand of the residential and tertiary sectors, whose share in the city's demand decreases by 4 points in 2035 compared to the BAU. At the city level, the energy mix remains similar to the mix in the BAU. Electricity gains considerable shares (+6 points) over 2015-2035 in the transport sector, mainly due to the modal shift towards public transport (with a growing share of tramways and hybrid buses).

In the DER scenario, the city’s energy consumption is barely impacted compared to the BAU, but on the supply side, the role of decentralised energies, driven by the development of PV equipment and heat pumps, becomes significant: they represent 16% of the supply mix by 2035 (7% for PV alone). Besides this result as such, it underlines the necessity to have a granular modelling approach, up to the buildings’ scale, to be able to capture the potential of such decentralised technologies.

4. Conclusions and perspectives

4.1. Key findings of the analysis

The overall objective of the study – the understanding of new paradigms and challenges for urban energy systems – has been answered through a two-pillar qualitative and quantitative approach.

A first thorough **literature review has focused on the qualitative understanding and assessment of identified paradigm shifts** which urban energy systems are likely to cope with in a context of sustainable development. This task has helped highlight the ongoing trends and most probable future developments in terms of technologies, innovative solutions, possible impacts on energy supply and demand equilibria and the derivation of the corresponding drivers for these changes.

The literature review has shown the specific necessity to address fine granularity (especially at buildings' and districts' levels) in the analysis of urban energy systems, the need to represent and account for potential synergy and optimisation effects, as well as the multidisciplinary requirements which should be considered in such assessments, i.e. economic, environmental, technical and social aspects.

Another clear outcome of the literature review, beyond these aspects, is the identification of the most crucial concepts and parameters to consider for developing strategic plans of urban areas. As a logical corollary, this task has been valuable to precise which system components and variables need to be addressed in any modelling exercise aiming at providing prospective insights for the long-term planning of urban energy systems.

The second pillar of this work consisted in the **application of Enerdata's EnerCity model for the calculation of three scenarios to understand the possible futures of the urban area of Grenoble Alpes Métropole**.

The model used for the assessment of the energy system of Grenoble Alpes Métropole is based on a three-level approach: an aggregation and analysis at the buildings level, districts level, and finally at the city level (city refers here to the administrative agglomeration), with a focus on potential synergies or linkages at each step of aggregation. The main objective is, as underpinned in the literature review, to better capture the effects of new patterns and trends in urban energy systems, including:

- greater decentralisation of the energy system, including the development of innovative solutions (e.g. PV, CHP, storage);
- new energy flow patterns based on "prosumption" and empowerment of all stakeholders;
- energy efficiency potentials at the buildings' level;
- synergy potentials of the energy system through multi-energy carriers' networks and links between sectors (through e.g. district heating, electric vehicles)

This requires to offer both an in-depth and detailed sectoral analysis combined with a systemic overview.

Three scenarios reflecting the above-mentioned axes were built to simulate the possible future energy pathways for the energy system of Grenoble Alpes Métrolpole: a baseline scenario (BAU), an energy efficiency scenario (EE) and a scenario with increased expansion of decentralised energies (DER).

The results show that current energy and climate policies (BAU) do not enable to decrease the urban energy demand (+0.1%/year until 2035). However, the energy mix evolves towards a slight development of district heating and solar thermal equipment in buildings.

Additional energy efficiency measures (EE scenario) lead to substantial cumulated energy savings: 9% over 2015-2035 compared to the BAU. Especially in the residential and tertiary sectors, consumption trends reverse and a demand reduction of respectively 19% and 17% is reached in those sectors in 2035 compared to 2015.

The development of decentralised energies (DER scenario) shows great opportunity for the studied urban area: decentralised energy sources (PV coupled with individual storage solutions, solar thermal, geothermal energy and heat pumps) could meet up to 16% of the energy needs of Grenoble Alpes Métropole by 2035. This increasing use of decentralised technologies, coupled with flexibility management tools, leads to the possibility to shift the load curve during peak times with various effects according to the considered districts. This underlines the importance of "timing" in energy flows as well as the potential arising from more flexibility and synergies between the energy system's components.

