Integrated long-term city energy planning.

Methodology for the modelling and prospective assessment of urban energy systems

PhD. Thesis

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Methodology for the modelling and prospective assessment of urban energy systems

A Thesis submitted by IÑIGO MUÑOZ MATEOS, in fulfilment of the requirements for the degree of Doctor of Philosophy at the University of the Basque Country (UPV/EHU) under the supervision of:
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Doctoral Programme in Energy Efficiency and Sustainability in Engineering and Architecture

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"All models are wrong, but some are useful"

George Box

"Two types of choices seem to me to have been crucial in tipping the outcomes [of the various societies' histories] towards success or failure: long-term planning and willingness to reconsider core values"

Jared Diamond

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Abstract

KEY WORDS: urban energy systems, urban energy planning, urban energy modelling, urban energy scenarios, urban decarbonisation

Reducing human-induced impact on the Earth and improving the wellbeing of its inhabitants, requires the reorganisation of the energy system, the renunciation of the infinite growth paradigm, and the change of actual consumption patterns towards a more sustainable lifestyle. World's commitments to reach carbon neutrality by mid-century need strong and rapid actions to drastically cut off greenhouse gases (GHG) emissions in the following decades. On this concern, cities have a key role to play in the transition towards a low-carbon and sustainable society. Due to their share in global primary energy consumption and GHG emissions, urban areas are both major contributors, but also potential solutions to climate change. Moreover, the expected rise in global urban population increases the relevance of its mitigation within the urban environment. Cities must then tackle diverse economic, social, and environmental issues in the upcoming years to achieve their decarbonisation and to ensure the wellbeing of their citizens. To deal with these challenges, transformation of urban areas into sustainable systems should be addressed through a holistic long-term vision and the efficient management of available resources. Nevertheless, the complexity of urban energy systems makes city energy planning a tough task.

This Thesis aims to develop a comprehensive framework for integrated long-term urban energy planning based on the modelling and prospective assessment of urban energy systems. This work brings the opportunity to solve the various challenges faced by urban energy modellers, as well as to supply policy-makers and urban planners with tools for the achievement of energy and climate objectives. Indeed, this Thesis seeks to shed light regarding specific issues and gaps faced when assessing urban energy systems, see the lack of clear approaches to develop comprehensive urban energy models and to incorporate their results into urban energy plans, the complexity and uncertainty when modelling future urban energy use, energy data scarcity at urban level, and the need of harmonised local and national energy and climate plans.

Addressing urban energy planning and modelling through different perspectives, this Thesis proposes three innovative approaches for: the coordination of national and urban energy planning, the energy modelling of the building sector, and the integrated energy modelling and impact assessment of urban energy scenarios. All while reducing data requirements and modelling complexity. Moreover, the combination of top-down and bottom-up approaches is carried out aiming to reduce the performance gap.

The harmonisation of these three methods provides a holistic framework towards the fields of urban energy planning and modelling. First, to align national and local energy and climate plans, a downscaling method is proposed to adapt national-level actions to the local context. Hence achieving the efficient contribution of urban areas towards national energy and climate goals. Second, a methodology integrating top-down and bottom-up approaches to develop an energy model of the building stock is presented. The method includes a procedure to define and shape useful building stock energy scenarios at city level. Third, gathering the previous approaches, an integrated methodology is developed, ranging from the energy characterisation of the urban energy system to the assessment of its energy scenarios. This last method considers all the elements from both demand and supply sides of the city and provides an evaluation of the future pathways the city can face so that local stakeholders can prioritise, based on different criteria, the one that best suits the city needs, interests, and targets. To validate its practical use and replicability, each methodology is illustrated with a real case study using the Spanish cities of Valencia and Bilbao as demonstrators.

The application of the proposed methodologies stress the lack of disaggregated urban information, which requires an intensive work of data treatment and hinders the characterisation of specific sectors such as tertiary buildings and transport. A data gathering effort is required form cities to reduce modelling assumptions and to improve the modelling of urban mobility. Indeed, a precise and richly detailed energy characterisation allows to accurately model a broad spectrum of scenarios, while avoiding the estimation of warped impacts. On this concern, energy modelling is proved to be a powerful instrument in the definition of feasible urban energy targets and strategies. Measures and targets transposition from the national to the local level is extremely significant to coordinate efforts towards the decarbonisation of both energy systems. Regarding modelling of urban energy scenarios, results show that the consideration of certain aspects such as past trends or national grid decarbonisation affects scenarios design, as well as their results. Finally, the intricacy reduction and data needs minimisation of the suggested methods, allow the straightforward generation of multiple scenarios, which in turn makes possible to assess a wide range of different futures, paving the way for decision-making by local stakeholders.

Resumen

Para reducir el impacto humano sobre la Tierra y mejorar el bienestar de sus habitantes son necesarios la reorganización del sistema energético, la renuncia al paradigma del crecimiento infinito y el cambio de los actuales patrones de consumo hacia un estilo de vida más sostenible. Los compromisos mundiales para alcanzar la neutralidad en carbono a mediados de siglo requieren de acciones contundentes y rápidas para reducir drásticamente las emisiones de gases de efecto invernadero (GEI) en las décadas venideras. En este contexto, las ciudades juegan un papel fundamental en la transición hacia una sociedad sostenible y baja en carbono. Debido a su peso en el consumo mundial de energía primaria y en emisiones de GEI, las áreas urbanas son causa y a la vez solución potencial al cambio climático. La mitigación de éste en áreas urbanas es aún más relevante si se tiene en cuenta el esperado crecimiento demográfico en las mismas. Las ciudades deberán por lo tanto abordar diversas cuestiones económicas, sociales y medioambientales en los próximos años para lograr su descarbonización y garantizar el bienestar de sus ciudadanos. Para hacer frente a estos retos, la transformación de las ciudades en sistemas sostenibles deberá abordarse mediante una visión holística a largo plazo y a través de la gestión eficiente de los recursos disponibles. La complejidad de los sistemas energéticos urbanos hace, sin embargo, que la planificación energética de las ciudades sea una ardua tarea.

El objetivo de esta Tesis es desarrollar un marco integrado para la planificación energética urbana a largo plazo basada en la modelización y evaluación prospectiva de los sistemas energéticos urbanos. Este trabajo busca aportar soluciones a los diversos retos a los que se enfrenta el modelado energético en entornos urbanos, así como proporcionar herramientas a los responsables y planificadores urbanos de cara a la consecución de los objetivos energéticos y climáticos. Más concretamente, esta Tesis pretende aclarar los problemas y lagunas específicas afrontadas durante el análisis de los sistemas energéticos urbanos como pueden ser la falta de enfoques claros para el desarrollo de modelos energéticos urbanos holísticos y la integración de sus resultados en los planes energéticos urbanos, la complejidad e incertidumbre a la hora de modelar el uso futuro de la energía en las ciudades, la escasez de datos energéticos a nivel urbano y la necesidad de armonizar los planes energéticos y climáticos locales y nacionales.

Abordando la planificación y modelización energética urbana a través de diferentes perspectivas, esta Tesis propone tres enfoques innovadores para: la coordinación de los niveles de planificación energética nacional y urbano, la modelización energética del sector edificios, y la modelización energética integrada y evaluación de impacto de escenarios energéticos urbanos. Todo ello reduciendo la necesidad de datos y la complejidad en la modelización. Asimismo, y con el objetivo

de reducir las diferencias entre valores reales y modelados, se propone la combinación de enfoques "top-down" ("de arriba abajo") y "bottom-up" ("de abajo arriba").

La armonización de estos tres métodos proporciona un marco holístico para la planificación y la modelización energética urbana. En primer lugar, para alinear los planes energéticos y climáticos nacionales y locales, se propone un método para desescalar y adaptar las acciones nacionales al contexto local. De este modo se consigue que las ciudades contribuyan de manera eficiente a la consecución de los objetivos energéticos y climáticos nacionales. En segundo lugar, se presenta una metodología que integra los enfoques "top-down" y "bottom-up" para desarrollar un modelo energético del parque de edificios urbano. El método incluye un procedimiento para definir y concebir escenarios energéticos del parque edificatorio de las ciudades. En tercer lugar, aunando las propuestas metodológicas previas, se desarrolla una metodología integrada que abarca desde la caracterización energética del sistema energético urbano hasta la evaluación de sus escenarios energéticos. Este último método tiene en cuenta todos los elementos tanto de la demanda como del suministro energético de la ciudad y proporciona una evaluación de los posibles futuros a los que puede enfrentarse la ciudad, de manera que los agentes locales puedan priorizar, basándose en diferentes criterios, el que mejor se adapte a las necesidades, intereses y objetivos de la ciudad. Para validar su uso práctico y su replicabilidad, cada metodología se ilustra con los ejemplos de las ciudades españolas de Valencia y Bilbao como casos de estudio reales.

La aplicación de las metodologías propuestas pone de manifiesto la falta de información desagregada a escala urbana, lo cual requiere de un intenso trabajo para el procesamiento de los datos disponibles y dificulta la caracterización de sectores específicos como edificios terciarios y transporte. Es necesario un esfuerzo de recopilación de información por parte de las ciudades para reducir las hipótesis de modelización, así como para mejorar el modelado de la movilidad urbana. Una caracterización energética precisa y detallada permite modelizar con precisión un amplio espectro de escenarios evitando al mismo tiempo la estimación incorrecta de sus impactos. En este sentido, la modelización energética ha demostrado ser un poderoso instrumento para la definición de objetivos y estrategias energéticas urbanas viables. La transposición de medidas y objetivos del nivel nacional al local es muy importante para coordinar los esfuerzos hacia la descarbonización de ambos sistemas energéticos. En cuanto a la modelización de escenarios energéticos urbanos, los resultados han demostrado que la consideración de ciertos aspectos como tendencias históricas o la descarbonización de la red nacional afectan al diseño de los escenarios y a sus resultados. Por último, la reducción en la complejidad de modelado y la minimización en la necesidad de datos por parte de los métodos sugeridos permite la generación de forma sencilla de múltiples escenarios lo que a su vez hace posible evaluar una amplia gama de futuros diferentes, allanando el camino para la toma de decisiones por parte de los agentes locales.

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List of figures

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List of abbreviations

AHP: Analytical Hierarchy Process

BaU: Business as Usual (scenario)

CAPEX: CAPital EXpenditures

CHP: Cogeneration Heat and Power

CNG: Compressed Natural Gas

CoM: Covenant of Mayors

DHW: Domestic Hot Water

ECM: Energy Conservation Measure

EEF: Electricity Emission Factor

EPC: Energy Performance Certificate

EU: European Union

EV: Electric Vehicle

GDP: Gross Domestic Product

GHG: Greenhouse Gas

GIS: Geographical Information System

GPI: Genuine Progress Indicator

GVA: Gross Value Added

HB: Housing Block

HDI: Human Development Index

ICE: Internal Combustion Engine (vehicle)

IEA: International Energy Agency

IIASA: International Institute for Applied Systems Analysis

IO: Input-Output (analysis)

IPCC: Intergovernmental Panel on Climate Change

LCC: Life Cycle Cost (analysis)

LPG: Liquefied Petroleum Gas

MCDA: Multi-Criteria Decision Analysis

NDC: Nationally Determined Contribution

NECP: National Energy and Climate Plan

OPEX: OPerational EXpenditures

RES: Renewable Energy Source

SDG: Sustainable Development Goal

SEAP: Sustainable Energy Action Plan

SECAP: Sustainable Energy and Climate Action Plan

PV: (solar) PhotoVoltaic (system/panel)

SFH: Single Family House

UN: United Nations

UNFCC: United Nations Framework Convention on Climate Change

WAM: With Additional Measures (scenario)

WEM: With Existing Measures (scenario)

WOM: WithOut Measures (scenario)

Specific abbreviatures chapter IV

BR: Building Renovation (scenario)

CFES: Cumulative Final Energy Saving

CCESC: Cumulative CO_2 Emissions Saving with constant EEF

CCESV: Cumulative CO_2 Emissions Saving with variable EEF

CPS: Consumption Patterns Scenario

HR: Heating Renovation (scenario)

SNPV: Scenario Net Present Value

SR: Systems Renovation (scenario)

Specific abbreviatures chapter V

CCES: Cumulative CO_2 Emissions Saving

CTPES: Cumulative Total Primary Energy Saving

CNRPES: Cumulative Non-Renewable Primary Energy Saving

SLCC: Scenario Life Cycle Cost

CHAPTER I: Introduction

Index CHAPTER I

1.1. Preliminary thoughts. The need for a transition

1.1.1. Energy, environment and human development

Energy use has always been strongly related to human development. Powering economies and supporting the evolution of societies all around the world, energy has been one of the main drivers of human progress. Since the industrial revolution however, this growth has been mainly sustained by the intensive use of fossil fuels and resources consumption. Nowadays, fossil fuels still represent almost 90% of primary energy use. Moreover, since the 1970's decade, primary energy consumption in the world has nearly tripled, while energy-related greenhouse gases (GHG) emissions have doubled according to the International Energy Agency (IEA) (2022a, 2022b) (see Figure 1.1). This increases the effects and risks of climate change[1].

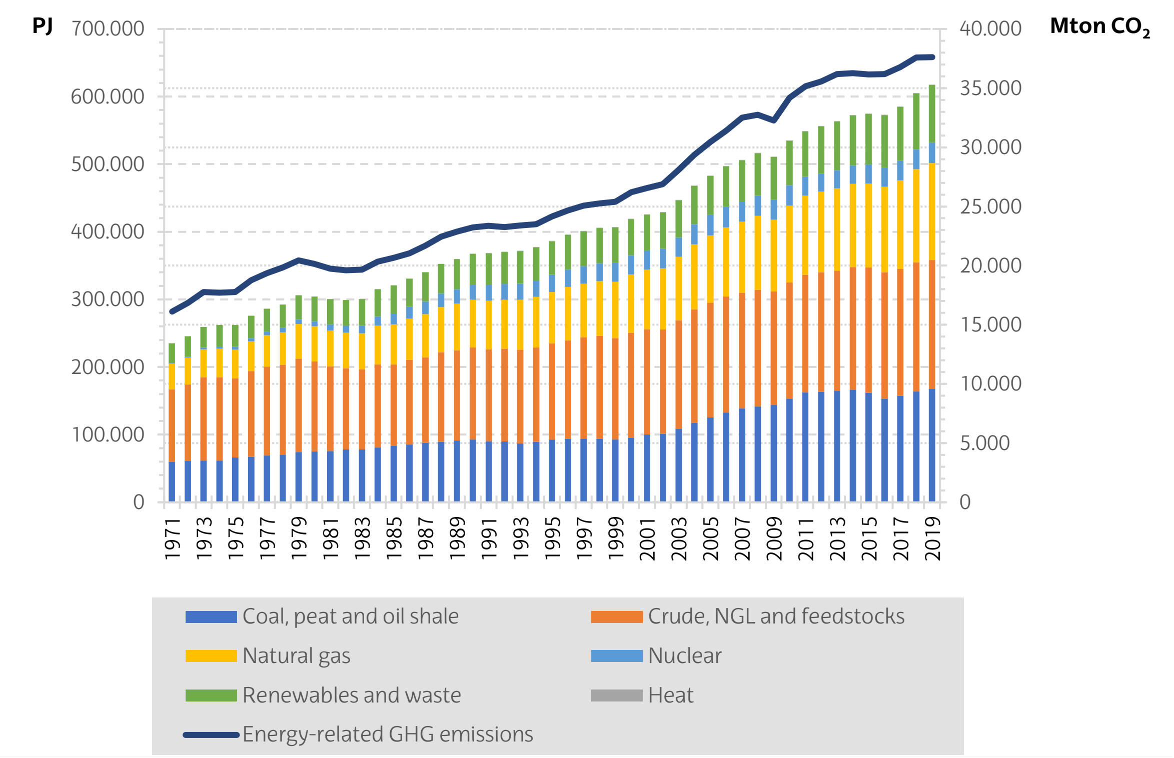

Figure 1.1. World primary energy consumption and GHG energy-related emissions (From IEA (2022a, 2022b))

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[1] According to the United Nations Framework Convention on Climate Change (UNFCC), climate change is defined as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods" (UNFCC, 1992).

According to the last report of the Intergovernmental Panel on Climate Change (IPCC) (2022a), the sum of anthropogenic emissions[2] will cause temperatures exceed 1,5°C and 2°C above pre-industrial levels during the 21st century "unless deep reductions in carbon dioxide (CO_2) and other GHG emissions occur in the coming decades" (IPCC, 2021). Along with this global warming concern, the overexploitation of natural resources, the degradation of ecosystems, the generation of large quantities of waste, and the discharge of other pollutants into the atmosphere would put additional pressure in an already stressed environment.

All these environmental issues show the result of pushing a system such as the Earth beyond its physical limits and demonstrate that the current model of socioeconomic development and the energy system on which it is based are both unsustainable. Indeed, at the origin of this "Tragedy of the Commons"[3] (Hardin, 1968) lies, to a large extent, the actual economic system. Founded on the belief of unceasing growth (essential for its survival), this economic model relies on the current fossil-fuelled energy system and on the intensive exploitation of raw materials to produce the goods and services constantly required by the system to keep functioning. This clashes with the physical boundaries of the Earth causing the already mentioned ecological effects.

In addition to environmental concerns, the current context is also unsustainable and unfair under a social perspective, with access to energy and resources unequally distributed among the world[4]. Moreover, this state of play could also lead to social and economic crises in the future. The exhaustion of natural resources and depletion of currently used fuels[5] would threat the actual supply of energy and other goods and materials raising the prices of these commodities and hampering a fair and equal access to them. This may result on the worsening of human welfare conditions (e.g. increase of all forms of poverty including energy poverty, together with health deterioration due to effects of pollution and climate change). Furthermore, geopolitical conflicts over the control of more limited resources may arise and have an impact on the lives of all the world's inhabitants.

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[2] Note that energy-related emissions represent 90% of total anthropogenic emissions (UNFCC, 2022a).

[3] The "Tragedy of the Commons" is a social dilemma in which individuals, acting independently on their own self-interest, make use of an available resource and, against the common interest of all users, cause the degradation and even depletion of this resource. In the current environmental context, the common resource (or "Commons") would refer to an open-access and non-regulated resource like the atmosphere, the lands, or the oceans, seas, and rivers. In the words of Hardin: "Therein is the tragedy. Each man is locked into a system that compels him to increase his herd [wealth] without limit - in a world that is limited".

[4] Amongst other forms of poverty and inequalities, energy poverty can be defined as the lack of access to affordable and sustainable modern energy services. Main signs of energy poverty are the lack of access to electricity and the use of inefficient and dangerous cooking and heating systems. Nowadays, 759 million world's inhabitants do not have access to electricity, while almost one third still rely on inefficient fuels whose combustion may cause health issues (UN, 2022a; UNCTAD, 2021).

[5] Peak theory was developed for the first time by Hubbert (1956), stating that, for a given region, the extraction rate of a resource increased and further declined until its depletion. Although, this theory was first used for peak oil production, it can be applied for other fossil fuels and natural resources. Updated production peaks for different fuels have been more recently reviewed by Capellán-Pérez et al. (2014), Maggio and Cacciola (2012), and Mohr et al. (2015).

The expected 25% increase of the world's population by 2050 compared with present day (UN Population Division, 2018) may accentuate the above mentioned environmental and socioeconomic problems if not addressed adequately. Hence, humanity faces a crucial challenge in the following years: to ensure a proper standard of living for all the world's inhabitants, that is, to keep a sustainable wellbeing in developed countries while supporting a sustainable development in low-income countries, all without affecting our environment. In other words, it is imperative to fulfil a development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987)[6].

Contributing to the enhancement of human welfare, energy plays a key role in the achievement of this goal. However, it should be used in a wise and sustainable way to prevent adverse impacts on the environment. To meet its environmental and social commitments, energy should be clean, its access universal, and its supply reliable (UN, 2022a; World Energy Council, 2022). The accomplishment of these conditions requires to rethink the present energy system.

1.1.2. Ecological economics

Current environmental context, derived from exacerbated consumption of energy and resources, is the result of the existing economic system and calls the former into question (Capellán-Pérez et al., 2015, 2014; Hall and Klitgaard, 2018; Klitgaard, 2013; Klitgaard and Krall, 2012). To avoid a social and environmental collapse, it is imperative to act upon both the current economic and energy structures[7]. Closely connected to the economic model, any real transformation of the energy system would require a change in the former. That is, to achieve a true transition towards a low-carbon and welfare-improved society, this should be framed within a shift in the approach of the actual economic system.

Several authors have advocated for a shift in the growth paradigm of this model. In early 70's, Nicholas Georgescu-Roegen (1971) remarked the incompatibility between the current economic system and the environment in which it is framed. The author observed that the former failed to include the physical aspects of the latter. Indeed, the work of Georgescu-Roegen demonstrates that,

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[6] This sentence describes the concept of sustainable development. Indeed, sustainable development refers to the different processes and pathways to reach sustainability, which in turn may be defined as the societal goal aiming for the improvement of human life quality on Earth based on the equilibrium of three main pillars: environmental, economic, and social.

[7] As assessed by Motesharrei et al. (2014) through their HANDY model, collapse can occur either by the overexploitation of natural resources or by increased economic discrimination. To avoid collapse, depletion rate of natural resources should be reduced to a sustainable level and economic wealth shared in an equitable way.

not only this economic model has harmful effects on the environment, but it is also based on an approach which goes against elementary laws of physics and thermodynamics. In fact, its operation can be assimilated to a perpetual motion machine as it does not consider an entropic loss (i.e. it does not consider the finite aspect of the environment in which is framed nor its degradation). This goes against the second law of thermodynamics, besides hindering the correct handling of challenges such as climate change and resources depletion (Hall and Klitgaard, 2018). In the 1972 report "Limits to growth" (Meadows, 1972) commissioned by the Club of Rome, the conflict between a growth-based economy and the world's ecological limits was prognosed. Finally, steady state economics vision proposed by Herman Daly (1977) split the need for growth from welfare and social development, supporting an economy with a stabilised population and a constant and smaller input of energy and materials. Under a thermodynamic point of view, this model would reduce to the lowest feasible the entropy generation by softening the depletion of resources (i.e. reducing the withdraw of low entropy elements from the environment) and lessening the disposal of waste and pollution (i.e. reducing the disposal of high entropy elements to the environment). In other words, this balance aims to minimise the entropy increase of the system.

These works contested the belief on perpetual growth of the current model and argued in favour of adjusting human activity to the Earth's physical conditions. Indeed, the present economic view[8] underestimates the role played by energy in economic activity and does not acknowledge the depletion and degradation processes which inevitably occur in a finite system. Moreover, it is conceived as a circular process which is impossible under a physical viewpoint, given the limited aspect of the system in which it is embedded. Opposed to this vision, ecological economics (and biophysical economics in particular) incorporates the laws of thermodynamics ("Nothing happens in the world without energy conversion and entropy production") and recognises the boundaries of the system. Considering the economic activity as a unidirectional process, it allows the correct assessment of available resources and the effects of matter diminution and degradation (i.e. exhaustion of raw materials and pollution) (see Figure 1.2).

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[8] Orthodox (or neoclassical) economics. Further description of the basic principles of this economic vision can be found in the works by Hall and Klitgaard (2018) and Sorrell (2010).

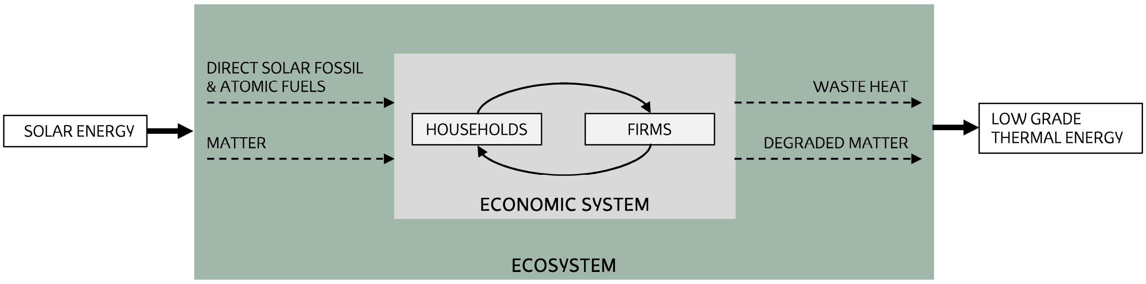

Figure 1.2. Ecological economics (From Hall and Klitgaard (2018))

1.1.3. Degrowth concept

Asserting the unfeasibility of unlimited growth in a finite environment, ecological economics approach has gathered support around the defence of a degrowth towards a steady-state economy, claiming that such process would achieve a true energy (and social) transition. Since the 2008 Paris conference on degrowth (Research & Degrowth, 2008) which laid the foundations of the movement (Research & Degrowth, 2010), the degrowth debate has become increasingly relevant in recent years (Weiss and Cattaneo, 2017), being even quoted in the last IPCC assessment (IPCC, 2022b, 2022c).This line of thought may be defined "as an equitable downscaling of production and consumption that increases human wellbeing and enhances ecological conditions at the local and global level, in the short and long term" (Schneider et al., 2010). In other words, it is an "intentional limiting and downscaling of the economy to make it consistent with biophysical boundaries" (Van Den Bergh and Kallis, 2012). Degrowth should be seen as a transition process to reach a sustainable steady state (Capellán-Pérez et al., 2015, 2014; Hall and Klitgaard, 2018; Latouche, 2010; Lawn and Clarke, 2010; Schneider et al., 2010), which should be achieved by participatory, voluntary, fair, equal, and democratic means (Schneider et al., 2010). Works by Kallis (2011), Khmara and Kronenberg (2020), and Weiss and Cattaneo (2017) reviewed key characteristics of the degrowth concept.

To mitigate climate change, actual economic model places its trust in mechanisms such energy efficiency and decoupling[9]. This, however, has been proved to be insufficient. Energy efficiency alone cannot offset increasing energy consumption caused by economic growth (Capellán-Pérez et al., 2015; Hall and Klitgaard, 2018; Moreau and Vuille, 2018; Schneider et al., 2010; Sorrell, 2010;

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[9] Decoupling can be defined as the disengagement of economic growth from resource use (United Nations Environment Programme, 2011).

Sorrell and Ockwell, 2010) (not to mention the potential rebound effect[10] it can cause), whereas only partial decoupling has been achieved (Csereklyei and Stern, 2015; Jakob et al., 2012). In fact, economies tertiarisation in developed countries masks energy embodied in goods and services and reduces domestic impact. However, this footprint is hidden in production offshoring and import of finished goods, giving a misleading perception of decoupling (Akizu-Gardoki et al., 2018; Arto et al., 2016; Jakob et al., 2012; Moreau and Vuille, 2018; Sorrell, 2010).

Degrowth lies on the idea of maximising human welfare and not economic output (Capellán-Pérez et al., 2015, 2014; Hall and Klitgaard, 2018; Latouche, 2010; Schneider et al., 2010). Genuine Progress Indicator (GPI) or Human Development Index (HDI) should be used to reflect this goal, instead of indicators such as the Gross Domestic Product (GDP) that only account for market-related variables (Lawn and Clarke, 2010; Schneider et al., 2010; Sorrell, 2010; Van Den Bergh and Kallis, 2012). Moreover, authors have demonstrated that a high level of development and welfare can be sustained without the requirement of growing quantities of energy (Arto et al., 2016; Lambert et al., 2014) (see Figure 1.3). Indeed, once a high standard of living is accomplished, a saturation point is reached, beyond which there is no improvement in life quality associated with energy consumption. Thus, in accordance with degrowth concept, developed countries could reduce their energy use without losing their well-being.

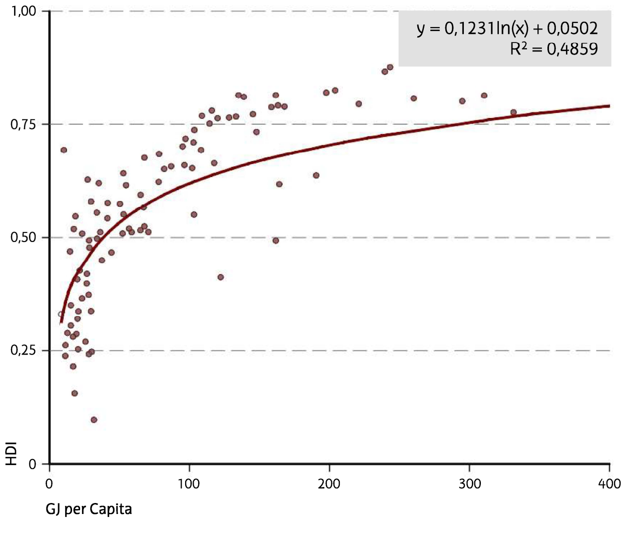

Figure 1.3. Energy consumption vs HDI (From Lambert et al. (2014))

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[10] The rebound effect (or Jevons paradox) can be described as an increase in resource use due to an increase in resource efficiency. Indeed, an enhancement in the efficiency with which a resource is used (or obtained) increases its supply and reduces its price. This price reduction entails in turn a rise in the demand of the resource, thus increasing its aggregate use and offsetting the efficiency gains.

Finally, a distinction should be made between degrowth and depression. On the one hand, degrowth represents a stable and intended shift towards a model with lower energy and resources needs. On the other hand, depression represents an unprepared degrowth within a growth-based system, which results on an environmental and social crisis (with a regression of health and welfare conditions) as a consequence of surpassing the Earth's boundaries. Thus, acknowledging that the actual system is environmentally, economically, socially, and physically unsustainable and heads towards crisis, degrowth shows itself as a sustainable, controlled, collectively-decided and willing adaptation to the limits of the surrounding environment (Schneider et al., 2010).

1.1.4. The transition challenge

Under actual circumstances, the transition towards a low-carbon society involves huge challenges. Restricted by the physical boundaries of the Earth, current energy and economic systems must change to prevent an environmental and social collapse. As long as the current growth paradigm prevails, any reduction or slowing of the production and consumption entails social and economic issues (e.g. foreclosures, firings, unemployment, poverty, amongst others). A mind-set change (in the words of Latouche (2010): "to become atheists of growth") and structural transformations are required to separate the development of human welfare from resources use. Solutions must be put forward to break "the dependence of modern economies upon continued economic growth" (Sorrell, 2010). It is important to no note that recent crises[11] have demonstrated that they can be seen as an opportunity to foster change if handled properly (Akizu-Gardoki et al., 2018; Khmara and Kronenberg, 2020; Schneider et al., 2010).

It is therefore impossible to discuss energy transition without considering a change of the current economic model and consumption patterns[12]. Though proclaiming a shift towards Renewable Energy Sources (RES) and energy efficiency, establishment and institutional solutions do not address the unsustainability of the economic system. While tackling climate change is a complex task which should imply bolder actions and a shift in our current socioeconomic system and way of life. Impacts resulting from this change would inevitably affect all the world's inhabitants. However, this should not mean a downgrade of social well-being. The burden of change should be fairly and

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[11] 2008 financial crisis, 2020 COVID19 crisis, 2022 Ukraine war.

[12] Samadi et al. (2017) argued that behavioural changes (motivated by the modification of individual preferences, modification of relative prices, or even politically imposed bans) towards energy-sufficiency lifestyles enclosed great potential (and may be even indispensable) for the achievement of climate goals. Moreover, the authors stated that the impact of lifestyle and consumption patterns changes should be quantitatively assessed in scenarios supporting energy planning and policy-making towards sustainable and low-carbon futures.

equally distributed. Impacts should be socialised and costs[13] and benefits from the energy transition spread. On this concern, democratic participation on climate policy formulation would help to create an agreed future energy vision, avoiding unequal and unfair energy and climate strategies (Sgouridis et al., 2022).

The aim of the energy transition must be to replace a perpetual-growing fossil fuel-based economy by a renewable-based steady state economy which should be able to ensure universal social welfare. It is crucial that this shift considers how to mitigate and adapt to social repercussions arising from the change of the economic growth-based approach: adapt to new consumption patterns based on the reduction, reuse, and recycling of goods and materials; handle the destruction, creation, and reconversion of job positions (not only from the energy-related sector which should transition from fossil to RES, but from the rest of economic sectors due to the decreased demand of goods and services in a steady state economy); assure universal access to affordable and clean energy supply and to other low-impact commodities (i.e. with little embodied energy); assure universal access to affordable and less-polluting transport services; sustainable use of land; amongst others. The constriction of the economy to adjust to the physical boundaries of the system should not be cause of harm to those with less resources. That is, the energy transition must not be detrimental to the most deprived.

Furthermore, the new energy model should avoid the replication of current business models, preventing the monopolistic exploitation of energy generation. Energy should not be exclusive competence of those controlling the current model but should be decentralised and democratised (Otamendi-Irizar et al., 2022). Indeed, energy generation should distribute the benefits of clean energy production. End-users should be empowered, increasing their capacity to decide over their own supply. Instead of being monopolised by a few players, ownership of the energy system should be shared between all its actors: consumers and producers. To promote this, decentralised low-scale energy generation should be fostered instead of large-scale projects that, although green, may have an impact on the surrounding ecosystem and land use and may face civil opposition. Indeed, to avoid (or at least mitigate) environmental and social issues related to renewable generation (Letcher, 2022), mechanisms and patterns of the current fossil fuel-based energy model should not

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[13] Note that several studies have argued that the costs derived from climate change (and its externalities) are far higher than the costs of tackling it (Black, 2022; IPCC, 2018; Stern, 2006).

be reproduced in a new renewable-based one. Moreover, energy use habits must be also reduced so that energy demand could be met by RES within the physical limits of the world[14].

The energy transition must guarantee universal human welfare within a sustainable use of resources. In this process of change, poverty should be eradicated, employment assured, health improved, and the environment preserved. Both degrowth and economic depression result in a reduction of resources consumption. However, the former follows a controlled and conscious path, while the latter is a physically-forced (as planet's limits are exceeded) and welfare-detrimental way. Whether the inevitable process of adjusting human development to the boundaries of the Earth is the result of a voluntary-driven process or a collapse, depends on a change in the perspective of the system and on the will and awareness of the people. Indeed, true change will only occur when Society becomes aware of its responsibility towards the planet. Long-term planning, strengthened with binding targets and commitments, is required to set the roadmap under which low-scale actions should be framed. While real change will come from the sum of bottom-up deeds.

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[14] Under present energy and economic systems, RES technologies cannot be pretended to meet current energy demand as they present specific issues such as intermittency and stability issues requiring flexible power systems (IRENA, 2021; Shair et al., 2021). Moreover, they, too, face the physical limits of the system: requiring rare elements which may also be depleted, cause environmental impacts related with their extraction (Golroudbary et al., 2022), or be source of geopolitical conflicts over their control (Stegen, 2015). Thus, RES alone are not the solution, and should go with a decrease in actual energy consumption levels.

1.2. Thesis context. The role of cities in the transition challenge

Within the multiple aspects of the energy transition challenge, this Thesis puts the scope on the part to be played by cities in the shaping of a low-carbon future. More precisely, this work will address the transition challenge under the perspectives of energy planning and energy modelling at urban level. That is, how through efficient planning assisted by proper energy modelling, cities can contribute to the decarbonisation, decentralisation, and democratisation of the energy system. Although essential requirements to achieve a true change, social and economic aspects (cf. sections 1.1.2 and 1.1.3) would be put aside to further focus on strictly energy-related concepts concerning the development of city energy models and urban energy plans. This section provides insights on urban characteristics and challenges, identifying specific gaps to be fulfilled with this work.

1.2.1. Urban figures and context

Historically, cities have been centres of human development and socioeconomic activity: production and consumption of goods and services, commercial and cultural exchanges, knowledge development, and technological advances have mainly taken place within urban areas. Attractiveness of cities has led to a demographic and economic gathering inside their borders. Indeed, cities hold today 55% of the global population (UN Population Division, 2018) and 80% of the world's monetary wealth (IEA, 2016a). However, under the actual energy and economic systems, this activity and people concentration results in a major impact on the environment.

Cities are currently responsible for 64% of the world's primary energy consumption and about 70% of CO_2 energy-related emissions (see Figure 1.4). If changes are not contemplated neither actions taken, the expected raise of urban dwellers, reaching almost 70% of the global inhabitants by 2050 (UN Population Division, 2018), will increase urban energy use, contributing to the increase of GHG and other pollutants emissions, resources depletion, waste generation, and other effects related to the overexploitation of the environment.

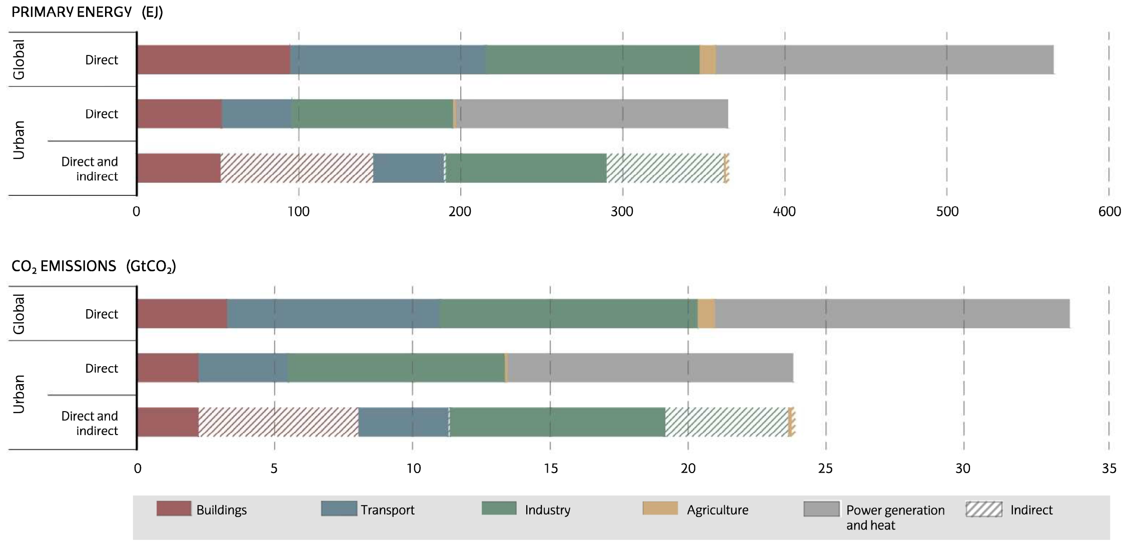

Figure 1.4. Urban primary energy consumption and CO_2 energy-related emissions (From IEA (2016a)*)*

This outlook highlights the relevance of cities within the global energy and environmental context and confirms that urban settlements are major contributors, but also potential solutions to climate change. Showing huge possibilities for energy savings, pollutant emissions reduction, and RES integration, cities are key actors in the mitigation (and adaptation) of climate change effects and in the achievement of the energy transition. On this concern, it should be noted that cities should also perform a pivotal role in the enhancement of social welfare: ensuring housing for new residents and strengthening the conditions of the present ones; guaranteeing access to a universal, affordable, renewable and trustworthy energy supply; improving and assuring universal and reliable water, transport, and other basic services; tackling health issues such as pollution[15] or waste mismanagement; and ending with energy and any other forms of poverty[16] present within urban areas. Significance of cities in the achievement of a new sustainable energy and economic model was already highlighted by the 1987 report of the World Commission on Environment and Development of the United Nations (UN) (World Commission on Environment and Development, 1987), which anticipated the urban challenge for the following years. More recently, the adaptation and mitigation of urban areas to climate change and their transformation into sustainable environments has been addressed in the UN Sustainable Development Goal (SDG) nº11 (UN, 2022b).

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[15] Air pollution in urban areas can occur indoors (usually caused by the use of inefficient fuels or traditional use of biomass) or outdoors (mainly caused by fuel combustion in vehicles) (IEA, 2016a).

[16] Energy poverty affects 20% of today's urban population and reveals itself in the form of use of cheap fuels (increasing air pollution issues), no access to electricity, and absence of space heating in cold periods (IIASA, 2013).

Furthermore, following the path set by the Paris Agreement[17], many cities are aiming to become carbon-neutral in the medium and long-term (IEA, 2021), mobilising efforts towards reducing their impact on the environment and improving the quality of life of their inhabitants. This points out the relevance of the contribution of urban areas towards the fulfilment of higher energy and climate goals. Indeed, at a regional level, the European Union (EU) Green Deal (European Commission, 2019) recognises the part to be played by urban areas in the development of sustainable strategies. Moreover, initiatives such as the Covenant of Mayors for Climate & Energy (2020) (CoM), support municipalities which have committed themselves to achieve (and in some cases exceed) the EU decarbonisation targets. Like the CoM, similar initiatives have risen rallying municipalities and other non-state actors which have pledged to reduce their environmental impact (C40 Cities, 2020; Carbon Neutral Cities Alliance, 2020; Climate Alliance, 2020; Climate Mayors, 2020; Global Covenant of Mayors, 2020; International Council for Local Environmental Initiatives, 2020; UNFCC, 2019). Under this context, a reciprocal relationship should then be established between national and local governments: the former should consider the latter as a tool to achieve its decarbonisation targets, while cities should be aware and responsible of contributing to national policies and commitments (IEA, 2016a).

As innovation hubs and testing ground for the development of sustainable initiatives, urban areas should act as leading characters in the transition towards a low-carbon society. With wide possibilities for the implementation of changes, cities however form complex systems to manage, integrating several energy sectors and energy vectors across different space and temporal scales, and often lacking the capacities and tools to act effectively. To tackle the multiple challenges cities face, transformation of urban areas into sustainable systems should be addressed through a holistic long-term vision and the efficient management of available resources.

1.2.2. The urban energy system: description of main elements and drivers

Cities can be considered as physical systems where the consumption, production, and exchange of diverse flows (e.g. water, energy, materials, nutrients, waste) occur. As a unique ecosystem, the sum of these processes shape the concept of urban metabolism (Facchini et al., 2017; Kennedy et al., 2011, 2007; Wolman, 1965). Being part of this metabolism and focused on the energy perspective, the urban energy system can be defined as the combination of "all the components related to the use and provision of energy services associated with a functional urban system [metabolism],

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[17] To mitigate and adapt to global warming and climate change effects, the Paris Agreement rallied the world's nations under the commitment of reducing their GHG emissions and reaching climate neutrality by 2050. Implementation of the Paris Agreement requires economic and social transformation, based on the best available science (UNFCC, 2022b).

irrespective where the associated energy use and conversion are located in space"[18] (IIASA, 2013). Indeed, this system consists of an interconnection of networks and elements (IEA, 2016a), involving different sectors and players.

Cities concentrate within their limits a diverse amount of activities and economic sectors which consume and/or produce energy, thus being part of the urban energy system. The elements of this system can be divided between demand side (buildings, transport, industry, agriculture) and supply side (heat and power grids infrastructures). Buildings and transport constitute the main end-use sectors of the demand side. Buildings incorporate residential and tertiary uses and are responsible for an important share of urban energy consumption. In turn, buildings have a large energy savings potential[19]. Moreover, as a stationary sector the monitoring and implementation of measures and policies is easy. Conversely, transport is harder to manage. Being a sector in transit, its impact is difficult to assess as it goes through the boundaries of the system. Urban mobility can encompass different means of transport (walking, cycling, road, rail, water, air) aimed for different purposes (passenger or freight transport). Furthermore, journeys within the urban system can be classified into two types: inner or cross-border flows. It should be noted that the city lay-out has a significant effect on transport demand. Lastly, supply side comprises energy conversion technologies and distribution infrastructures. Urban areas do not usually hold substantial primary energy sources potential[20] nor large energy conversion plants[21]. Instead, decentralised systems for the harnessing of local energy sources (e.g. solar thermal, solar photovoltaic (PV), excess heat, or municipal solid wastes) and distributed energy networks (e.g. District Heating or Smart Grids networks) contribute to reduce the dependency of cities on energy imports. Conversely to national-scale energy systems, the urban energy system is characterised by being predominantly energy-demanding, while energy extraction and transformation processes are barely available nor present. That is, one of the main attributes of this system is the mismatch between high energy demand and low on-site energy supply (see Figure 1.5). Thus, demand side plays a major part: determining the factors that influence energy demand and how they do so, are important tasks when assessing the urban energy system (IIASA, 2013).

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[18] Note that the IIASA definition considers a functional perspective when assessing urban energy systems. That is, it does not merely consider the agents and activities geographically located within the urban system, but it also takes into account the impacts from other outside elements required for the operation and development of it. This functional perspective contemplates services both provided and required by cities, advocating for the integration of "production" and "consumption" approaches. Thus, the urban energy system would entail "direct" energy flows and "embodied" energy in goods and services imported into and exported from the urban system. These approaches are explained in section 2.3.3.1.

[19] More restrictive energy building codes that require deep energy renovation of buildings and nearly-zero energy buildings, energy-efficient heating and cooling technologies, RES technologies integration, local energy communities, amongst others.

[20] Understood as renewable (solar, wind, hydro, geothermal or biomass) or non-renewable (fossil fuels) sources (IEA, 2004).

[21] Understood as primary to secondary energy transformation processes (e.g. electricity and heat generation or petroleum product manufacture) (IEA, 2004).

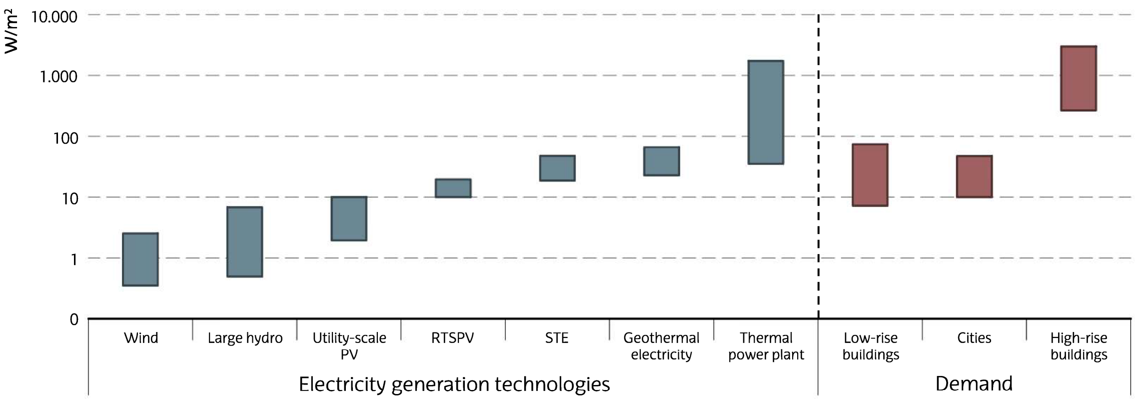

Figure 1.5. Energy supply densities vs urban energy demand (From IEA (2016a))

Energy use in urban areas is affected by several drivers (IEA, 2016a; IIASA, 2013; IPCC, 2014a) (see Figure 1.6). First, geographical location and climate conditions determine resources (energy or materials) availability and heating and cooling needs[22]. Second, demography, socioeconomic factors, and lifestyle patterns have a crucial influence on energy consumption. As an example, household income impacts energy use: as income growths, expenditure on energy services increases. Moreover, under current consumerism paradigm (influenced by the actual economic system), this income rise usually entails an increase in the consumption of other goods and services, which in turn have an associated embodied energy. Third, the economic structure of the city (e.g. service-based or industry-focused economy), its role in the national and/or global context, and urban governance have an effect on the city energy use as well. On the one hand, the economic structure will determine the direction and amount of materials, energy, goods, and services flows within the city. On the other hand, city governance and the ownership model of the city energy networks may facilitate the implementation of specific energy policies[23]. Last but not least, urban form (i.e. the design of the built environment, the transport network lay out, and the spatial distribution of land uses) also affects energy consumption. High dense areas and mixed, connected and accessible land spaces reduce energy use.

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[22] It should be noted that just as climate influences urban energy demand, urban areas may also affect local climate through the urban heat island phenomenon (IIASA, 2013).

[23] Conversely to free-market structures, which often hinder their enactment, municipal-owned energy companies or local energy companies can foster environmental or social policies at city level (IIASA, 2013).

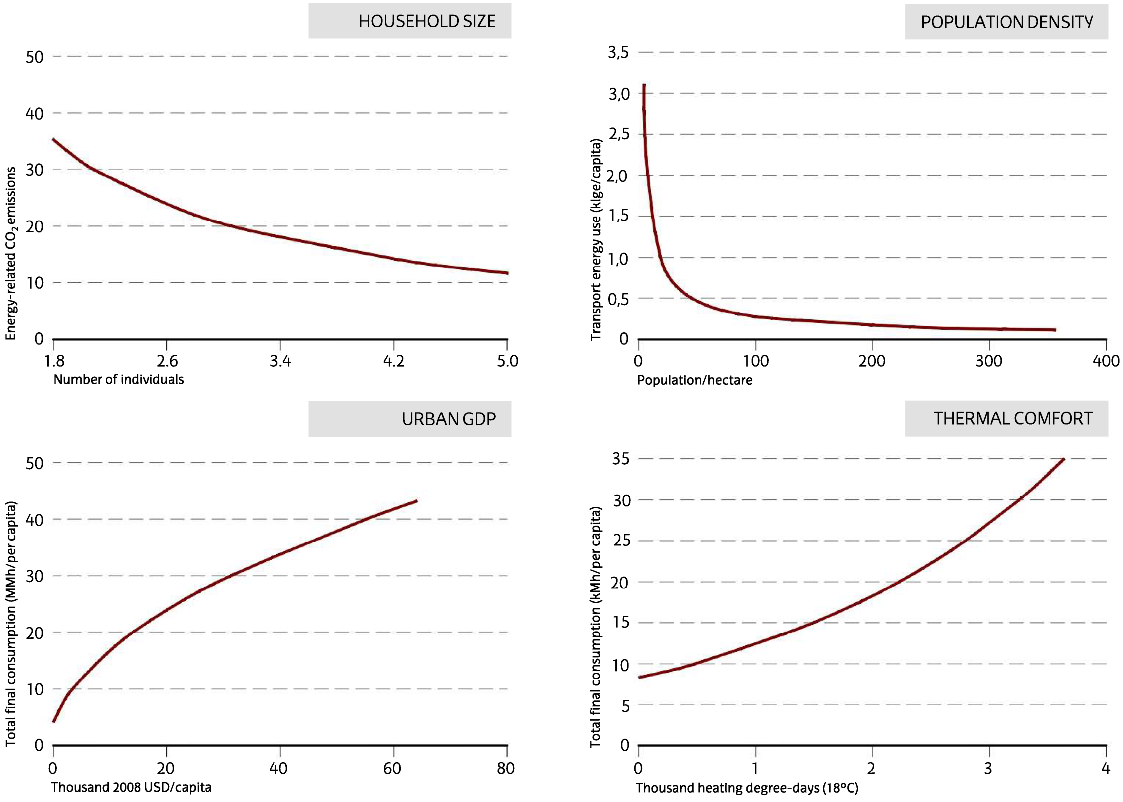

Figure 1.6. Urban energy drivers (From IEA (2016a))

1.2.3. Urban systems challenges

In the upcoming years cities will address several challenges to become sustainable and liveable places. Urban areas should work for guaranteeing decent living conditions for all their inhabitants, eradicating poverty situations, transforming slums into adequate neighbourhoods, and assuring universal, affordable, and reliable access to clean energy, water, and other basic services. Particularly in developing countries, where urban population is expected to increase, anticipating the required infrastructures and services to accommodate new residents is crucial. These growing cities can benefit from the experience of the ones in developed countries and leapfrog pollutant and outdated solutions[24] (IEA, 2016a). Making cities more habitable also include tackling pollution and noise issues, usually related with current mobility patterns and traffic congestion. Clever conversion and rearrangement of land-use and design of efficient urban forms may facilitate the transition towards other transport habits (e.g. reduced use of private transport and promotion of walking, cycling, and

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[24] Indeed, "no single model of urbanisation is necessarily best" (IEA, 2016a). Developing cities do not nave to expand as other ones have evolved in the past, but will unfold based on their particular background, cultural and social choices, and institutional capacities.

public transport), cutting down contamination and making urban areas more comfortable for their inhabitants. Moreover, to become more resilient and reduce their vulnerability to external shocks, cities must adapt to climate change (e.g. tackling heat island effect through nature-based solutions or increased green spaces, and foreseeing the impacts of adverse climate conditions and natural disasters), besides reducing their impact on the environment by decreasing their consumption of energy and other resources in both direct and embodied forms. Finally, opposing the current socioeconomic model, cities may even rethink their urban planning approaches which used to aim at city growth to sustain urban economy and development. Indeed, whether deliberately (due to climate awareness) or unintentionally (due to population decline or limited economic resources), some cities (especially in developed countries) are curbing urban growth to focus on the existing urban fabric, posing new challenges to urban planners such as the adaptation of existing energy and water infrastructures, land-use revision, or citizen engagement (Florentin, 2019).

All these issues are interrelated, thus requiring a holistic vision and the integration of several fields (like urbanism, engineering, economy, social, amongst others) to address them. To effectively cope with all these challenges, integrated urban planning is a must. Indeed, the challenge for urban planners is to harmonise environmental, economic, social, and other relevant subjects at city level in both cross-cutting and vertical ways. On the one hand, cities strategies should consider comprehensively land-use and mobility (which are indeed closely linked), water and energy supply, provision of goods and services, waste management, or noise and pollution control, all while ensuring the social welfare of their citizens. On the other hand, the impact of some of these matters usually transcends city boundaries (e.g. land-use, mobility, or energy supply), hence needing the coordination between different government and administrative levels. Specific competences should be lent or at least shared with local authorities to successfully deal with cross-border issues.

Concerning the energy planning and energy modelling challenges within the urban environment, the following stand out. First, urban energy planners and modellers often face the dispersion, inconsistency or even absence of energy data at urban-scale. This lack of information makes difficult the accurate estimation of urban energy use and the quantification of cities climate impact (IEA, 2016a). Limited urban data hinders the development of detailed urban energy models, makes difficult the establishment of targets and policies and their monitoring, and renders uncertain how climate actions performs towards energy and emissions reductions (IEA, 2016a; IPCC, 2014a). Moreover, the existence of various approaches to account urban energy consumption reflects the complexity of the urban assessment[25]. On this concern, the struggle when defining clear boundaries

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[25] See section 2.3.3.1.

for urban energy systems complicates the accounting and allocation of energy consumption and its impacts.

Second, urban borders are vaporous and permeable, thus hampering the coordination and effective implementation of energy measures across jurisdictional borders. This raises the question of what the scale of urban energy planning should cover: macro (metropolitan), meso (district), or micro (neighbourhood) (IPCC, 2014a). However, to perform an integrated planning approach, cities would often require technical, financial, and legal support from upper levels (regional or national) as they are usually limited requiring capacities and competences to carry out climate actions efficiently. To coordinate all this support a multilevel governance context that empowers cities through the transfer of competences and increased enforcing power is still needed (IPCC, 2014a). Moreover, urban energy planners should harmonise and align their city plans and policies with the national ones to successfully contribute towards upper energy and climate goals.

Third, cities must deal with the challenging task of meeting their energy demand, themselves having a low supply potential. Due to limited energy resources and generation within their borders, cities are generally energy importers. Urban energy planners must tackle the unbalance between energy demand and available urban supply, primarily focusing on demand-side management (given its greater weight and potential than the supply one) (IIASA, 2013) and fostering local renewable generation integrated in decentralised networks (IEA, 2016a). The integration of RES technologies however can cause challenges in the increasingly electrified and complex energy networks of cities. Thus, designed urban energy systems must be flexible to overcome the intermittency of RES and to guarantee a secure supply. Urban energy strategies must include solutions comprising new infrastructures (e.g. District Heating and Smart Grids networks) and diverse energy technologies (e.g. decentralised energy generation technologies and storage systems) to decentralise and bring energy generation into the cities (Arrizabalaga, 2017). Hence, making urban energy systems more resilient and less dependent on external factors such as energy prices rises or supply shortages.

Last but not least, considering the interconnected and globalised world in which cities are embedded, a holistic vision must be adopted to truly decarbonise them. This challenge implies that urban areas should not only focus on their direct energy use but should also address the energy embodied in the goods and services consumed within their limits. Otherwise achieved savings in direct energy use in buildings or mobility may be offset by the energy spent elsewhere to produce the commodities consumed in the city. Moreover, urban energy planners should be aware that systemic solutions are the only real and effective ways to tackle energy and environmental issues when developing strategies and policies at city level. Although harder to implement, systemic changes (e.g. the ways energy is used in buildings, or the ways of travelling around the city) usually have greater impacts in the city energy consumption than technological improvements (IEA, 2016a;

IIASA, 2013). To achieve cities true decarbonisation, urban strategies must combine technological solutions with policies that promote changes in habits and consumption patterns.

1.2.4. Work justification and main contributions to urban energy planning and modelling

In view of the growing significance of cities in terms of their contribution to tackle climate change effects and the complexity and challenges of urban energy systems it is timely to put forward urban energy planning methodologies and tools which solve the multiple urban issues, overcome the gaps in urban assessment, and support the decarbonisation of our cities.

Urban energy planners, policymakers and other relevant urban stakeholders should be provided with convenient information related to the current and future energy demand of the city. This should help them to properly understand the actual energy performance of the city while also bring insights on future outcomes, so that, considering the existing situation, energy measures and policies can be put forward and their further impacts assessed. All of this can be supported by the energy modelling of the city as an integrated energy system. Indeed, the modelling of all energy processes occurring currently within the city as well as the energy-related impacts from future socioeconomic and technological developments, supplies energy planners and policymakers with valuable information and assists the decision-making process. Modelling should support urban energy planning through the most accurate representation possible of the city present and future, in order to elaborate coherent roadmaps and set ambitious yet feasible targets without overestimating impacts.

However, while national-level energy planning (supported by national-level energy models) has a vast background, methodologies and tools at city scale have been less studied. There is still a gap needing for clear approaches and methodologies to develop urban energy models or to adapt existing national approaches to the urban level (Yazdanie and Orehounig, 2021). Standardized methods are also required to correctly account for urban energy use and to assess city energy plans and policies and their contribution towards upper energy and climate targets (IPCC, 2014a). Therefore, it appears necessary to structure a methodology on how to address urban energy modelling, overcoming the different challenges described in the previous section 1.2.3 (i.e. lack of data, boundaries definition, cities specific contexts, or modelling of decentralised energy systems and supply networks amongst others). On this concern, this Thesis seeks to develop the knowledge in the field of urban energy modelling by identifying the data required to build an urban energy model (and how to overcome its possible lack), determining its valuable outputs and how to exploit them, defining the scope of the model and its focus, outlining its development, structure, and operation, and explaining how the model should be approached.

Along with the uncertainty about how energy use in urban areas will evolve in the years to come, lies the lack of scientific and technical approaches for the development of specific future pathways adapted to particular local contexts (IPCC, 2014a; Yazdanie and Orehounig, 2021). This Thesis addresses this gap by putting forward a procedure to generate comprehensive urban energy scenarios. That is, which type of scenarios to be built, how to set them up, and what to include in them (i.e. which combination of socioeconomic/demographic phenomena, technology penetration, and level of energy action ambition to be modelled in each scenario). Also, how to shape future energy demand based on impacts from endogenous (e.g. effects from the natural trend of the system) and exogenous (e.g. savings resulting from implemented energy measures and policies) events, and how to adapt scenarios according to the city context, interests, and data availability.

Another challenge that the development of urban energy models faces is the lack of energy data at urban level. This affects the energy characterisation of the city and also hinders the understanding of urban energy drivers (i.e. hampering the identification and establishment of relationships between drivers and energy use, which in turn may complicate the development of energy scenarios). Acknowledging this gap and pending a further collection of city data (IPCC, 2014a), models that do not depend on huge amounts of data for their construction and performance have to be developed. This Thesis decouples the obtaining of a detailed model from the need of extensive information (i.e. it does not sacrifice accuracy due to lack of data). Indeed, it advocates for straightforward methods to develop urban energy models without relying on substantial quantities of data for the characterisation of the city baseline nor for the modelling of energy scenarios.

Finally, current policies point out at insufficient levels of achievement in terms of GHG reductions and energy-economy decoupling. Therefore, even though ambitious long-term goals such as becoming carbon-neutral seem positive, efforts to achieve them are very far from being a reality. Uncertainty in urban accounting together with lack of methods to assess the implementation and results of energy measures hinders the monitoring and fulfilment of energy and climate objectives (IPCC, 2014a). Another reason for the poor performance of energy actions and non-compliance of energy targets is the lack of coordination across local and national governance levels. Indeed, a balanced harmonisation of both approaches has not yet been carried out efficiently. This Thesis fulfils this gap by evaluating the alignment of urban and national plans and by proposing a methodology for the coordination, harmonisation, and alignment of plans and policies across jurisdictional boundaries to successfully fulfil both urban and national energy and climate targets.

1.3. Thesis hypotheses and objectives

1.3.1. Research question

Challenges such as tackling climate change, decarbonising our society and decoupling human development from energy and resource use, ensuring sustainable and affordable energy for all, and diversifying and securing its supply, should be addressed through a long-term vision and the efficient management of available means. All while improving human wellbeing and guaranteeing energy and social equity. To fully achieve these goals, energy planning is essential.

The motivation behind this work is indeed to support cities in their long-term energy planning, providing the tools and methods that would enable municipalities to define their energy transition strategies. Correctly assisting policymakers and other relevant local stakeholders in the decision-making process is fundamental as the direction followed by cities will have enduring consequences in their energy, environmental, and socioeconomic dimensions.

To fulfil this task, urban energy modelling rises as a useful instrument which can support municipalities in their decarbonisation effort. Urban energy models help policymakers to properly understand the actual energy performance of the city while also bringing insights on how the energy use within it may evolve. Trough the modelling of energy scenarios, energy measures and policies can be assessed and energy strategies designed, endorsing low-carbon future city visions.

Altogether, this work seeks to shed light on the complexities and challenges faced on the urban energy planning and modelling fields by asking the following question:

Which features does an urban energy model need to meet and how city energy scenarios should be modelled and further used to effectively support the development of integrated long-term urban energy plans?

1.3.2. Objectives

This Thesis aims to develop a comprehensive framework for integrated long-term city energy planning based on the modelling and prospective assessment of urban energy systems, which should help decision-makers in the elaboration of energy transition strategies and low carbon policies at urban level. This framework should include the methods and guidelines seeking to fulfil the following main objectives.

- *To integrate energy modelling into urban energy planning in a useful way*

  Adequately targeted and wisely used modelling contributes to the effective development of useful urban energy plans. The present work aims to consider energy modelling through the whole planning process: from the diagnosis phase to the setting of targets and definition of strategies, using modelling outputs to assist decision-making. Indeed, the objective is to integrate modelling results (like the current city energy characterisation or future city energy scenarios) in the elaboration of urban energy plans, identifying issues and opportunities, assessing impacts from the considered measures and policies to be implemented, and supporting the establishment of feasible measures and achievable goals.

- *To model the urban energy system in a precise and comprehensive way*

  Urban energy modelling must be accurate and integrated to add real value into energy planning and policy-making processes. To elaborate honest and effective energy strategies, rigorous modelling is needed to trustworthy represent the city energy performance, to estimate the reach of achievable savings, and to precisely quantify the effect of diverse impacts. To this end, this work intends to model in a reliable way both the actual and future city energy performance, seeking to reduce the gap between actual energy use and modelled results, and attempting to minimise the inherent uncertainty of any prospective analysis. It also looks for reducing the need for large amounts of data to build a detailed model. Moreover, the objective as well is to adopt a holistic approach in the modelling of the city as an integrated energy system, by considering the wide context in which cities are framed. That is, taking into account in the modelling process all city exogenous/endogenous elements and events, and supra/sub local players and entities which have an impact on the energy demand of the city.

- *To generate useful urban energy scenarios in a straightforward way*

  Properly modelled urban energy scenarios represent a useful input for energy planners and policymakers. To be helpful and effective, modelled urban energy scenarios should provide both a quantitative and qualitative prospective view of the city. That is, they should reflect illustrative visions of possible future outcomes for the city while also being able to measure different impacts resulting from them. This work aims to conceive and model city energy scenarios in such a way that they effectively contribute to urban energy planning. The different future storylines developed are consistent and based on the city background and context. Considering diverse criteria, decision-makers can select amongst the different pathways conceived, the one which best matches the goals of the city. Moreover, modelling of future energy demand in the different scenarios allows the quantitative analysis of these. This work intends the clear and plain shaping of this future energy use, avoiding complex predicting and forecasting techniques which require large amounts of data, usually unavailable at city level.

Along these main specific objectives, the work developed will also pursue the accomplishment of these crosscutting objectives.

- To combine bottom-up and top-down approaches in urban energy modelling.
- To perform the energy characterisation of the city, describing the energy performance of all elements that constitute the urban energy system.
- To generate urban energy scenarios, modelling future energy demand while taking into account impacts from endogenous and exogenous phenomena.
- To overcome issues related with urban energy modelling such as lacking data, allocation problems, or boundaries definition.
- To consider cities specificities, context, and background when performing their energy modelling.

1.4. Thesis structure

This Thesis is structured in six chapters. Chapter I introduces the work carried out, describing the context in which the Thesis is framed: urban energy transition, description of urban energy systems, and future challenges. This chapter also displays the research question to be answered and the main goals to be achieved within the Thesis, along with its structure. Chapter II reviews the background on which the Thesis is based and assesses the current states of urban energy planning and urban energy modelling. Chapters III, IV, and V address three different lines of research in the context of urban energy planning and modelling. Chapter VI encloses the main conclusions from this work, identifying its limitations and highlighting future work to be addressed.

Concerning the methodological approach followed in this work, it is represented in Figure 1.7. Chapters III, IV, and V address urban energy modelling through different perspectives shaping an integrated approach towards the topic while combining top-down and bottom-up approaches. The harmonisation of these works seeks the structuring of an integrated framework to model the present, and possible futures, of urban energy systems and which should support the elaboration of coherent and coordinated urban energy plans.

Chapter III addresses the issue of the alignment of local and national energy and climate plans and how strategies from both levels should be coordinated. Introducing a top-down approach to downscale and adapt measures from upper to lower scales, this work suggests how the modelling of adjusted measures to the local conditions and the assessment of their impacts supports the setting of feasible and accurate urban energy targets harmonised with national commitments and plans.

Chapter IV serves as an example illustrating the modelling of a particular component of the urban energy system. Indeed, it focuses on one of the most relevant end-use sectors in urban energy systems: the building sector. This chapter deals with the energy modelling of the city building stock aiming to describe the current status of the built environment and providing insights on how to shape future scenarios in this sector. A combined bottom-up and top-down method to support the characterisation of the baseline situation and modelling of building energy scenarios is proposed.

Finally, chapter V[26] enlarges the work developed in chapter IV and presents an integrated methodology for the modelling and impact assessment of city energy scenarios. Indeed, the whole

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[26] The work developed in this chapter was published as *Muñoz, I., Hernández, P., Pérez-Iribarren, E., Pedrero, J., Arrizabalaga, E., Hermoso, N., 2020. Methodology for integrated modelling and impact assessment of city energy system scenarios. Energy Strateg. Rev. 32, 100553. https://doi.org/10.1016/j.esr.2020.100553*

urban energy system (both demand side, with all the end-use sectors, and supply side) is modelled and energy scenarios at the whole city level are generated. These are further assessed and prioritised based on different criteria. This chapter intends to gather both urban energy modelling (through the representation of the whole urban energy system) and urban energy planning (through the impact assessment and scenario prioritisation) fields in one single approach.

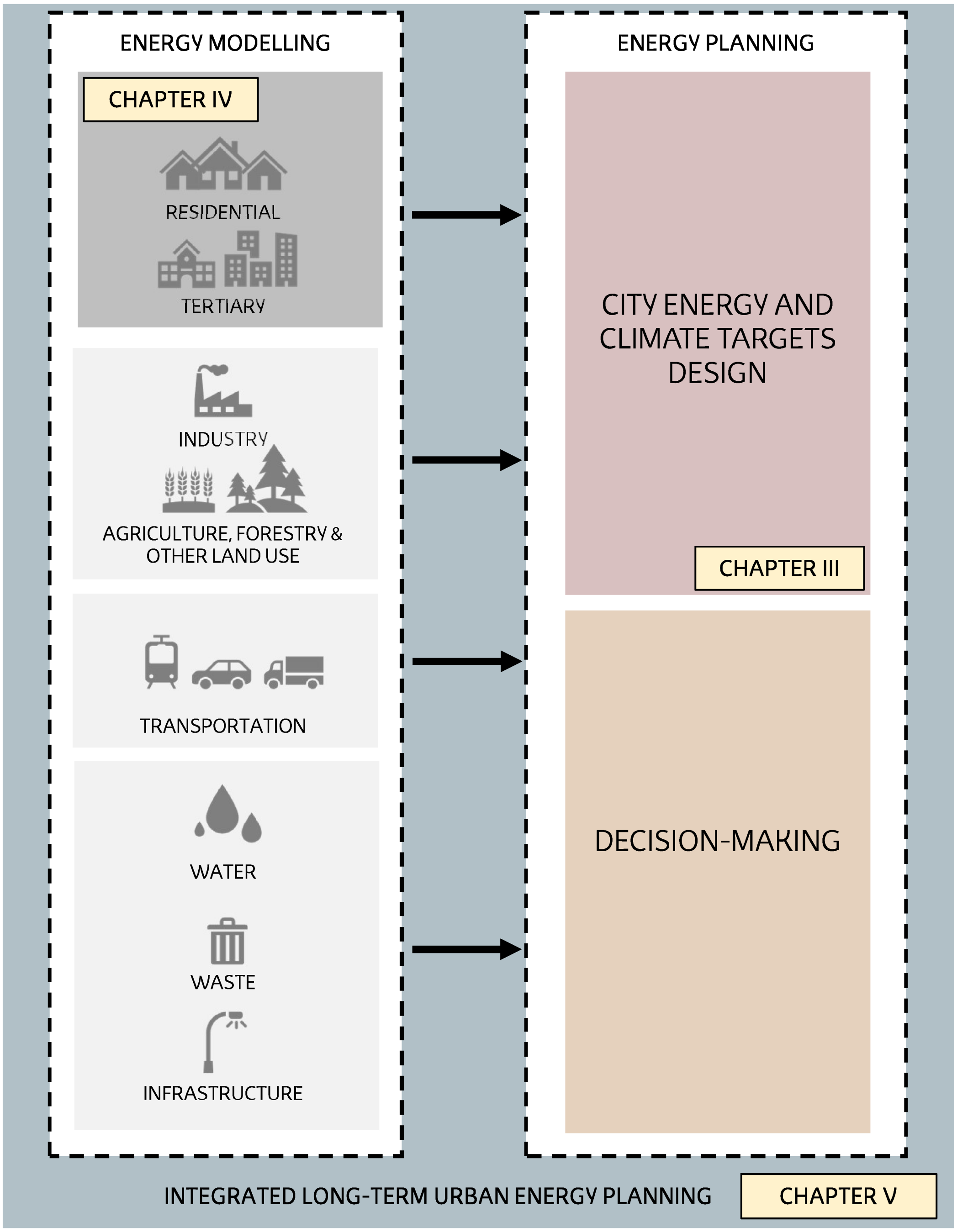

Figure 1.7. Thesis structure and methodological approach

Each one of these chapters addresses a specific topic, uses different modelling tools and approaches, and assesses different case studies. Although each analysis can be replicated separately (as they develop stand-alone methodologies), the key value added behind this Thesis comes from the harmonisation of the proposed works for a holistic approach to the subjects of urban energy planning and modelling. Moreover, this work can be reproduced using other modelling tools than the ones used in the case studies. Indeed, this Thesis intends to provide modelling insights and guidelines for the development of urban energy models (including the energy characterisation and energy scenarios generation of urban energy systems) that can be applied in already existing tools or used for the development of new ones. In other words, it does not aim for the selection of a particular model or tool for the assessment of urban energy systems, but on the conceptual design of the model itself (i.e. which elements to be included and how; how to build energy scenarios and how to use them).

A summary of the main characteristics and main contributions to the fields of urban energy planning and modelling in the analyses carried out in chapters III, IV, and V are displayed in Table 1.1.

Table 1.1. Thesis main contributions

	Urban Energy Modelling			**Urban Energy Planning**
	Contribution	Sector(s) modelled	Modelling tool	Contribution
Chapter III	Modelling of specific energy measures and policies in building and transport sectors	Building	Ad-hoc excel model	Alignment of local and national plans: downscaling and transposition of energy measures and policies from the national to the local level
		Transport	LEAP	
Chapter IV	Building stock energy model development: energy characterisation and energy scenarios modelling	Building	ENERKAD & LEAP	Decision-making support: scenarios assessment
Chapter V	City energy model development: energy characterisation and energy scenarios modelling	Building Transport Public lighting Industry Supply side	LEAP	Decision-making support: scenarios assessment and prioritisation based on different criteria

CHAPTER II: Background

Index CHAPTER II

2.1. Concepts and definitions

2.1.1. Energy Planning

Energy planning can be defined as "*the process of developing long-range policies to help guide the future of a local, national, regional or even the global energy system*" (Bhatia, 2014).

In the context of this Thesis, energy planning will be focused on the urban energy system, previously described in section 1.2.2. Urban energy planning is further reviewed in section 2.2.

2.1.2. Model

A model can be defined as "*a physical, conceptual, or mathematical representation of a real phenomenon that is difficult to observe directly*" (Encyclopedia Britannica, 2022). In other words, it is "*a simplified description of a complex entity or process*" (Bhattacharyya and Timilsina, 2009).

In the energy context, an energy model will try to represent the performance of any energy or energy-related system: a device (like a boiler or a solar PV system), a building, a power plant, a city, or a country. Energy models can use different methods and approaches to model future energy use. Bhattacharyya and Timilsina (2009) distinguished two different approaches: simple methods which do not rely on any theoretical foundation (e.g. growth-rate method, elasticity-based demand forecasting, intensity method) and sophisticated approaches, which in turn can be divided between econometric, end-use, and hybrid approaches[27]. A more extensive review of approaches for modelling future energy demand was carried out by Suganthi and Samuel (2012) including methods such as time series, regression, cointegration, or genetic algorithms amongst others.

Regarding energy models classification, considering the review carried out by Lopez-Peña (2014), these can be separated mainly depending on their economic representation and environmental feedbacks, on their modelling technique and on their modelling approach (see Table 2.1). Other criteria for energy models classification were reviewed by Bhattacharyya and Timilsina (2009). An assessment of mainstream energy models is performed in both works. On this concern, it is also worth to note the extensive reviews carried out by Connolly et al. (2010) and Ringkjøb et al. (2018) assessing a large number of energy modelling tools.

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[27] Econometric and end-use approaches can be also identified respectively as top-down and bottom-up approaches. These are further explained next.

Table 2.1. Energy models classification (Adapted from Bhattacharyya and Timilsina (2009) and Lopez-Peña (2014))

Dimension	Category	Description
Economic and environmental feedbacks	Partial equilibrium	- Unidirectional economy to energy relation - Unidirectional energy to environment relation - No economy-environment relation - Technical detail - Lack of economic detail
	General equilibrium	- Bidirectional economy-energy relation - Unidirectional energy to environment relation - No economy-environment relation - Economic detail - Lack of technological detail
	Integrated assessment model[28]	- Bidirectional economy-energy relation - Bidirectional energy-environment relation - Unidirectional environment to economy relation
Modelling technique	Optimisation	- Given the system variables (and user-defined constraints conditions), obtains the optimal configuration of that system that minimises or maximises a defined objective function (e.g. minimising environmental impacts) - Assumes perfect information and full rationality
	Simulation	- Represents the evolution of the system given the development of a set of technical, policy, and socioeconomic variables - Can describe realistic (i.e. imperfect) rationality of the system agents in their decisions
Modelling approach	Top-down	- Econometric approach: based on economic theory (try to validate economic rules empirically). The energy system is represented through aggregated production functions - Aggregated level (e.g. national level) - Uses upper-level aggregated data (usually widely available) - Uses statistical analysis of historical data to establish relationships between macroeconomic variables and energy consumption. Hardly captures technological breakthroughs - Captures economy-wide effects - Does not capture technological changes nor other non-price related policies - General equilibrium models usually follow a top-down approach
	Bottom-up	- End-use approach: based on detailed engineering representation of the energy system - Disaggregated level (e.g. sectoral level) - Uses low-level detailed data (sometimes difficult to obtain) - Does not need nor rely on historical data. Can react fast to impacts of new technologies - Captures sectoral and technological details - Does not capture price-induced nor other macroeconomic effects - Partial equilibrium models usually follow a bottom-up approach
	Hybrid	- Combines features of both econometric and end-use approaches

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[28] Integrated assessment models were further reviewed and classified by Capellán-Pérez (2016).

As previously commented, energy models are used to characterise an energy system, representing its present and future energy performance. Indeed, energy models have been widely used for energy planning, supporting decision-making and policy formulation. This Thesis will address the modelling of the particular energy system which is the urban energy system and all its components previously described in 1.2.2. Urban energy modelling is further reviewed in section 2.3.

Energy modelling tools used in this work

Table 1.1 introduced the energy modelling tools which have been used for the different analysis carried out in this work. These are hereunder briefly described. The rationale supporting their use in the different case studies is provided too.

On the one hand, ENERKAD (Tecnalia Research & Innovation., 2019) is used in chapter IV to assess the performance gap in building stock energy modelling. ENERKAD is a bottom-up GIS based tool which calculates annual and hourly energy demand at building, district or city scale, based on basic cartography, cadastral, and climatic information of the area under study. Following a physics-based approach, ENERKAD bases its calculations on the heating degree hour method, considering different characteristics of each building inferred from cadastral available data like building use and construction year. This tool has been chosen amongst others due to its low data requirements and for its ability to model every single building in a given geographical area.

On the other hand, LEAP energy modelling tool (Heaps, 2021) is used in chapters III, IV, and V to respectively model a city vehicle stock, a city building stock, and finally a whole urban energy system. LEAP is a bottom-up energy modelling tool aimed at scenario simulation. Indeed, it is a recognised tool for energy systems modelling and energy planning assessment (Beuzekom et al., 2015; Connolly et al., 2010; Mirakyan and De Guio, 2013). LEAP's timeframe extends from a medium to long-term on an annual time-step basis (although calculations can also contemplate seasonal or hourly profiles) and, conversely to other tools, it supports the modelling of any energy sector (e.g. buildings, transport, industry, or supply side), energy service (e.g. heating, cooling, or lighting), and energy vector (e.g. electricity, heat, RES, or fossil fuels). This flexibility supports a wide range of modelling methodologies and allows the design, modelling, and assessment of any energy system (from a district to a national level). On this concern, LEAP has been already used for the modelling of urban energy systems (R. Chen et al., 2019; Collaço et al., 2019; Hu et al., 2019; Lin et al., 2018; Yang et al., 2017; Zhang et al., 2019; Zivkovic et al., 2016). Hence, because of its flexibility along with its low data requirements compared with other tools, LEAP has been chosen for the modelling of the different energy systems assessed in this work.

2.1.3. Scenario

A scenario can be defined as "*a plausible description of how the future may develop based on a coherent and internally consistent set of assumptions*" (IPCC, 2022d). In other words, it is *an illustrative pathway exploring the way that the future may unfold* (Ghanadan and Koomey, 2005).

Scenarios differ from forecasts regarding their relation with uncertainty. The former "explore a range of possible outcomes resulting from uncertainty" while the latter "aim to identify the most likely pathway and estimate uncertainties" (Ghanadan and Koomey, 2005). Conversely to forecasts, scenarios have the "ability to capture structural changes explicitly by considering sudden or abrupt changes in the development paths" (Bhattacharyya and Timilsina, 2009). Since predicting the future is impossible, scenarios work well in the medium and long-term, when "systems are less well defined and interrelationships between factors are less stable and predictable" (Ghanadan and Koomey, 2005), that is, when "the range of possible future outcomes [uncertainty] becomes greater" (World Energy Council, 2015). That is why several scenarios are usually created, allowing to assess alternative contexts for exploring different futures (Benedict, 2017). Indeed, each scenario will scout a different narrative (or scenario storyline) which can be defined as a "qualitative description of plausible future world evolution, describing the characteristics, general logic and developments underlying a particular scenario" (IPCC, 2022d).

Table 2.2. Scenarios classification (Adapted from Börjeson et al. (2006))

Scenarios type	Description	Approach
Predictive *"What will happen?"*	Describe likely future situations based on past and present trends (close to conventional forecasts)	Forecasting
Explorative *"What can happen?"*	Focus on the proposition of more alternative developments	Forecasting
Normative *"How can a specific target be reached?"*	Propose pathways to fulfil determined targets	Backcasting

According to Börjeson et al. (2006), scenarios can be classified into three categories: predictive, explorative, and normative scenarios (see Table 2.2). The first two scenario types could be included under a "forecasting" approach: beginning from a starting point in the present they try to describe, in a more accurate (predictive) or fictional (explorative) way, future situations under the effect of endogenous and exogenous factors. On the other hand, the third scenario type (normative) could be described as a "backcasting" approach: starting from a certain future situation it seeks to contemplate different possible pathways to reach it. Differences between both approaches are further highlighted by Robinson (1982) and Wang et al. (2015).

Concerning the factors that shape the future, they can be separated into drivers, critical uncertainties[29] and pre-determined elements (World Energy Council, 2015). A driver can be defined as "*any natural or human-induced factor that directly or indirectly causes a change in a system*" (IPCC, 2022d). Thus, in the context of the energy system, an energy driver will be any variable that steer ("drive") the trajectory of energy use. Common energy drivers are population, income, energy prices, technological development, environmental concerns, or political governance amongst others (IPCC, 2014b; World Energy Council, 2017).

Scenarios are closely linked to energy planning and energy modelling and have been widely used to support policy-making. Indeed, scenarios may help in the establishment of realistic objectives by assessing and accurately quantifying the impacts of modelled futures, the potential of specific technologies, and the achievable savings of particular actions and policies in a given context (forecasting approach). The other way round, they can be also useful in the selection of the best way (amongst various shaped pathways) to fulfil already-set targets (backcasting approach). In the context of this Thesis, insights and guidelines for the generation of urban energy scenarios will be provided. Urban energy scenarios are further reviewed in section 2.3.3.3.

2.1.4. Energy terminology

Throughout this Thesis, reference will be made to recurring concepts which are explained below.

- *Primary and secondary energy:* primary energy refers to energy available and directly extracted from natural resources. Primary energy can be renewable (solar, wind, hydro, geothermal or biomass) or non-renewable (coal, crude oil, natural gas, or uranium). Secondary energy refers to energy produced, transformed or converted from primary energy to be transportable. Secondary energy includes liquid fuels (like diesel, gasoline and other petroleum products), electricity, and heat (IEA, 2004; Our World in Data, 2022).

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[29] Amongst critical uncertainties lay the concepts of "wild cards" or "black swans" which are events of a low-probability (nearly unpredictable) but with a high impact (World Energy Council, 2015). Yet another example of the impossibility of exactly predict the future.

- *Final energy:* final energy refers to the secondary energy that is finally delivered to the end-user. That is, the energy consumed by end-use devices (e.g. natural gas consumed by boilers, electricity consumed by home appliances, or diesel consumed by cars) (European Environment Agency, 2022; Our World in Data, 2022).

- *Useful energy:* useful energy can be defined as the energy "delivered by conversion devices in the form required to provide an energy service" (Paoli et al., 2018). In other words, useful energy is "the portion of final energy which is actually available after final conversion to the consumer for the respective use" (Ahmadi et al., 2020; European Nuclear Society, 2022). That is, useful energy refers to the output from end-use devices to supply a specific energy service (e.g. heat from boilers for space heating, light from lightbulbs for lighting, or kinetic movement for cars) (Our World in Data, 2022). Final energy and useful energy are related to each other by the efficiency of the end-use device.

- *Energy service:* energy services are the tasks to be performed using energy (e.g. space heating, domestic hot water (DHW), cooling, appliances, or lighting in buildings; or travel by means of an energy-powered vehicle) (IPCC, 2022d).

- *Transformation/conversion process:* any process where primary energy is converted into secondary energy (e.g. cleaning of natural gas, refining of petroleum products from crude oil, electricity and/or heat generation from renewable and non-renewable sources) (IEA, 2004).

In the context of this Thesis the terms "[final] energy use" or "[final] energy consumption" will be used to express final energy consumption, while "useful energy demand" or "useful energy requirements" will refer to the useful energy needed to supply a specific energy service. Figure 2.1 illustrates the above-defined terms.