To go beyond this analysis, two ways forward seem important to indicate: the need for quality data at urban scale, and further model developments which could enhance the analysis capabilities and planning support for urban areas. These two elements are further developed in the following sections.

4.2. The need for availability and quality of urban energy data

The use of such integrated energy system models at urban scale requires an extensive amount of input data at several granularity scales, including on buildings and districts. Running such models is based on the prerequisite of having access to robust data at city/agglomeration level, either through publically available data or provision of data by the relevant stakeholders.

For the specific case of Grenoble Alpes Métropole presented in this study, sufficient input data have been found or kindly provide by the local authorities, and for specific series, additional assumptions were made in case of missing datasets. But applying the model for other urban areas still requires access to quality data (e.g. historical energy consumption and drivers by sector, emissions levels, etc.) at different scales of the area considered. As summed up by [IIASA, 2012], transparency about assumptions and methods used as well as data disclosure are key for both data quality and integrity, but also for well-informed policy choices.

This data requirement will most likely prove to be even more significant in the ongoing context of the increasing role of information and communication technologies (ICT), where the balance between energy demand and supply will increasingly be depending on individual consumption patterns and decentralised electricity supply. Here again, collection and communication on disaggregated data at the local level will play a key role. Data availability, quality and collection represent today some of the biggest challenges for urban energy systems modelling.

4.3. Perspectives for further modelling work

The EnerCity model applied for this study allows to answer several crucial aspects of the future challenges of urban energy systems, as identified in the literature review. This includes in particular the ability to consider urban energy systems as integrated entities (linking sectors to each other, accounting for the equilibrium between consumption and energy supply), and to allow for an economic assessment not only based on the sole investment figures for the various technologies, but rather considering the full costs of the various options offered to urban areas.

Nonetheless, several perspectives can be envisaged to improve the modelling framework in a future work, including:

- **Potential future role of gas/biogas technologies**
  Along with electricity and district heating networks, the potential future role of gas and biogas technologies in urban areas could be assessed through a dedicated model upgrade. This would allow to assess in particular the competitiveness of gas networks in the urban context (e.g. expansion capacity vs other types of fuels and vs thermal insulation of dwellings).

- **Energy poverty and sustainability of the system**
  Further work can be envisaged on the topic of energy poverty. An upgrade of the model would allow to understand to which extent financing can be awarded for thermal insulation of households with the lowest income, depending on the specific context of the urban area considered. Such work would require to adapt the modelling framework and add a macro-economic layer to ensure a closure with socioeconomic variables such as e.g. incomes, value added, unemployment, etc. More generally, the

introduction of detailed socioeconomic variables and analysis could allow to better assess the sustainability of the urban energy system considered by taking into account not only purely economic parameters and results, but also the social and environmental dimension of the system. A great variety of indicators could be created according to the availability of data: quality of the environment, pollution level indicators, comfort and hygiene, education of population, participation in energy management decisions, etc.

- **Multi-dimensional indicators for urban energy systems**
  Given the increasing role of sustainability, a new generation of indicators should be developed to assess future energy systems. These should account for various dimensions such as economics, technical aspects, environmental compatibility, social aspects, etc. In particular, two broad categories of indicators seem relevant to develop at this stage: integrated attractiveness indicators for intelligent systems (e.g. showing how smart solutions at buildings' level can help stabilise the local electricity network, comply with environmental constraints, offer more comfort and reliability to end-users etc.) and more broadly sustainability indicators allowing to rank urban areas among various criteria (overall “liveability” of the area) taking into account all externalities (environmental impacts, social impacts, etc.). Such indicators and their democratisation may possibly contribute to further boost innovation and achieve objectives set at a more global scale. Regarding power generation infrastructure for example, the IEA has developed a first approach, that could serve as a basis for such work, to move from the traditional merely economic “costs” view towards a complete holistic “value” approach of energy technologies and networks [IEA/CEM,2016].