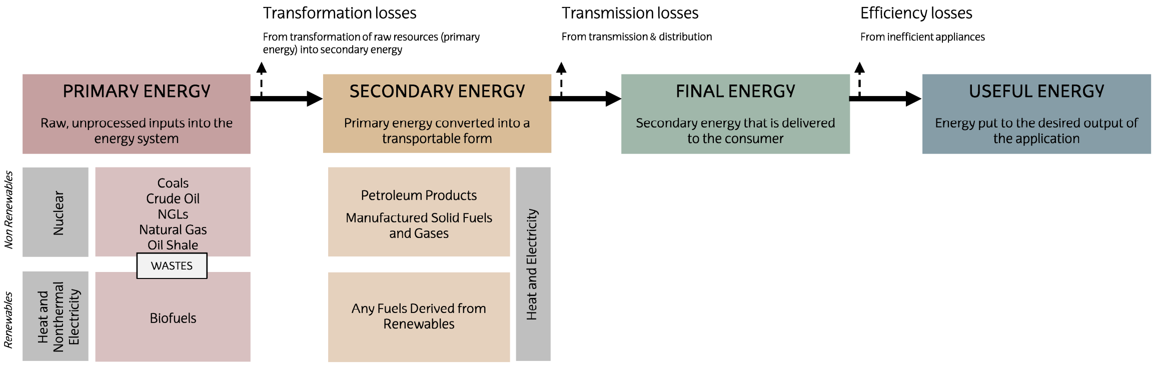

Figure 2.1. Energy terminology (From Our World in Data (2022) and IEA (2004))

- *Embodied energy:* embodied energy refers to the energy used in the production of goods and services regardless of the location and timing of this energy use. That is, the energy used in the production of goods and services produced and consumed locally, but also in the ones imported (produced externally but consumed locally) and exported (produced locally but consumed externally) (IIASA, 2013; IPCC, 2022d). The same concept can be applied to emissions: embodied emissions. The consideration or not of the embodied energy (or emissions) and its allocation depends on the adopted approach (further explained in section 2.3.3.1).

2.2. Urban energy planning

2.2.1. Context

Due to the increased relevance of urban areas in the energy transition challenge, urban energy planning has taken on a new significance. Once focused on land-use, mobility, air quality, or noise action policies, city planners have integrated in the last years energy-related aspects in their planning frameworks, even developing specific energy and climate action strategies. Cities have set themselves climate objectives and developed local action plans including mitigation and adaptation measures to reduce their impact on the environment. To assist cities in the achievement of climate commitments, networks have risen to coordinate efforts towards this task. This kind of initiatives support municipalities in the development of medium and long-term energy plans by providing common frameworks, procuring assistance and capacity building, and rallying cities around shared targets.

However, energy planning in cities face particular questions making it a complex task. Specific local contexts with specific economic structures, boundaries definition, allocation issues, and jurisdictional competences are, amongst others[30], actual problems met by urban energy planners. Moreover, acknowledging that cities are embedded in a national and global context, the harmonisation and coordination of local and upper strategies is crucial for both planning levels to be effective. The interrelation and alignment between different levels (national, regional, and local), and the integration of end-use sectors and technological solutions in an interconnected energy system, are key aspects to be considered when pursuing the development of holistic long-term urban energy plans. Moreover, unlike land-use, noise, pollution, or other more traditional planning frameworks, urban energy planning lacks a regulatory frame that endorses and governs its development.

On this concern, institutional frameworks regarding urban energy planning are not fully-grown yet (Yazdanie and Orehounig, 2021). Moreover, due to urban specificities, each city will develop urban energy strategies according to their own backgrounds, contexts, particularities, and capacities. That is, “no single model of urbanisation is necessarily best” (IEA, 2016a). Nevertheless, common procedures in the development of urban plans can be found. According to Mirakyan and De Guio (2013), an integrated urban plan should comprise 4 phases: preparation and orientation, detailed analysis, prioritisation and decision, and implementation and monitoring (see Table 2.3). Likewise, in

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[30] See Cajot et al. (2015) for more challenges related to energy planning in the urban context.

the case of the CoM initiative, a framework is proposed based on similar steps (initiation, planning, implementation, monitoring and reporting) for the development of Sustainable Energy and Climate Action Plans (SECAP) (Bertoldi et al., 2018d).

Table 2.3. Phases in the development of an integrated urban energy plan (From Mirakyan and De Guio (2013))

	Phase description	Methods and tools	Involved actors
Phase I Preparation and orientation	The starting point is assessed, issues are identified, and solutions and targets are outlined	Workshops, Strengths Weaknesses Opportunities Threats (SWOT) analysis	Decision makers, urban planners and experts
Phase II Detailed analysis	Alternative scenarios are quantitatively assessed	Energy system models	Urban planners and experts
Phase III Prioritisation and decision	An integrated plan with specific measures is drafted	Multi-Criteria Decision Analysis (MCDA) methods	Decision makers, urban planners and experts, local stakeholders
Phase IV Implementation and monitoring	The integrated plan is developed and periodically revised and improved	Depends on the final measures to be implemented	Decision makers, urban planners and experts, local stakeholders

Regarding energy policies covered by urban energy plans, these are conditioned by the own particularities of urban energy systems. Indeed, being urban areas mostly net importers and predominantly energy-demanding systems, policies related to the demand side are the most productive measures at city scale (IIASA, 2013). Cities should focus their efforts on demand management since the potential of supply side options at urban level is very constraint. Available urban energy policies include taxes, codes, standards, subsidies, audits, certifications, and education campaigns amongst others (see Table 2.4). The CoM initiative also provides a guide with policies, key actions and good practices for climate change mitigation at urban scale (Bertoldi et al., 2018a).

Table 2.4. Examples of urban energy policies (Adapted from IPCC (2014a))

	Buildings	**Transport**	**Energy systems**	**Other**	**Level of urban policy leverage**	**Impact on GHG emissions**
Reduced demand/ Behaviour change		- Tolls - Congestion pricing			-	+
Recycling/ Reducing waste				- Education		
Urban form/ Density	- Certification - Urban planning	- Smart growth/ Urban containment - Urban planning - Pedestrian zones/ Traffic calming/ Transit-oriented corridors				
Improved planning management	- Commissioning - Audits	- Integrated planning	- Demand response measures			
High-performance/ Passive design	- Codes/Standards - Integrated planning - Certification	- Bike sharing - Urban planning				
New/ Improved technology	- Real-time information	- Subsidies for fuel efficiency - Bike sharing - Real-time information	- Low carbon tech targets			
Materials efficiency	- Codes/Standards - Taxes - LCA - Certification					
Energy efficiency	- Codes/Standards - Taxes - Preferential lending	- Subsidies for fuel efficiency - Standards - Targets	- Taxes Credits/Permits			
Fuel/ Energy switching/ RES		- Taxes - Biofuel incentives	- Taxes Energy security policies	- Tradable credits		
Carbon sinks/ Sequestration				- Tradable credits	+	-

Urban planners should bear in mind however, that systemic approaches and policy integration are the true levers of urban change (IIASA, 2013). That is, the integration of land-use planning with mobility policies, the integration of different energy vectors interconnected across different end-use sectors, the combination of different technologies with storage solutions and flexible networks, or the integration of urban flows (water, waste, or energy), along with structural changes in the city economic organisation and in the consumption patterns and lifestyle habits of their inhabitants yield the largest improvements in terms of climate change mitigation. These particular systemic approaches allow to overcome lock-ins of inefficient and carbon-intensive urban designs and patterns (e.g. mobility models focused on private transport or supply infrastructures based on fossil fuels). Moreover, in the case of growing cities, these can avoid these vicious lock-ins by leapfrogging to modern solutions saving money, emissions and efforts (IEA, 2016a).

Efficient urban energy planning is essential for achieving sustainable urban environments, improving citizens welfare, and fulfilling climate targets. A clear action plan must include concrete and transparent targets, binding commitments, metrics to monitor its progress, and be subjected to regular evaluation (IEA, 2016a). Urban policy makers should also promote transparency and consider citizen engagement when developing local energy plans. Furthermore, they should be aware of the multi-scope aspect of urban decarbonisation and therefore adopt a holistic vision, cleverly aligning their objectives and actions with the national ones to effectively contribute to upper targets while meeting simultaneously the goals at both local and national scales. On this concern, every urban energy plan should be assigned with responsibilities and duties according to the city capacities and resources. Competences should be granted to municipalities and coordination fostered between the national and local governance frameworks.

2.2.2. Urban energy plans and climate objectives

In the last years, local energy plans have been developed (Reckien et al., 2014; Salvia et al., 2021), a part of them being fostered by city networks initiatives. City networks gather municipalities around climate-related objectives and engage local authorities in meeting them through the development of roadmaps and deployment of mitigation (and in some cases adaptation) measures. These initiatives have revealed themselves as an efficient tool to support the fulfilment of climate objectives in absence of national legislation on this concern by boosting voluntary commitments (Melica et al., 2018; Pietrapertosa et al., 2019), influencing the governance, policies and measures of cities which address climate change (Busch et al., 2018), advancing knowledge and methods for climate change mitigation at local scale (Fünfgeld, 2015), achieving energy consumption reductions (Pablo-Romero et al., 2016), and supporting urban adaptation (Heikkinen et al., 2020). Moreover, city networks are especially influential over small municipalities, usually with less experience and resources to tackle climate change. Whereas larger cities may develop their plans independently or in response to national legislation without requiring any support due to a higher level of climate awareness, broader knowledge in energy planning, and greater institutional capacity (Reckien et al., 2018).

It should be noted that the development of city energy plans and fulfilment of urban climate goals is not an exclusive task of local authorities. Other municipal actors like individual citizens, private companies, neighbourhood communities, non-governmental organisations, and other local stakeholders should be considered as they have an important role to play in urban energy planning (Andersen et al., 2021; Hettinga et al., 2018; Secinaro et al., 2021), in addition to a huge potential in undertaking rapid climate actions thanks to their great flexibility and few faced obstacles (Gilligan and Vandenbergh, 2020). These municipal stakeholders can support the elaboration of urban energy strategies like the cities networks initiatives, by providing different types of knowledge and perspectives, increasing the participation in the decision-making, and reaching agreements regarding common goals (Gustafsson et al., 2015; Soma et al., 2018), without forgetting the social benefits they may generate. Indeed, local energy communities and initiatives do not only achieve energy savings and foster renewable generation, but also promote the decentralisation and democratisation of the energy system, increase local employment, encourage urban regeneration programmes, and stimulates local economy and innovation (Mey et al., 2016; Otamendi-Irizar et al., 2022).

Table 2.5. Definition of climate goals (From Greenhouse Gas Protocol (2014))

Goal type	Description
Base year goal	Represents a reduction (in emissions/energy) relative to the specific level in a historical base year.
Fixed level goal	Represents a reduction (in emissions/energy) to an absolute level in a target year.
Base year intensity goal	Represents a reduction in intensity (emissions/energy intensity) relative to specific intensity level in a historical base year.
Baseline scenario goal	Represents a reduction (in emissions/energy) relative to a baseline scenario level.

Regarding the set-up of energy and climate-related objectives at urban level, the Global protocol for community-scale GHG emission inventories (Greenhouse Gas Protocol, 2014) differentiates 4 approaches to build climate goals (see Table 2.5): base year goals, fixed level goals, base year intensity goals, and baseline scenario goals. Moreover, it also remarks that these goals may refer to the city overall emissions or energy levels, to specific sectors, or to certain scopes (see section 2.3.3.1), thus care must be taken to avoid double accounting issues. To keep track of the city emissions and energy levels is essential to monitor the progress of implemented policies and actions, for which it is required to update historical data and base year inventories when structural changes in the inventory boundary occurs, or when data is refined or enlarged.

When developing urban energy and climate targets, these should take into account the current situation of the city and its background. Kennedy et al. (2014) stated that city characteristics had an impact on the strategies developed to reduce emissions. The IPCC (2014a) remarked that the longer the time horizon and greater the wealth of cities, the higher abatement goals. Although ultimately, baseline emissions usually drove the level of emissions reductions to be achieved in most cities, i.e. higher emissions in the base year imply higher intended reductions (Croci et al., 2017; Hsu et al., 2020b; IPCC, 2014a; Pablo-Romero et al., 2015). Moreover, urban climate targets should not be outlined as "political statements or aspirational goals" away from the real capabilities of cities as this could lead to their non-compliance (Hsu et al., 2020b). That is, targets should not be set arbitrarily and should reflect true mitigation potentials. Per capita metrics are more meaningful than absolute ones to track urban abatement goals (IPCC, 2014a). Also, urban goals should not be directly translated from upper objectives but adapted to the local context. Pasimeni et al. (2014) advocated for the downscaling of upper policies to the local level so that these could be tailored to the local conditions in order that municipalities could effectively contribute to higher objectives from a bottom-up approach. Furthermore, Maya-Drysdale et al. (2020) verified a lack of long-term vision in the planning frameworks of cities. These rather focused on medium-term goals which were revisited when the time came, thus leading to a discontinuity in the long run planning. Moreover, cities had not their objectives connected to the national ones, which caused problems when establishing long-term and integrated strategies. Leal and Azevedo (2016) remarked the lack of alignment and continuity between local short/medium-term goals and global long-term targets and referred to the unsuitability of setting the same objectives, in relative terms, for cities with different starting point situations. Altogether, there is still a need of methodologies which clearly adjust upper climate objectives to lower scales.

2.2.3. The multi-scope aspect of the urban decarbonisation challenge

The different challenges faced in the definition and accomplishment of urban climate related targets indicate the need of a holistic approach when planning and carrying out climate actions at local level. Cities do not act as isolated energy systems but are rather embedded in a complex and wide network where energy, climate change and land-use interact, having an impact across different space and temporal scales (municipal-short term, country/regional-medium term, and global-long term) (IEA, 2016a; Pasimeni et al., 2014). As stated by Thellufsen et al. (2020) municipalities should find their part to play in a way that the whole system is benefited. Cities should act locally but being aware of the national and global context in which they are framed. Maya-Drysdale et al. (2020) argued about the need of an integrated approach to decarbonise the energy systems of European cities. The authors pleaded for the development of holistic long-term strategic visions, and open-minded scopes when considering structural changes in the energy system.

Energy use that occurs in urban areas does not only depend on the consumption sources lying within the city borders but is also influenced by external factors which have an impact on the city itself. National/supranational policies and regulations are out of the jurisdiction of municipal authorities but exert a relevant influence in the energy performance and decarbonisation strategies of the city too (Elliot et al., 2020; Zhao et al., 2019).

External impacts out of the scope of the local competences should be considered and jointly managed by local and supralocal entities in order to handle their effects on the city energy consumption. Hsu et al. (2020a) remarked the need of the integration of governance levels "beyond and below the state". Holtz et al. (2018) developed a framework to support low-carbon transition developments considering the contribution and competences of urban areas. Corfee-Morlot et al. (2009) advocated for an intertwined framework in which urban initiatives would improve nationally led policies by providing lessons learnt, while the upper policies would foster more efficient and tailored locally led climate strategies. Sperling et al. (2011) stated that municipal energy planning should be framed within the national energy strategy while at the same time responsibilities should be given to local institutions along with the required support and tools to carry out energy planning. Pietrapertosa et al. (2019) highlighted that municipalities may require attention and support from higher instances to conduct climate actions in a coordinated way. The CoM tried to find a solution to this problem through the creation of the "Covenant Territorial Coordinators" formed by provincial, regional, metropolitan, or groupings of local authorities, which support smaller municipalities in their contribution and coordination towards the fulfilment of objectives set for larger territorial areas (Melica et al., 2018).

Altogether, harmonisation and integration of policies between institutional levels and across jurisdictional borders is still required, along with the alignment of targets and measures (IPCC, 2014a). Cities may have jurisdiction over core energy elements such as buildings, public transport, or urban planning (which out of the scope of national frameworks may provide additional reductions), but would often need support from national governments to be successful in carrying out integrated energy plans, as they lack from financial resources and legislative capacities to enact effective energy policies (IEA, 2016a). Hence, local governments should be granted with competences and executive authority to enforce energy and climate actions with deeper impacts and supported with sufficient funding. To achieve this, an integrated governance environment comprising the multiple levels involved in the energy transition should be put in place too (IEA, 2016a; IPCC, 2014a).

2.3. Urban energy modelling

2.3.1. Context

Like national energy models depict the operation of national energy systems, urban energy models portray the energy performance of cities. Indeed, the objective of urban energy modelling is to represent the energy flows that occur inside and across the city boundaries, through the evaluation of the performance of the different parts of the urban energy system such as buildings, vehicles or energy generation systems. Urban energy modelling serves to characterise all the components of the urban energy system at their current situation, while also allows to generate future energy transition scenarios. Their subsequent assessment should provide urban energy planners, policymakers and other local stakeholders with enough information to make decisions and formulate urban energy strategies and policies to achieve low-carbon and sustainable cities. That is, energy modelling of cities should support operational and investment decisions (to optimise the operation, dispatch and capacity of energy technologies), include scenario planning (to investigate a range of different futures), and provide an analysis of power systems (to assess system dynamics). Altogether, urban energy models "provide quantitative, system-level analyses to support energy strategy development and decision-making" (Yazdanie and Orehounig, 2021).

However, conversely to national energy modelling, urban energy modelling has a more recent background, thus facing specific issues and challenges that have yet to be solved. In the review by Abbasabadi and Mehdi Ashayeri (2019) different approaches and tools for modelling urban energy use were identified, reflecting on the need for a framework and tools for a more integrated evaluation of different city energy aspects. The necessity of integrated modelling approaches was also highlighted by Keirstead et al. (2012) which carried out a review of methods and approaches to model urban key fields like technology, building and systems design, urban climate, policy assessment, and urban transportation and land use. The authors remarked that the complexity of urban energy systems, data uncertainty and the integration of models were the main challenges faced in urban energy modelling, while agent-based modelling and improved data were potential opportunities to tackle them. Additional gaps and challenges related to urban energy modelling were reviewed by Yazdanie and Orehounig (2021). The authors also proposed a set of solutions to fill these gaps and to tackle the identified challenges (see Table 2.6).

Table 2.6. Urban energy modelling challenges and proposed solutions (From Yazdanie and Orehounig (2021))

Category	Challenges	Solutions
Technical & Methodological	- Data gaps (availability and accessibility, quality and consistency, granularity, data management) - Transparency and reproducibility - Balancing model resolution, complexity, and computational tractability - Emerging technologies (smart grid integration, demand side management) - Integrated models - Uncertainty in modelling - Modelling human behaviour	- Tackling data issues (data sharing platforms, mathematical methods to fill gaps, privacy and security controls, ICT and robust communication architectures) - Improving urban energy modelling approaches (comprehensive scenario design, integrating modelling approaches, high performance computing and model design, parallelisable modelling techniques, smart grid and demand response modelling) - Support studies (pilot projects, benefit studies, stakeholder feedback)
Institutional	- Municipal recognition as energy planners - Capacity building within municipal governments - Interdisciplinary cooperation - Disseminating urban energy modelling knowledge - Communicating model results	- Regulatory measures, institutional frameworks, and standards (centralised energy data collection and regulation authority, incentivise and mandate data sharing, open data licenses, scientific standards, central institutional frameworks to support municipal energy planning) - Training programs - Financing and research calls

Regarding the available tools for urban energy modelling and scenarios generation at city scale, reviews were carried out by Ferrari et al. (2019) and Beuzekom et al. (2015). Moreover Mirakyan and De Guio (2013) reviewed a set of softwares for their proposed integrated urban energy planning methodology. Amongst the reviewed tools, Lind and Espegren (2017) used the TIMES modelling framework (IEA, 2022c) to compare the results of different energy measures implementation in Oslo, while low-carbon transition scenarios were evaluated in an IEA report (IEA, 2016b) for Helsinki and other Nordic cities. The same energy model was also used in the EU project InSmart (G. Simoes et al., 2018; Gargiulo et al., 2017) and by Yazdanie et al. (2017). In the former, outputs from specific transport and building models were used in TIMES to generate scenarios which were later assessed through a MCDA method. Whereas in the latter, policies such carbon taxes and measures like building renovations, installation of decentralized energy generation systems and the deployment of storage solutions were evaluated in the Swiss city of Basel. Other modelling tools such as LEAP (Heaps, 2021) or EnergyPlan (Aalborg University, 2022) have also been used to generate energy scenarios at city level. Lin et al. (2018) used LEAP to determine the GHG peak in a Chinese city in three different scenarios, while EnergyPlan was used by De Luca et al. (2018) to identify the measures to achieve a nearly zero carbon city in an Italian case study.

Last but not least, it is worth to note a question that arises regarding energy modelling and energy transition, and which is, what is the part to be played by energy models (and energy scenarios) in the current context of an energy transition? Moreover, how to model the energy transition? And, how to model structural changes in the energy system? These questions, that concern energy modelling at different levels (i.e. national, regional, or urban), are also relevant when developing energy models and energy scenarios at city scale and should be taken into account. On this concern it should be noted the work from different authors, which, although not specifically focused on it, could be replicated in the urban energy modelling field. García-Gusano et al. (2018) questioned that whether at the time of an energy transition and even energy decoupling, it would be justifiable to keep some relationships (based on energy drivers) which have been proved in the past but may lose their significance in future times. Indeed, Craig et al. (2002) noted that long-term energy forecasts (subject to experience changing times) have failed to represent future situations by overestimating consumption and underestimating uncertainty[31]. Closely linked to the energy transition, Samadi et al. (2017) argued in favour of the introduction of lifestyle changes towards sustainable sufficiency in scenarios. Indeed, the energy transition needs of behavioural and consumption patterns shifts to achieve its goals. The potential of sufficiency should be then included and quantitatively assessed in energy scenarios. Moallemi and Malekpour (2018) developed an exploratory modelling approach to model sustainable transitions based on three steps: conceptualisation of the transition dynamics, scenario exploration, and contingency planning. The authors advocated for the combination of qualitative (supported by participatory process) and quantitative (supported by energy models) approaches. Regarding participatory approaches, Sgouridis et al. (2022) remarked that participation of key actors in the modelled system widened the possibilities of assumptions and policy options, while also prevented both adverse reactions towards inequal-perceived policies and the "pre-analytic" vision of modellers. The qualitative development of scenarios would support the quantitative modelling of these. This vision-driven approach (similar to backcasting) would be preferable in the context of the energy transition. Indeed, the modelling of ambitious targets in scenarios, although sometimes daunting, could give and idea of the challenges to achieve them and consequently develop strategies to reach them. Finally, the authors also stated that the full compliance of energy models with the existent energy system should be avoided (or at least reduced) as it constrained the range of pathways and averted the possibility of envisioning a radical transition. On this concern, optimisation modelling techniques may be constrained to generate energy scenarios which comply with the current rationality of the system (thus preserving it), while simulation modelling techniques would be more open to portray futures assuming other logics for the system.

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[31] On this concern, scenarios are better fitted to model transitions as they can contemplate immediate and/or unexpected changes and events (see section 2.1.3).

2.3.2. Energy modelling of cities building stock

2.3.2.1. Building stock energy models classification

Building energy modelling provides useful information regarding the current and future state of the building stocks of cities (Hong et al., 2020), enabling the impact assessment of the implementation of energy measures in the sector (e.g. envelope renovation, windows replacement, energy systems replacement and fuel changes, or integration of RES solutions). Thus allowing energy planners to decide upon different pathways to decarbonise the building sector and to select the best suited for the city.

As reviewed by Langevin et al. (2020), Li et al. (2017), and Swan and Ugursal (2009), building energy modelling can be grouped into two main approaches: top-down and bottom-up (see Table 2.7). The first establishes long-term relationships between energy use and macroeconomic variables (e.g. population, GDP, or energy prices) to model energy consumption. Top-down approaches were used by Copiello and Gabrielli (2017), Serrano et al. (2017), and Ürge-Vorsatz et al. (2015) to identify the drivers which guided energy consumption in the building sector. Although able to represent the economic impacts resulting from the implementation of energy measures, they fail to capture technological changes and lack of detail while portraying end-uses. Conversely, bottom-up models are based on the explicit definition of low-level energy uses and discrete technologies to estimate energy consumption. To this end, this approach requires a large amount of micro-level data (mainly climate and building data) to model energy consumption, which sometimes can be hard to process due to a lack of standardised city datasets (Y. Chen et al., 2019; Reinhart and Cerezo Davila, 2016). Moreover, the bottom-up focus can be further divided into statistical (or data-driven) and physics (or engineering) based models. The former are usually based on regression models or other mathematical methods, whereas the latter use physical parameters to outline the energy use of buildings. Reviews made by Abbasabadi and Mehdi Ashayeri (2019), Bourdeau et al., (2019), Ferrando et al., (2020), and Kavgic et al., (2010) deepened into the description of bottom-up approaches and evaluated available tools. Martinez Soto and Jentsch (2016) compared the results from different tools using both approaches for the same case study, concluding that the accuracy of the models outputs highly depended on the quality of the input data. Moreover, they also remarked that the statistical approach was more sensitive to input parameters than the physics-based approach. Also, Johari et al. (2020) advocated for the integration of bottom-up approaches to tackle data issues and inherent uncertainty, as well as to combine urban energy models with climate, thermal comfort, and mobility models.

Table 2.7. Building stock energy models classification (Adapted from Kazas et al. (2017)*,* Langevin et al. (2020)*,* Li et al. (2017)*, and* Swan and Ugursal (2009)*)*

Approach	Modelling technique
Top-down	*Econometric* Statistical and mathematical methods based on economic theory.
	Technological Add aggregated technological characteristics (e.g. appliance saturation trends or building codes) to econometric models.
	System dynamics Quantitative models of aggregate-level building and technology stocks and flows.
Bottom-up	*Statistical (or data-driven)* - *Regression analysis:* use historical data to predict future energy use. - *Conditional demand analysis:* perform regression based on the presence of end-use appliances. - *Machine learning/neural network:* use algorithms to find patterns in energy use. - *Agent-based:* represent causality at individual building level and behavioural patterns.
	Physics-based (or engineering) - *Population/end-use distribution: use appliances distribution to calculate energy use.* - *Archetypes: classify the building stock into clusters to further model and scale-up the energy performance of each cluster.* - *Sample: similar to the archetype technique but using actual data from building samples.* - *Brute force: model and simulates each single building of a building stock.*

Regarding the use of bottom-up models to represent the energy consumption of the building sector at city scale, Dall'o' et al. (2012), Mastrucci et al. (2014), and Torabi Moghadam et al. (2018) adopted a statistical approach in their models by using regression methods to outline the energy use of buildings, while energy models based on the physics approach were developed by Calderón et al., (2015), Hedegaard et al. (2019), Kazas et al. (2017), Kim et al. (2019), Monsalvete et al., (2015), and Schiefelbein et al. (2019). The former method was also used by Y. Chen et al. (2017) and García-Pérez et al. (2018) to model the energy consumption of buildings in the cities of San Francisco and Barcelona respectively, and to assess the impacts of different energy measures. An hybrid approach was followed by Yu (2018) to forecast city-wide building energy demand. The author proposed a two-step methodology in which the results from the physics-based approach were adjusted using a regression analysis. Last but not least, it should be noted that most of these bottom-up models have integrated Geographical Information System (GIS) tools in their analysis (Calderón et al., 2015; Y. Chen et al., 2017; Dall'o' et al., 2012; Fichera et al., 2016; García-Pérez et al., 2018; Gargiulo et al., 2017; Mastrucci et al., 2014; Reiter and Marique, 2012; Schiefelbein et al., 2019; Torabi Moghadam et al., 2018), making the data collection and treatment easier for modellers, and providing energy planners key data to inform and support the decision-making process (Alpagut et al., 2021; Li, 2017; Urrutia-Azcona et al., 2021).

2.3.2.2. *Performance gap and model calibration*

One of the major issues of building energy models is however the gap between theoretical and actual consumption values, called the prediction or energy performance gap. Cozza et al. (2021) reviewed the main causes of the deviation between real and theoretical values, defining two types of variation sources with regard to the optimal consumption: the theoretical consumption deviation due to inaccuracy of inputs and assumptions for building modelling and the inaccuracy of occupant behaviour modelling; and the actual consumption deviation due to equipment malfunctioning, limitations in the measurements systems, errors in the construction stage (causing deviations between the design phase and the final construction), and non-optimal use of the building by the occupant. Similar remarks were shared by Zou et al. (2018) who listed some of the factors influencing the occupant behaviour (e.g. lifestyle and cultural background, energy-related attitude of occupants, interaction of occupants, and comfort perception amongst others) and suggested the use of agent-based or stochastic modelling approaches to tackle this issue. Li et al. (2019) remarked that user behaviour was generally oversimplified, causing gaps between simulated and measured values. Majcen et al. (2015) developed a statistical model to assess the performance gap in Dutch households, also concluding that the occupant behaviour had the largest effect in the real-theoretical variance of heating consumption. Dwelling parameters (e.g. dwelling type, floor area and age) used in the estimation of theoretical values had also an important weight in the overestimation of consumption values. Cuerda et al. (2020) also identified modelling input data (weather and building related information) and behavioural modelling as the main factors influencing the energy performance gap. The authors warned about the fact that the use of standard values (instead of monitored data) to estimate heating savings could make expected payback periods not to be achieved (as the final savings would be in fact lower). This was also shared by Majcen et al. (2016, 2013) who indicated that the use of theoretical values to estimate energy savings could make reduction targets look easily achievable. Hence, modellers should use, when possible, actual consumption data to make better estimates. Finally, Charlier (2021) and Balaras et al. (2016) remarked that consumption values under the theoretical ones could be due to low indoor comfort conditions or reduced operating hours of space heating, characteristic of energy poverty situations, i.e. households that will adopt restrictive behaviours because of limited monetary resources to meet well-being comfort standards.

On their work, Cozza et al., (2021) and Zou et al. (2019) proposed solutions (such as improving modelling accuracy, reworking standard values, or increasing training and communication amongst stakeholders for a better usage of buildings) to fully address the causes of energy performance gap. Also, to mitigate its effects, the calibration of models “aims to minimise the discrepancies between measured and simulated data” (Coakley et al., 2014). Agami Reddy (2006) reviewed calibration procedures of building energy models and distinguished three methods: manual iterative, automatic, and statistical. O'Neill et al. (2011) observed that calibration methods have mostly relied on the first one (i.e. manual procedures), while only few methodologies have suggested the automatisation of the process (O'Neill et al., 2012). Some of them (optimisation-based, pattern-based, and Bayesian calibration methods) were listed by Hong et al. (2020). Coakley et al. (2014) highlighted the main issues in the calibration of models (e.g lack of standards, inputs quality, ad-hoc nature, or automatisation absence amongst others) and remarked that most of the current approaches were based on modellers experience, techniques being opaque and trial-and-error built. To overcome these issues, Ferrando et al. (2020) advocated for the use of measured data and its integration in the characterisation of buildings energy use. Considering that, some authors have adjusted the results of their bottom-up building energy models using hourly monitored data to reduce the discrepancies between real and theoretical final energy consumption values (Ji and Xu, 2015; Kim et al., 2019; Ledesma et al., 2021; Oliveira Panão and Brito, 2018; Raftery et al., 2011). Royapoor and Roskilly (2015) followed the calibration approach proposed by (Mustafaraj et al., 2014) consisting in a two-step method where the theoretical values of key modelling input parameters are further refined using field collected data. Lara et al. (2017) and Monetti et al. (2015) adopted optimisation-based approaches, while Hedegaard et al. (2019) and Yu (2018) used Bayesian analysis to calibrate their models. Finally, Taylor et al. (2019) and Uidhir et al. (2020) adjusted their aggregated results to the real values by using simple scaling factors.

2.3.3. Energy modelling of urban systems

2.3.3.1. Urban energy accounting

When modelling any system, a crucial aspect is the definition of the system scope. That is, establishing its boundaries and deciding what would be included in the analysis. Due to the complexity of urban systems, defining the model scope and quantifying the energy use of the own urban system is a hard task, as different boundaries can be defined and different accounting approaches chosen.

Regarding the outline of urban boundaries three approaches stand out depending on the focus of the assessment (IPCC, 2014a). On the one hand, the administrative approach is chosen if the urban system is delimited by its territorial or political borders. On the other hand, when the urban system is delineated according to economic, social, and other interconnections shaping the operation and development of the city, the functional approach is followed. Finally, the morphological approach limits the urban system based on the form of the city land use.

Concerning the accounting approaches two main perspectives can be defined: the production-based (or territorial) approach and the consumption-based approach (Athanassiadis et al., 2018; Baynes and Wiedmann, 2012; IIASA, 2013; IPCC, 2014a; Kennedy et al., 2010; Lombardi et al., 2017; Munksgaard and Pedersen, 2001). The production-based approach considers the energy use that takes place physically and in a direct form within the city borders. That is, all the energy consumption that occurs inside the city boundaries is assigned to the city itself (e.g. fuel combustion for heating, fuel use for in-boundary transport, or fuel use for the local production of electricity, heat, goods or services either for domestic consumption or for exports). Under this approach, energy use is allocated to the producer (of energy, goods, or services). This is the method used for the energy and emissions reporting under the UNFCCC framework. It is worth to note that an extension of the production-based approach can be considered: the production plus supply chain approach, in which territorial energy use (direct) is accounted along with the indirect energy use related to the local consumption of key commodities (such as electricity, heat, water supply, food, or building materials) produced outside the city borders.

The consumption-based approach considers the energy use (direct and indirect) related to domestic consumption of fuels, products and services regardless of their origin (local or imported). That is, the embodied energy from goods and services produced outside but consumed within the city is allocated to it, thus including impacts occurring beyond the urban boundaries. Accordingly, this approach does not assign to the city the energy used in the production of goods and services which are further exported out of its borders. Instead, this embodied energy would be allocated to the final consumer elsewhere outside the city. Under this approach, energy use (direct or embodied in goods and services) is allocated to the final consumer rather than to the original producer of these commodities (i.e. energy, goods, or services). To allocate the different energy flows (direct and embodied) to the final consumer, the consumption-based approach usually relies on Environmentally-Extended Input-Output[32] analysis. Finally, this perspective allows to quantify the trade linkage between cities and their environment, provides a greater understanding of cities climate responsibility, and raises awareness concerning the indirect energy use of cities trough the consumption of imported goods and services (Wiedmann, 2009).

The selection of one or another accounting approach yields different results. The production perspective reflects the economic structure of urban areas, while the consumption accounting provides insights on the available income, consumption patterns and specific lifestyle of the city. Thus, under a production perspective, high industrialised urban areas will account for higher energy

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[32] It should be noted that available Input-Output (IO) tables to perform this kind of analysis usually have national or regional-level resolution, thus complicating the assessment at urban level. Adapting these tables to a city level is a challenging task due to the large amount of local data required.

use than service-oriented cities. Conversely, under a consumption approach, embodied energy will be allocated to the consumer city, hence accounted energy use may increase in tertiary-based highly importer cities (while decrease in exporter ones)[33]. The approach choice has also implications in the development and assessment of urban policies. Indeed, production-based accounting is useful when designing policies oriented to local production (of energy, goods, or services), land planning, housing, mobility, and other fields where cities can undertake direct actions. Moreover, it is also very helpful when planning structural changes in the city economic organisation, or in the dematerialisation and efficiency improvement of urban production (Baynes and Wiedmann, 2012). Although more difficult to implement, consumption-based accounting supports strategies directed to promote changes in consumption and lifestyle patterns by raising the consciousness about the embodied energy in goods and services produced elsewhere but consumed within the city.

Altogether, both approaches should be complemented to provide a holistic assessment of the direct and indirect energy use within urban areas. As urban areas are transitioning from industrial to tertiary centres (especially in developed countries), most of the emissions currently occur outside the boundaries of cities. Thus, the impact of embodied energy in urban areas is higher and hidden in production offshoring and import of finished goods. If not accounted, this may give a false impression of decarbonisation and decoupling. Being mostly net importers systems, the consumption-based approach reflects the use of embodied energy by cities (especially in developed countries with tertiary-based economies) and widens the range of urban climate policy opening the possibility of fostering consumption-oriented policies (Christis et al., 2019; Wiedmann, 2009). Along with the reduction of direct energy use, cities should not lose sight of the need of decreasing the consumption of embodied energy in goods and services. These commodities enclose an energy use which, although occurring outside urban borders, is driven by socioeconomic activities held in the city. Thus, a change in lifestyle habits and consumption patterns is required to avoid that the use of energy happening somewhere else and embodied in the goods and services demanded within the city exceed energy savings achieved locally.

Together with these accounting perspectives, city GHG emissions can be differentiated into three scopes according to the Greenhouse Gas Protocol (2014) (see Figure 2.2). Scope 1 refers to the emissions which source is physically located within the city boundaries. Scope 2 refers to the

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[33] This is especially relevant when accounting for cities energy use in developed and developing countries. That is, cities in developing countries are in disadvantage when assessed through a production-based approach, as their economies are usually focused on producing (and thus to use energy) finished goods and other products consumed in developed countries where the embodied energy in these commodities would not be considered. However, when a consumption perspective is adopted, embodied impacts from these finished goods and products are allocated to the importer cities (usually in developed countries) to the extent that they may even exceed the impacts of their own local activity. Moreover, in high-income countries, local and national energy uses tend to equalise when a consumption-based accounting approach is considered (IIASA, 2013).

emissions related to the use of electricity, steam, heating or cooling supplied by grids which may (or not) cross the city boundaries. Scope 3 refers to the emissions discharged outside the city borders but driven by activities taking place within it (e.g. embodied emissions in goods and services consumed within the city). Thus, the production-based approach will only consider scope 1 emissions, while production plus supply chain[34] and consumption-based approaches will consider scope 1, scope 2, and scope 3 emissions.

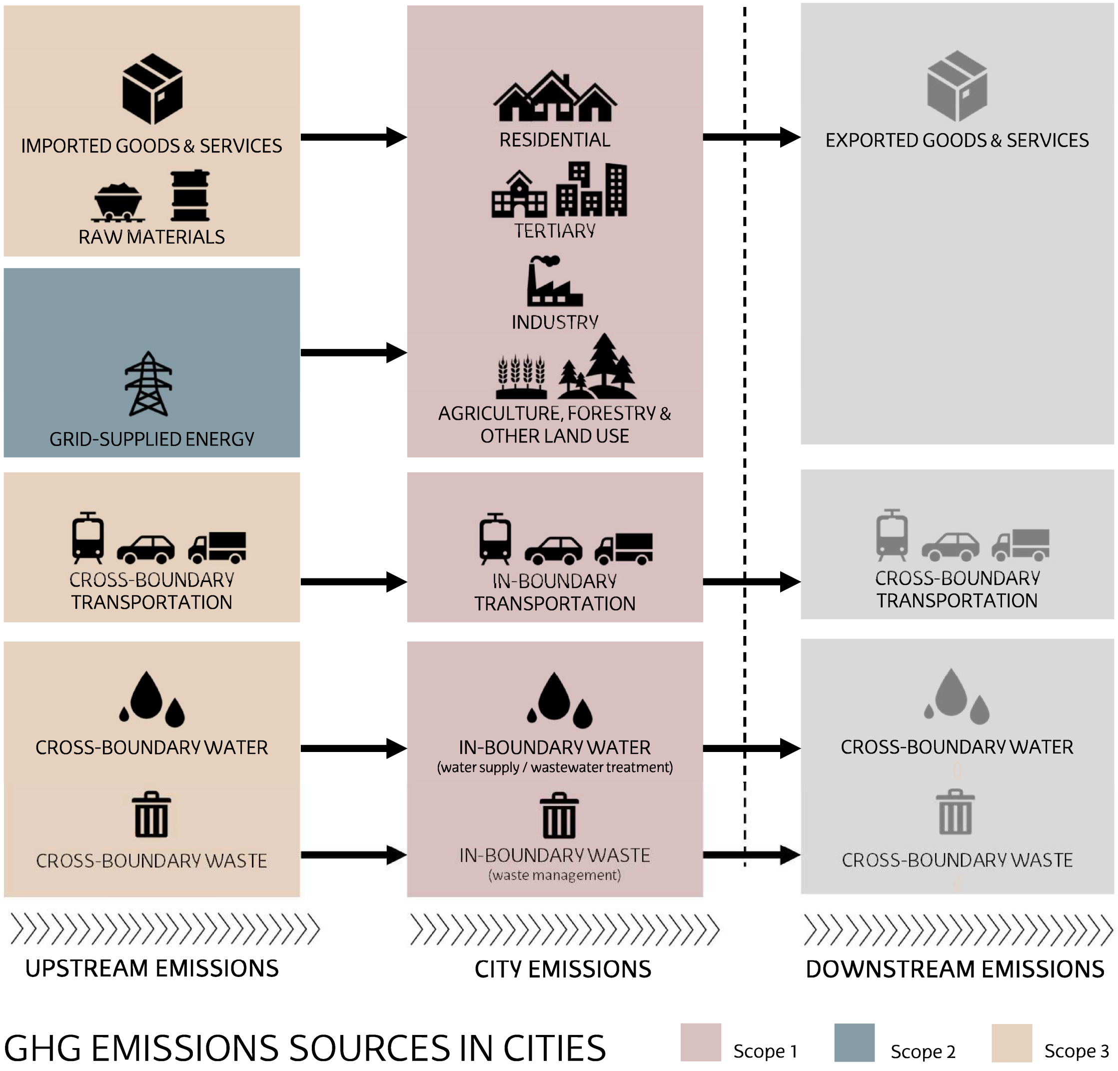

Figure 2.2. GHG emissions (and energy) scopes according to Greenhouse Gas Protocol (2014)

Growing literature is assessing the implications of considering different accounting approaches and scopes. Zhang et al. (2014) and Lin et al. (2017) assessed the differences when using a consumption-based approach versus a production-based one in the city of Beijing, whereas a report by the British

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[34] The simplest and most common production plus supply chain approach only includes scope 1 and scope 2 emissions.

Standards Institution (2014) compared the production plus supply chain perspective with the consumption-based approach when carrying out the GHG emissions inventory for the city of London. Harris et al. (2020) compared both production and consumption-based approaches for 10 European cities, noting that under a production-based approach cities energy consumption tended to decline in the future, while under a consumption perspective it slightly increased, thus reflecting the tertiarisation process in urban areas in developed countries. Meanwhile, Christis et al. (2019) evaluated the results from both approaches for the city of Brussels, concluding that "environmental impact of cities should not only be measured through the productive activities taking place on their territory, but through the combination of both their productive and consumption activities". To highlight the increasing relevance of embodied energy impact, Dias et al. (2014) performed an Environmentally-Extended IO analysis to estimate the direct and indirect GHG emissions and energy consumption associated with households consumption of goods and services of a Portuguese city, while G. Chen et al. (2017) and Baabou et al. (2017) developed Multi-Regional IO models to account for the impact of trade and imported goods in cities. Indeed, the former revealed that more than half of the carbon footprint of the Australian cities of Melbourne and Sidney was embodied in imports of goods and services, whereas the latter concluded that transport and food and manufactured goods consumption were the main contributors to the ecological footprint of the 19 Mediterranean cities assessed.