- **Emissions and climate**
  Lastly, the model developed could be upgraded with the implementation of a dedicated emissions and climate module. Based on the already available representation of energy supply and consumption mechanisms, additional equations can be implemented, e.g. in the supply side with specific emission factors for carbon emitting technologies. This would allow to provide detailed GHG balances at the scale of the urban areas, showing in particular which sectors are the most responsible for which types of GHG emissions (CO_2, CH_4, N_2O, etc.). This is an all the most important step as it would allow to assess quantitatively the emissions related impacts of demand-side energy efficiency and other energy and climate policies at the urban level.

5. References

[ADEME, 2009]	*Evolution des coûts d'investissements relatifs aux installations collectives bois énergie*, ADEME, 2009
[Albergel et al., 2014]	*Mise en place d'une méthodologie pour un bilan environnemental physique du transport de marchandises en ville*, A. Albergel, E. Ségalou, J.-L. Routhier, C. de Rham, 2014
[Balmorel, 2005]	*Modelling of energy supply systems by the Balmorel model*, R. Gatautis, H.-F. Ravn, Energetika, N. 2, pp. 8-20, 2005
[Buzar, 2006]	*Estimating the extent of domestic energy deprivation through household expenditure surveys,* S. Buzar, S. Bouzarovski, CEA Journal of Economics 1(2): 6-19, 2006
[Enerdata, 2016]	*Global Energy & CO_2 data*, Enerdata, http://globaldata.enerdata.net/home/, last access 01.12.2016
[European Commission, 2014]	*Strategic Energy Technology Plan (SET)- Towards an Integrated roadmap: Research and Innovation Challenges and Needs of the EU Energy System,* European Commission (incl. stakeholders to the consultation and comments and from the SET Plan Steering Group), 2014
[European Union, 2011]	*Cities of tomorrow, Challenges, visions, ways forward,* European Union, 2011
[Grubler and Fisk, 2013]	*Energizing sustainable cities: assessing urban energy,* A. Grubler and D. Fisk, 2013
[IIASA, 2012]	*Global Energy Assessment – Toward a Sustainable Future,* Cambridge University Press, Cambridge UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012
[IDEX, 2012]	*Etude de faisabilité et de dimensionnement d'un réseau de chaleur avec chaufferie biomasse*, Bertrand DESPRES, Rapport de stage, IDEX, 2012
[IEA, 2016]	*Energy Technology Perspectives 2016 – Towards Sustainable Urban Energy Systems*, International Energy Agency, 2016
[IEA/CEM, 2016]	*Next-generation wind and solar power – From cost to value,* International Energy Agency, Clean Energy Ministerial, 2016
[INSEE, 2016]	*INSEE Statistiques*, INSEE, http://www.insee.fr/fr/statistiques?debut=0, last access 01.12.2016
[Insight-E, 2015]	*Energy poverty and vulnerable consumers in the energy sector across the EU: analysis of policies and measures*, S. Pye and A. Dobbins for Insight-E, 2015
[IMF, 2016]	*International monetary Fund,* http://www.imf.org/external/pubs/ft/fandd/2015/12/jamal.htm*,* last access 05.01.2016
[IRENA, 2016]	*Renewable energy in cities*, IRENA, 2016
[Keirstead and Shah, 2013]	*Urban Energy Systems - An integrated approach*, J. Keirstead, N. Shah, 2013
[OECD, 2013]	*Definition of Functional Urban Areas (FUA) for the OECD metropolitan database*, OECD, 2013
[Patterson, 2009]	*Keeping the Lights On: Towards Sustainable Electricity,* W. Patterson, 2009
[Rifkin, 2009]	*The Empathic Civilization: The Race to Global Consciousness in a World in Crisis,* J. Rifkin, 2009
[Rutter, Keirstead, 2012]	*A brief history and the possible future of urban energy systems*, P. Rutter, J. Keirstead, 2012
[Smil, 1991]	*General Energetics: Energy in the Biosphere and Civilization,* V. Smil, 1991