Another interesting remark regarding the differences in the emissions inventories depending on the chosen approach was highlighted by Dodman (2009) and Kennedy et al. (2012). The authors noticed that emissions per capita in cities were lower than their national counterparts as the former usually included emissions from agriculture, industry and intra-national mobility that are not accounted in local inventories. However, when embodied emissions (from food, services, and produced goods) were allocated to the cities, emissions per capita resulted to be similar at both national and local level. Moreover, Tong et al. (2018) and Wang et al. (2020) concluded that local authorities could act directly on emissions from scope 1, which may be considered as the mitigation potential under the capacity of the city. Although beyond the competences of the city, emissions from scopes 2 and 3 could lead to significant changes in the local GHG inventories if considered. On this concern, some studies remarked that the main reductions may be originated from factors outside the decision-making capacities of cities. Kennedy et al. (2012) and Azevedo and Leal (2021) stressed that most of the main reductions achieved at local level were related to the decarbonisation of the national electricity grids (scope 2), thus out of the range of the competences of municipalities. Reductions due to other factors like demographic and socioeconomic changes could also exceed the reductions achieved by the actions planned and carried out by local authorities (Azevedo and Leal, 2021; Messori et al., 2020). The effect of these impacts should be isolated when crediting cities for their achievements, so that the real contribution of cities to national/global goals is not blurred, overestimated, nor wrongly calculated.

2.3.3.2. *Urban energy characterisation*

The first step when developing an urban energy model is the energy characterisation of the city. That is, the elaboration of a baseline where the energy performance of the studied urban area is outlined, including the description of the demand and supply sectors as detailed as possible. The energy characterisation of the city is the basis to build energy scenarios on which to evaluate the deployment of different strategies and actions. On this concern, accurate and enough data is crucial to set-up the city model. Yazdanie and Orehounig (2021) listed the data requirements of urban energy models, including: demand side, supply side, technical performance, technology installation potentials, energy resource potentials, infrastructure, emissions, and microclimate and weather data. Martos et al. (2016) reviewed a list of the energy-related aspects which should be considered for city energy characterisation, and which included urban transport, buildings, RES integration, green areas, and water and waste management. Carreón and Worrell (2018) revised the urban energy flows and services which shaped the urban metabolism. Based on a GIS display, a method was developed by Fichera et al. (2016) to characterise the energy demand of three main city end-use sectors: buildings, transport and street lighting. Although focused on inventorying GHG emissions at urban level, Kennedy et al. (2010) assessed different methods for the energy characterisation of cities (especially regarding the accounting of electricity, heating and industrial fuels, and ground transportation). Chévez et al. (2019) presented a methodology for the energy diagnosis of cities, i.e. the construction of the energy baseline of cities. Whereas Pérez et al. (2019) proposed a methodology for the development of urban energy balances including cities final energy consumption of end-use sectors, cities local energy generation, and cities energy imports.

Concerning the energy characterisation of specific city end-use sectors, a review of the energy modelling of the building stock (including its energy characterisation and further energy scenarios modelling) has been already carried out in section 2.3.2. Amongst the works reviewed the following can be highlighted. Gargiulo et al. (2017), Fichera et al. (2016), and Marique et al. (2014) characterised the energy demand of buildings by combining cadastral data (such building type, floor area, construction date, or envelope characteristics) with socioeconomic and energy data from regional and local surveys. Regarding the data requirements for the energy characterisation task, Y. Chen et al. (2019) and Dall'o' et al. (2012) developed methodologies to define databases for urban buildings stocks, since data was usually disperse and hampered the correct characterisation of buildings energy use.

The energy characterisation of the transport sector is harder than the building one due to a higher spatial and temporal variability. Letnik et al. (2018) reviewed urban freight transport models and modelling techniques, also pointing out transport policies and measures implemented in European cities and subject to be modelled. Strulak-Wójcikiewicz and Lemke (2019) proposed a dynamic modular simulation framework for urban transport considering social, economic, and environmental dimensions. While bottom-up approaches were adopted by Gargiulo et al. (2017), Fichera et al. (2016), and Marique and Reiter (2012) to characterise urban transport energy consumption, based on the number of trips and on their characteristics (e.g. travel distance, vehicle undertaking the journey, and fuel consumption per vehicle). The three works included methods to generate the transport demand, i.e. the number and type (e.g. home-to-work or home-to school) of journeys that occurred between the different urban areas or neighbourhoods.

Regarding the characterisation of cities supply side, two aspects should be considered and described in the model: energy generation systems and distribution infrastructures. Modellers should be aware that no large-scale energy generation systems are usually located within urban borders, thus cities are generally net importers of electricity and fossil fuels, coming to them through different transport and distribution networks. However, small decentralised on-site generation systems can be present in some cases, fulfilling a share of the city energy requirements. On this concern the tools and methodological approaches reviewed by Allegrini et al. (2015) could be helpful with regard to the modelling of district-scale energy supply-side systems such district heating networks, renewable energy generation systems or storage technologies.

Some major difficulties which are faced in this first modelling stage should be noted. First, the definition of urban boundaries can reveal itself as a hard task. Determining which land extension should be considered as urban area can be difficult since the main city area can be surrounded by small towns and neighbourhoods which can form a bigger agglomeration. Hence, a choice must be done between administrative and physical limits. This decision lies normally on the local authorities which should make the call based on the scope of their action range. Related to the selection of boundaries, modellers should also decide how to account and allocate energy consumption (see section 2.3.3.1). Last but not least, one of the biggest issues when characterising urban energy use is data collection. Data introduced in the model should be as much detailed and accurate as possible. However, information at local scale can be hard to find, in occasions scattered and sometimes completely lacking. An intensive work is usually required to process the available information, sometimes adapting regional or national data to disaggregate or complete it. Modellers will probably be also forced to rely on assumptions (which must be documented and justified) to overcome the lack of data.

2.3.3.3. Urban energy scenarios

Besides portraying the current energy performance of the city as an integrated system, an urban energy model can be also used to generate scenarios in which future events are shaped and insights are provided on how the energy use in the city will evolve. Thus, just as the modelling of the city current situation allows to evaluate the opening state from which to start taking actions, the modelling of scenarios enables the assessment of alternative pathways the city can face, assisting energy planners and policymakers in making decisions based on the results issued from modelled futures. That is, decision-makers can choose amongst different scenarios aiming for the decarbonisation of the city and select the best suited to the local context. Scenarios can model the effect of socioeconomic and/or demographic phenomena taking place within the city, the impact of the deployment of certain technologies, the outcomes from the implementation of specific energy actions or policies, or a combination of the above. An infinite number of scenarios can therefore be built, some with a more conservative approach, others with a bolder scope, some focusing on one sector or another, or on the penetration of one technology or another.

Similarly to national or regional-scale energy scenarios, energy scenarios at city level are modelled by a combination of exogenous and endogenous elements and events such as the evolution of socioeconomic variables or the impact of implemented energy measures. That is, energy consumption is assumed to evolve as a function of demographic, economic and social developments as well as affected by the policies and interventions carried out by local authorities or other stakeholders (e.g. neighbourhood communities, bottom-up initiatives, private investors and others) within the city. To determine how energy use will unfold in the future is indeed one of the key challenges faced by modellers, who should be aware that urban future energy use will be ultimately influenced by:

- socioeconomic (e.g. city-specific GDP, sector gross value added (GVA), household income, or fuel prices) and demographic variables and other energy drivers (e.g. climate, urban structure, technological development: funding and learning curve rates);
- experienced past trends, actual situation and futures insights of the city (the latter to be discussed with local authorities and other urban stakeholders);
- local and national/regional energy-related plans and policies already committed: energy, environmental, socioeconomic and wellbeing targets to be reached by the city;
- specific energy interventions to be shaped: modellers may analyse the city proposed measures or even raise new ones.

Regarding energy drivers (see section 2.1.3), their identification and the determination of their causal relationship with energy consumption is a relevant task which may help understanding current energy use while also portraying its future evolution. Athanassiadis et al. (2017) studied a set of drivers to explain the energy use of ten cities. Carreón and Worrell (2018) also highlighted environmental, technological, economic, and social variables which explained cities energy use. Ürge-Vorsatz et al. (2015) and Copiello and Gabrielli (2017) assessed the influence of socioeconomic factors in the building sector. For the transport sector case, Zhao et al. (2017) evaluated the influence of different drivers for the transport sector energy consumption in China's cities. All in all, a wide variety of approaches, methodologies and mathematical models exist in order to model future energy use based on drivers, historical trends, or other parameters (see section 2.1.2). On this concern, regression and econometric methods have been broadly used to understand the causality of energy use by determining the influence of specific driving parameters on energy consumption (Copiello and Gabrielli, 2017; García-Gusano et al., 2018). These methods rely on data analysis[35] to establish causal relationships between drivers and energy consumption. The identification of these links can be difficult as both energy and socioeconomic datasets are usually incomplete at urban level (including historical datasets which are rarely available). Moreover, driver-energy consumption correlations found at country level may not be suitable at city scale. Modellers should consider the characteristics of the city in order to directly use or adapt country-level data to the urban scale. Finally, it is important to bear in mind that, since the relationships between driver and energy use are set based on historical data, these links are evidenced in the past but may not be proved in the future. Hence, it is the modeller's decision whether to keep the relationship in the future, or to partially or completely decouple energy use from the driver (this is especially relevant in transition periods where evidenced trends in the past may lose their significance).

Scenarios can therefore be separated into two groups depending on the modelled path: baseline[36] and alternative scenarios. The former contemplate a reference evolution of the system (e.g. keeping the evidenced trends and driver-energy use correlations in the past and without envisaging actions aimed at change), whereas the latter may explore alternate contexts (e.g. breaking up past tendencies, decoupling former driver-energy use relationships, or assuming events and interventions which imply changes in the evolution of future energy use). To assume a reference

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[35] Regarding data used in regression and econometric methods, this can be available as time series data (a sample of data for a single object at different time periods) (see corresponding works in the review carried out by Madlener et al. (2011)), cross-section data (a sample of data for multiple objects at the same time period) (see works by Athanassiadis et al. (2017) and Zhao et al. (2017)), or panel data (a sample of data for multiple objects at different time periods) (see work by Copiello and Gabrielli (2017)).

[36] Baseline scenarios can be further divided into Reference scenarios or scenarios WithOut Measures (WOM) (scenarios which do not contemplate any measure and keep the natural trend of the system), and Business as Usual (BaU) scenarios or scenarios With Existing Measures (WEM) (scenarios where the trend of the system is kept but measures already committed are included) (EEA, 2015; Strachan, 2011).

evolution of the system is necessary not only to be able to compare the alternative unfolding of the system with a baseline situation (in which the system may find itself at any given year), but as a benchmark from which to generate the alternate pathway itself. Whether using a forecasting or backcasting approach to model alternative scenarios, a reference evolution of the system (either growing, declining, or constant) must be considered. On this concern, the modelling assumptions of the baseline scenario are key as they will have an impact on the reach of the resulting alternative scenarios. Indeed, if it is assumed that the natural evolution of the system is to grow (i.e. increased energy use and emissions), more efforts in the alternative scenarios would be required to counteract this trend. Conversely, if it is assumed that the historical growth tendency of the system would be balanced or even offset by current technological shifts or expected actions (thus resulting on a steady or even decreasing trajectory), the reduction margin of the alternative scenarios would be narrower, while at the same time abatement targets might be achieved more easily (even more ambitious goals might be set) due to the consideration of a more favourable reference evolution. Essentially, the baseline scenario should be objective, avoiding being neither too conservative nor too optimistic. Moreover, it should account for the present context of the system and its effect on the evidenced past behaviour of the former.

Therefore, as a benchmark for the generation and evaluation of alternate futures, the decision of "what" to be included in the baseline scenario is crucial since depending on the policies and measures to be assessed in the alternative scenarios some factors should be accounted or not. As an example, the introduction of electric vehicles (EVs) and the renovation of buildings could be regarded as processes that in the future will be developed naturally or by means of policies already enacted, therefore these "trends" should be isolated from the more specific additional measures or policies to be modelled and evaluated in further scenarios. That is, only the impacts of additional measures should be assessed when comparing results from the baseline and alternative scenarios (Ürge-Vorsatz et al., 2016). The analysis would remain to determine to what extent the tendency of the system will be to persist on past trends or conversely to evolve towards technological and consumption patterns changes[37]. Alternative scenarios (sometimes called scenarios With Additional Measures (WAM)) can inherit driver-energy correlations from baseline scenarios albeit including more explorative views. In these scenarios different futures can be assumed and the impact of additional measures and policies assessed. In order to consider city alternative pathways (which may include changes in technological devices, in the behaviour of its inhabitants, or in the

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[37] On this concern, the value of using outdated hypotheses rather than updated contexts to develop baseline scenarios can be contested, especially in quick changing times. Moreover, the perpetuation of historical-based visions in baseline scenarios may favour the normalisation and preservation of the belief that the system is likely to keep on past trends. This may create the illusion that change is hard to achieve and may serve as a justification for the prorogation and even non-compliance of committed policies or actions (Grantham Institute, 2017; Nature Energy Editorial, 2017).

socioeconomic structure of the city) modellers should know the peculiarities of the city and the future vision of its inhabitants and local authorities to set-up accurate scenarios: how the energy is consumed and supplied in the city, is there any energy source available in the city, how has the city evolved in the last years, what the city future plans consist of, are there any preferences for a specific technology or policy, or are structural changes expected in the city, amongst other questions. As noted by Wang et al. (2015), a certain degree of uncertainty has to be dealt with in every scenario as modelling technological and behavioural changes is always difficult.

Using different energy models and approaches, different authors have proposed methods to develop energy scenarios at city level. Dagoumas (2014) elaborated a set of scenarios for the city of London following a top-down approach and using a macroeconomic model. On the other hand, following a bottom-up perspective, Reiter and Marique (2012) modelled building and transport consumptions and compared eight scenarios for the Belgian city of Liège. Combining GIS and simulation and optimisation models, Mohajeri et al. (2019) assessed the sustainable development of a Swiss village. By generating two scenarios (expansion and densification) the authors modelled the impacts of the future urban form in the heat, cooling, and electricity demand of the village, and optimised the integration of RES systems to cover these demands. Farzaneh et al. (2016) elaborated two energy scenarios (baseline and optimal scenarios) for the Indian city of Delhi. Based on a bottom-up structure and integrating different drivers, the authors projected the energy demand of the main city sectors (residential, commercial, and transport) in the first scenario while the electricity demand and supply were subsequently optimised under an economic perspective in the second. In a similar way, Jalil-Vega et al. (2020) modelled six scenarios for the city of Sao Paulo (Brazil) seeking to supply the energy demand of the city in the most cost-effective pathway under given constraints. Following the same optimisation approach, Noorollahi et al. (2017) modelled the supply side of a Japanese city seeking to diversify and maximise the renewable share in the city electricity supply, Samsatli and Samsatli (2018) optimised the operation of integrated heat and electricity networks in an eco-town in England, and Alhamwi et al. (2017) presented a GIS-based model seeking the optimisation and flexibilisation of urban electricity supply. Lastly, urban transport scenarios modelling future energy consumptions and associated pollutant emissions in that specific sector were developed by Shabbir and Ahmad (2010) for two Pakistani cities, and by Li and Yu (2019) for China's urban passenger transport sector. Both studies proposed different pathways to assess different transport policies and technological improvements. Meanwhile, Zhang et al. (2018) developed a top-down general equilibrium model to assess different transport scenarios.

2.3.3.4. Urban energy scenarios assessment

To integrate modelling results into urban energy planning, the assessment of the modelled scenarios must be carried out. Due to the diversity of possible energy futures (i.e. scenarios), each one of them containing different assumptions and criteria, Grunwald (2011) suggested that energy scenarios should be subject to an assessment of both their results and insights to effectively support decision-making. However, most studies assessing energy scenarios at urban scale simply compare the evolution through time of the energy use and associated emissions between different scenarios. One step ahead, optimisation models provide the best system configuration but only for a single magnitude (e.g. the TIMES modelling framework gives the least-cost supply system under certain restrictions to meet the energy demand). Hence, if a holistic analysis of the possible futures of the city wants to be carried out, an integrated evaluation should be made, and impacts from different dimensions like environmental, economic and social aspects should be assessed simultaneously. Ürge-Vorsatz et al. (2016) conducted a review of the impacts of low-carbon actions to be considered in a green economy context, pointing out different assessment methods and their challenges. Kilkis (2019) revised a set of indexes for benchmarking cities, also highlighting the importance of considering multiple dimensions concurrently when assessing the sustainability of urban energy systems. Sharifi (2020) reviewed different indicators and assessment methods for the evaluation of smart cities.

For each evaluated dimension clear indicators must be defined. Kuznecova et al. (2014) developed a set of indicators grouped in five dimensions (technical, social-economic, environmental, risk, governance) to assess the resilience of urban thermal energy metabolism. The EU Smart Cities Information System published a key performance indicators monitoring guide (SCIS, 2017) which could be used as a reference. Indicators should plainly reflect if the city targets are achieved or not, thus their selection and definition is a critical step. Some indicators can vary between different cities and differ from national or regional ones. Whenever possible, indicators should also try to account for externalities beyond the assessed direct impacts. As an example, Lawn and Clarke (2010) advocated for the GPI against GDP as an indicator for measuring wellbeing as it "accounts for a number of benefits and costs that normally escape market valuation".

Finally, when multiple dimensions have to be considered, weighting and prioritising them is necessary to choose between the proposed scenarios. Assessing the influence of one or another criteria should be conducted by local stakeholders who know best the city needs and capacities. Gargiulo et al. (2017) and Arrizabalaga (2017) used MCDA methods for the selection of scenarios as a basis for the elaboration of urban energy plans.

CHAPTER III: Methodology for the coordination of national and urban energy planning

Index CHAPTER III

3.1. Introduction

The Paris Agreement set the path to mitigate climate change and adapt to its effects. Through their Nationally Determined Contributions (NDCs), the signatory countries pledged to reduce their GHG emissions looking for reaching world carbon neutrality by mid-century. Together with this global commitment, the EU launched in 2019 its Green Deal (European Commission, 2019) seeking to decouple the European economy from energy and resource use and aiming to become carbon neutral by 2050. Under this framework, the EU has launched a set of climate actions to achieve these goals (cf. European Climate Law (European Commission, 2020a) and European Climate Pact (European Commission, 2020b)). In line with these, the Member States had to submit their National Energy and Climate Plans (NECP) for the period 2021-2030 (European Parliament, 2018) where, similarly to the NDCs regarding the Paris Agreement goals, each country must define its transition roadmap in accordance with the EU targets.

At lower scale, cities have also committed their efforts towards sustainable development. At EU level, the CoM has been gathering since 2008 those local governments which voluntarily have committed to achieve and even exceed the EU climate and energy targets, reducing their GHG emissions and ensuring access to secure, sustainable and affordable energy for all. In a similar way as for the countries and their NECPs, cities commit themselves to submit a SECAP which must serve as a roadmap to achieve the pledged goals. Since urban areas in the EU embody 75% of the total population of the region (UN Population Division, 2018), this initiative addresses a field which represents a large share of the region energy consumption. Globally, similar initiatives have also risen, gathering municipalities and other non-state actors which have pledged themselves to reduce their environmental impact (see section 1.2.1).

The decarbonisation of the world energy system is thus a challenge that involves actors across multiple levels (Pasimeni et al., 2014). In order to be effective, carried out actions should be coordinated among the several scales which integrate the whole system. Actors ranging from global to local levels should harmonise their planning frameworks and actions to align their roadmaps (Maya-Drysdale et al., 2020). Low-level strategies should be built in accordance with the upper ones to achieve major objectives.

This chapter evaluates the alignment of urban and national plans. The objective is to determine the part that cities should play in the implementation of national strategies by transposing national targets to the local level. In short, this analysis aims to provide insights on the alignment of local and national energy and climate strategies looking for the correct coordination of them and for the effective contribution of cities towards the fulfilment of upper climate goals.

3.2. Chapter main contributions and objectives

The increase in the recent years of national climate commitments to decarbonise the economy and accelerate the energy transition should be reflected and translated to local strategies so that the build-up of local targets could drive new projects and more ambitious measures at urban level, while achieving national targets too. However, the current lack of coordination between cities and higher instances is hindering the efforts towards the fulfilment of this assignment. Thus, the correct and coherent downscaling and adaptation of national policies into local strategies and plans is extremely relevant in order to structure an integrated and harmonised energy transition strategy. At the same time, this is a very challenging task due to local specificities, economic structures, and jurisdictional competences. Furthermore, no criteria is set in how cities should adopt national objectives.

The aim of this chapter is to overcome these issues by determining how to adequate measures from the national plan (which by reason of responsibility and competence fall under the scope of municipal stakeholders) to the urban level. To support the design of local strategies harmonised with upper ones a method is proposed based on the downscaling of national measures to the local level. Specific goals and actions are transposed and allocated to the city according to its characteristics and capacities. In addition, the analysis carried out in this chapter also targets the performance assessment of urban energy plans regarding their alignment with the national strategy by quantifying the degree of compliance of the local-implemented measures with the corresponding ones from the national plan.

Since most of key energy planning and policy-making is still decided at country level (Khan and Sovacool, 2016), the suggested downscaling approach will serve to accurately translate national strategic planning to a lower level and to establish local strategies aligned with upper goals. Moreover, Sperling et al. (2011) suggested that national governments should pass on responsibilities to cities, but coordinating and guiding them (by providing them with information and tools) in order to achieve a coherent national energy strategy which integrates the aligned energy actions of cities. The proposed method seeks to support this coordination and guidance.

Within the Thesis context, this chapter focus on the design of urban energy and climate targets, main pillars of any city energy plan. The transposition of specific energy measures from the national to the local level and their subsequent modelling at the city scale, allows to assess and quantify the reach of their impacts, thus supporting the establishment of realistic goals which should drive the city long-term energy planning (see Figure 1.7 and Table 1.1). The main objectives of this chapter can be summarised as follows:

- To assess how and to what extent energy efficiency and mitigation actions planned at urban level support the fulfilment of the national strategy.
- To determine the part to be played by urban areas in the implementation and achievement of national energy and climate strategies by proposing a method to downscale, adapt and allocate specific targets and energy measures from the national to the local scale.
- To support the update or development of new city energy and climate plans by effectively aligning the city plan with the national one, coordinating the decarbonisation efforts of both levels, and achieving the efficient contribution of urban areas towards higher climate targets.

3.3. Methodology

The evaluation of the effectiveness of climate governance at subnational level stills a field of further research (Hsu et al., 2020a). Indeed, few information is available on the accomplishment of urban climate targets, and the impact of mitigation actions at local scale remains uncertain or even non-evaluated (IPCC, 2014a). Literature on the assessment of cities and other subnational entities contribution towards global and national climate targets is fragmented (Bertoldi et al., 2018c) and opposing views can be found. On the one hand, some studies concluded that the implementation of climate-related actions by local and other subnational actors would slightly complement the reductions managed by national entities but would not be enough to reach the Paris Agreement goals (Erickson and Tempest, 2014; Roelfsema et al., 2018; Salvia et al., 2021). On the other hand, some authors suggested that efforts made by subnational entities would be in line with upper goals (Kona et al., 2018; Reckien et al., 2014), and may even overachieve national-set targets in some cases (Hsu et al., 2020b; Kuramochi et al., 2020).

The previous studies based their approach on the scale-up of low-level actions to estimate the impact of their net aggregation at national level. Hsu et al. (2020b), Kona et al. (2018), Reckien et al. (2014), and Salvia et al. (2021) focused on the aggregation of targets in local energy plans to evaluate if cities were on track to fulfil the goals set by their respective countries. (Kuramochi et al., 2020) aggregated the impact of commitments by Non State Actors (e.g. regions, cities and businesses) to quantify their emissions reduction potential, while Roelfsema et al. (2018) used an Integrated Assessment Model to evaluate the reduction potential of Transnational Emission Reduction Initiatives. Both studies estimated the overlap between these low-level initiatives and the national-driven measures. Ramaswami et al. (2017) developed a methodology to measure the effect of local actions toward China’s national mitigation target. This aggregation focus is however often incomplete as remarked by (Hsu et al., 2019). The authors highlighted the complexity of quantifying the impact of climate change mitigation actions carried out by subnational actors. They stated that the contribution of these players remained uncertain mainly due to disperse data, overlap issues, and the absence of methodologies to consistently account for this subnational scale contribution.

Conversely to these bottom-up methods, a top-down approach is here proposed: starting from the national level, a share of savings to be achieved by the city is allocated to it. That is, national targets are adapted and transferred downstream from the country to the local level. Not all the measures from national plans are or can be transposable to the local level. Local specificities and jurisdictional frameworks hamper the downscaling of certain measures. The proposed method targets the ones eligible at local level, i.e. measures from urban end-use sectors on which local stakeholders can act. Whereas some measures lie under the jurisdiction of national authorities (e.g. national power grid development), others are usually left to municipal responsibility. That is, national administrations may transfer a set of competences to local authorities in certain domains. Accompanied by funding, municipalities are then responsible for converting these grants into projects and specific measures at local level. Thus, energy and climate actions centred on fields out of municipal competences are not contemplated (e.g. industry, agriculture, inter-cities mobility, or national electricity system). Conversely, the methodology is focused on the transposition of measures which fall under the competence of local stakeholders such the energy efficiency measures in the building and intra-mobility fields.

The overall procedure of the methodology is described in Figure 3.1. On a first step, matching measures from both national and local plans are identified from the ones within local stakeholders competences. Secondly, these are downscaled and adapted to the local conditions through the use of different criteria. Third, the adjusted measures are modelled and finally their achieved savings compared with the estimated reductions presented in the energy plan of the city. This allows to quantify to what extent measures from the former comply with what is assigned to the city by the national plan. Hence pointing out urban planners if the city plan is in line with the national strategy, or whether it needs an overhaul.

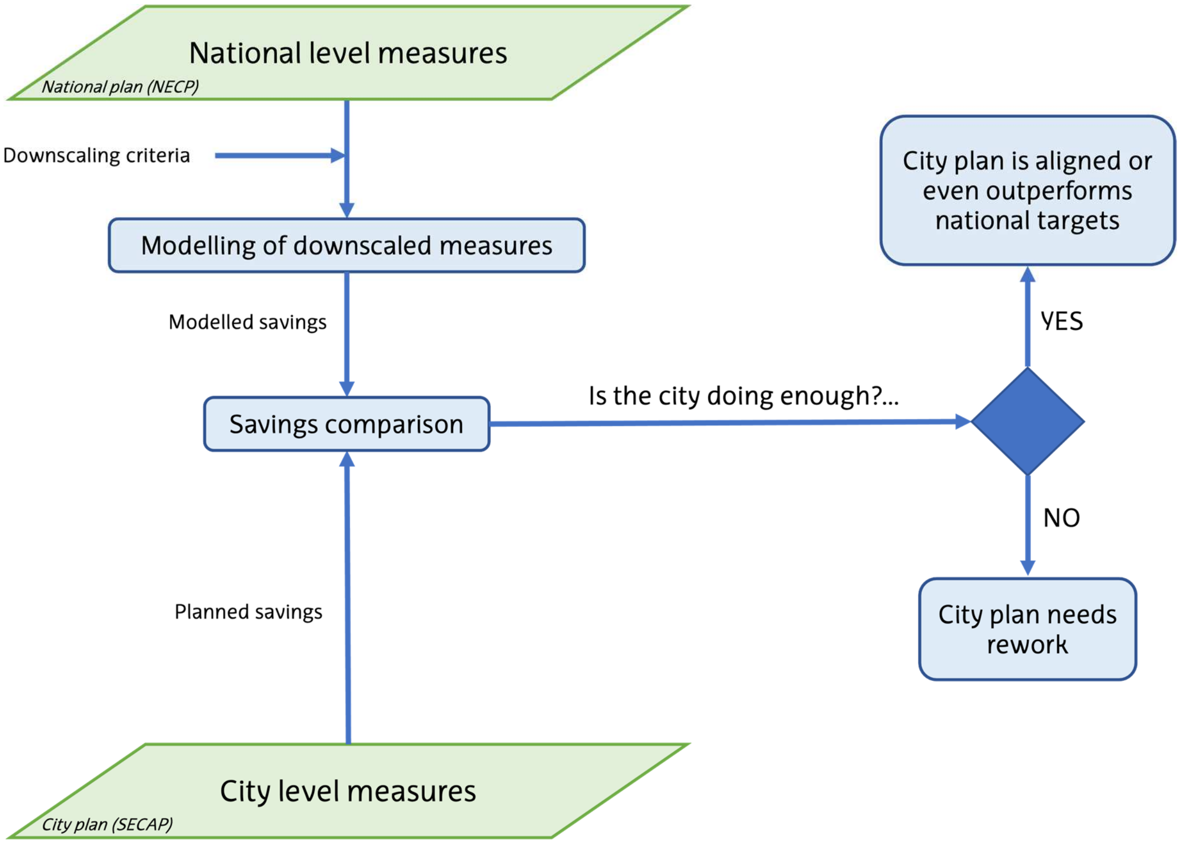

Figure 3.1. Methodological approach for the coordination of national and urban energy planning

The downscaling criteria used in this analysis relies on accessible data and the selected factors are coherent with the sectors in which they are applied. Their selection is based on specific indicators for each end-use sector (e.g. building or vehicle stock, and expenditures on home appliances) and which are usually available for both levels (national and local), thus making easy the replication of the method to other cities. Furthermore, the downscaling approach can be used not only to assess existing plans, but also to develop new local plans and set-up local goals in accordance with national ones.

3.4. Case study

The methodological approach described in section 3.3 is illustrated using the Spanish case of Valencia, which amongst the three most populated cities in the country (Madrid, Barcelona, Valencia), is the only one with updated 2030 mitigation goals. First, Spain's and Valencia's energy and climate plans are reviewed. Second, the considered measures in the analysis from both levels are explained. Finally, the downscaling and modelling of the assessed measures is described.

3.4.1. National and city energy and climate plans review

3.4.1.1. Spanish NECP

Framed on the national long-term strategies through which EU countries aim to comply with the Paris Agreement goals and the EU long-term strategy the Spanish NECP (Ministerio para la Transición Ecológica y el Reto Demográfico, 2020a) represent the roadmap in which the country define its energy strategy until 2030.Like the rest of the NECPs, the Spanish one is structured into five main dimensions. For each one of them, objectives and measures are included. The plan comprises a total of 78 measures. A description of the dimensions and their specific 2030 targets is shown in Table 3.1.

The plan was developed using the TIMES-SINERGIA model in combination with other macroeconomic, health, power system and environmental models. Two scenarios were created: trend and objective (corresponding to WEM and WAM scenarios respectively). The former creates a trend vision without new additional measures, whereas the latter includes the planned measures that lead to the fulfilment of the 2030 objectives. The plan includes the evaluation of the current situation and the projections for both scenarios, as well as the environmental and macroeconomic impact assessment of the planned measures.

Last but not least, the Spanish plan remarks the role to be played by national, regional, and local administrations. Sharing competences in several topics, the participation and coordination between the different levels is required to achieve the transition to a low-carbon society and the decarbonisation of urban areas.

Table 3.1. Description of the Spanish NECP dimensions and their associated targets

Dimension	Main goals	Specific targets	Number of included measures
Decarbonisation	- Decarbonisation and electrification of the end-use sectors - RES integration in both final energy consumption and power generation	23% reduction of GHG emissions compared to 1990	26
		42% use of RES in final energy consumption (31% in heat & cold sector and 28% in transport sector)	
		74% use of RES in power generation	
Energy efficiency	- Energy efficiency improvement - Long-term building renovation strategy - Energy efficiency in public buildings strategy	39,5% energy efficiency improvement compared to the EU PRIMES reference scenario 2007	17
		36.809 ktep total cumulated saving in final energy consumption in the 2021-2030 period	
Energy security	- Energy dependency reduction - Diversification of energy sources and supply - Preparation against possible limitations or interruptions in the energy sources supply - Flexibility increase of the national energy system	Reducing the energy dependency from 73% in 2017 to 61% by 2030	6
Internal energy market	- Electric interconnection improvement - RES integration in the national grid - Optimisation of the electric market - Strengthening of the gas market - National Strategy against Energy Poverty	Reaching a 15% interconnectivity by 2030	11
Research, innovation and competitiveness	- Development and funding of research and innovation programmes	Investments of at least 2,5% of the GDP in research and innovation programmes	18

3.4.1.2. Valencia SECAP

Located by the Mediterranean Sea and with a population of 800.215 inhabitants (2020), Valencia is Spain's third largest city. The city signed the CoM in 2009 and published its Sustainable Energy Action Plan (SEAP) for the period 2010-2020 the following year (Ajuntament de València, 2010). In 2015, the city renewed its commitments and launched its SECAP (Ajuntament de València, 2019) in 2019.

SECAPs are the result of the pledges of cities to the CoM initiative. This initiative fosters the development of urban energy planning by committing the partner cities to mitigate and adapt to climate change. Table 3.2 shows the 2030 objectives to which the city of Valencia has engaged itself, including the main commitment of the CoM signatory cities of reducing 40% their emissions by 2030 (with respect to the base year of their choice).

Table 3.2. Valencia's SECAP 2030 objectives

	Reference (2007)	**Objective (2030)**
40% reduction GHG emissions (kton $CO2_{eq}$)	2.684	1.610
27% energy savings (GWh)	9.698	7.079
27% RES in final energy consumption (GWh)	32	1.911

As determined by the CoM commitments, the SECAP includes a baseline emission inventory and a climate risk and vulnerability assessment. The plan includes 123 mitigation and 86 adaptation measures.

3.4.2. Measures downscaling

While most of the NECP measures fall under the competence of national authorities (e.g. energy supply security, national power grid development, or research and innovation programmes), some of them involve local responsibilities. These are the ones which have been the subject of the analysis.

From the 78 measures included in the Spanish plan, 7 have been extracted and matched with 14 corresponding measures from the city plan. The selected and compared measures have quantified targets, are directly transposable to the local level, and are applicable in end-use sectors (buildings and urban mobility) where local stakeholders have the capacity to act.

The downscaling of the national-level measures and their linkage with the city-level ones are further described in the sections 3.4.2.1, 3.4.2.2, and 3.4.2.3. While achieved savings from the downscaling of the NECP measures to the local level are compared with the estimated SECAP savings in section 3.5.

3.4.2.1. Residential buildings

To quantify the savings obtained through the downscaling of the measures at local level, the energy characterisation of Valencia's residential building stock has been performed combining a bottom-up approach with top-down data. Indeed, following a bottom-up perspective, the residential building stock of the city has been clustered by construction period and typology (i.e. housing blocks or single family houses) thanks to cadastral data supplied by the city. Moreover, different combinations of energy systems for space heating and DHW have been defined for each household typology based on regional statistical data (Instituto para la Diversificación y Ahorro de la Energía. IDAE, 2019). Table A.1 in appendix A shows the final disaggregation of Valencia's residential building stock. For each construction period and building typology, useful energy demands for every energy service in the residential sector have been considered based on the EU EPISCOPE-TABULA project (2020) (see Table A.2 in appendix A), along with efficiencies for each energy system (see Table A.3 in appendix A). Lastly, the distribution and efficiency data of space heating and DHW energy systems have been adjusted to match the actual final energy consumption reported in the city statistical yearbook (Ajuntament de València, 2018), which in turn has been disaggregated by energy service based on regional statistical data (Instituto para la Diversificación y Ahorro de la Energía. IDAE, 2011) Disaggregated residential sector final energy consumption is shown in Table A.4 in appendix A.

With the residential building stock characterised, residential sector building-related measures are downscaled and their implementation at city level modelled. Assessed measures from both national and local plans are displayed in Table 3.3, as well as their description and their national-local relationship.

Table 3.3. Residential sector assessed measures

NECP measure	NECP measure description	SECAP measure	SECAP measure description
2.6 Energy efficiency in existing buildings of the residential sector	Envelope renovation of 1.200.000 households by 2030 (from a considered package of 16.598.127 (Ministerio de Transportes Movilidad y Agenda Urbana, 2020))	M.d.5 Building envelope renovation	Renovation of the thermal insulation and enclosures in around 2% to 4% of the city dwellings
	Energy systems renovation in 3.000.000 households by 2030	M.d.9 Boilers renovation	Renovation of the thermal energy systems and diversification of the fuels used for heat applications in around 5% to 15% of the city dwellings
		M.d.10 Cooling equipment renovation	Replacement of the old cooling systems by more efficient ones in around 10% to 30% of the city dwellings
2.7 Renovation of the residential equipment	Substitution of 2.443.000 old devices annually	M.d.4 Appliances renovation	Replacement of the low-graded appliances by highly efficient ones in around 10% to 30% of the city dwellings

Measure "2.6 Energy efficiency in existing buildings of the residential sector"

This measure consists of two specific actions: the renovation of the dwellings envelope and the renovation of the energy systems for space heating, DHW, ventilation and cooling. The first step consisted in determining the number of renovated households and renovated energy systems which should be allocated to the city. This assignment has been performed based on the Spanish long-term energy renovation strategy in the residential sector (Ministerio de Transportes Movilidad y Agenda Urbana, 2020) (aligned with the Spanish NECP) which allocates the number of households (separating them by typology and construction period) to be renovated for every Spanish region. Thus, the number of main dwellings with space heating systems to be renovated within the Valencia's region has been identified. Based on statistical data from national (Ministerio de Transportes Movilidad y Agenda Urbana, 2019a) and regional (Portal Estadístico de la Generalitat Valenciana, 2020) databases, the specific number for the city has been extracted and is shown in Table 3.4. It should be noted that the national renovation strategy do not consider the households built after 2007 to be renovated. Also, in the case of Valencia's region, the renovation strategy neglects the housing blocks from 1981 to 2007, as it considers they are not a priority.

Table 3.4. Households to be renovated by 2030 in Valencia and Spain

	Construction period	Valencia	Spain
Single Family Houses (SFH)	‹1900	144	25.377
	1901-1940	299	40.973
	1941-1960	590	83.203
	1961-1980	834	167.067
	1981-2007	447	241.662
Housing Blocks (HB)	‹1900	275	9.094
	1901-1940	697	20.002
	1941-1960	1.705	73.345
	1961-1980	9.877	388.302
	1981-2007	0	151.054
	TOTAL	**14.868**	**1.200.079**

From Table 3.4 it can be found that households which renovate their envelope in Valencia represent 1,24% from the targeted national stock. The same percentage has been considered for the dwellings which should renovate their space heating and cooling energy systems. Thus, if 3.000.000 households are planned to replace their heat and cold energy systems at national level, 37.167 dwellings in Valencia should substitute theirs. It should be noted that households whose envelope is renovated are supposed to renovate their energy systems as well. Hence, from the 37.167 dwellings which renovate their energy systems, 22.299 replace only their systems without renovating their envelope. It has been also considered that the distribution of renovated energy systems among construction periods is the same as for the renovated households (see Table 3.4).

After the allocation of the measure to the city, its modelling at urban level has been carried out. Considering the deployment pace of the national strategy, the total number of households to be annually renovated is shown in Figure 3.2. The rate of energy systems renovation follows the same trend.

To calculate the energy savings achieved, it has been assumed that the envelope renovation entails a reduction in the space heating and cooling useful energy demands of the old dwellings that are renovated. Considering that, renovated households manage to reach the post-2007 dwellings standards (see Table A.2 in appendix A). Regarding heating systems renovation, old boilers and heaters are replaced by new condensing boilers and new heat pumps in a 30%/70% proportion respectively, thus assuming the partial electrification of heat demand. Improved efficiencies of the new energy systems are shown in Table A.3 in appendix A.

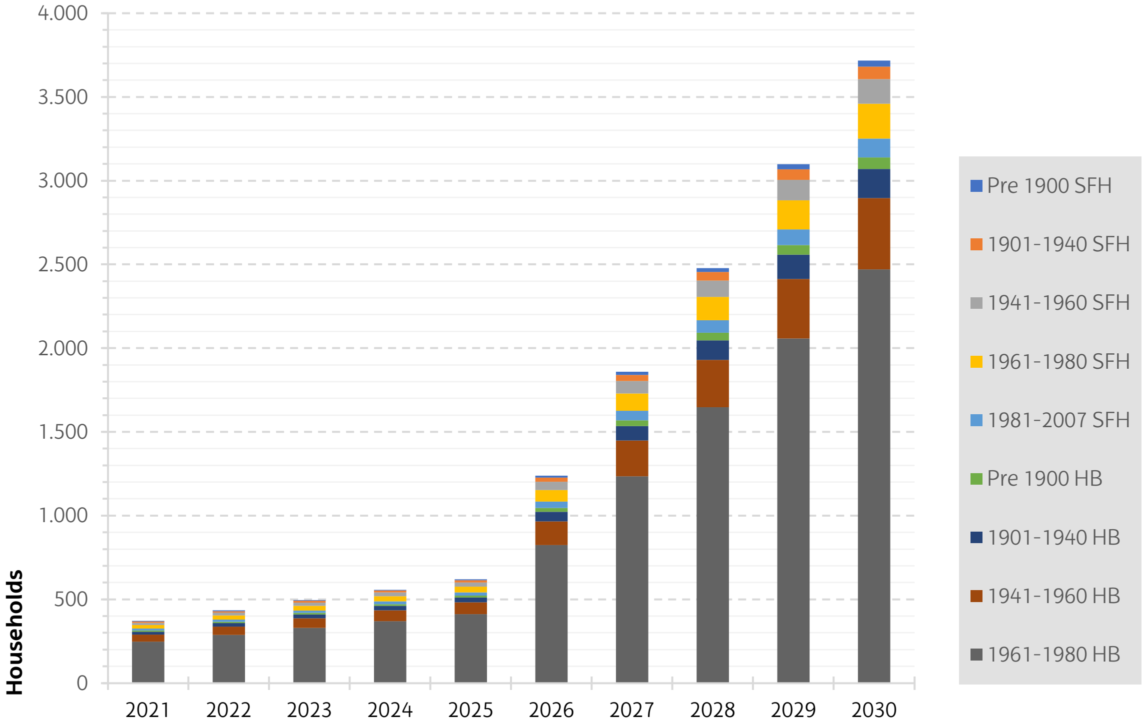

Figure 3.2. Households to be yearly renovated in Valencia

Measure "2.7 Renovation of the residential equipment"

This measure establishes the annual renovation of 2.443.000 home appliances like refrigerators, freezers, washing machines, dishwashers, dryers, and ovens at national level. This number has been downscaled at local level, and a number of devices to be yearly replaced have been allocated to the city.

Firstly, considering an average price for such devices (Organización de Consumidores y Usuarios, 2020), the total expenditure associated to this measure at country level has been estimated. Secondly, the average expenditure per person on home furnishings and appliances at both city and country level have been extracted from the city statistical yearbook (Ajuntament de València, 2018). Considering the respective populations, it has been estimated that 1,9% of these expenses at national level takes place in the city of Valencia. Thus, it has been determined that 45.771 devices should be annually replaced in the city. Table A.5 in appendix A shows the considered assumptions to calculate the achieved savings through the replacement of home appliances.

3.4.2.2. Private tertiary and municipal buildings

As for the residential sector, the energy characterisation of the tertiary building stock has been carried out. On the one hand, private and public services aggregated final energy consumption has been extracted from the city statistical yearbook (Ajuntament de València, 2018).On the other hand, the gross floor area of the city tertiary sector has been extracted from the latest cadastral data available (Ministerio de Hacienda y Función Pública, 2022). Regarding municipal buildings, their gross floor area has been issued again from city statistics (Ajuntament de València, 2018). Final energy consumption has been disaggregated by energy service using the European Commission and Joint Research Centre (2015) database. Final results are shown in Table A.6 in appendix A, while Table 3.5 summarises the assessed measures in the private tertiary and public buildings.

Table 3.5. Private tertiary and municipal buildings assessed measures

NECP measure	NECP measure description	SECAP measure	SECAP measure description
2.8 Energy efficiency in buildings of the tertiary sector	Yearly energy renovation of 3% of the public buildings gross floor area	M.a.13 Lighting renovation	Replacement of lighting devices in the concerned buildings
		M.a.14 Indoor lighting presence control	Installation of motion sensors in the concerned buildings
		M.a.15 Heat and cooling demand optimisation	Envelope renovation, energy systems renovation, management and control of the energy demand in the concerned buildings
	Yearly energy renovation of 5.000.000 m^2 gross floor area from tertiary buildings (both private and public)	M.e.7 Lighting renovation	Replacement of the old lighting bulbs by more efficient ones in the concerned buildings
		M.e.8 Building envelope renovation	Renovation of the thermal insulation and enclosures in the concerned buildings
		M.e.11 Boilers renovation	Renovation of the thermal energy systems and diversification of the fuels used for heat applications in the concerned buildings
		M.e.12 Cooling equipment renovation	Replacement of the old cooling systems by more efficient ones in the concerned buildings

Measure "2.8 Energy efficiency in buildings of the tertiary sector"

After the energy characterisation of the sector has been completed, a yearly amount of floor area to be renovated in the city has been allocated to Valencia. Comparing the number of tertiary buildings from both local (Ministerio de Hacienda y Función Pública, 2022) and national level (Instituto Nacional de Estadística, 2020) databases, it has been observed that 1,94% of Spain's tertiary buildings are located in Valencia. Accordingly, a proportional allocation of the floor area which should undergo an energy renovation has been assumed. Considering that the measure from the Spanish NECP establishes that 5.000.000 m^2 should be yearly renovated at national level, 1,94% of this floor area (96.978 m^2) has been assigned to the city. Moreover, it has been also considered that 3% of the municipal buildings gross floor area endure energy efficiency improvements. Hence, 42.317 m^2 of municipal public buildings and 54.661 m^2 of private tertiary buildings should sustain energy efficiency measures (comprising envelope renovation and energy systems and lighting renovation) every year in the city of Valencia according to the NECP measure downscaling. Table 3.6 shows the current city tertiary gross floor area and the total gross floor area to be renovated by 2030 in the city separated by municipal and private tertiary buildings.

Table 3.6. Municipal and private tertiary current gross floor area and gross floor area to be renovated by 2030 in Valencia

	Municipal buildings	Private tertiary buildings	TOTAL
Total gross floor area (m^2) (2018)	1.408.898	14.276.509	**15.685.407**
Total gross floor area to be renovated (m^2) (2030)	423.169	546.613	**969.782**

Regarding the modelling of the achieved savings in this sector, reductions shown in Table A.7 in appendix A have been considered. This table displays the energy savings achieved in the different tertiary buildings energy services thanks to the implementation of energy actions such envelope renovation, energy systems replacement and lighting renovation (Ministerio de Transportes Movilidad y Agenda Urbana, 2020). Achieved savings in the buildings of the sector have been calculated bearing in mind the yearly floor area that undergo energy efficiency measures and applying the estimated savings (see Table A.7) to the useful energy demands defined for each subsector and energy service (see Table A.6).

3.4.2.3. Transport

For the calculation of the energy savings achieved by the downscaling of NECP transport-related measures to the local level, LEAP energy modelling tool has been used (see description and rationale in section 2.1.2). LEAP features a transport analysis method which allows the computation of the final energy consumption of the transport sector based on the expected evolution of vehicles stock (current stock, vintage profile, and sales of road vehicles in the city have been issued from (DGT-Dirección General de Tráfico, 2020a)), average mileage (DGT-Dirección General de Tráfico, 2020b), and fuel economy (LIPASTO, 2020). Vehicle stock is calculated based on sales data and the decommissioning of old vehicles. That is, the stock of vehicles is made to evolve trough the retirement of old vehicles and their substitution by new ones. Table A.8 in appendix A shows the final disaggregation of the city vehicle stock and summarises the different assumptions, whereas Table 3.7 describes the transport sector assessed measures and their national-local linkage.

Table 3.7. Transport sector assessed measures

NECP measure	NECP measure description	SECAP measure	SECAP measure description
2.1 Low emissions zones and modal shifts	This measure includes: - 35% reduction of passenger-km in urban areas by 2030 (and 1.5% reduction annually in inter-urban commutes) through modal shifts - Establishment from 2023 onwards of delimited central areas with restricted access to the most emitting and polluting vehicles in all the Spanish cities with more than 50.000 inhabitants - Development of Sustainable Urban Mobility Plans and Travel to Work plans	M.f.5 Sustainable Urban Mobility Plan	Drafting and implementation of a Sustainable Urban Mobility Plan. (Includes actions such as walking and cycling promotion, regulation to the city centre, restrictions on polluting vehicles, public transport fostering)
		M.f.20 Travel to Work plans	Travel to work and freight transport routes optimisation
2.2 Efficient use of transport	Foster a more rational use of transport by optimising the freight transport and by promoting the shared mobility concept	M.c.2 Efficient driving courses for municipal and public transport services employees	Raising awareness amongst professional drivers and training them to save fuel by means of efficient driving techniques. Already tested courses in the city reached 14% saving in fuel consumption
		M.c.3 Speed controllers in public cars	Installation of speed controllers in the concerned municipal vehicles to limit speed
		M.c.8 Routes optimisation	Routes optimisation of public transport and municipal services vehicles. The plan estimates a 1%-3% travels reduction

2.3 Vehicle fleet renovation	Promotion of more efficient vehicles to achieve additional savings to those obtained by the natural renovation of the vehicle fleet	M.c.5 Public vehicle fleet renovation	Replacement of the old vehicles by new ones using electricity or biofuels
		M.c.9 Public transport fleet renovation	Replacement of the old vehicles by new EVs or using hybrid/natural gas technologies
		M.f.2 Private vehicle fleet renovation	Replacement of the old vehicles by new ones using electricity or biofuels. The plan estimates that between 10% and 30% of the private fleet will use alternative fuels by 2030
2.4 Electric vehicles fostering	Introduction of 5.000.000 EV by 2030	Measure implicitly considered in M.c.5, M.c.9, and M.f.2	

Addressing the same action field (transport needs reduction and modal shifts), NECP measures “2.1” and “2.2” have been downscaled, modelled, and compared with their corresponding SECAP measures jointly. The same approach has been adopted for the measures “2.3” and “2.4” (fleet renovation and electrification). Table 3.8 describes the specific modelling assumptions of the two assessed packages of measures which are developed next.

Table 3.8. Modelling assumptions of the two assessed packages of transport measures

	Measures 2.1 & 2.2	**Measures 2.3 & 2.4**
Stock evolution/renovation rate	- Stock renewal follows the historical trend.	- Stock renewal follows the historical trend.
Fuel economy	- Introduced new vehicles have improved fuel economy. - Fuel economy of all vehicles worsens as vehicles age.	- Introduced new vehicles have improved fuel economy. - Fuel economy of all vehicles worsens as vehicles age.
Mileage	- Distances travelled by all vehicles are reduced. - All vehicles drive less kms as they age.	- Distances travelled by all vehicles remain constant. - All vehicles drive less kms as they age.
Sales evolution	- Introduced new cars are predominantly fossil-fuelled with a shift from diesel to gasoline in line with the pattern of the recent past years. - Penetration of alternative fuel vehicles stays low.	- Penetration of new EVs is increased. Sales of fossil-fuelled vehicles are reduced to a very low level (especially in two wheels, light utility vehicles, and buses).

Measures "2.1 Low emission zones and modal shifts" and "2.2 Efficient use of transport"

Spain's NECP considers feasible to reduce traffic by 35% in urban environments by 2030. Similarly, 15% of interurban transit should decrease by 2030. Both reductions should be achieved through the establishment of Sustainable Urban Mobility Plans at local levels and Travel to Work plans, fostering the reduction of transport demand, modal shifts towards public transport and non-motorised means as walking or cycling, and optimising the journeys.

To assess the impacts of the adaptation of the national measures to the city scale, the mileage of the vehicles has been lowered to model the traffic reduction assumed by the national plan. In line with this one, a 35% reduction of all vehicles mileage has been established by 2030. This reduction is considered to affect the journeys which take place within the city boundaries. Aligned with the Spanish NECP too, and concerning the interurban trips, an additional 15% mileage reduction allocated to the distance travelled inside the city has been assumed. Moreover, starting from this baseline reduction, a modal shift has been considered assuming the modal changes estimated by the national plan. Table 3.9 displays the changes in mileages due to the transposition of the national transport-policies targets.

Table 3.9. Considered mileage changes in the downscaling of the NECP measures 2.1 and 2.2

Vehicle type	Urban traffic reduction	Interurban traffic reduction	Modal shift	Total mileage reduction by 2030
Cars	-35%	-15%	-5%	-55%
Two wheels	-35%	-15%	0%	-50%
Light utility vehicles	-35%	-15%	0%	-50%
Buses	-35%	-15%	+3%	-47%

The assumed reductions and shifts within the road vehicles mileage implicitly contemplate the transport demand decrease and the change towards other means of transport (e.g. walking, cycling, or rail transport). Additionally, a 10% efficiency improvement by 2030 is also taken into account representing the implementation of efficient driving techniques for professional drivers as stated in the national plan. This efficiency improvement is considered in light utility vehicles and buses.

Measure "2.3 Vehicle fleet renovation" and "2.4 Electric vehicle fostering"

The Spanish national plan underlines the role of the vehicle fleet renovation in the improvement of the energy efficiency in the transport sector. It is important to highlight that the NECP does not assume a faster or more aggressive rate of vehicle renovation but aims at a higher penetration of alternative-fuelled vehicles following the natural renewal of the fleet. The national plan focuses on the renovation of cars, two wheels, light utility vehicles, and buses and their substitution by more efficient and less pollutant ones (measure "2.3"). Alongside this natural renovation, the plan envisages the introduction of EVs replacing the old ones (measure "2.4"). Hence, additional savings to the natural fleet renovation are achieved through the introduction of more EVs, modelled via an increase of total sales of these vehicles as shown in Figure 3.3.

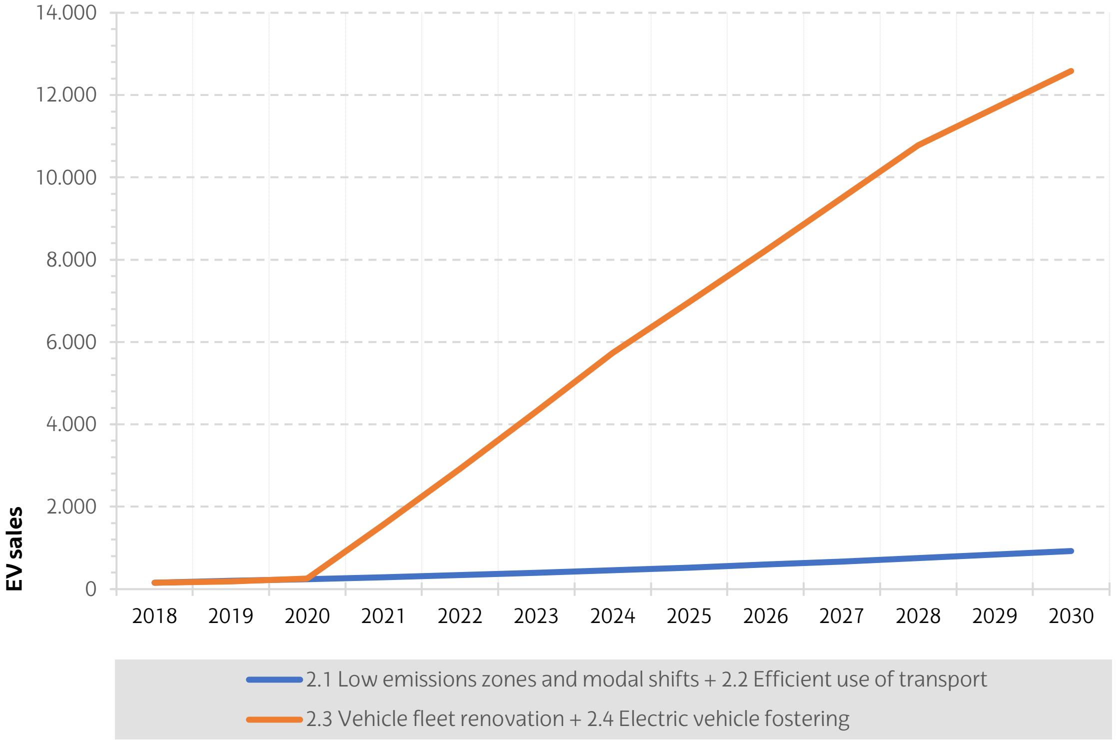

Figure 3.3. Comparison of EVs sales in the two modelled packages of transport measures

The number of EVs allocated to the city has been calculated as follows. The Spanish NECP plans the introduction of 3.000.000 electric cars and 2.000.000 electric two wheels, light utility vehicles, and buses by 2030. Following the national current stock distribution and the share of Valencia's vehicles over the national aggregate (DGT-Dirección General de Tráfico, 2020a), Table 3.10 shows the EVs to be introduced in Valencia by 2030.

Table 3.10. Number of EV to be introduced by 2030 in Valencia and Spain

Vehicle type	Share of Valencia's fleet over national fleet	2030 national EV vehicles objective	2030 EV vehicles allocated to Valencia
Cars	1,47%	3.000.000	44.052
Two wheels	1,79%	1.183.036	21.149
Light utility vehicles	0,97%	796.884	7.698
Buses	1,73%	20.080	348

3.5. Results and discussion

After modelling the downscaling of the Spanish NECP measures to the city of Valencia, results obtained by 2030 are compared with the savings expected by the city SECAP measures. Figure 3.4 shows the comparison results between the SECAP estimated savings and the downscaled modelled results from the NECP for the buildings-focused measures of both plans.

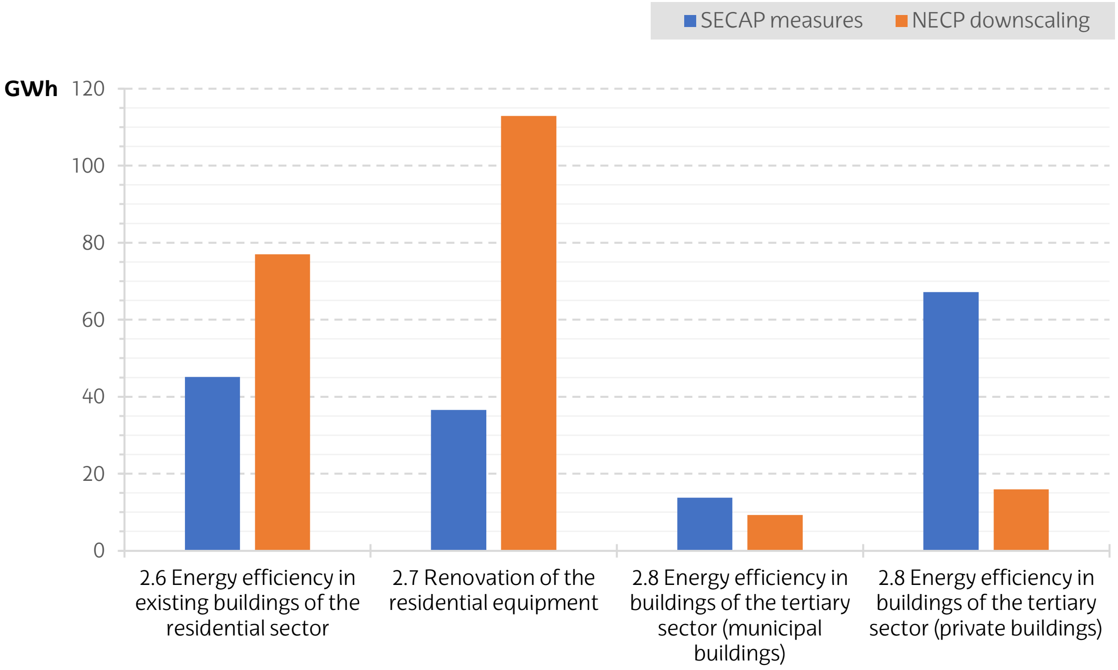

Figure 3.4. Comparison between the achieved savings (in final energy consumption) estimated by the city SECAP and the ones obtained from the downscaling of NECP measures for the residential and tertiary sectors

In the residential sector, SECAP measures associated to the NECP measure “2.6 Energy efficiency in existing buildings of the residential sector” report a total saving of 45.151 MWh in 2030 against the resulting 77.015 MWh from the NECP downscaling. In a similar way, SECAP only estimates a reduction of 35.637 MWh by 2030 as opposed to the 112.914 MWh obtained from the adaptation to Valencia of the NECP measure “2.7 Renovation of the residential equipment”. These results show that SECAP measures do not meet the targets set by the NECP downscaling for the residential sector.

Concerning tertiary buildings, SECAP measures estimate a total saving of 13.778 MWh by 2030 in public buildings, whereas the downscaling of the NECP measure “2.8 Energy efficiency in buildings of the tertiary sector” only yields a reduction of 9.319 MWh. Regarding private buildings, SECAP targets a total saving of 67.201 MWh by 2030, while the national plan only allocates a reduction of 15.969 MWh to the city.

These results show that the tertiary buildings energy reduction target allocated to the city by the national plan is considerably lower than the one estimated by the city plan. This means that either the city SECAP is highly ambitious or the adaptation of the NECP is too conservative. On this concern it should be remarked that the Spanish NECP only assumes that a considerably low 5% of the national gross floor area of the tertiary sector would sustain energy efficiency measures by 2030. As it can be extracted from Table 3.6, the downscaling of the measure results on a 6% of the tertiary gross floor area of the city to be renovated by 2030. Thus, the implementation of energy measures is carried out on a very small amount of floor area, therefore yielding low energy savings. On the other hand, it should also be noted the low traceability of the energy savings estimated by the city SECAP: neither the considerations for the savings estimation nor the number of buildings where the plan measures are implemented are detailed.

Figure 3.5 displays the comparison of results between the estimated savings by the city plan and those obtained from the downscaling of the national one for the transport measures taken from both plans.

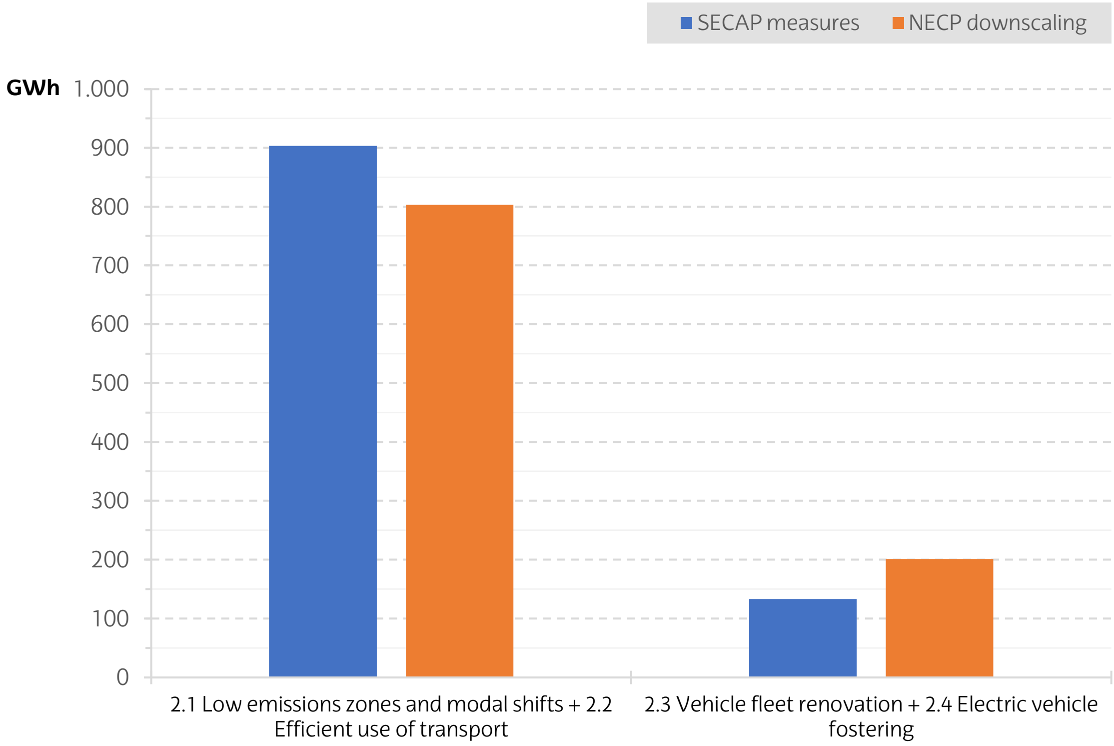

Figure 3.5. Comparison between the achieved savings (in final energy consumption) estimated by the city SECAP and the ones obtained from the downscaling of NECP measures for the transport sector

On the one hand, the downscaling of the Spanish NECP measures "2.1 Low emission zones and modal shifts" and "2.2 efficient use of transport" achieves a total saving of 803.194 MWh by 2030, while the corresponding measures of the SECAP estimate a reduction of 903.181 MWh. On the other hand, the SECAP only returns a reduction of 133.115 MWh by 2030 compared with the 201.001 MWh calculated through the adaptation of NECP measures "2.3 vehicle fleet renovation" and "2.4 Electric vehicle fostering" to the city level.

Regarding the differences obtained in the transport measures some remarks can be made. SECAP measures focusing on modal shifts return higher savings than the downscaling of the NECP measures, indicating that the local plan outperforms the reductions allocated by the national strategy to the city. Nevertheless, the considered SECAP measures such as the SUMP and Travel to Work plans do not detail the specific actions carried out within them nor how they achieve the resulting savings. This may warp the planned reductions. Concerning the renovation and electrification of the vehicle fleet, the SECAP intends to reach 1% to 3% EV by 2030, whereas the downscaling of the NECP measures achieves a 14% electrification of the city fleet (see Table 3.11). The SECAP assumes however the introduction of other type of vehicles (hybrids and biofuels) which have not been considered in the downscaling of the measures (as the national plan does not specify them) and that may explain the relative high compliance with the downscaled national measure despite the low electrification ratio of the city fleet planned by the local plan. As a summary, Table 3.11 displays in quantified specific actions the outperformances and shortcomings of the city SECAP with regard to the NECP.

Altogether, the results show that the city measures were not fully aligned with the national plan. Valencia should increase its efforts in the residential sector by raising the number of buildings to be renovated and appliances to be replaced. Similarly, the city should apply more aggressive actions to reach the number of EVs allocated by the national plan to it. Not aligned, but in a positive way, the city measures planned in the tertiary sector (and especially in private tertiary buildings) achieved higher savings than those allocated by the national plan. This effort could be however oriented to fulfil the fields where the city underscores.

Table 3.11. Specific actions comparison between SECAP measures and the downscaling of NECP measures to the local level

SECAP measure	NECP measure	Specific action	SECAP quantification	NECP transposition quantification	Downscaling criteria
M.d.5	2.6	Dwellings to renovate their envelope	2-4%	5%	Dwellings to be renovated according to (Ministerio de Transportes Movilidad y Agenda Urbana, 2020)
M.d.9		Dwellings to change heating/DHW energy system	5-15%	13%	Transposed from the dwellings to renovate their envelope
M.d.10		Dwellings to change cooling system	10-30%	13%	Transposed from the dwellings to renovate their envelope
M.d.4	2.7	Dwellings to change appliances	10-30%	42%	Average expenditure on home appliances
M.a.13 M.a.14 M.a.15	2.8	Tertiary floor area to renovate its envelope and energy systems (municipal)	Non specified	30%	City/country tertiary buildings ratio
M.e.7 M.e.8 M.e.11 M.e.12		Tertiary floor area to renovate its envelope and energy systems (private)	Non specified	4%	City/country tertiary buildings ratio
M.f.5 M.f.20	2.1	Traffic reduction	Non specified	-35% urban traffic (and -15% inter-urban traffic)	Directly transposed from NECP
M.c.2 M.c.3 M.c.8	2.2	Driving optimisation	Non specified	10% efficiency improvement	Directly transposed from NECP
M.c.5 M.c.9 M.f.2	2.4	Share of EV in city fleet by 2030	1-3%	14%	City/country vehicle fleets ratio

It should be noted that there is an uncertainty in the estimation of savings planned in Valencia's SECAP. Most of the measures contemplated in it rely on indirect actions (e.g. awareness campaigns, taxation policies, or subsidy programmes) whose impacts are hardly quantifiable. Moreover, with an action range limited to municipal assets, Valencia's SECAP relies on indirect tools to influence private stakeholders. Local policymakers should consider how to act upon fields out of their direct scope and define targets and measures in a clear and realistic way. Unachievable and meaningless actions should be avoided. Furthermore, the method to calculate the impacts of the actions of the city plan needs to be reviewed and fine-tuned to prevent oversized or hardly justifiable results.

Finally, it is important to discern the real impacts allocable to actions performed by local stakeholders so as not to not overestimate the results, nor wrongly assign targets to the cities. At this point, and focusing on electricity-related emissions, the decarbonisation of the national electricity supply by 2030 could be used to report larger reductions on CO2 emissions. However, these however should not be attributed to the city. To address this concern, an emission analysis has been carried out. The emissions reductions achieved by the assessed measures have been calculated. Considered emission factors for each fuel are indicated in Table D.1 in appendix D. In the special case of electricity, the local emission factor reported in the SECAP has been taken into account. Two cases have been evaluated, one with a constant electricity emission factor (EEF) (which is the case considered in the GHG emissions reductions planned within the city SECAP) and another one considering a variable EEF in line with the grid decarbonisation projected by the NECP. Figure 3.6 shows the emissions reductions achieved for the assessed measures.

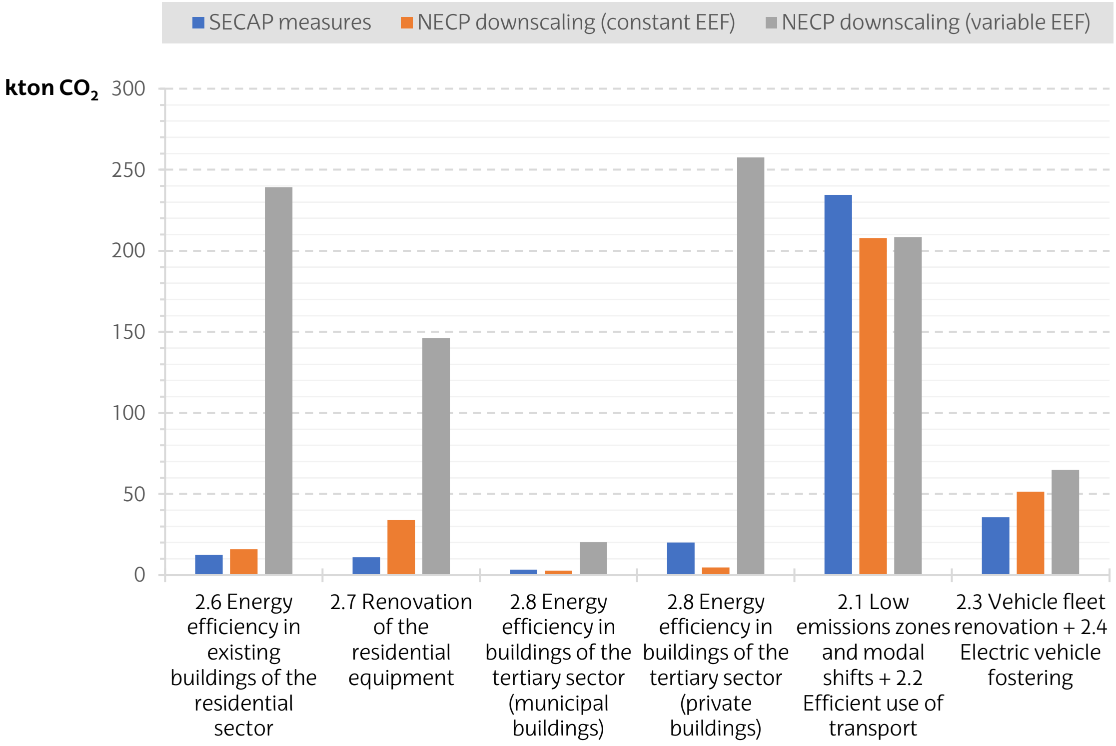

Figure 3.6. Achieved GHG emissions reductions of the assessed measures

On the one hand, when considering a constant EEF (orange), results are similar to the ones obtained in terms of energy. That is, the SECAP does not reach the emissions reductions allocated to the city in the residential and vehicle fleet electrification measures but outperforms the NECP in the tertiary buildings and mobility ones. This was expected as the assessment is focused on the comparison of achieved relative savings, and the same emission factors are used in both local and national levels. On the other hand, the assumption of a variable EEF in the downscaling of measures (grey) yields larger differences. If the impact of the expected reduction of the national EEF is considered in the transposition of measures at city level, the city SECAP (which considers a constant EEF) is far from reaching the allocated target for GHG savings, particularly in the building-related measures. Indeed, the differences whether considering a constant or variable EEF are greater in more electric-intensive sectors, indicating that bigger reductions are achieved in these sectors when a variable EEF is assumed. Conversely, the variation whether using or not a variable EEF is minimal in sectors with a low electricity use (e.g. transport).

The decarbonisation of the power grid is a nationwide decision which nevertheless has a local impact. Indeed, its consideration makes emissions abatements increase (especially in sectors involving a large electricity use). The evolution of the EEF needs therefore to be addressed carefully when developing local climate plans. A consistent and justified approach (constant or variable EEF) should be adopted when adapting upper targets to align local strategies with these higher goals. On the one hand, the selection of a variable EEF allows the city to accomplish its targets more easily (mainly through the electrification of its energy demand) but hinders its real achievements as it attributes to the city the reductions reached by the decarbonisation of the grid (out of the scope of local authorities). On the other hand, although the choice of a constant EEF may yield worse results, it clearly identifies the impacts due to the direct actions of the city. In other words, a variable EEF benefits high-electrified sectors and electrification measures, as further emissions savings are achieved without requiring energy use reductions[38]. On the contrary, the impact of electrification measures is not as high when a constant EEF is considered as the decarbonisation of the grid is not accounted. Indeed, a constant EEF allows to correctly assess the savings achieved by energy reduction measures (regardless of the sector and fuel mix) and which are truly allocable to the city efforts. Hence, cities should not exclusively hand over the fulfilment of their energy and climate targets to the decarbonisation of the national grid but achieve these goals through the harmonisation of different strategies such as energy demand reduction, energy efficiency, electrification, or RES exploitation.

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[38] On this concern it should be noted that, although achieving energy reductions through the greater performances of electric systems, electrification measures do not specifically target the reduction of energy services demand (e.g. reduction of heating useful energy demand, or decrease of transport need), thus not fully addressing the need of decreasing primary energy use.

3.6. Chapter conclusions

This chapter has presented an approach to assess the alignment of local and national energy and climate plans and to transpose national targets to local contexts. Through the downscaling and modelling of the national plan energy measures, the proposed method allocates a saving target to the city. Depending on the measure, different criteria are used. The assigned reductions are then compared with those estimated by the city energy and climate plan showing the extent to which the former complies with the saving targets set for the city by the national plan. This methodological approach could support the update or development of new city energy plans by effectively aligning and coordinating the city plan with the national one, achieving an efficient contribution of urban areas towards higher climate targets.

A case study was carried out downscaling seven measures from the Spanish NECP to the city of Valencia. These were then compared with the corresponding ones in the city SECAP. Results from this assessment have shown that the city plan does not meet the expected energy reductions (obtained through the downscaling of the national plan) for the measures concerning the residential sector and the electrification of the transport fleet. However, the former is more ambitious than the latter in the tertiary and transport modal shift related measures, yielding greater savings than the ones allocated to the city by the NECP.

The assessment of the SECAP measures has shown that the impact of these are sometimes difficult to verify either because they are actions not involving direct savings or because the calculation procedures or assumptions are poorly referenced or even opaque. A revision of the methods used for the estimation of SECAP measures would be needed. Further to this, energy modelling has revealed itself as a useful tool to estimate the achievable savings in a more accurate and traceable way, besides supporting the setting of feasible energy and climate goals aligned with higher ones.

In light of the results, the accurate transposition of national measures and their adaptation to local conditions is essential. Actions implemented at local level must be planned with a comprehensive approach and coordinated through the multiple levels in which the city is framed in order to be effective. The downscaling methodology presented in this chapter allows to allocate and distribute targets from the national to the urban level, while considering the local context and its specificities. When developing urban energy strategies, the setting of feasible local targets is key. These should be based on the correct adaptation of national measures to the local conditions and on the accurate estimation of obtainable savings at local level. The wrong transposition of measures and the wrong calculation of their impacts could lead to the establishment of reduction targets which may look easily reachable, but which are in fact unachievable at local level. Energy modelling may serve as a powerful instrument in the definition of feasible targets and strategies, and to accurately estimate the impacts of measures. At national level, NECPs base their goals and actions on the modelling of energy scenarios. At local scale, the development of urban energy scenarios would support the implementation of local energy plans. Drafted strategies can be accurately assessed and different pathways to comply with national targets can be explored.

CHAPTER IV: Integration of bottom-up data for modelling building stock energy scenarios

Index CHAPTER IV

4.1. Introduction

The transition towards a low-carbon society concerns different players from the current economic system. Amongst them, the building sector should play an important role in the decarbonisation challenge. Indeed, residential and tertiary buildings sum up to 30% of the world's total final energy consumption, being responsible of 9% of the CO_2 emissions (scope 1) according to the latest data from the IEA (2020). In the EU case, the whole building sector represents 40% of the region's total final energy consumption, causing 16% of the energy-related CO_2 emissions (European Commission, 2020c).

Therefore, objectives in the building sector involve the reduction and decarbonisation of its energy use. On this concern, the EU has developed a legislative framework (European Commission, 2018, 2012, 2010) to achieve an energy efficient and decarbonised stock by 2050. Each Member State must transpose into their national laws and building codes these directives which include measures such the establishment of long-term renovation strategies, the revision of energy requirements for new and renovated buildings, the prerequisite of energy performance certificates (EPC) when selling or renting a dwelling, or the obligation of the nearly zero-energy building condition for all new buildings from 2021 onwards. Regarding the renovation of buildings, the EU launched a specific framework within its Green Deal, the Renovation Wave (European Commission, 2020d), which seeks to double energy renovation rates in the next ten years.

To support the elaboration and implementation of these policies, building energy modelling reveals itself as a powerful tool to assess the impact of different energy strategies and measures applied in the sector. Building energy models can generate valuable information which allows policymakers to better understand the current energy use of the building stock while also providing insights on its future energy consumption. Hence, these models are key tools assisting the decision-making and urban energy planning processes. The development of an accurate building stock energy model is nevertheless challenging as it faces some difficulties such as the limited data at city level, or the performance gap.

This chapter enlarges the approach used for the characterisation and modelling of energy measures in residential buildings in the previous chapter (see section 3.4.2.1) and presents a novel methodology to shape the energy performance of the building stock of cities. Using only available data from accessible sources, the whole stock of the city is characterised in detail. This complete description is the basis to model the impact of different energy strategies implemented in the building sector, aiming to assist policymakers in the decision-making and energy planning processes. The proposed methodology seeks to simplify the building energy modelling process by relying on a straightforward method which uses plain data and avoids complex modelling techniques. The followed approach combines bottom-up data with aggregated top-down data reported by the city, overcoming the performance gap issue. At this regard, the presented method makes use of current consumption data intending to quantify the deviation between modelled and actual energy use. Moreover, through the integration of the current city energy consumption and low-scale data (i.e cadastral and building-related data), a highly disaggregated and accurate energy model of the whole city building stock is obtained while preserving the real energy consumption reported by the city. Thus, not having to rely on theoretical calculations (which may not take into account behavioural and socioeconomic factors, nor consumption patterns) to represent the actual energy use of the building sector.

4.2. Chapter main contributions and objectives

As stated by Hong et al. (2020), when modelling the energy performance of a whole city building stock, the integration of urban datasets and building energy modelling tools is key to correctly portray the bidirectional energy and environmental effects between buildings and the urban environment. One of the major challenges to accurately depict these interactions is the definition of a reliable building stock energy model (Reinhart and Cerezo Davila, 2016). Following a bottom-up physics-based approach, several authors have clustered the building stock of a city through the definition of archetypes which are then scale-up to represent the energy use of the whole sector at city level (Fernandez et al., 2020; Kim et al., 2019; Schiefelbein et al., 2019; Torabi Moghadam et al., 2018; Uidhir et al., 2020). A building archetype represents a group of buildings with similar properties (Abbasabadi and Mehdi Ashayeri, 2019; Reinhart and Cerezo Davila, 2016). Modelling of these archetypes is based on theoretical simulations which usually do not incorporate behavioural, occupancy, or socioeconomic aspects, thus incurring in a performance gap. Moreover, archetypes-based building energy models should avoid to directly extrapolate individual buildings energy performances to the whole building stock of the city (Hong et al., 2020), otherwise they often fail to capture actual urban environment effects (Abbasabadi and Mehdi Ashayeri, 2019). An inaccurate estimation of the energy consumption made by the city building stock has an impact on the urban energy planning process, as the modelled baseline is not adjusted to the reality of the city. To tackle this deviation, the use of measured data (Reinhart and Cerezo Davila, 2016) or the adoption of data-driven approaches (Abbasabadi and Mehdi Ashayeri, 2019; Bourdeau et al., 2019) has been indicated as a solution that implicitly includes user behaviour and which would serve to reduce the performance gap.

Considering this, the main objective of this chapter is to propose a method for the development of a building stock energy model at whole city level. This model should be accurate enough in its baseline construction and straightforward in the energy scenarios generation process, so that it would efficiently support urban energy planning. The proposed methodology starts from a bottom-up approach and seeks to simplify the modelling process by only using cadastral data usually available within the city. Moreover, it integrates a top-down perspective by considering reported real energy consumption data, thus implicitly considering factors such consumption patterns or socioeconomic effects in the energy use of the building sector.

A preliminary analysis is carried out, where results issued from a bottom-up building energy GIS based model are compared with actual energy use reported by the city energy facility. This contrast aims to quantify the difference between actual and theoretical energy consumption values and to determine how some particular parameters cause this gap. To this purpose, the obtained deviation is assessed with a set of socioeconomic and buildings characteristics data. It should be noted that this analysis may also support the identification of critical buildings on which actions are required either because current energy consumption is higher than the theoretical one (e.g. inefficient buildings or where an inefficient energy use is made) or because less energy than indicated is consumed (e.g. households in energy poverty situation).

Regarding the main target of the chapter, the proposed method to model the energy use of a city building stock combines top-down and bottom-up data and overcomes the prediction gap. Low-scale data is used for the clustering of the building stock floor area by activity (e.g. residential, offices, education, health, commerce...), construction period, and heating system. Whereas the aggregated city-level energy use data is employed to obtain the useful energy required by every energy service (i.e. space heating, DHW, cooking, cooling, lighting, appliances) in those buildings. This approach allows the comprehensive disaggregation of the building sector final energy consumption by activity and energy service, while matching the actual energy use of the city building stock. This will ensure that modelled actions in future energy scenarios will start from an adjusted starting point, hence their impacts will be estimated in a more accurate way, avoiding misleading and skewed results. Altogether, the integration of bottom-up and top-down data for modelling the building stock of a city is aimed at the elaboration of an accurate and detailed energy diagnosis of the city that will correctly support the generation of urban energy strategies at city level.

The methodology outlined in this chapter is integrated within the urban energy planning and modelling framework of this Thesis as a specific module addressing one of the main final energy users of the urban energy system: the building sector. Indeed, results from the energy modelling of the former provide urban energy planning with valuable information (in the form of prospective analysis and assessment of building-related energy measures) which should support decision-making (see Figure 1.7 and Table 1.1). The main objectives of this chapter can be summarised as follows:

- To integrate bottom-up and top-down approaches in the energy modelling of the building stock, combining cadastral and other low-level data with upper-level aggregated data, to represent building energy use at city level.
- To understand the energy performance of the building stock of cities and to identify the causes of the energy performance gap between actual and modelled energy use.
- To establish an accurate energy diagnosis of the building stock of the city from which to outline energy measures and policies.

4.3. Methodology

4.3.1. Performance gap analysis

This analysis will focus on the quantification of the performance gap[39] in the residential sector and on the identification of the factors that cause it. As in Nouvel et al. (2015), a comparison by ZIP code is carried out between the city natural gas metered consumption and the modelled results from a physics-based building stock energy model. Differences are then compared with socioeconomic data available by ZIP code so that the performance of the model can be assessed by determining how specific factors affect its results.

The physics-based building stock energy modelling tool ENERKAD (see description and rationale in section 2.1.2) is used to model the energy performance of the city building stock. Indeed, this tool has been chosen for the analysis as it simulates the energy performance of every single building in the stock (Brute force approach. See Table 2.7). This allows to accurately consider the specific characteristics of buildings in a particular ZIP code, instead of relying on archetypes or building samples which may not be representative in that specific city area.

ENERKAD results however, are obtained using theoretical values and based on normalised conditions, which may contain potential deviations with respect the actual use of energy. This fact reinforces the need to integrate real consumption data to model the energy performance of the city building stock. This is carried out in the second part of the study with the proposal of a methodological approach for the development of a building stock energy model which combines a bottom-up perspective with top-down data.

4.3.2. Methodology for the development of a building stock energy model: integration of top-down and bottom-up data and modelling of building stock scenarios

This section describes the proposed methodological approach for the development of a building stock energy model which integrates top-down and bottom-up data. The methodology includes the procedure for the characterisation of the baseline situation and the method to generate building stock energy scenarios.

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[39] A review of the performance gap is carried out in section 2.3.2.2.