[UCLG, 2010]	*Local Government Finance: The Challenges of the 21st Century. Second global report on decentralization and local democracy, GOLD 2010*, United Cities and Local Governments (UCLG), 2010
[UNDESA, 2012]	*Challenges and ways forward in the urban sector,* United Nations Department of Economic and Social Affairs (UNDESA), 2012
[UN Habitat, 2008]	*State of the World's Cities Report 2008/2009: Harmonious Cities*, UN Habitat, 2008
[UN Habitat, 2009]	*Urban Indicators Programme Guidelines,* UN Habitat, 2009
[US LEAN, 2015]	*Community Choice Aggregation – Frequently Asked Questions - May 2015,* US Local Energy Aggregation Network, 2015
[WB, 2000]	*Cities in transition,* World Bank urban and local government strategy, 2000
[WEF, 2013]	*Energy Vision 2013 - Energy transitions: Past and Future,* World Economic Forum, 2013

6. Annex: summary of articles selected in the literature review

The following tables give an overview of the articles selected in the literature review along with a summary of their content (sorted by date of publication and name):

Article 1	**Energy Technology Perspectives 2016**
Date of publication	2016
Author(s)	International Energy Agency (IEA)
Type of document	Yearly publication of the IEA
Area of expertise	Energy and Climate, Sustainable Policies and Technologies, Forecasts
Central topic	Transition of urban energy systems towards sustainability and the role of technologies and policies
Method used	Quantitative analysis based on intern scenarios and model, case studies
Summary	The publication provides a detailed insight into global energy forecasts and trends, with a focus on technology and policy opportunities available for accelerating the transition to sustainable urban energy systems.
Key elements brought	- Components of the Urban Energy System - Policies and recommended actions - Quantified analysis: building energy demand and reduction, options for a sustainable transport, supply options (heat and smart networks) - Governance and financing: multilevel, local, intergovernmental coordination, policies by topic

Article 2	**Renewable Energy in cities**
Date of publication	2016
Author(s)	International Renewable Energy Agency (IRENA)
Type of document	International publication
Area of expertise	Energy and Renewables
Central topic	Transition of urban energy systems towards sustainability and the role of technologies and policies
Method used	Approach based on own estimates, best practices and examples
Summary	The publication presents in details the potential development of renewable technologies in cities, with a focus on three priority areas buildings; sustainable options for transport (electric mobility and biofuels); and creating integrated urban energy systems.
Key elements brought	- Delimitation of cities and existing definitions - “Rethinking the entire system with all the related interactions and uses”: detailed solutions - Drivers of renewable development: presentation of technological, political options (incl. cities as aggregator)

Article 3	**Advancing Toward a more Sustainable Urban Energy System- Policy and Technology Considerations**
Date of publication	2015
Author(s)	IEA and World Resources Institute Ross Center for sustainable cities
Type of document	Presentation document from EIA and WRI leaders
Area of expertise	Energy and Climate, Sustainable Policies and Technologies
Central topic	Transition of urban energy systems towards sustainability and the role of technologies and policies
Method used	No indication
Summary	The document provides a condensate overview of key features of urban energy systems, and challenges.
Key elements brought	- Characteristics of the Urban Energy System - Background and challenges - Role of technology in supporting urban energy transitions: technology and behaviour; urban energy and systems integration - Analysis of policy tools and financing schemes at the urban level

Article 4	**Strategic Energy Technology Plan (SET) - Towards an Integrated roadmap: Research and Innovation Challenges and Needs of the EU Energy System**
Date of publication	2014
Author(s)	Inputs from the stakeholders to the consultation in the framework of the development of the SET Plan Integrated Roadmap and from the SET Plan Steering Group
Type of document	Consultation document
Area of expertise	Contributions of various actors representing the entire European energy system, coming from the European energy technology platforms, sector associations, the research community, market actors and investors
Central topic	Identification of key energy system challenges, and associated portfolio of main technological and non-technological solutions based on Research and Innovation actions.
Method used	Bottom-up process with the collection of feedbacks from 150 stakeholders from the energy system in various fields (research community, market actors and investors)
Summary	The document presents a detailed analysis of the main challenges for the EU energy systems identified by the various EU stakeholders, and the technological options that are available and could bring significant potential to cope with the current challenges and changes identified.
Key elements brought	- Although not focused on urban energy systems, the document provides a detailed insight of current key energy system challenges in the EU: 1) active consumer at the center of the energy system 2) Demand focus - increasing energy efficiency across the energy system 3) Systems optimisation 4) Secure, cost-effective, clean and competitive supply - Technological innovations that can cope with the above mentioned challenges and practical recommended actions - Emphasis on cross-cutting aspects and holistic approach to meet challenges such as the inclusion of socio-economics considerations to back policies, role of innovative financing, education

Article 5	**Energizing sustainable cities: assessing urban energy**
Date of publication	2013
Author(s)	A. Grubler and D. Fisk (IIASA)
Type of document	Book published under the auspices of the Global Energy Assessment (GEA); first international assessment explicitly based on the urbanisation issue
Area of expertise	Scientists/ team of internationally renowned scholars
Central topic	Energy-related urban sustainability issues based on a global coverage overview
Method used	Empirical and conceptual approach, and stress-test of general explanations through cases studies
Summary	Energy is one of the key challenges, but also one of the key opportunities in the required urban sustainability transition. The book embeds energy issues into the broader sustainability issue of cities and provides the first comprehensive global assessment of urban energy use and of the specifics of urban energy demand and supply from a systemic point of view. It presents new data and analysis, and policy insights. Main sustainability challenges of cities are assessed in detail and public and private sector opportunities and constraints of a sustainability transition are examined in detail. Technological and policy options are presented in terms of their respective role as drivers of urban energy demand as well as potentials for reductions in energy use and associated emissions.
Key elements brought	- Emphasis on the specifics of urban energy systems and urban transport systems, which present 1) “a high density of population, activities, and the resulting energy use and pollution” 2) “a high degree of openness in terms of exchanges of flows of information, people, and resources, including energy” 3) “a high concentration of economic and human capital resources that can be mobilised to institute innovation and transitional change”. Urban transport systems have to meet a “high density of travel demand within limited space” - Description of major urban energy challenges in moving towards more sustainability: energy access, comprehensive global coverage overview, challenges imposed by high energy demand density, supply constraints including reliability and security - Drivers of urban energy uses, elements about the correlation between some variables and urban energy use

Article 6	**Energy Vision 2013 - Energy transitions: Past and Future**
Date of publication	2013
Author(s)	World Economic Forum in Partnership with IHS CERA
Type of document	International report providing an industrial vision of energy systems evolutions
Area of expertise	Contribution from internationally recognised researchers and leaders of utilities and energy companies
Central topic	Energy transitions: past evolutions, drivers and challenges
Method used	Empirical approach through contributions and literature
Summary	The report provides a framework for understanding the potential transformations of the energy sector. It examines historical trends in energy transitions and their causes in order to determine which factors may drive changes in the future energy mix. Key trends of the current energy sector and options for future energy transitions toward low-carbon electricity and transportation are detailed, as well as the different features and resulting new challenges of a transition towards low-carbon compared to past energy transitions.
Key elements brought	This report offers an original work based on the contribution of various academicians, but also business or political leaders to share their view about energy transition and the future of energy systems Albeit not focused on urban energy, it provides a cross-sectoral and multi-topic analysis of energy systems transition(s), their drives and the potential future ways towards more sustainability.

Article 7	**Urban Energy Systems - An integrated approach**
Date of publication	2013
Author(s)	J. Keirstead, N. Shah
Type of document	Book published within the BP Urban Energy Systems Project at Imperial College London
Area of expertise	Urban sustainability researchers, engineers
Central topic	Urban energy use, efficiency and technologies
Method used	Literature review, case studies and presentation of analytical tools
Summary	The book provides a multi-disciplinary analysis of urban energy systems and how energy demands in cities can be met more sustainably. It presents state-of-the-art techniques for examining urban energy systems as integrated systems of technologies, resources, and people.
Key elements brought	- Conceptualisation and definition of urban energy systems, described as “the combined processes of acquiring and using energy to satisfy the energy service demands of a given urban area” - Identification of solutions with strong energy and emissions reduction potential: buildings retrofit, distributed and district energy systems, renewables - Integrated and system-based analysis of transition in urban energy systems: transition in fuels and shift in technology (socio-technical systems transition)