The objective is to model the current and future final energy consumption of the building stock of a city starting from the use of basic cadastral information (to cluster the city floor area) and actual energy consumption data to characterise the city baseline. To avoid the performance gap, useful energy providing the different energy services is calculated to match the current energy use of the building stock based on the present distribution of the city floor space (i.e. disaggregated by activity, construction period and heating system) and on the reported energy consumption. Accordingly, useful energy demand is not estimated through theoretical-based calculations but is based on actual energy use. This overcomes the fact that theoretical estimations usually fail at capturing real user consumption patterns and occupancy, since all these factors would be implicitly included in the metered actual energy use. Once the present energy situation of the city building stock is detailed, scenarios can be generated by simply acting upon the floor area allotment. Figure 4.1 resumes the methodological approach which is explained next.

Instead of considering buildings technical parameters like geometry, envelope properties (e.g. thermal transmittance), equipment use, climate data, internal gains, and occupancy schedules, the proposed methodology is founded on basic cadastral information to model the energy consumption of the city building stock. That is, it does not require detailed building-related data, but only uses floor area as main input. Rather than estimating the consumption in a set of building archetypes and extrapolating the results to the entire stock, the final energy use of the building sector is calculated directly as a whole combining real consumption data and the city-built floor space separated by use, age, and heating system. This achieves a full adjustment to the actual data while keeping a high level of detail.

Besides the lesser amount of data required, another main advantage of the proposed approach is the accuracy improvement in the definition of useful floor area by directly using cadastral data. Indeed, area reported in the cadastre refers exclusively to building floor spaces susceptible to a relevant energy use and separates the ones that may not be heated such as garages, storage rooms, landings, or common corridors. This approach also avoids issues which may appear in buildings with mixed uses (e.g. residential building with a commercial premise on the ground floor and/or an office on another storey of the building), since for each activity, energy consumption will not be modelled based on the whole building floor space (like in archetype based-models), but on the specific area corresponding to each specific activity. On this concern, since the whole building does not have to be modelled, uncertainty is reduced as no additional inputs likely to introduce error in the model are required: no additional geometry data is needed to calculate the building gross floor area, nor assumptions required to define its useful floor space.

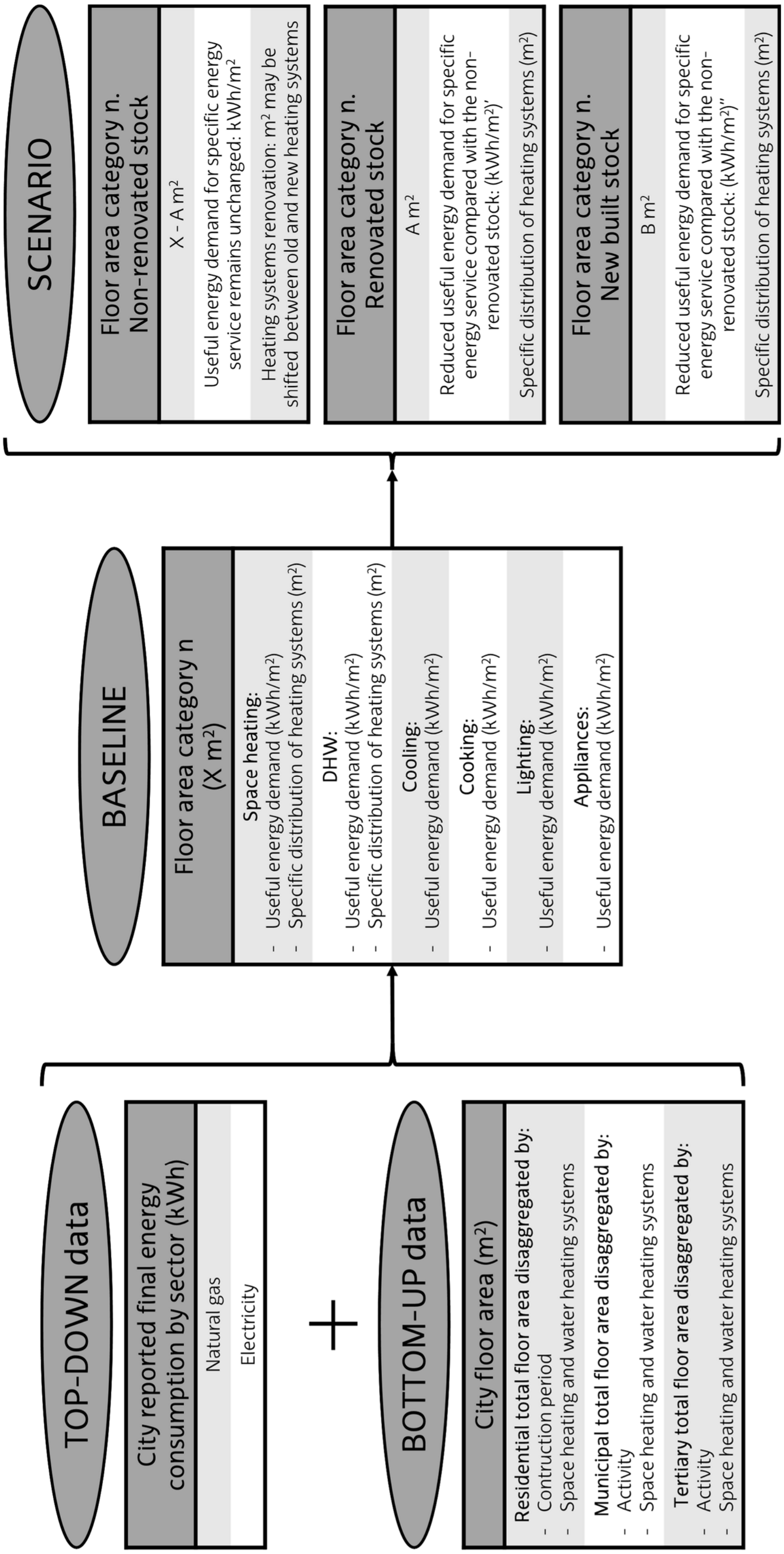

Figure 4.1. Methodological approach for the modelling of building stock energy scenarios

On the one hand, the city building stock floor area is disaggregated by age and activity using cadastral data. To further allot the city building stock floor space amongst different heating supply systems, cadastral information is complemented with heating systems inventories, municipal reported data and building EPCs. These may be estimated based on different calculation techniques and may contain valuable data which can be extracted and used for different purposes such as building stock energy modelling (Hjortling et al., 2017; Pasichnyi et al., 2019; Semple and Jenkins, 2020). However as remarked by several authors, these should be handled with care when estimating the energy demand in buildings as they might present data inconsistencies (Iribar et al., 2021; Las-Heras-Casas et al., 2018), and usually overestimate or underestimate the actual energy demand of buildings (Fernandez et al., 2020; Iribar et al., 2021; Majcen et al., 2013; Oliveira Panão and Brito, 2018). Hence, the proposed method relies on these certificates only to retrieve the information related to buildings heating systems. The processing of all this data allows to cluster the whole city building floor area by activity, construction period (in the residential sector case) and heating supply system.

On the other hand, useful energy requirements for every energy service are adjusted to match actual energy use. Indeed, reported city final energy consumption is combined with the disaggregated city floor area to calculate useful energy for heating, cooling, and other energy services in each activity within the city building stock. Regarding heating needs (space and water), these are calculated thanks to the floor area clustered by heating system. Considering the actual consumption of the main fuel used for heating, and given the floor area supplied by this fuel, specific space heating and DHW useful energy demands per floor area unit (i.e. kWh/m^2) are defined[40] for each activity. These adjusted specific useful energy demands are further assumed for the whole floor area stock (of the given activity) and used to obtain the final energy consumption of other fuels used for heating services. The same strategy is used for estimating cooling, lighting, and appliances useful energy demands using the actual electricity consumption. This approach allows to disaggregate the whole city energy use by floor area activity, energy service, and fuel.

The detailed characterisation of the final energy consumption in the building sector is thus achieved. Indeed, each m^2 of the city building stock is characterised by a specific useful energy demand (depending on the activity given to this floor area) and assigned to a specific heating system (itself characterised by a fuel and by an efficiency), thus making possible to obtain the final energy consumption of the different fuels used for heating services. Similarly, the floor area disaggregation also allows to detail the energy used for other energy services (such as cooling, lighting, and appliances) within the different activities in the building sector. This baseline diagnosis serve as reference starting point for the set-up of energy scenarios. Impacts from the deployment of energy

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[40] To convert final energy consumption into useful energy, specific efficiencies are assumed for each heating, cooling, or other energy service technology.

conservation measures (ECM) and other energy efficiency strategies can be modelled by shifting areas between the floor area categories and heating supply technologies classification. Besides the current stock of buildings, renovated and new buildings with improved useful energy demands are also defined for each building category, while enhanced efficiencies for new heating technologies are considered. When a determined area of a particular building category is renovated, this floor space amount is transferred from the current stock to the renovated stock of this specific category. Thus, savings are achieved by shifting specific amounts of floor space from a stock to another with lesser useful energy requirements. Similarly, some buildings may have their heating systems changed or upgraded. In each building category, a certain sum of heated floor area supplied by inefficient or old heating systems can find such technologies replaced by newer ones (with better efficiencies), thus reducing the energy use of this particular building category.

As for the characterisation of the current building stock energy use, the proposed methodology does not rely on building archetypes nor statistical methods to model the future energy use of the building stock model. Impact of ECMs are not based on the scale-up of savings achieved in a technical-detailed single-modelled building (e.g. thermal transmittance improvements modelled in a set of building archetypes) nor on complex mathematical or algorithmic relationships (e.g. regression analysis), but estimated in a straightforward way by shifting the disaggregated (by building category and heating system) city building stock floor area. Scenarios are therefore developed, and their impacts calculated, without relying on complex tools nor methods and without requiring extensive data.

4.4. Case study and Results discussion

To validate the proposed methodology, a case study is carried out in the Spanish city of Bilbao. Located in the North of the country, Bilbao is, with almost 350.000 inhabitants, the tenth largest city of Spain. Lying on the coast of the Cantabrian Sea, the city benefits from a mild climate, thus not requiring high heating nor cooling needs.

4.4.1. Bottom-up data pre-processing

The proposed method for the development of a building stock energy model bases the characterisation of the current city energy use and the generation of scenarios on the integration of a bottom-up perspective with current top-down consumption data. Concerning the former, this refers to the clustering of the city building sector floor area by activity and heating system. The processing of this data is a key aspect in the methodology and will be used in both the performance gap analysis and in the development of the building stock energy model of Bilbao.

Table 4.1. Floor area categories defined for Bilbao building stock

Sector	Activity	
Residential	RHB1900	Pre 1900 Housing Blocks
	RHB1940	1901-1940 Housing Blocks
	RHB1960	1941-1960 Housing Blocks
	RHB1980	1961-1980 Housing Blocks
	RHB2007	1981-2007 Housing Blocks
	RHB2018	Post 2007 Housing Blocks
	RSF2018	Existing Single Family houses
Municipal	MUNEDUC	Municipal Educational floor area
	MUNSPRT	Municipal Sport floor area
	MUNADMI	Municipal office and administrative floor area
	MUNOTHR	Other Municipal floor area
	MUNAZKN	Municipal multi-purpose building area
Tertiary	TERCOMM	Tertiary Commercial floor area
	TEROFFI	Tertiary Office floor area
	TEREDUC	Tertiary Educational floor area
	TERLODG	Tertiary Lodging floor area
	TEROTHR	Other Tertiary floor area
	TERHLTH	Tertiary Health floor area

Basic floor area information is issued from the regional cadastre (Diputación Foral de Bizkaia, 2022). This makes possible to disaggregate the whole city building floor area by activity. In the case of residential buildings, floor space has been also separated by construction period. It should be noted that the cadastre considers 13 uses (including other floor areas such as garages, storage rooms, or plot lands) which have been rearranged as convenient depending on the energy consumption profile of the specific activities and considering the final floor area classification shown in Table 4.1. Residential categories cover the entire housing area of the city disaggregated by construction period. Municipal categories refer to the different buildings and premises owned by the municipality. Whereas tertiary categories gathers all the remaining floor space that does not fall in the previous categories.

Besides the classification of the floor area by use, a further disaggregation by heating system is needed. This is achieved by using the information contained in buildings EPCs, heating systems inventories, municipal consumption inventories, and other available registers. All this information was mainly supplied by the own municipality, the regional government, and the regional energy agency[41], and was subject to an intensive processing work to unify and prioritise the different sources and to solve possible errors and overlaps. It should be noted that, information is not available for the whole building stock. Indeed, most EPCs refer to individual dwellings. In such cases, EPC data has been considered the same for the rest of dwellings in the same building. Extrapolation has been also carried out for buildings with no information at all. That is, for each ZIP code, the most representative heating system and configuration (individual or central) by building typology (use and construction period) has been allocated for buildings lacking information. Table 4.2 shows the available heating systems in the city and their considered efficiencies adapted from the Spanish long-term energy renovation strategy in the residential sector (Ministerio de Transportes Movilidad y Agenda Urbana, 2020).

The clustering of the building stock floor space by use and heating system plays a pivotal role in the proposed methodology since it will further allow to calculate the useful energy required by the different energy services within the building stock through the integration of top-down actual energy use with this floor space disaggregation. Floor area disaggregation by activity and heating system is detailed in Table B.1, Table B.2, Table B.3, Table B.4, Table B.5, and Table B.6 in appendix B.

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[41] Regarding data collection, it should be noted that most of it was supplied under the framework of the EU ATELIER project (2022) by the different institutions. While city-aggregated energy inventories are usually publicly available, other information such EPCs, dwellings consumptions, or other low-level data might be available only upon request (usually due to data privacy reasons).

Table 4.2. Efficiencies of current available heating systems within Bilbao building stock

System	Individual configuration		Central configuration[42]	
	Space heating	DHW	Space Heating	DHW
Conventional natural gas boiler	85,00 %	76,50 %	76,50 %	68,85 %
Condensing natural gas boiler	95,00 %	85,50 %	85,50 %	76,95 %
Light heating oil boiler	75,00 %	67,50 %	67,50 %	60,75 %
LPG boiler	75,00 %	67,50 %	67,50 %	60,75 %
Air heat pump	220,00 %	198,00 %	198,00 %	178,20 %
Electric boiler	100,00 %	90,00 %	90,00 %	81,00 %
Biomass boiler	75,00 %	75,00 %	75,00 %	67,50 %
Micro CHP	-	-	50,00 %	50,00 %

4.4.2. Performance gap analysis

4.4.2.1. Analysis scope and data

The target of this analysis is to assess the difference between actual and modelled (based on theoretical conditions) values in the residential sector and to compare it with socioeconomic and building characteristics data, in order to determine how these factors have an influence on this performance gap.

Regarding modelled values, the ENERKAD modelling tool (see description and rationale in section 2.1.2) has been used to estimate the theoretical energy use in residential buildings. For actual consumption values, natural gas billed data was provided by the gas utility within the city (Nortegas, 2022). This data was supplied by ZIP code and tariff[43]. As showed in Table 4.3, tariffs are separated according to the annual gas use, of which it can be assumed that tariffs 1 and 2 correspond to consumptions from individual gas boilers, while tariffs 3 and 4 can be related to the energy use made by central gas boilers in residential buildings, or individual or central gas boilers in tertiary premises and buildings.

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[42] Central configurations usually demand a larger amount of useful energy to supply heating energy services. To model the increased final energy consumption of these systems, a lower efficiency (with regard individual configurations) has been considered. Similarly, to consider losses in the supply of water heating services, worse efficiencies have been assumed for systems fulfilling this energy service.

[43] Although aggregated data is available within the city energy inventory, broken down data was requested to the gas utility under the framework of the EU ATELIER project (2022). It should be noted that the provision of this information is subject to data privacy compliance.

Table 4.3. Natural gas tariffs description

Tariff 1	Tariff 2	Tariff 3	Tariff 4
< 5.000 kWh/year	5.000 – 50.000 kWh/year	50.000 – 100.000 kWh/year	> 100.000 kWh/year
Individual gas boilers in dwellings	Individual gas boilers in dwellings	Central gas boilers in residential buildings Individual and central gas boilers in tertiary premises and buildings	Central gas boilers in residential buildings Individual and central gas boilers in tertiary premises and buildings

As the analysis focuses on residential buildings, data from tariffs 3 and 4 has been excluded since residential and tertiary energy use is mixed. Therefore, the analysed sample has been limited to dwellings equipped with individual natural gas boilers. This means that, from ENERKAD results, only those referring to dwellings equipped with individual gas boilers have been considered. This system configuration supplies 53% of the city residential heated floor area.

Concerning socioeconomic and building characteristics data, this was issued from different local (Ayuntamiento de Bilbao, 2022), regional (Instituto Vasco de Estadística, 2022), and national (Instituto Nacional de Estadística, 2022) databases. Detailed by ZIP code, this data is displayed in Table B.10 in appendix B and includes information like income, average dwellers age, working population, foreign population, number of dwellers per household, average building age, number of dwellings per building, amongst others.

4.4.2.2. *ENERKAD modelling*

The assumptions and data handled to estimate the energy use within the studied sample (i.e. individual gas boilers dwellings) using the building stock energy modelling tool ENERKAD are summarised below. The model uses climatic data, cadastral and building-related technical information, and occupancy hourly profiles to perform its calculations.

Climatic data such as hourly temperature or radiation has been obtained from the EnergyPlus database for the city of Bilbao (EnergyPlus, 2022), while months with heating needs are adjusted using the Heating Degree Days (HDD) calculation method from Eurostat (European Commission, 2022a)(see Table B.7 in appendix B).

Buildings geometry was issued from cadastral data (Diputación Foral de Bizkaia, 2022), while the data processing for the allocation of heating systems has been described in section 4.4.1. Concerning building-related technical parameters (see Table B.8 in appendix B), reference thermal transmittance values for buildings envelope elements were extracted from the EU building stock observatory (European Commission, 2022b) and updated to closer conditions for the city of Bilbao, meeting the requirements of the Spanish building code (Ministerio de Transportes Movilidad y Agenda Urbana, 2022a). On this concern it should be noted that thermal transmittance values are assigned to the buildings according to their construction period. Regarding windows thermal transmittances, these have been updated in line with the last years renovation subsidies (Ente Vasco de la Energía, 2022). Old buildings which have been renovated (and have therefore improved the thermal transmittance of their envelope) have not been considered due to the lack of records and the difficulty to identify them.

Finally, hourly occupancy and energy consumption profiles (see Table B.9 in appendix B) are obtained from the analysis of real consumption data monitored in a case study with similar characteristics to Bilbao from the EU OPTEEMAL project (2022). Furthermore, a set-point temperature of 20°C has been assumed.

4.4.2.3. *Method application*

Figure 4.2 illustrates the followed process. For each ZIP code, actual data is extracted from the energy use reported by the energy utility (Nortegas, 2022) while theoretical values are issued from ENERKAD. It should be noted that ENERKAD only considers space heating and DHW while billed data may contain gas energy use for other services such as cooking. The share of this energy service has been removed from the billed data based on statistical data (Instituto para la Diversificación y Ahorro de la Energía. IDAE, 2019). Moreover, actual and theoretical final energy use (kWh) is converted into specific useful energy (kWh/m^2) by applying the residential floor area supplied by individual gas boilers (processed from cadastral data and EPCs in section 4.4.1 and adjusted with the share of empty dwellings by ZIP code (Ayuntamiento de Bilbao, 2020; Instituto Vasco de Estadística, 2022)), and assuming the same energy efficiency considered in ENERKAD for these heating systems (85%).

On this concern, the conversion into useful energy is required so that the obtained deviation might be coherently evaluated along with available socioeconomic data. Indeed, for a given ZIP code, socioeconomic and building characteristics data applies to the whole residential stock, whereas actual and theoretical energy use values refers to a specific sample of dwellings (i.e. those supplied by individual gas boilers). Hence, useful energy has been calculated for the analysed sample and further assumed for the rest of the dwellings within the same ZIP code regardless of the heating system in place. This allows to compare the two set of data: difference between theoretical and actual useful energy and socioeconomic and building characteristics data.

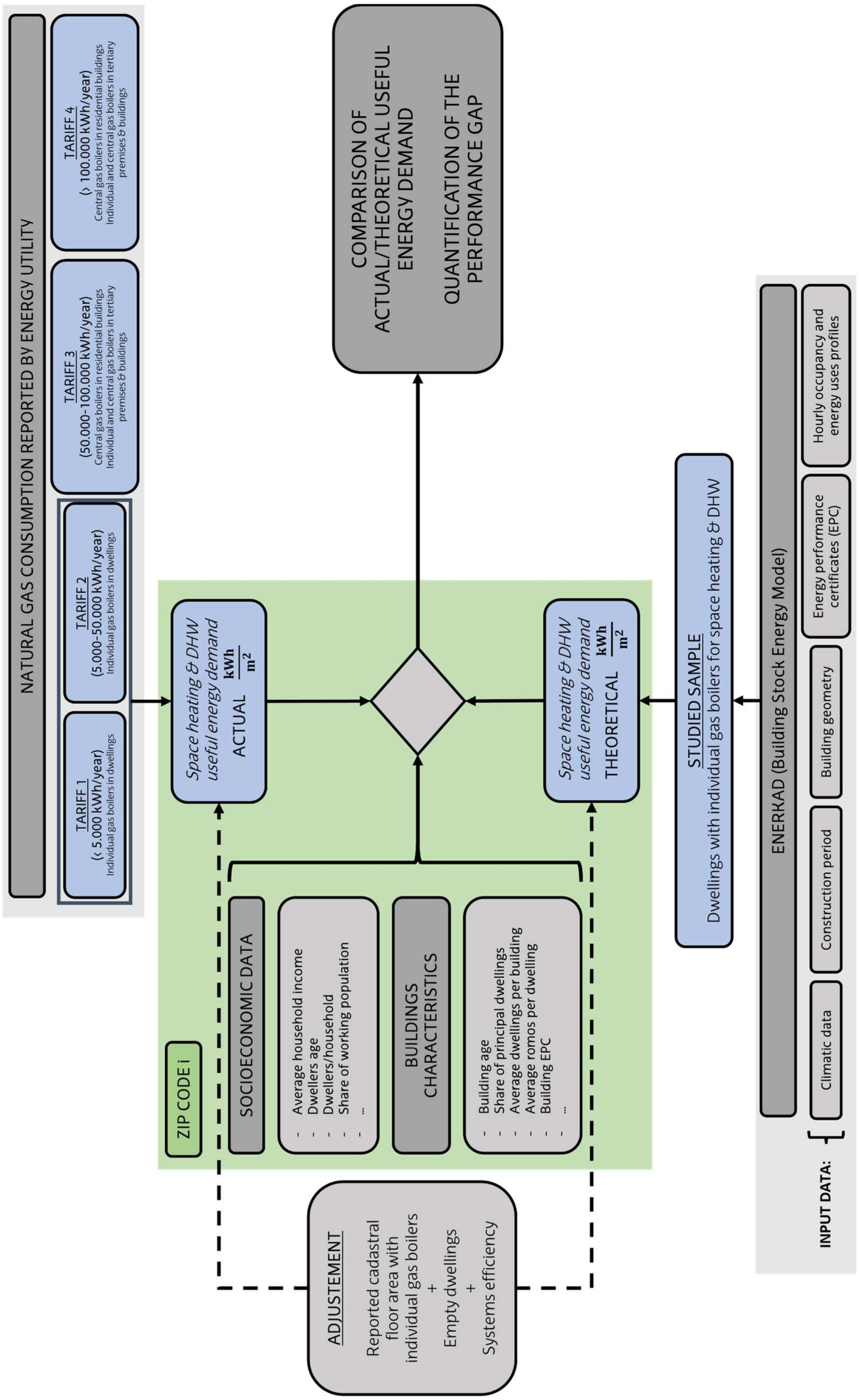

Figure 4.2. Performance gap analysis process

Once the deviation between theoretical and actual useful energy has been quantified, it is assessed with the set of socioeconomic and building characteristics data, allowing the identification of the parameters causing the performance gap. Results from this analysis are further discussed in 4.4.2.4.

4.4.2.4. *Results and discussion*

For each ZIP code, residential useful energy requirements for heating (space and water) obtained from billed data are compared with the ones calculated with ENERKAD. Figure 4.3 displays the map of the city of Bilbao split by ZIP code. The colour coding indicates the obtained deviation between theoretical and actual useful energy demand for heating.

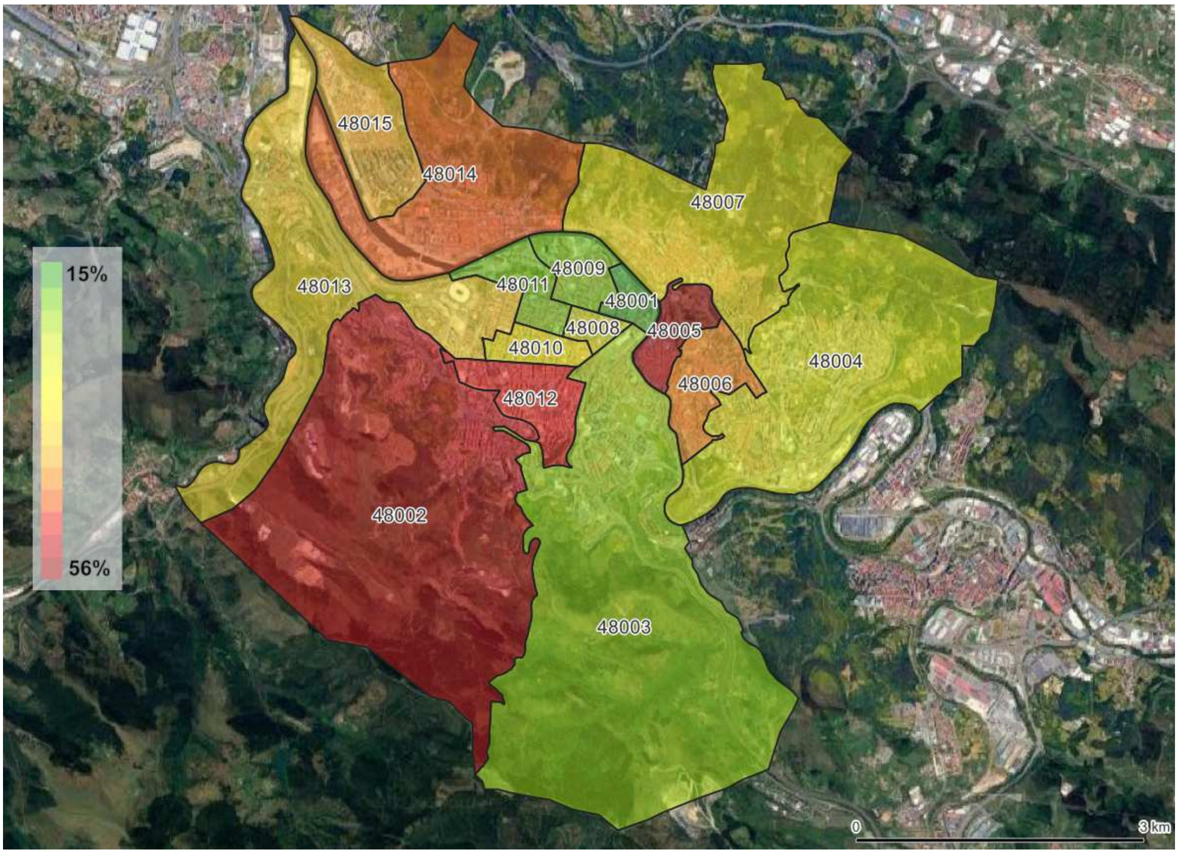

Figure 4.3. Bilbao city map split by ZIP code

From Figure 4.4, it can be observed that in a general way the model overestimates heating useful energy demand in residential buildings. Theoretical values exceed the actual ones for every ZIP code, with an average deviation of 28%. Deviations may be caused by inaccuracies of technical data fed into the model (e.g. wrong buildings geometry, outdated thermal transmittance values, inexact floor area, or erroneous heating systems reported by the EPCs) and assumptions concerning user behaviour towards energy use. Indeed, considerations such as set-point temperatures, occupancy profiles, or whether dwellers actually switch on their heating systems, are factors difficult to implement in an accurate way in the model since they depend exclusively on users' consumption patterns which may be influenced by particular socioeconomic situations. To identify the causes of the model deviation, the obtained differences have been compared with available socioeconomic data and building characteristics for each ZIP code. Descriptive statistics are shown in Table B.11 and Table B.12 in appendix B. A set of parameters has been identify as potentially influencing the performance gap. Their impact towards it is assessed next.

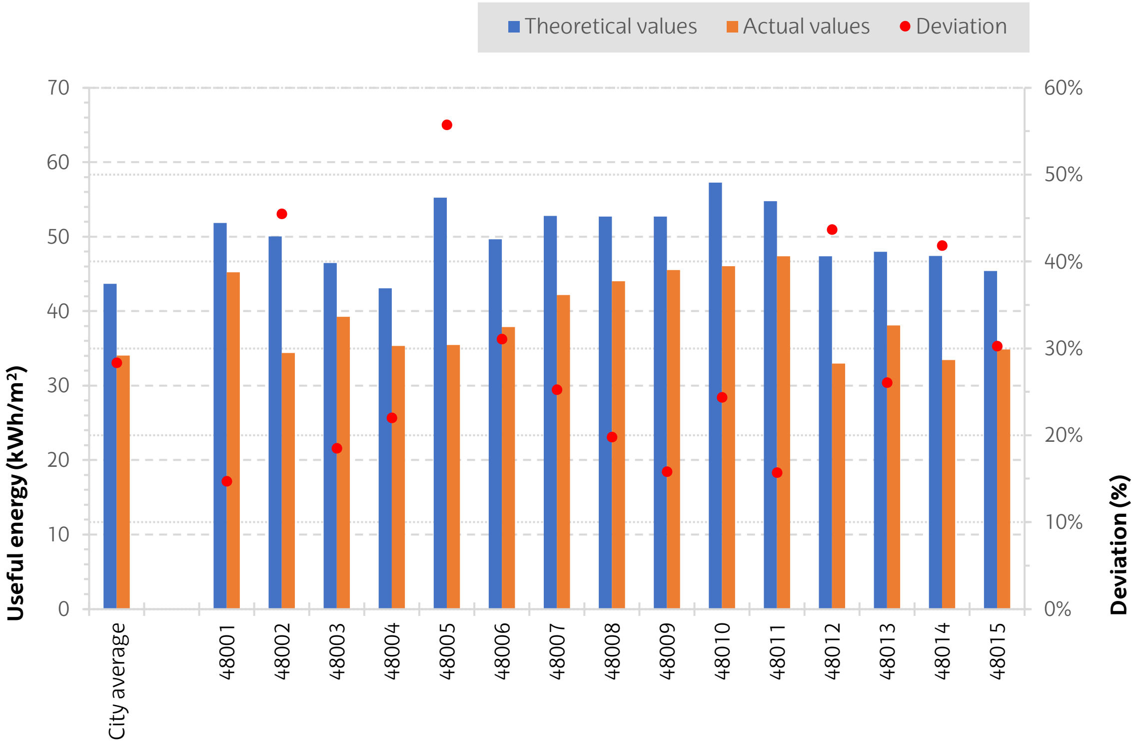

Figure 4.4. Comparison of theoretical-actual useful energy demand for heating by ZIP code

First, as it can be seen in Figure 4.5, the deviation between theoretical and actual useful energy decreases for higher incomes. That is, the gap between theoretical results and the actual energy use conditions is lower in ZIP codes with wealthier households. Conversely, the gap is greater for lower incomes, indicating that the model does not correctly adjust the energy consumption of this population group. The larger the deviation may mean poorer indoor thermal comfort which in turn may be related to energy poverty situations. Indeed, households in these circumstances prioritise economic saving over comfort, resulting in lower set-point temperatures and few operating hours of space heating. These results are in line with the works of Balaras et al. (2016) and Charlier (2021), and may help identify zones where buildings renovation is a priority[44].

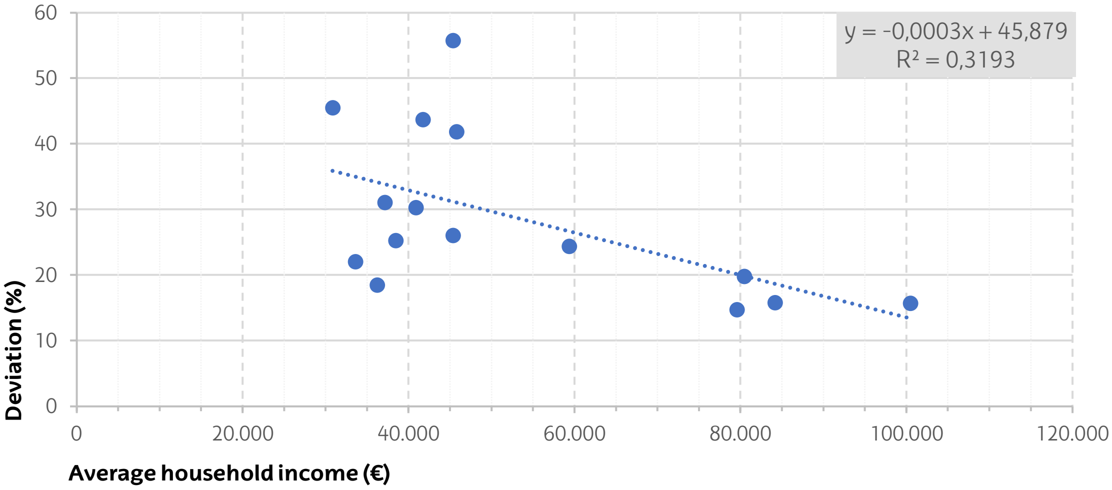

Figure 4.5. Average household income vs theoretical-actual useful energy deviation

The age of buildings is another relevant parameter which may be affecting model results and that can be acted upon to adjust them. As shown in Figure 4.6, the older the buildings, the greater the deviation. That is, consumption may be overestimated in aged buildings, meaning that these buildings may not be as inefficient as they are currently being considered in the model. Indeed, some may have been renovated or their envelopes may have better thermal transmittance values than those being assumed in the model. The same result is confirmed by Figure 4.7, where ZIP codes with worse efficiency indexes present higher deviations, thus validating the fact that consumption is overestimated in, a priori, less efficient buildings[45]. These results are shared by Majcen et al. (2015, 2013).

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[44] As remarked by Charlier (2021), access to social housing or renovation policies are more appropriate than other measures such energy subsidies, since even with an energy price reduction, these households would still be vulnerable. On the contrary, reducing their useful energy demands through renovating their dwellings, helps spending fewer financial resources on energy.

[45] Indeed, ENERKAD considers poorer thermal transmittance values for older buildings.

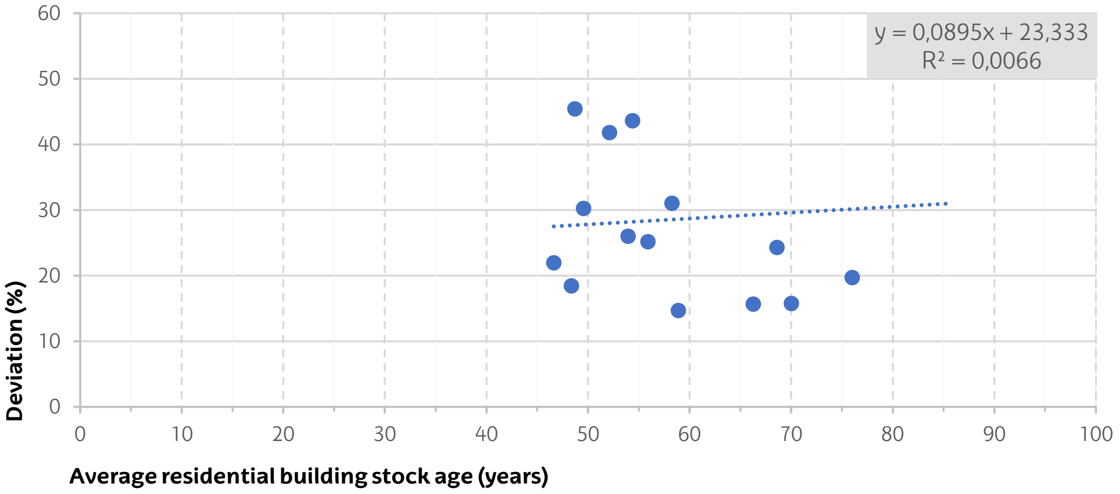

Figure 4.6. Average residential building stock age vs theoretical-actual useful energy deviation

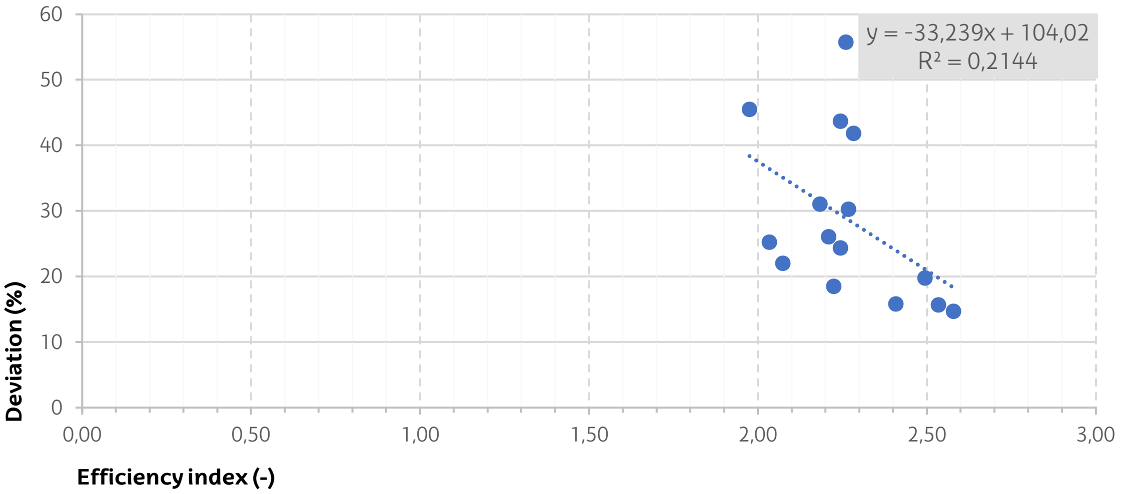

Figure 4.7. Efficiency index vs theoretical-actual useful energy deviation

Finally, the obtained deviation with regard the number of dwellers per household has been also plotted and displayed in Figure 4.8. In this case, deviation increases with fewer dwellers per household. However, fewer people living per dwelling should usually result in lesser energy use in specific energy services such as DHW. Hence, the higher theoretical values with regard actual values in ZIP codes where fewer people live per dwelling may be indicating that factors like occupancy profiles and heating systems operating hours could be being overestimated in the model.

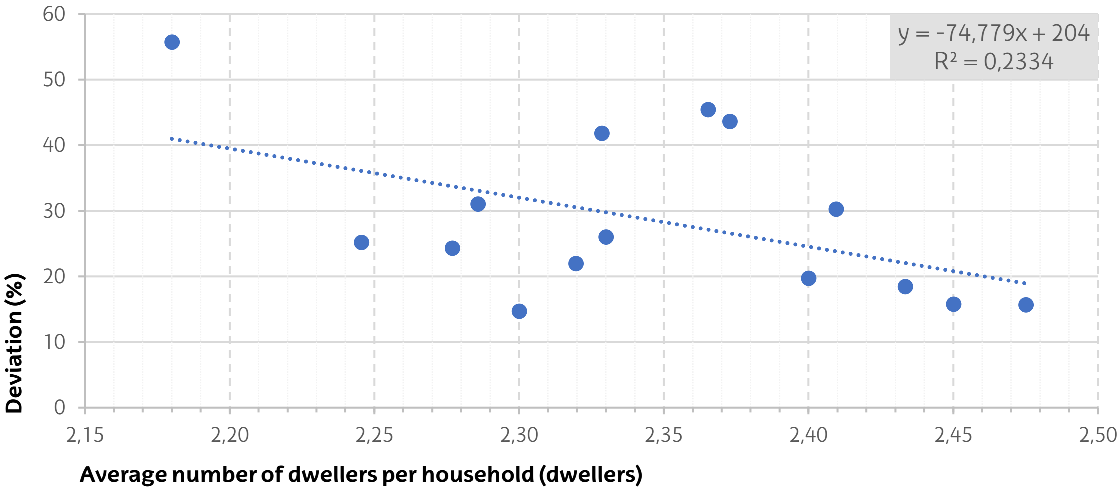

Figure 4.8. Average number of dwellers per household vs theoretical-actual useful energy deviation

To calibrate the model and reduce the performance gap, certain parameters should be therefore adapted to better reflect actual use conditions. First, the impact of household income on energy consumption should be considered. That is, the effect of household budget available for energy expenditure should be introduced to take into account energy poverty situations which should be prioritised for renovation. Second, input parameters to the model should be revised and updated. On the one hand, technical parameters affecting buildings efficiency should be adequately defined for each building typology. Thermal transmittance values should be refined with current values whenever possible instead of using normalised ones. On the other hand, user consumption patterns should be integrated more accurately to correctly adjust energy consumption to actual use conditions.

To adjust these parameters and improve the model results, additional accurate actual data is needed. An inventory of ECMs undertaken in buildings would support the update of technical parameters introduced in the model. A revision of EPCs should be also carried out to fix data deviations. Furthermore, actual energy use data is key to calibrate user habits. Indeed, energy use hourly data or other information that could be extracted from energy bills, is extremely helpful to determine users' patterns fitted with current conditions, allowing the introduction into the model of current occupancy profiles, heating systems operating hours, yearly heating periods, peak loads, and thermostat set-points amongst others. Real energy consumption data by building could be also useful to detect rebound effects in more efficient buildings. This information should be complemented with socioeconomic data to establish a link between social variables and current energy consumption. This would be integrated into the model to represent thermal comfort perception and whether is achieved or not depending on household available income and on the ability to pay the bills.

As a conclusion, data availability is crucial for the calibration process and for the statistical analysis. Both of them require reliable and the most detailed possible data concerning actual energy consumption to obtain accurate results. Unfortunately, this disaggregated data is hard to obtain at city level[46]. Through actual data monitoring, invoices from energy facilities and municipal inventories, local authorities should make an effort to gather as much energy data as possible to support the development of building stock energy models adjusted to the actual energy use of the city.

4.4.3. Building stock energy model development

4.4.3.1. Analysis scope and data

To tackle both the lack of data and the performance gap issues highlighted in the previous section 4.4.2, a methodology is hereunder proposed to model the energy performance of cities building stocks lowering data-dependency and considering the actual energy use of the sector. All while achieving fine-tuned disaggregation of buildings energy use.

Unlike the previous analysis, this one is focused on the entire city, without ZIP code distinction. Instead, final energy consumption of the city is disaggregated by floor area activity, energy service and fuel. Moreover, not only dwellings with individual natural gas systems but all buildings and consumed fuels within the city are taken into account.