Article 8	**Challenges and ways forward in the urban sector**
Date of publication	2012
Author(s)	United Nations Department of Economic and Social Affairs (UNDESA)
Type of document	International public report, part of the Sustainable Development in the 21st century (SD21) project
Area of expertise	Urban sustainability experts
Central topic	Recommendations, goals, measures and actions to move towards “urban sustainability”
Method used	The report is based on literature research and on the inputs given by urban sustainability experts
Summary	The report highlights some of the top challenges and priorities for the next 30-50 years in the urban sector. It points out some trends and figures as well as successes and failures, based on examples. The report draws conclusions from lessons learnt and lists steps that could and should be taken on the way forward towards sustainability
Key elements brought	Albeit not focussed on energy systems, the report gives an interesting overview of the main changes impacting urban sustainability, including urban energy: -Key changes: from climate change awareness to action in uncertainty; from buildings to systemic solutions; from recentralisation to decentralisation and metropolitanisation; from administration to new public management; from globalisation to city branding; from (neo)liberalisation to financialisation, privatisation and municipalisation; from commercial to non-market solutions (monetary value on goods that are not traded in regular marketplaces); from top-down to bottom-up and e-governance; from urban voids to public space and public realm; from idolising the new to valuing heritage and low-tech Challenges and solutions/recommendations, including energy as a central issue “individual access to energy also becomes a social and human right”

Article 9	**Global Energy Assessment- Toward a Sustainable Future**
Date of publication	2012
Author(s)	IIASA
Type of document	International publication
Area of expertise	International interdisciplinary specialists: scholars, industry groups, and policy experts on a wide range of issues related to energy
Central topic	Major challenges for energy systems at the global level
Method used	Chapter 16: literature assessment and examples of sectoral transitions
Summary	The GEA provides an analysis of major global challenges and their linkages to energy; the technologies and resources available for providing energy services; future energy systems that address the major challenges; and the policies and other measures to realise sustainable energy futures. Especially, the Chapter 16 focusses on transitions in energy systems, their characteristics and the associated potential/opportunities
Key elements brought	Albeit not explicitly focused on urban energy systems, this chapter describes in details the features and opportunities of the energy system transition, which enables to have a deeper understanding of transition mechanisms. - Characteristics of energy transitions based on historical transformations - Role of experiments in the current change of energy systems through an assessment of the technological options and resources available to build future energy systems: Combining Different Primary Energy Sources to overcome intermittency, and to increase reliability and availability; Addressing Multiple End-uses; Delivering combination of Energy and Non-energy Services; Energy storage; Aggregating the Distributed Energy Resources (mini-grids) ; Business Models for Energy Service Delivery; Role of Policy and Institutional Issues - Assessment of the policies needed to address the identified current challenges

Article 10	**Cities of tomorrow - Challenges, visions, ways forward**
Date of publication	2011
Author(s)	European Commission
Type of document	Publication from the European Commission based on the contributions of urban experts and representatives of European cities
Area of expertise	Contribution from various academic or political experts in the field of urbanism, energy and sustainability
Central topic	Sustainable cities
Method used	Collection and synthesis of contribution to provide common reflexion and a harmonised vision of what cities of the future should be
Summary	This document aims at better understanding the challenges that different European cities have to address to achieve a “desirable future” and analyses their possible future impacts, as well as the opportunities and the key role that cities can play.
Key elements brought	- Importance of a holistic approach to environmental and energy issues as many components are interwoven and in order to identify opportunities able to reconcile conflictual objectives: “Challenges cannot be addressed individually; their interrelations and contradictions need to be properly understood.“ - Challenges for energy system in cities coupled to socio-economic challenges (e.g. value of inclusion, cohesion…). Clearly defined vision of the city of the future, incl. energy.