Following the methodological approach proposed in Figure 4.1, a building stock energy model for the whole city of Bilbao is developed. To this purpose, LEAP energy modelling tool (see description and rationale in section 2.1.2) has been used. Within the developed model, the entire built-up area of the city is considered (i.e. residential, municipal-owned and other tertiary) and useful energy requirements for every energy service demanded in buildings (i.e. space heating, DHW, cooking, cooling, lighting, appliances) are outlined. As a result, the model allows to obtain a wide and detailed view of the final energy use in buildings in the city. In other words, for every floor area category and every energy service, fuel consumed by the different building systems (e.g. boilers, lighting, home appliances, amongst others) is calculated.

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[46] Indeed, at the time of the analysis only ZIP-level data was available. If more granular data becomes available, results could be improved as the assessed dataset would be increase.

The model supports the revision of the last city energy diagnosis, where natural gas use was wrongly distributed amongst residential and tertiary sectors and reported LPG and light heating oil was poorly downscaled from regional data (i.e. top-down estimation). Moreover, besides the update of the city energy diagnosis and its disaggregation by floor area category, energy service, and fuel (natural gas, light heating oil, LPG, biomass, and electricity), the detailed description of the building sector final energy use allows to accurately model energy measures and their impacts in buildings consumption. The combination of different ECMs (e.g. envelope renovation, heating systems renovation, or lighting improvement) shapes different building stock energy scenarios amongst which the city can decide the most suitable within its capacities.

Inputs to the model comprise bottom-up data processed in 4.4.1 and total natural gas and electric energy use reported by the corresponding city energy utilities (see Table 4.4) and available within the city energy inventory. Actual natural gas energy consumption is used to calculate useful energy required for space heating and DHW energy services, while current electricity consumption is used to obtain the useful energy demanded by cooling, lighting, and appliances energy services. For remaining fuels used for heating (e.g. LPG, light heating oil or biomass), their final consumptions are calculated based on the obtained useful energy demands for heating combined with the reported floor space which is supplied by these specific fuels. It is worth to note that the contribution of solar thermal collectors towards the fulfilment of DHW needs has been assumed based on the available data regarding these systems reported by the regional energy agency (Ente Vasco de la Energía, 2022) (see Table B.13 in appendix B).

Table 4.4. Reported electricity and natural gas energy use (GWh) within city buildings (2018)

<table>
<tr><th></th><th>Residential</th><th>Tertiary</th><th>Municipal</th><th>TOTAL</th></tr>
<tr><td>Electricity</td><td>419</td><td>501</td><td>28</td><td>948</td></tr>
<tr><td>Natural gas (Tariffs 1 & 2)</td><td>330</td><td>-</td><td>-</td><td rowspan="2">730</td></tr>
<tr><td>Natural gas (Tariffs 3 & 4)</td><td colspan="2">368</td><td>32</td></tr>
</table>

4.4.3.2. LEAP modelling

LEAP modelling framework has been used to develop the city building stock energy model. Unlike building-focused tools which require specific parameters such geometry, climatic data, or thermal transmittance values, the proposed approach to model the energy performance of the building stock does not need this kind of data. In this sense, the use of LEAP is suitable to perform the proposed approach requiring only as input the clustered floor area and the calculated useful energy demands (the calculation process to obtain these is developed in section 4.4.3.3, while results are shown in section 4.4.3.4). Moreover, instead of calculating the energy use per building, LEAP's flexibility allows to structure a reference (building stock) energy system based on the performed floor space clustering (see Table 4.1), returning fine-tuned results and avoiding issues in buildings with mixed uses. Disaggregated floor areas in Table B.1, Table B.2, Table B.3, Table B.4, Table B.5, and Table B.6 in appendix B, along with useful energy demands (see Table 4.7, Table 4.8, and Table 4.9), and efficiencies (see Table 4.2) are fed into LEAP to model the base year.

Finally, LEAP emerges as a versatile tool allowing to perform a wide set of scenarios without requiring a large amount data. Different scenarios can be simulated and compared simultaneously, thus being able to assess energy measures either individually or jointly and strengthening the analysis in terms of sensitivity. Furthermore, broader scenarios can be generated by incorporating aspects which are not usually included in conventional building physics-based tools such as the impact of new buildings, or the effect of socioeconomic phenomena. Scenario data assumptions introduced in LEAP are further explained in section 4.4.3.3 and detailed in Table B.14, Table B.15, Table B.16, Table B.17, Table B.18, Table B.19, Table B.20, and Table B.21 in appendix B.

4.4.3.3. Method application

Clustered city building floor area (see Table B.1, Table B.2, Table B.3, Table B.4, Table B.5, and Table B.6 in appendix B) is combined with reported natural gas and electricity consumptions (see Table 4.4) in order to obtain the useful energy demands for every energy service within all the city floor area categories. For each sector (residential, municipal, tertiary), actual natural gas energy use is used to define space heating and DHW useful energy demands[47], while reported electricity use determines cooling, lighting and appliances useful energy ones. Figure 4.9 illustrates the process followed for the definition of space heating and DHW useful energy requirements.

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[47] To transform final energy consumption into useful energy, efficiencies from Table 4.2 are used.

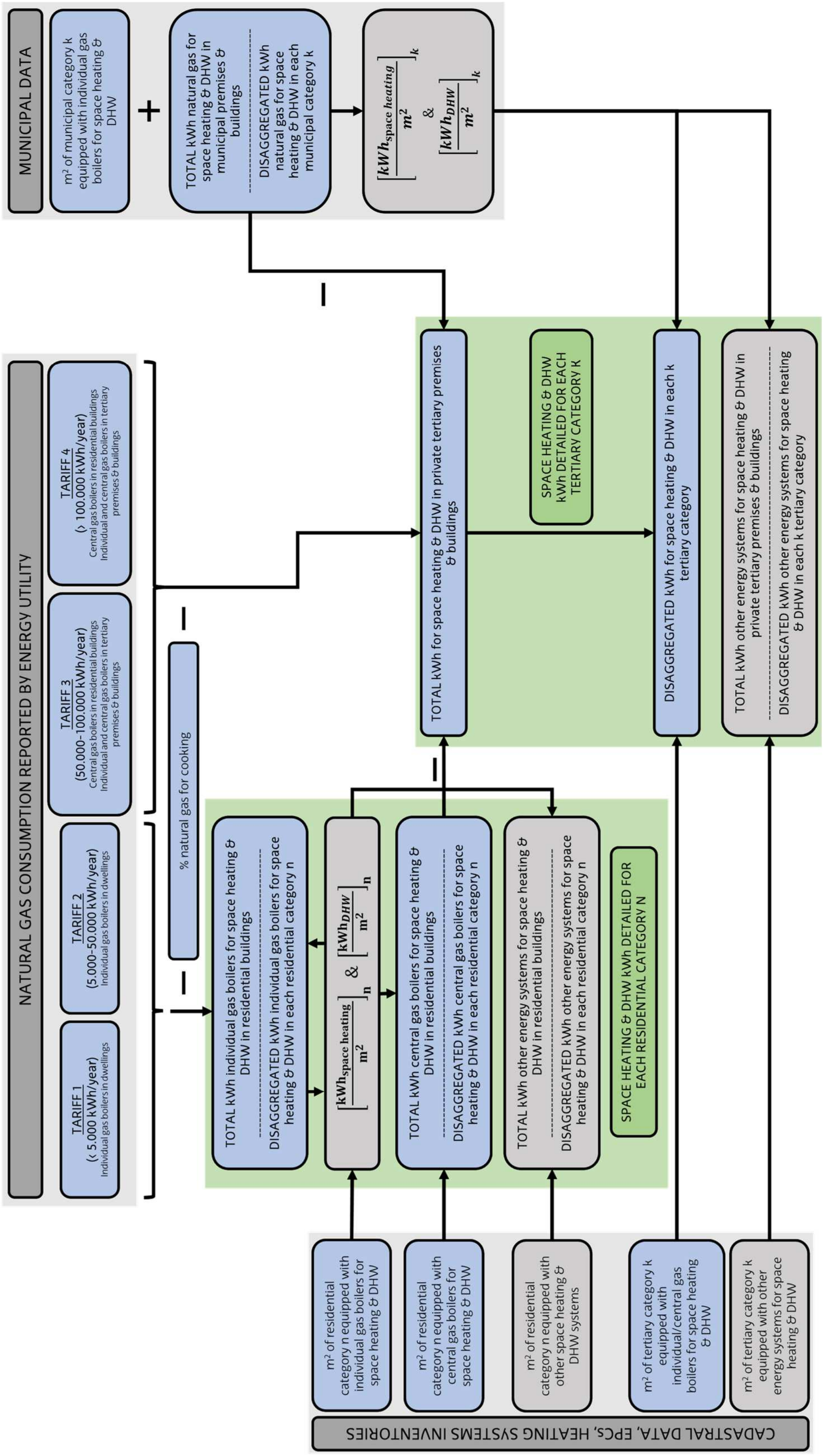

Figure 4.9. Space heating and DHW useful energy demands definition process

As a first adjustment, natural gas used for cooking purposes is removed from the reported data based on regional statistical data (Instituto para la Diversificación y Ahorro de la Energía. IDAE, 2019). As previously commented, natural gas tariffs 3 and 4 mix consumptions of residential and tertiary sectors, thus only consumption registered within tariffs 1 and 2 (gathering the final consumption of individual gas boilers in the residential sector) is used to define residential space heating and DHW useful energy demands by combining it with the floor area supplied by individual gas boilers (see Table B.1 and Table B.2 in appendix B). It should be noted that ,distinction between space heating and DHW energy services in tariffs 1 and 2 is based again on regional statistical data (Instituto para la Diversificación y Ahorro de la Energía. IDAE, 2019). Once useful energy requirements are defined, the part of natural gas used in central boilers in the residential sector can be calculated and therefore separated from the reported consumption in tariffs 3 and 4.

Additional assumptions for the definition of space heating and DHW needs are worth to note. First, the share of empty dwellings within the city has been contemplated (Instituto Vasco de Estadística, 2022), so that energy use is distributed amongst the occupied ones. Second, in order to distinguish the different space heating and cooling useful energy demands between dwelling categories, results from ENERKAD have been used and adjusted with results from the performance gap analysis (see section 4.4.2.4), thus integrating user-related aspects.

Regarding the characterisation of the tertiary sector, municipal energy inventories are available. That is, natural gas used in buildings owned by municipal authorities is reported. This allows to differentiate between municipal and non-municipal tertiary natural gas energy use in tariffs 3 and 4. Furthermore, reported municipal data serves to define space heating and DHW useful energy demands for the different municipal-owned floor area categories. For non-municipal tertiary floor area categories, space heating and DHW useful energy requirements are calculated using municipal results based on ENERKAD results and national databases (CIBSE, 2008; Ministerio de Transportes Movilidad y Agenda Urbana, 2019b).

Once space heating and DHW useful energy demands are defined for every floor area category, final energy use of other fuels which also deliver these energy services can be estimated by combining these useful energy demands with the efficiencies in Table 4.2 and with the corresponding floor areas supplied by each system, and therefore fuel. Regarding electric-related energy services (i.e. cooling, lighting, appliances), diverse sources are used to define their useful energy requirements in the residential (Ente Vasco de la Energía, 2013) and municipal and tertiary (CIBSE, 2008; Ministerio de Transportes Movilidad y Agenda Urbana, 2019b) sectors. Resulting useful energy demands for every energy service and floor area category are listed in section 4.4.3.4.

After the energy characterisation of the city building stock has been performed, scenarios up to 2050 are proposed and simulated in LEAP. Different ECMs in buildings have been modelled. For each sector (residential, municipal, tertiary), 9 scenarios have been modelled. Each scenario simulates the impact of a specific ECM given a specific deployment rate. A brief description is displayed in Table 4.5, while specific assumptions are listed in Table B.14, Table B.15, Table B.16, Table B.17, Table B.18, Table B.19, and Table B.20 in appendix B.

Table 4.5. Assessed ECMs and deployment rates

ECM	Deployment rate	Description	ECM scenario
Building renovation (BR)	Low renovation rate	Buildings are renovated at a slow pace. Current trend is followed.	BR1
	Medium renovation rate	Buildings are renovated at a medium pace. Based on the Spanish building renovation strategy (Ministerio de Transportes Movilidad y Agenda Urbana, 2020), a building renovation ratio is allocated to Bilbao for 2030 and extended to 2050.	BR2
	High renovation rate	Buildings are renovated at a fast pace. Boldest rate: more than 80% of the city building stock is renovated by 2050.	BR3
Heating systems renovation (HR)	Low renovation rate	Conventional space heating and DHW systems are replaced by their upgraded counterparts. Low technological change.	HR1
	Medium renovation rate	Conventional space heating and DHW systems are replaced by their upgraded counterparts. Fossil fuels are completely removed by 2050 and medium heat electrification is fostered.	HR2
	High renovation rate	Conventional space heating and DHW systems are replaced at their end of life by upgraded versions of these systems. Fossil fuels are completely removed by 2050 and high efficiency heat electrification is fostered. Solar thermal systems are also introduced to reduce the share of DHW useful energy demand supplied by other fuels.	HR3
Systems renovation (SR)	Medium renovation rate	Half the cooling, lighting and appliances devices are renovated by 2050.	SR1
	High renovation rate	All the cooling, lighting and appliances devices are renovated by 2050.	SR2

Building renovation scenarios focus on the assessment of the impacts from passive measures[48]. That is, savings obtained through the reduction of space heating (and in minor extent cooling) useful energy demands resulting from the improvement of the thermal transmittance of the buildings envelopes. As buildings are renovated (at different rates depending on the scenario), amounts of floor areas move from the non-renovated to the renovated stock of each floor area category. Since renovated stocks are defined with reduced useful energy requirements, savings are achieved.

Heating systems renovation scenarios are based on the replacement of old space heating and DHW systems by more efficient ones. In this case savings are not achieved by a reduction of the useful energy demand, but by a technological change that enhances the performance of the system, therefore reducing its energy use. Old systems may be just updated (e.g. conventional boiler replaced by condensing boiler), or replaced by different fuels (e.g. conventional boiler replaced by heat pump). Similarly to the building renovation ones, the modelling approach for these scenarios is based on the rearrangement of areas supplied by one or another system. That is, heated floor area covered by inefficient systems is reduced, while the one supplied by systems with higher performances is increased. Thus achieving an energy consumption reduction, as well as a shift in the used fuels for heating.

Systems renovation scenarios represent the implementation of ECMs within other energy services like cooling, lighting or appliances. These have been modelled in the exact same way as for the heating systems renovation scenarios. That is, conventional systems are progressively replaced by more efficient technologies through a change of the floor space covered by old or new devices.

Additionally to the ECM scenarios, extra scenarios (onwards called Consumption Patterns Scenarios or CPS) have been modelled representing the impact of a change in user consumption patterns. Whether because of climate awareness, due to rising energy prices, or due to legal requirements, a reduction of the useful energy requirements for specific energy services have been considered. In the case of dwellings a decrease in the space heating set-point temperature from 20°C to 18°C and a reduction of DHW consumption from 28 l/person.day to 24 l/person.day have been assumed. These user behaviour changes achieve 34% and 14% useful energy saving in space heating and DHW respectively. In the case of the municipal and tertiary sectors, the energy savings and energy efficiency measures enacted by the Spanish government in 2022 (BOE, 2022) have been modelled. Table B.21 in appendix B details the different measures, their achieved reductions, and the energy services and floor area categories affected. The impact of all these measures start in 2022 and is

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[48] It should be noted however that additionally to the building envelope renovation, the replacement of heating systems is also assumed in buildings carrying out an envelope renovation, thus an extra saving is achieved through the improvement of the heating systems efficiencies.

assumed to progressively permeate all end-users in residential, municipal and tertiary buildings by 2040.

Common to all scenarios, the following assumptions have been considered. According to the Basque environmental law (BOPV, 2019), all liquid fossil fuels are removed from buildings by 2030, while green electricity (i.e. carbon-free electricity) is assumed in municipal buildings. Regarding new built floor space in the city, only new residential floor area has been considered and modelled based on historical data (Instituto Vasco de Estadística, 2022), while municipal and tertiary floor areas are assumed to remain unchanged.

Scenarios can be assessed individually to evaluate the specific impact of a specific ECM, or as a combination of different ECMs. Indeed, a set of additional scenarios has been generated as a combination of the previous ones. Thus, allowing to evaluate the combined effect of different ECMs, that is the savings achieved by both useful energy demand reduction (building renovation scenarios) and systems efficiency improvements (heating systems renovation and systems renovation scenarios). Each one of the additional scenarios combines different ECMs and is oriented towards a specific city energy strategy that local authorities may promote. City strategy scenarios are further described in section 4.4.3.4.

Finally, a holistic assessment of the modelled scenarios has been carried out with the purpose of helping local stakeholders in the decision-making process. To quantify the impacts of the different measures and strategies modelled in the scenarios, each one of these has been evaluated under an energy, environmental and economic perspective. Defined indicators to measure each of these dimensions are described in Table 4.6. Regarding the environmental assessment, considered emission factors are detailed in Table D.1 in appendix D, while for the economic evaluation fuel prices and measures investment costs have been extracted from different databases: (Instituto para la Diversificación y Ahorro de la Energía. IDAE, 2020; Ministerio para la Transición Ecológica y el Reto Demográfico, 2018) and (CYPE, 2022) respectively. Data is detailed in Table B.22, and Table B.23 in appendix B.

Table 4.6. Defined indicators for scenario assessment

Dimension	Indicator	Formula	Description
Energy	Cumulative Final Energy Saving (CFES)	$CFES = -\sum_{i=2019}^{2050}(Total\ final\ energy_i - Total\ final\ energy_{2018})$	Sum of yearly final energy consumption savings (compared to the base year) achieved all along the scenario period
Environmental	Cumulative CO_2 Emissions Saving with variable EEF (CCESV)	$CCESV = -\sum_{i=2019}^{2050}(CO_2\ emissions_i - CO_2\ emission_{2018})$	Sum of yearly CO_2 emissions savings (compared to the base year) achieved all along the scenario period. Considering the decarbonisation of the national electricity grid
	Cumulative CO_2 Emissions Saving with constant EEF (CCESC)	$CCESC = -\sum_{i=2019}^{2050}(CO_2\ emissions_i - CO_2\ emission_{2018})$	Sum of yearly CO_2 emissions savings (compared to the base year) achieved all along the scenario period. Not considering the decarbonisation of the national electricity grid
Economic	Scenario Net Present Value (SNPV)	$SNPV = \sum_{i=2019}^{2050}\left(\frac{-Investment\ costs + Operational\ savings + Residual\ value}{(1 + discount\ rate)^i}\right)$	Net balance between investment costs spent and operational savings achieved all along the scenario period

Operational savings refer to net economic savings achieved by reductions in fuel consumption.

Regarding environmental indicators, the consideration of both a constant and a variable EEF intends to quantify the impact attributable to the decarbonisation of the national electric grid. On the one hand, when considering the grid decarbonisation (i.e. using a changing EEF), larger savings are easily achieved without the city needing to make additional efforts. This however hinders the actual performance of the measures implemented by local stakeholders. On the other hand, not considering the grid decarbonisation (i.e. using a constant EEF) allows to clearly identify the impacts due to the direct action of the municipality as emissions from electricity consumption will be exclusively driven by local consumption (Bertoldi et al., 2018b). At the same time, it points that, if further emissions reductions are to be achieved without relying on external factors (e.g. the grid decarbonisation), more aggressive efficiency measures should be adopted. For the CCESV indicator, the Spanish national grid decarbonisation pathway proposed in the Spanish long-term decarbonisation strategy (Ministerio para la Transición Ecológica y el Reto Demográfico, 2020b) has been assumed with a 74% renewable energy penetration in the national electric mix by 2030, and a carbon-free power system by 2050.

Concerning the SNPV indicator, a positive value would indicate that operational savings offset investment costs, thus involving an economic return. Whereas a negative SNPV value would mean that economic return is not achieved during the scenario period. Investment costs and operational savings for every ECM scenario are detailed in Table B.24 in appendix B.

4.4.3.4. Results and discussion

City building stock energy characterisation

The energy characterisation of the city comprises the definition of useful energy requirements (through the integration of clustered cadastral floor area and reported energy use) and the disaggregation of the city energy use by floor area category, energy service, and fuel. Table 4.7 displays the obtained useful energy demands for every energy service in the residential floor area categories.

Table 4.7. Residential useful energy demands (kWh/m^2) by energy service and floor area category

	Space heating	DHW	Cooking	Cooling	Lighting	Appliances
RHB1900	23,82	17,12	6,68	5,14	3,29	19,12
RHB1940	24,92			5,05		
RHB1960	19,84			5,20		
RHB1980	17,03			4,69		
RHB2007	15,54			5,09		
RHB2018	8,51			5,90		
RSF2018	40,32			5,18		

DHW, cooking, lighting and appliances useful energy demands are common for every category as they do not depend on the envelope of the building. Indeed, these energy services are more dependent on the number of dwellers rather than on physical properties. However, for modelling purposes, they have been referred to square meter. Useful energy required for cooling has been obtained considering the share of this energy service in total electricity use in the residential sector (Ente Vasco de la Energía, 2013), the share of dwellings equipped with cooling systems (Ente Vasco de la Energía, 2013), and an average efficiency for these cooling devices (DEEDS EU project, 2022).

For the definition of space heating useful energy requirements in each dwelling category, ENERKAD theoretical results have been adjusted using the results from section 4.4.2.4. Depending on its distribution along the different ZIP codes, a calibration factor has been applied to each category. Thus, whether a specific dwelling type is more common in a wealthier, older, or denser ZIP code, its space heating useful energy demand has been corrected, allowing to integrate the user patterns of the specific dwellers living in each category. Figure 4.10 displays the differences between theoretical and adjusted final useful energy demands. The relative differences between categories can be also observed. While theoretical values decrease as the categories are newer[49], adjusted values reflect some of the results obtained in section 4.4.2.4. Although not being the oldest category, dwellings from 1901 to 1940 (HB1940) have the larger useful energy requirements for space heating. This may be explained by the impact of income on energy consumption. Indeed, these households are concentrated in 4 of the 5 more affluent ZIP codes, resulting on an actual higher useful energy demand for space heating because of a greater eagerness for achieving thermal comfort. Conversely to theoretical values, category HB1900 has not the largest space heating useful energy demand. These households are located on a low-middle income ZIP code with lesser ability to pay for energy bills. Moreover, this result is also in line with the fact that older buildings may not be such inefficient as initially considered, while new buildings may demand more energy than theoretically expected. Indeed, it can be observed how after the calibration, space heating useful energy demands in newer buildings are increased in relative terms.

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[49] Theoretical values issued from the ENERKAD model are based, amongst other assumptions, on the thermal transmittance values assigned to the buildings depending on their age. Thus, theoretical useful energy demand decreases as the building is newer since it is assumed to be more efficient.

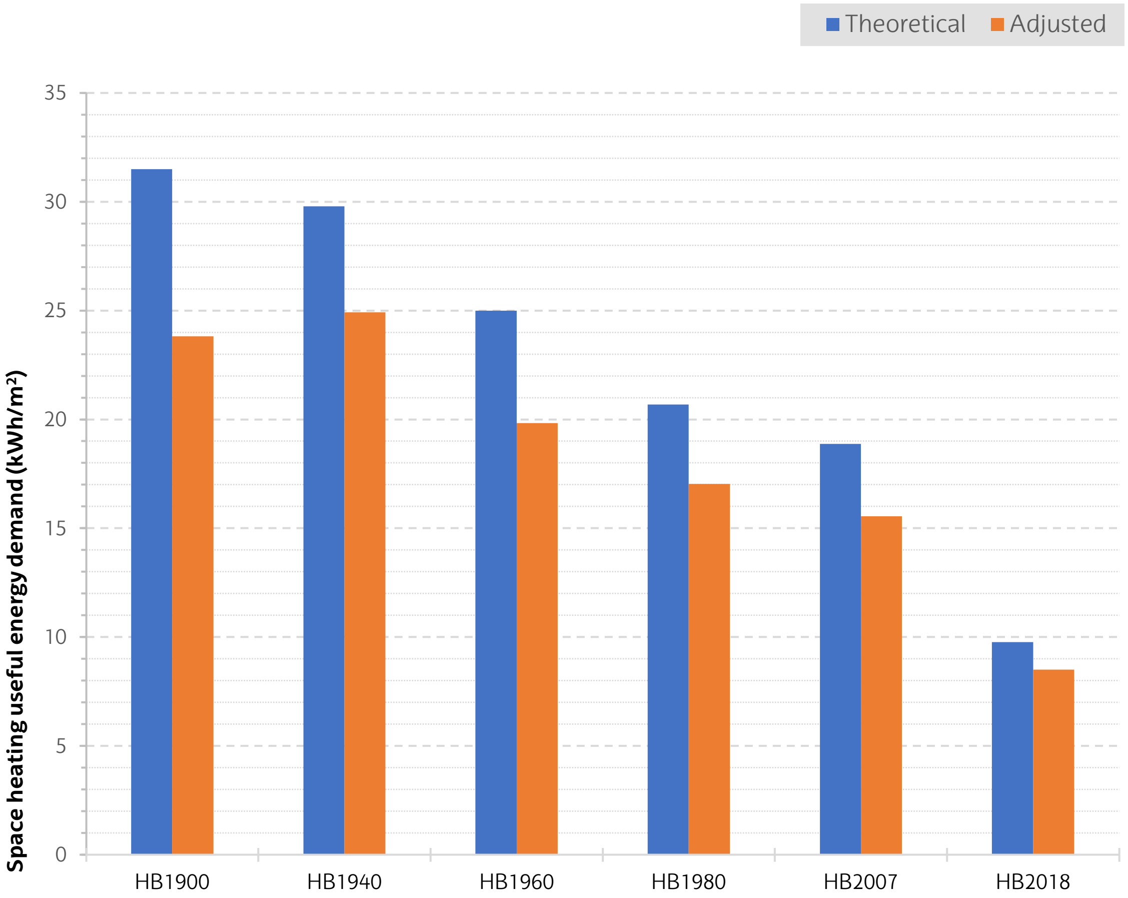

Figure 4.10. Space heating theoretical and adjusted useful energy demands by residential floor area category (excluding single family houses category (SH2018))

For municipal and tertiary floor area categories, calculated useful energy demands are shown in Table 4.8 and Table 4.9.

Table 4.8. Municipal useful energy demands (kWh/m²) by energy service and floor area category

	Space heating	DHW	Cooking	Cooling	Lighting	Appliances
MUNEDUC	18,50	2,22	2,40	-	14,08	4,48
MUNSPRT	0,49	81,92	-	-	68,29	-
MUNADMI	25,64	1,53	-	19,51	15,05	17,41
MUNOTHR	17,54	23,68	-	34,06	26,27	30,38
MUNAZKN	38,69	52,23	-	30,93	66,08	52,86

Table 4.9. Tertiary useful energy demands (kWh/m²) by energy service and floor area category

	Space heating	DHW	Cooking	Cooling	Lighting	Appliances
TERCOMM	22,61	0,88	-	10,78	73,07	3,61
TEROFFI	39,46	1,53	-	19,51	17,41	20,13
TEREDUC	35,09	2,22	2,40	-	14,08	4,48
TERLODG	86,33	47,75	7,21	62,53	52,12	123,85
TEROTHR	0,28	27,95	-	-	40,48	-
TERHLTH	104,29	29,80	7,21	76,34	45,07	107,09

Figure 4.11 shows the final energy consumption of the city building stock in the base year (2018). Residential floor area categories represent 53% of Bilbao's building stock energy followed by tertiary ones (44%). Municipal-owned floor area only make 4% of the city building sector consumption. Dwellings built between 1960 and 1980 (HB1980) are the floor category with the highest energy use within the city (401 GWh). It is also the floor area category with the largest floor area (6.114.245 m²).

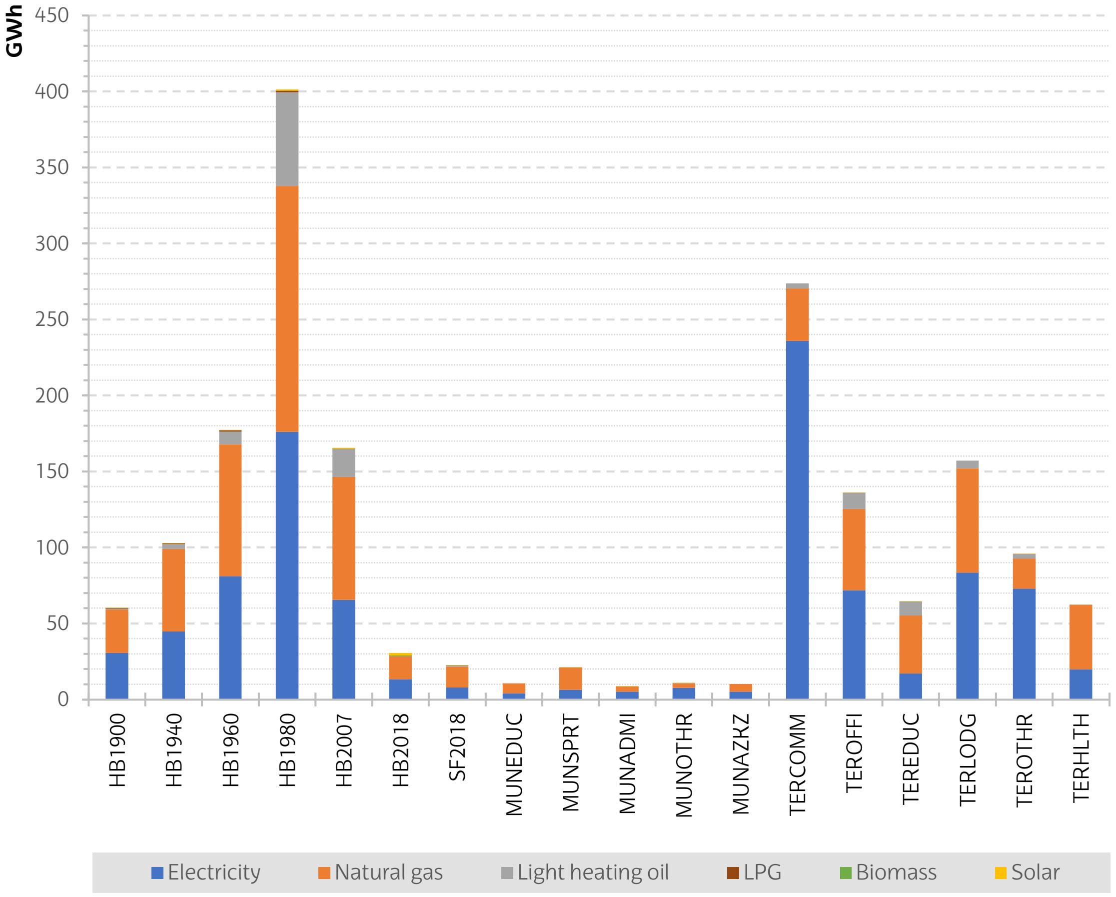

Figure 4.11. Bilbao building stock final energy consumption by activity and fuel (2018)

As displayed in Figure 4.12, space heating is the most demanded energy service within the city building stock, with a total final energy consumption of 538 GWh (30%), followed by DHW with 397 GWh (22%) and lighting with 387 GWh (21%). However, depending on the sector (residential, municipal, tertiary), energy is used differently: heating (space and water) and appliances services are predominant in the residential sector, while lighting is the most used service, followed by space heating, in the tertiary sector.

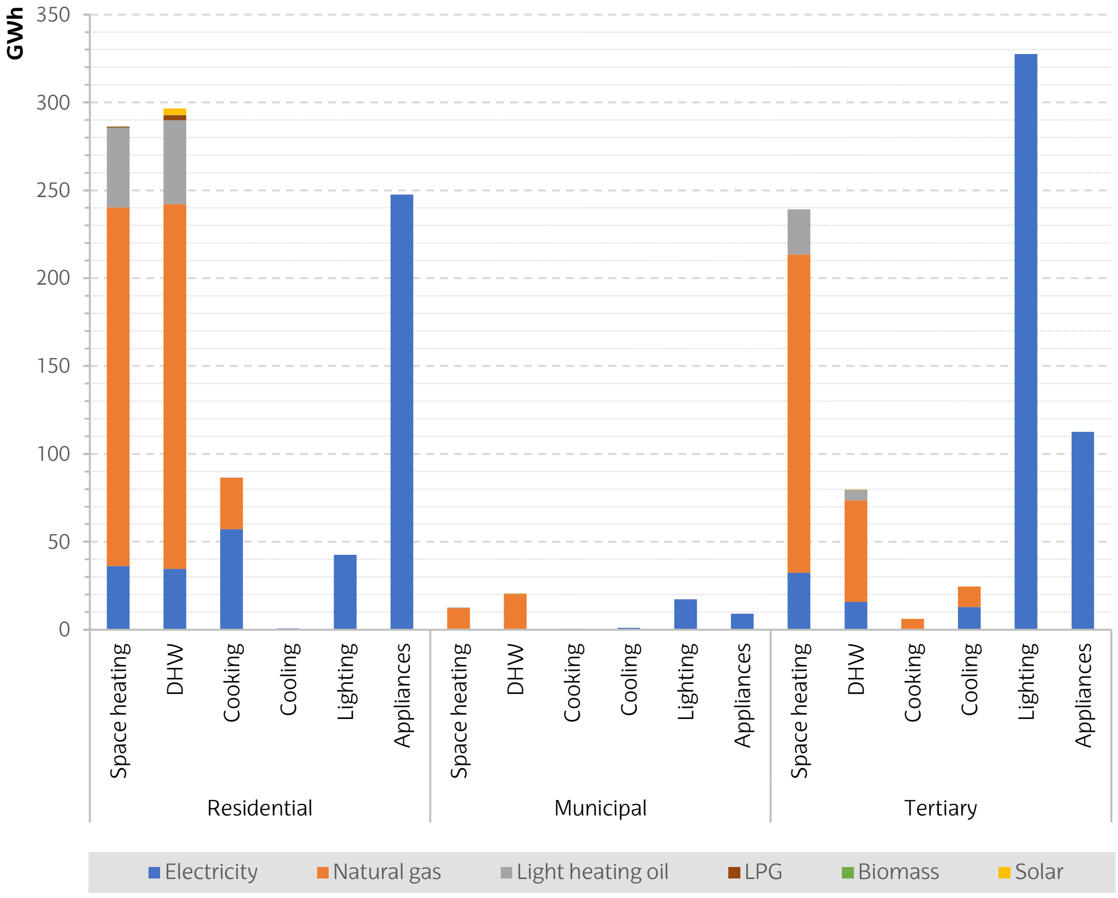

Figure 4.12. Bilbao building stock final energy consumption by sector, energy service, and fuel (2018)[50]

As previously displayed in Table 4.4, electricity and natural gas are the most used fuels in the city building stock. Electricity is mainly consumed in cooking, lighting, and appliances services, while 13% of total electricity use within the city building stock is dedicated to heating (space and water). Moreover, through the clustering of the city floor area by heating system, the proposed method allows to refine the final energy consumption of some fuels. Indeed, natural gas was wrongly allocated between residential and tertiary sectors, more gas natural being consumed in the former

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[50] Natural gas final energy consumption for cooling services in tertiary sector is explained by the trigeneration system existing in the city hospital.

than in the latter. Regarding light heating oil and LPG consumptions, these were estimated through a top-down approach in the city inventory, while the bottom-up approach based its calculations on the amount of floor area supplied by these systems. Deviations with regard the city inventory for these fuels are listed in Table 4.10.

Table 4.10. Deviations with regard to the reported city inventory

	Reported city inventory (2018)			Modelled results			Deviation		
	Natural gas	Light heating oil	LPG	Natural gas	Light heating oil	LPG	Natural gas	Light heating oil	LPG
Residential	330	55	18	441	93	3	34%	69%	-81%
Tertiary	368	29	2	257	32	0	-30%	8%	-100%
TOTAL	**698**	**84**	**20**	**698**	**125**	**3**	**0%**	**49%**	**-83%**

Residential sector scenarios

Figure 4.13 shows the evolution of final energy consumption in the different scenarios in the residential sector. Both heating systems renovation scenarios HR2 and HR3 achieve respectively a 43% and 36% final energy reduction by 2050 with regard 2018, while the boldest building renovation scenario BR3 reaches a 27% final energy decrease.

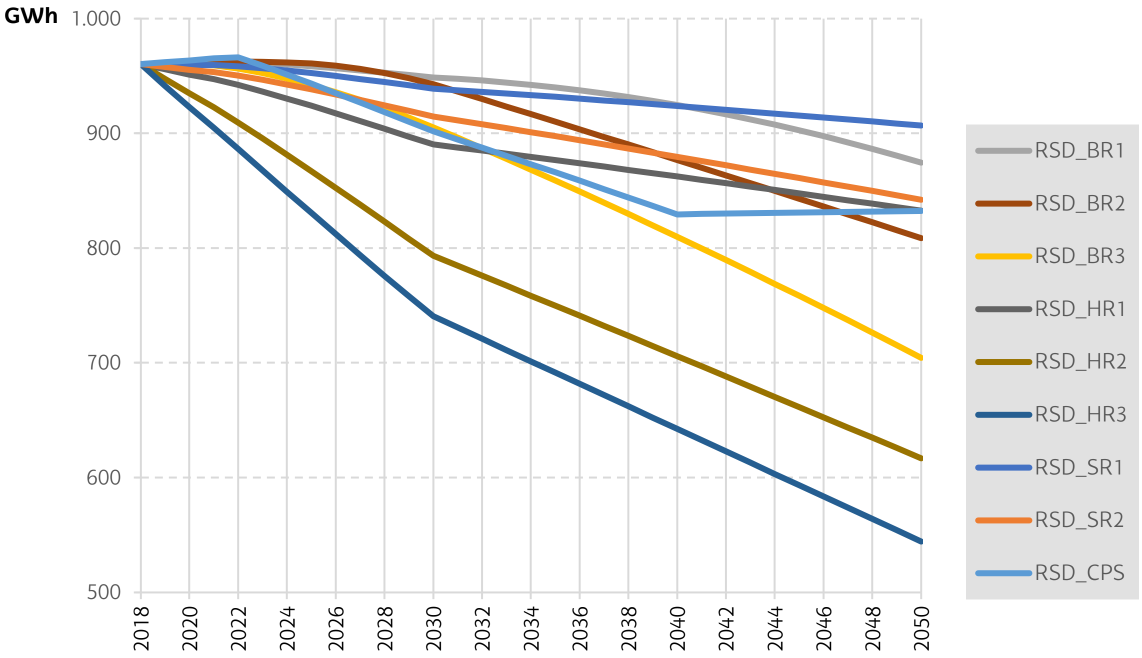

Figure 4.13. Final energy consumption evolution by scenario in the residential sector

Regarding CO_2 emissions reductions, the residential sector is carbon-free by 2050 in both HR2 and HR3 scenarios when considering the national grid decarbonisation (see Figure 4.14). If this effect is not taken into account (see Figure 4.15), HR3 scenario achieves a 39% abatement by 2050 with regard 2018 followed by BR3 scenario (31% reduction).

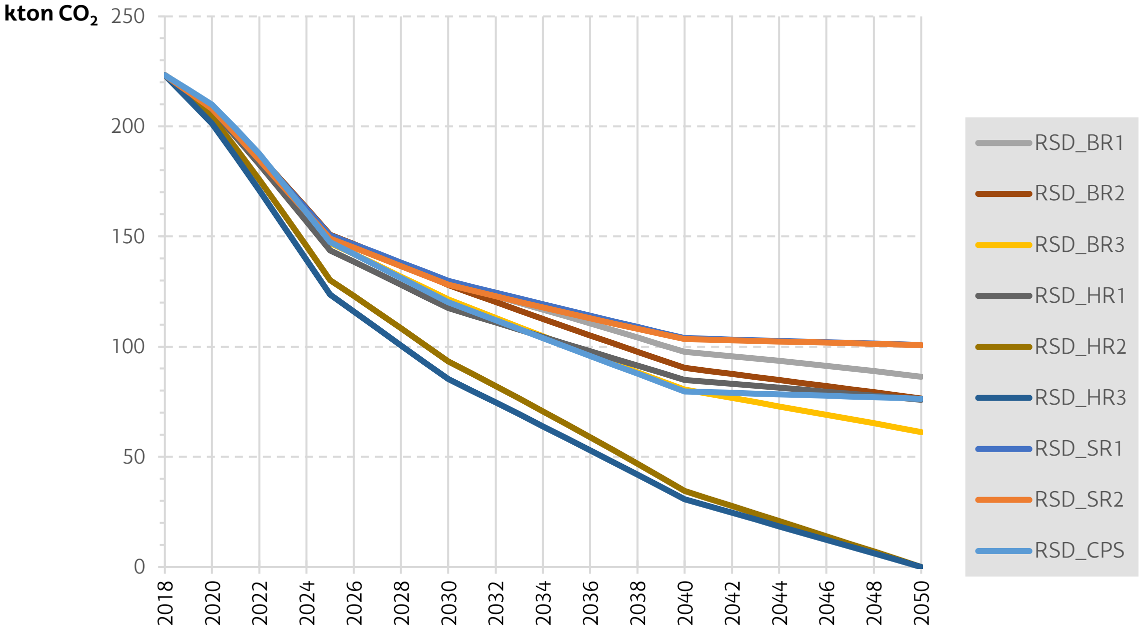

Figure 4.14. CO_2 emissions evolution by scenario in the residential sector. Variable EEF

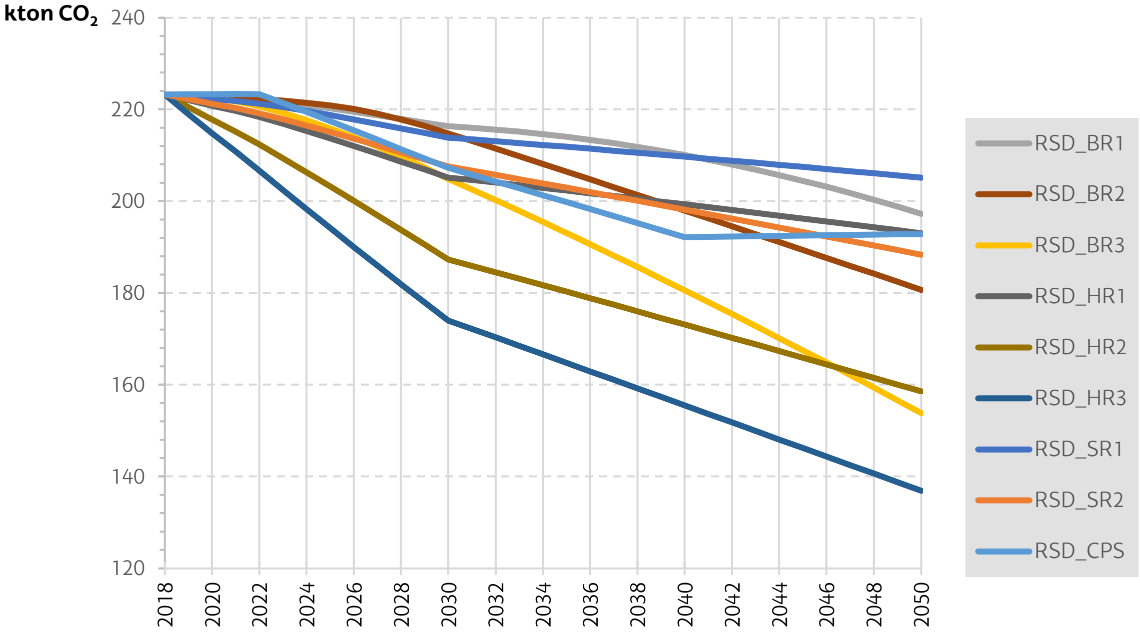

Figure 4.15. CO_2 emissions evolution by scenario in the residential sector. Constant EEF

As an example to illustrate the mechanics behind the modelling of energy use evolution in the scenarios, the following figures show the final energy consumption evolution in the BR3 and HR3 scenarios. In Figure 4.16 it can be seen how final energy consumption decreases in the BR3 scenarios through the renovation of the city residential floor area: current floor area categories are reduced (RHB1900, RHB1940, amongst others), while the floor area of renovated categories increases (RNV2030 and RNV2050).

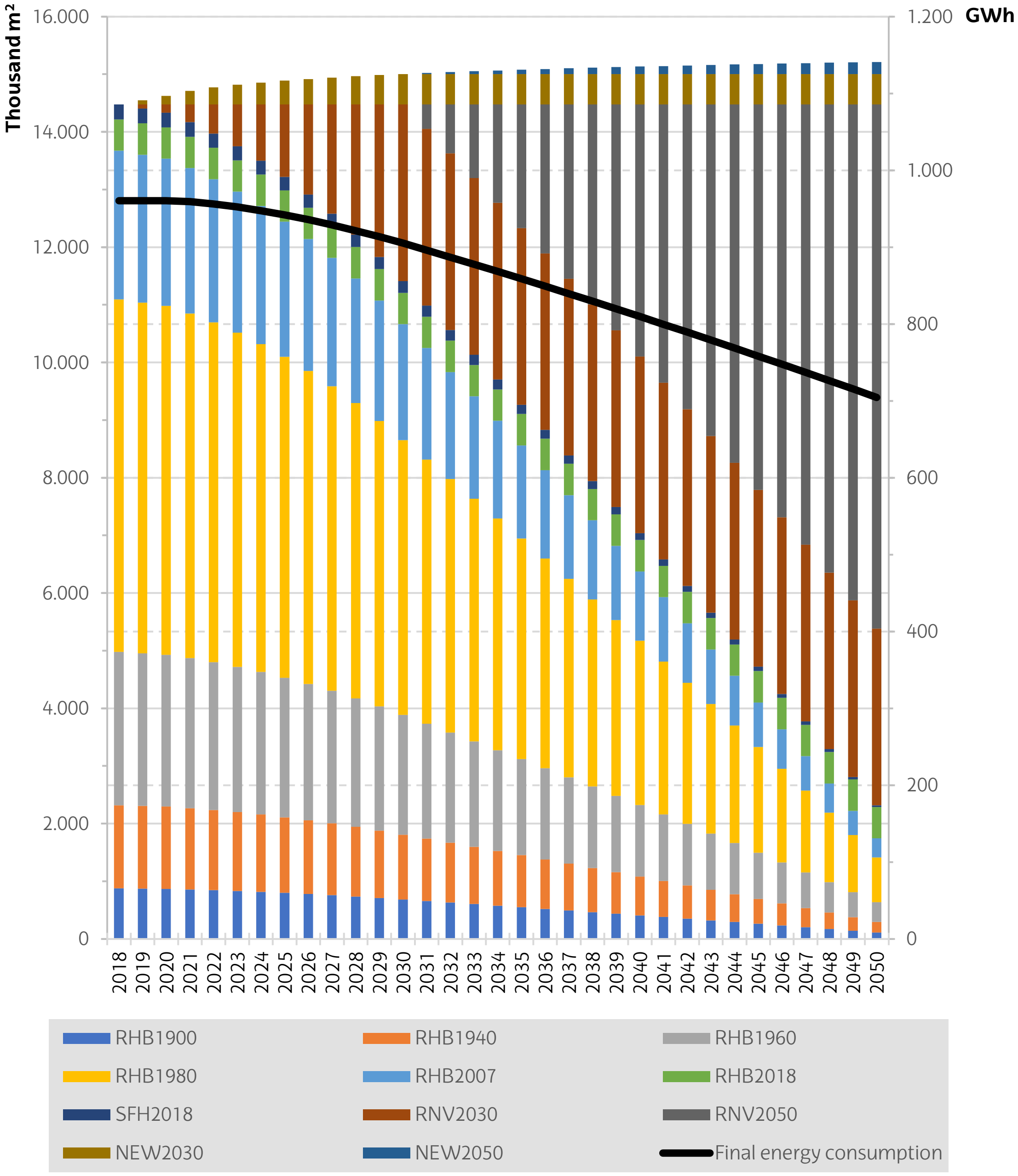

Figure 4.16. City residential floor area and final energy consumption evolutions in scenario BR3

In a similar way, Figure 4.17 explains how through the renovation and replacement of old inefficient heating systems by more efficient and cleaner ones energy savings are achieved.

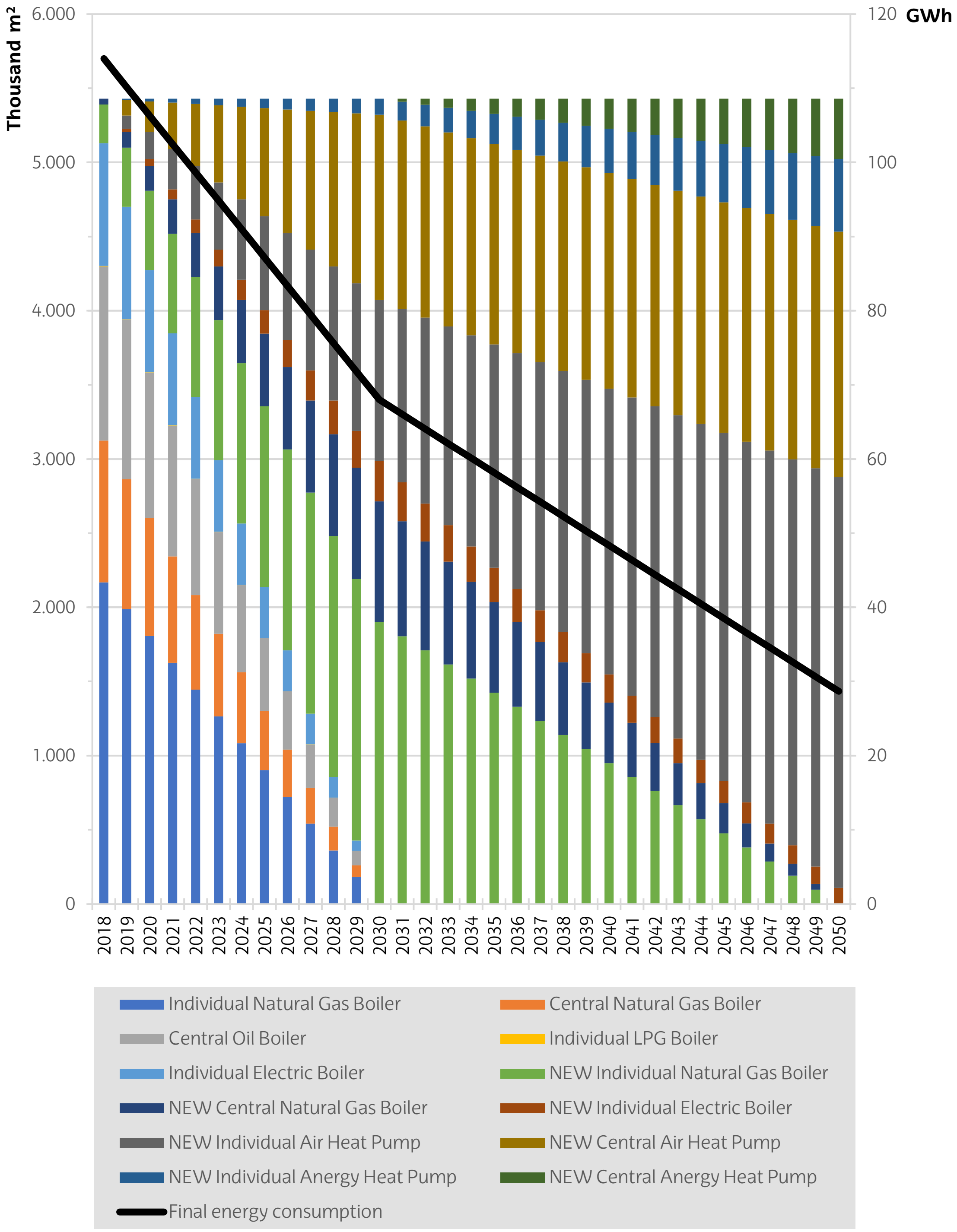

Figure 4.17. RHB1980 category heated floor area by heating system and space heating final energy consumption evolution in scenario HR3

Table 4.11 summarises the results of the different scenarios in the residential sector. Heating systems renovation scenarios HR3 and HR2 achieve the largest CFES, CCESV, and CCESC, followed by building renovation BR3. These are however the three most expensive scenarios (further see investment costs in Table B.24 in appendix B). It should be noted that in the heating system renovation scenarios, two renovation cycles[51] are carried out thus increasing the scenarios costs. Only systems renovation scenarios SR1 and SR2 and the consumption patterns scenario CPS achieve a positive SNPV, meaning that operational savings offset investment costs in the scenario period. Indeed, in the CPS case no expenditure is required to reduce energy and emissions levels.

Table 4.11. ECM and CPS scenarios results in the residential sector

Scenario	**CFES (GWh)**	**CCESV (kton CO_2)**	**CCESC (kton CO_2)**	**SNPV (M€)**
RSD_BR1	875	3.121	332	-146
RSD_BR2	1.781	3.261	561	-265
RSD_BR3	3.384	3.512	978	-526
RSD_HR1	2.413	3.438	596	-424
RSD_HR2	6.236	4.611	1.244	-460
RSD_HR3	7.896	4.759	1.697	-472
RSD_SR1	855	2.982	330	69
RSD_SR2	1.920	3.012	607	138
RSD_CPS	2.497	3.437	620	95

Municipal sector scenarios

Figure 4.18 shows the evolution of final energy consumption in the different scenarios in the municipal sector. Heating systems renovation scenarios HR2 and HR3 achieve a similar 42% and 41% final energy consumption reduction respectively by 2050 compared to 2018, followed by systems renovation scenario SR2 (22% decrease). Although HR3 focuses on a high efficiency electrification no further reductions with regard HR2 are achieved indicating that a wider penetration of these high-efficient systems (see Table B.19 in appendix B) would be necessary (especially in categories with high heat demands such as MUNSPRT or MUNADMI) to reach larger abatements.

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[51] A first cycle is carried out between 2019 and 2030 where all the current heating systems are replaced. Then, a second cycle is carried out from 2030 to 2050 progressively renewing the heating systems stock.

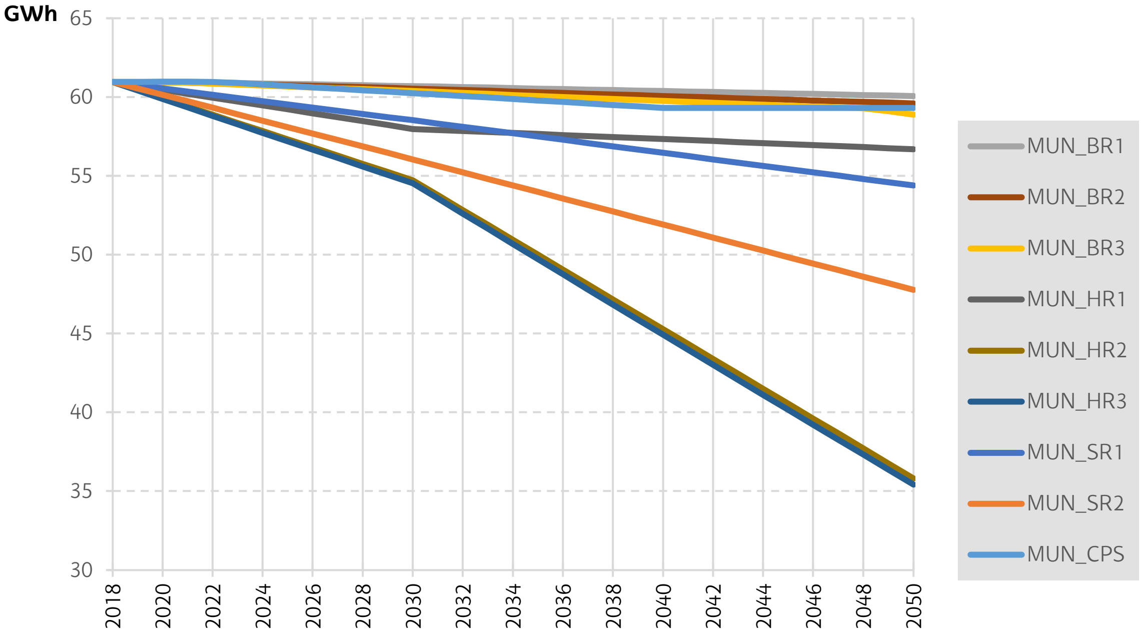

Figure 4.18. Final energy consumption evolution by scenario in the municipal sector

Concerning CO2 emissions abatements (see Figure 4.19), heat electrification in scenarios HR2 and HR3 achieves a carbon-free stock by 2050. As previously commented, under the Basque environmental law (BOPV, 2019), municipal services are required to use carbon-free electricity since 2020, thus identical results are obtained considering or not the decarbonisation of the national grid.

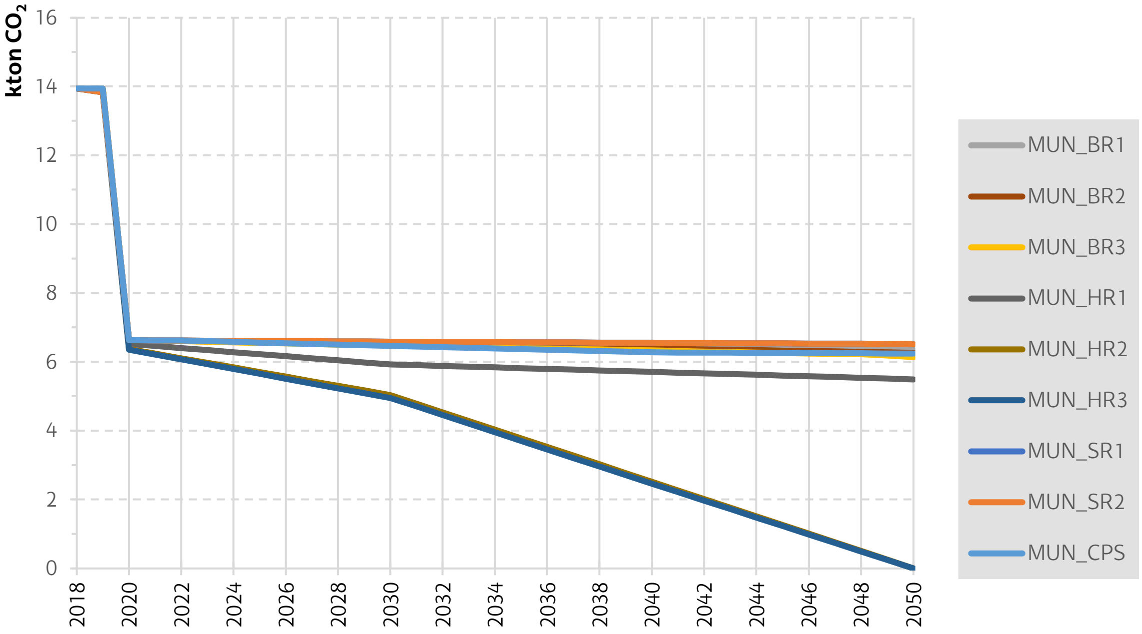

Figure 4.19. CO_2 emissions evolution by scenario in the municipal sector

Table 4.12 summarises the results of the different scenarios in the municipal sector. Building renovation scenarios do not yield a great CFES, not compensating for their high cost. However, because of normative implications (i.e. Basque environmental law), they achieve a large CCESV and CCESC. Mandatory green electricity in public services also explains why CCESV and CCESC produce the same results. Regarding HR2 and HR3 scenarios, these are the ones that reach the largest CFES, CCESV and CCESC. Systems renovation scenario SR2 ranks third in CFES, CCESV and CCESC, and has the highest SNPV.

Table 4.12. ECM and CPS scenarios results in the municipal sector

Scenario	CFES (GWh)	CCESV (kton CO_2)	CCESC (kton CO_2)	SNPV (M€)
MUN_BR1	13	231	231	-15
MUN_BR2	21	232	232	-22
MUN_BR3	28	234	234	-30
MUN_HR1	92	250	250	-16
MUN_HR2	364	322	322	-17
MUN_HR3	372	323	323	-18
MUN_SR1	108	229	229	7
MUN_SR2	217	229	229	14
MUN_CPS	32	234	234	1

Tertiary sector scenarios

Figure 4.20 shows the evolution of final energy consumption in the different scenarios in the tertiary sector. Systems renovation scenario SR2 reaches the highest decrease in final energy consumption by 2050 with regard the base year (37%), followed by heating systems renovation scenarios HR3 (31%) and HR2 (28%).

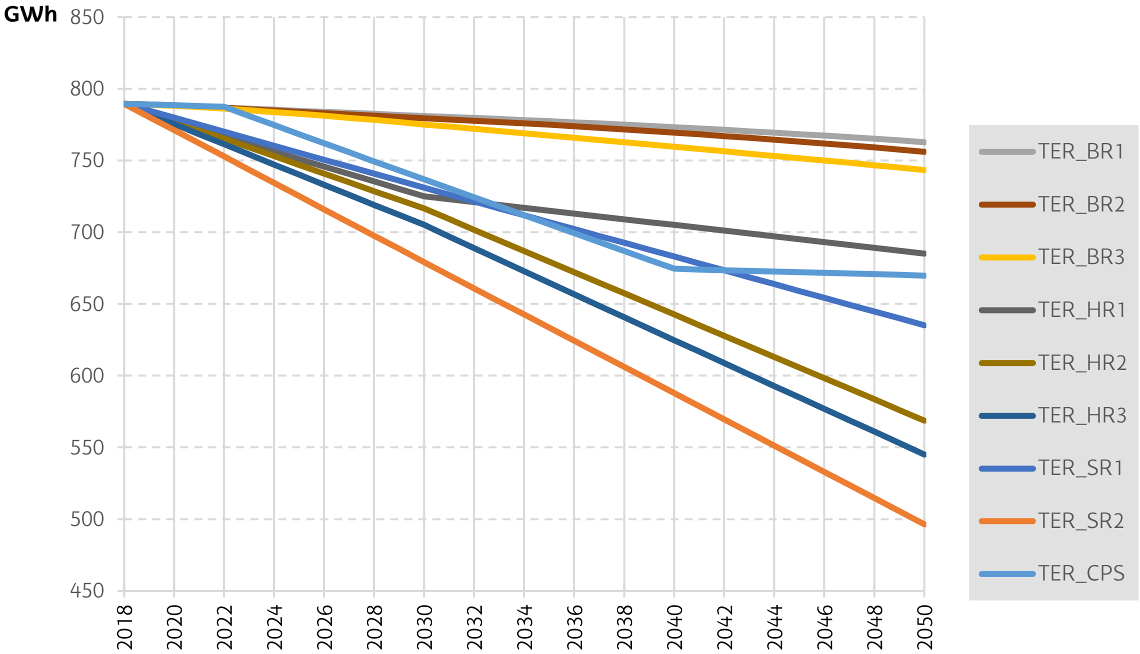

Figure 4.20. Final energy consumption evolution by scenario in the tertiary sector

Considering the national grid decarbonisation, HR2 and HR3 scenarios achieve a carbon-free tertiary stock by 2050 (see Figure 4.21). Conversely, if not taken into account (see Figure 4.22), SR2 accomplishes a 40% CO_2 abatement by 2050 with regard 2018, followed by HR3 (26%) and HR2 (22%).

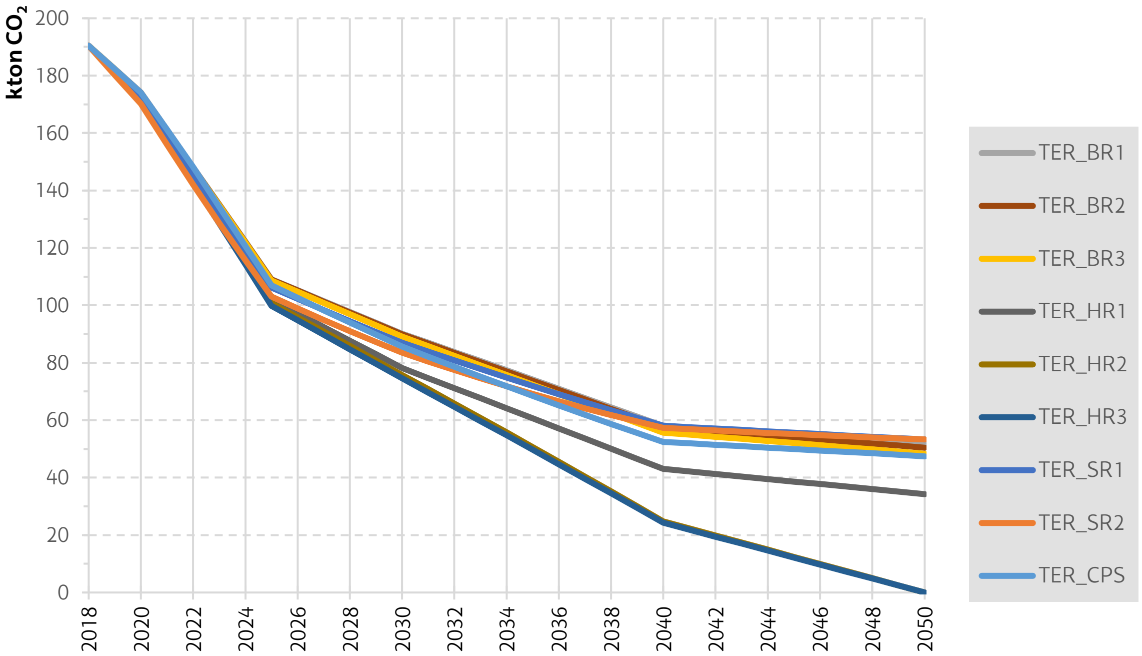

Figure 4.21. CO_2 emissions evolution by scenario in the tertiary sector. Variable EEF

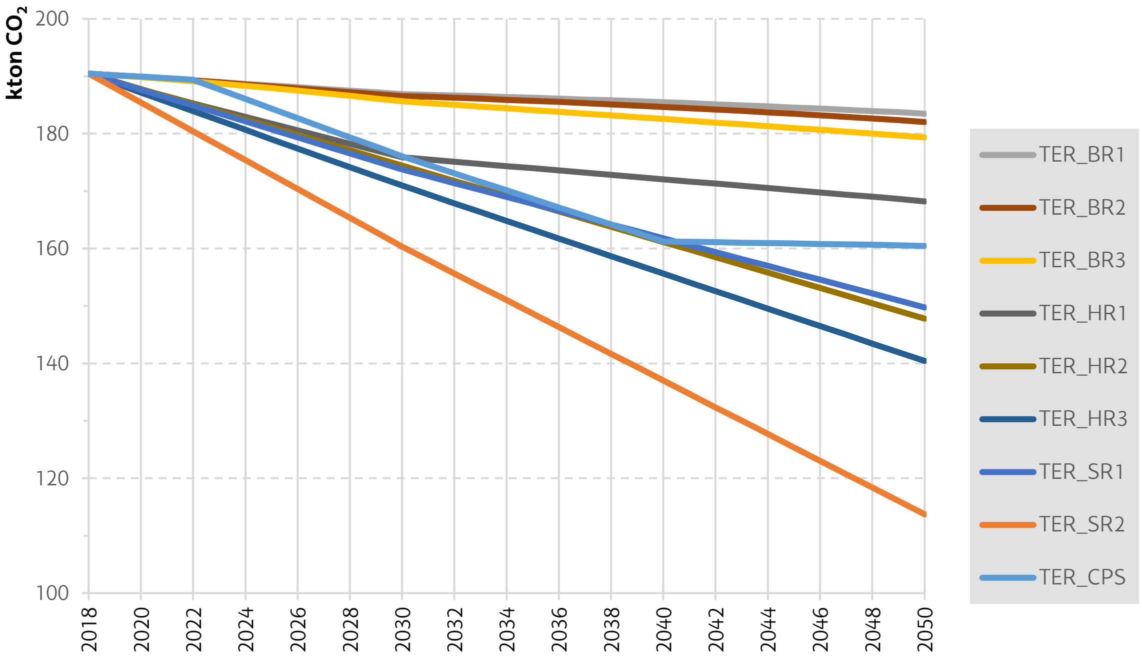

Figure 4.22. CO2 emissions evolution by scenario in the tertiary sector. Constant EEF

Table 4.13 summarises the results of the different scenarios in the tertiary sector. Systems renovation scenario SR2 achieves the largest CFES. This is explained due to the significant share of lighting and appliances in final energy consumption in the tertiary sector (see Figure 4.12). Moreover, if the decarbonisation of the grid is not considered, it is also the scenario with the greatest CCESC. Conversely, if a variable EEF is assumed, heating systems renovation scenarios HR2 and HR3 achieve the highest CCESV. Indeed, if the decarbonisation of the grid is taken into account, additional savings are achieved with the electrification of the heat services modelled in HR2 and HR3 scenarios, fulfilling a higher CCESV than in SR2 (as this scenario do not intervene on heating). Regarding economic return, consumption patterns scenario CPS yields the best SNPV. Indeed, the reductions in space heating, cooling, and lighting use imposed by the new Spanish regulation (see in Table B.21 in appendix B) achieve large energy, emissions, and economic savings without the need of capital investments, but only through behavioural changes.

Table 4.13. ECM and CPS scenarios results in the tertiary sector

Scenario	CFES (GWh)	CCESV (kton CO_2)	CCESC (kton CO_2)	SNPV (M€)
TER_BR1	402	3.304	126	-61
TER_BR2	490	3.319	145	-105
TER_BR3	703	3.355	190	-220
TER_HR1	2.145	3.683	469	-236
TER_HR2	3.491	4.074	704	-213
TER_HR3	3.927	4.096	839	-221
TER_SR1	2.561	3.346	694	171
TER_SR2	4.847	3.410	1.288	343
TER_CPS	2299	3429	593	595

City strategy scenarios

After assessing the different ECM scenarios separately, city strategy scenarios integrating a mix of ECM have been modelled, enabling the assessment of the effects of combined ECMs.

Regarding ECM building renovation (BR) scenarios, an important remark has to be made. Indeed, a workshop was held during which local stakeholders discussed the results from building renovation scenarios. Though agreeing in the need of ambitious renovation targets, the participants highlighted the lack of human and material resources to carry out the bolder scenario (BR3) in the short term (i.e. more qualified workers and means such as scaffolds are needed to cover the requirements of this scenario). Thus, a new scenario was generated named BR3', where the buildings renovation rate was adjusted (see Table B.16 in appendix B). Results from this scenario for each sector are displayed in Table 4.14.

Table 4.14. Adjusted building high renovation rate (BR3') scenario results

Scenario	CFES (GWh)	CCESV (kton CO_2)	CCESC (kton CO_2)	SNPV (M€)
RSD_BR3'	2.482	3.372	745	-384
MUN_BR3'	25	233	233	-26
TER_BR3'	669	3.349	183	-202

Taking this adjustment into account, the composition of the 3 different city strategy scenarios is displayed in Table 4.15. Social scenario prioritises the reduction of useful energy demand through fostering building renovations. In the specific case of the residential sector, this scenario also aims for the improvement of thermal comfort seeking to tackle energy poverty situations (Charlier, 2021). Technological scenario is focused on the enhancement of the efficiency of building systems, thus promoting their renovation. Finally, an ambitious scenario has been generated, combining the two approaches.

Table 4.15. City strategy scenarios description

City strategy scenarios	Sector	ECM scenarios								Consumption patterns scenarios
		BR1	BR2	BR3’	HR1	HR2	HR3	SR1	SR2	CPS
Social	Residential			X		X		X		X
	Municipal			X		X		X		X
	Tertiary			X		X		X		X
Technological	Residential		X				X		X	
	Municipal		X				X		X	
	Tertiary		X				X		X	
Mixed	Residential			X			X		X	X
	Municipal			X			X		X	X
	Tertiary			X			X		X	X

Next figures show the evolution of final energy consumption for the different city strategy scenarios in each sector. In the residential sector, the mixed scenario achieves a 57% final energy reduction by 2050 with regard 2018, the technological scenario reaches a 56% abatement, while the social scenario accomplishes a 51% decrease (see Figure 4.23). In the municipal (see Figure 4.24) and tertiary (see Figure 4.25) sectors results are similar: mixed scenarios fulfil the largest reductions (64% in municipal and 67% in tertiary). In those sectors abatements reached by the mixed scenarios are identical to the ones obtained in technological scenarios (64% in municipal and 67% in tertiary). On the one hand this is mainly due to the short useful energy demand reductions for space heating achieved in these sectors and which is reflected in the relatively poor performance of the social scenario in these sectors (54% in both municipal and tertiary). While on the other hand the large reductions achieved by the heating systems renovation scenario (HR3) and systems renovation scenario (SR2) which are share by both technological and mixed scenarios drive the similar results.

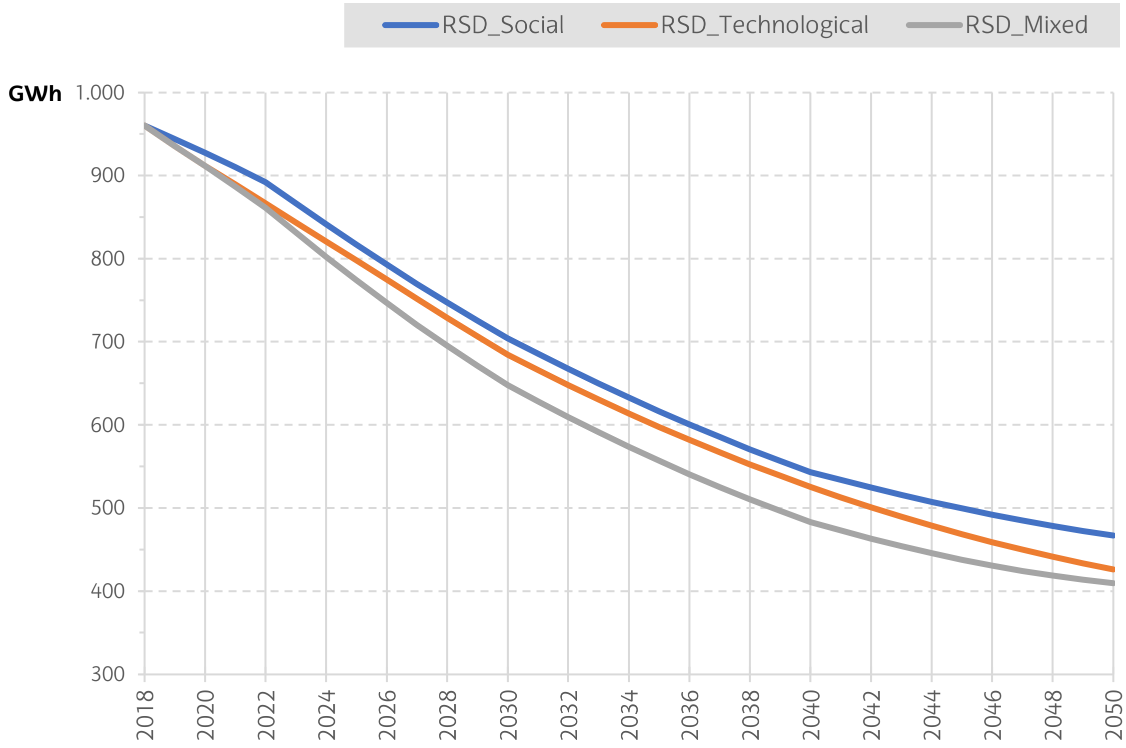

Figure 4.23. Final energy consumption evolution by city strategy scenario in the residential sector

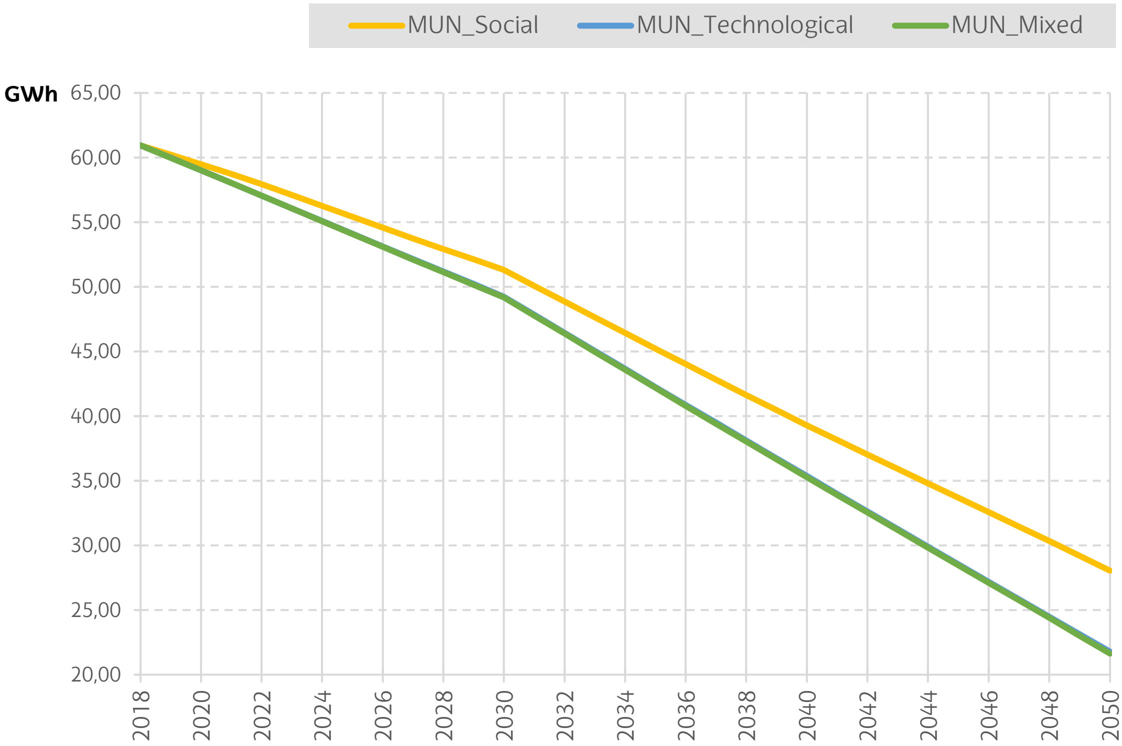

Figure 4.24. Final energy consumption evolution by city strategy scenario in the municipal sector

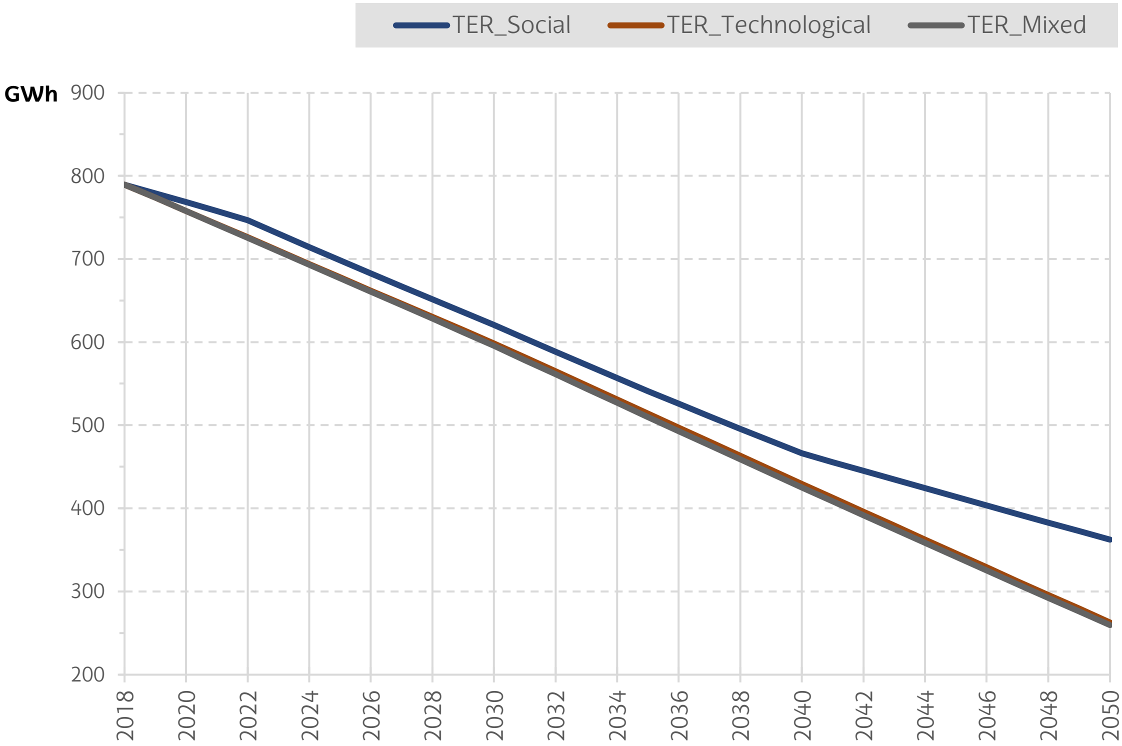

Figure 4.25. Final energy consumption evolution by city strategy scenario in the tertiary sector

Regarding CO_2 abatements, all scenarios achieve the full decarbonisation of the city building stock when considering a variable EEF (see Figure 4.26). When assessed separately, building renovation (BR) and systems renovation (SR) scenarios did not manage a carbon-free stock as they did not (or did it partially) intervene on the whole heating systems stock within the city. However, with the combination of these scenarios with the heating systems renovation ones (HR), 100% CO_2 emissions decrease by 2050 with regard 2018 is achieved, thanks to the full electrification of heat assumed in HR scenarios. Conversely, if a constant EEF is assumed (see Figure 4.27) only a full decarbonisation is achieved in the municipal sector in line with the compliance of the Basque environmental law (carbon-free electricity in public facilities and services). Regarding the rest of sectors in this case, mixed scenario achieved the largest abatements (57% in residential and 65% in tertiary), followed by technological (54% in residential and 65% in tertiary), and social scenarios (50% in residential and 51% in tertiary).

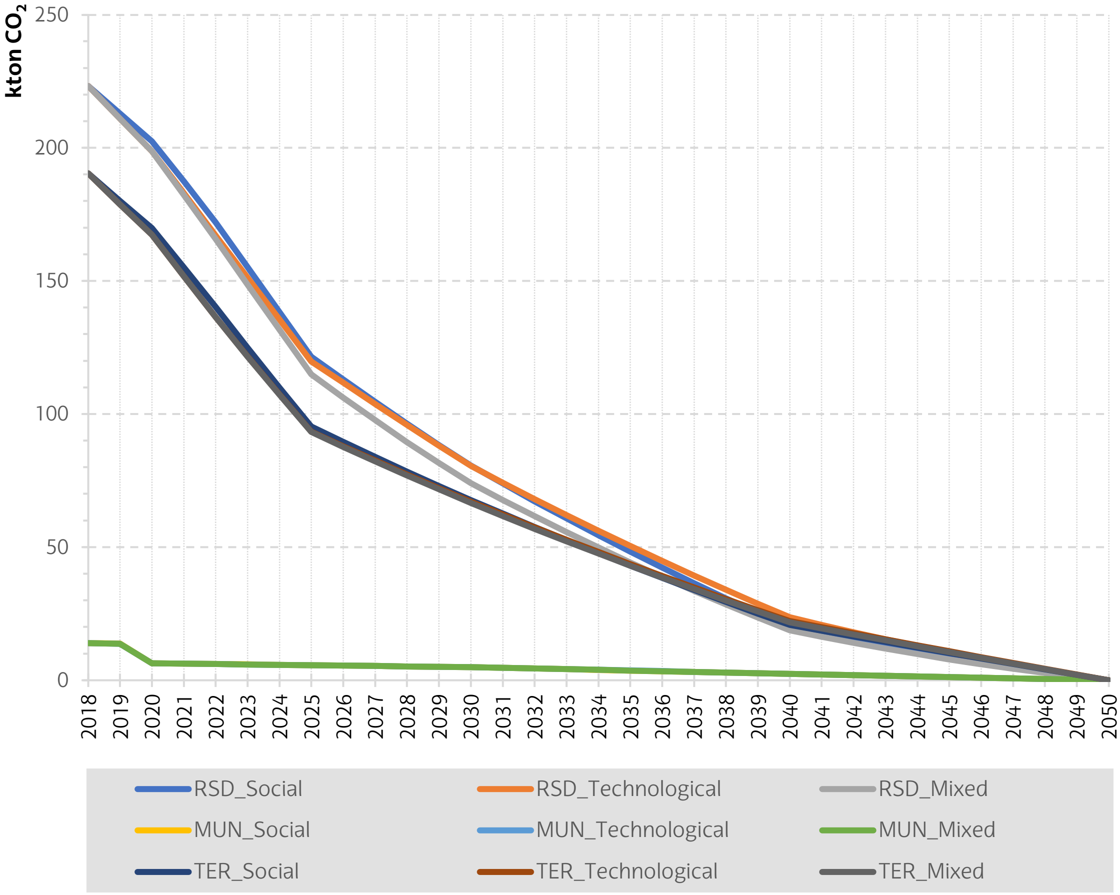

Figure 4.26. CO_2 emissions evolution by city strategy scenario in the different sectors. Variable EEF

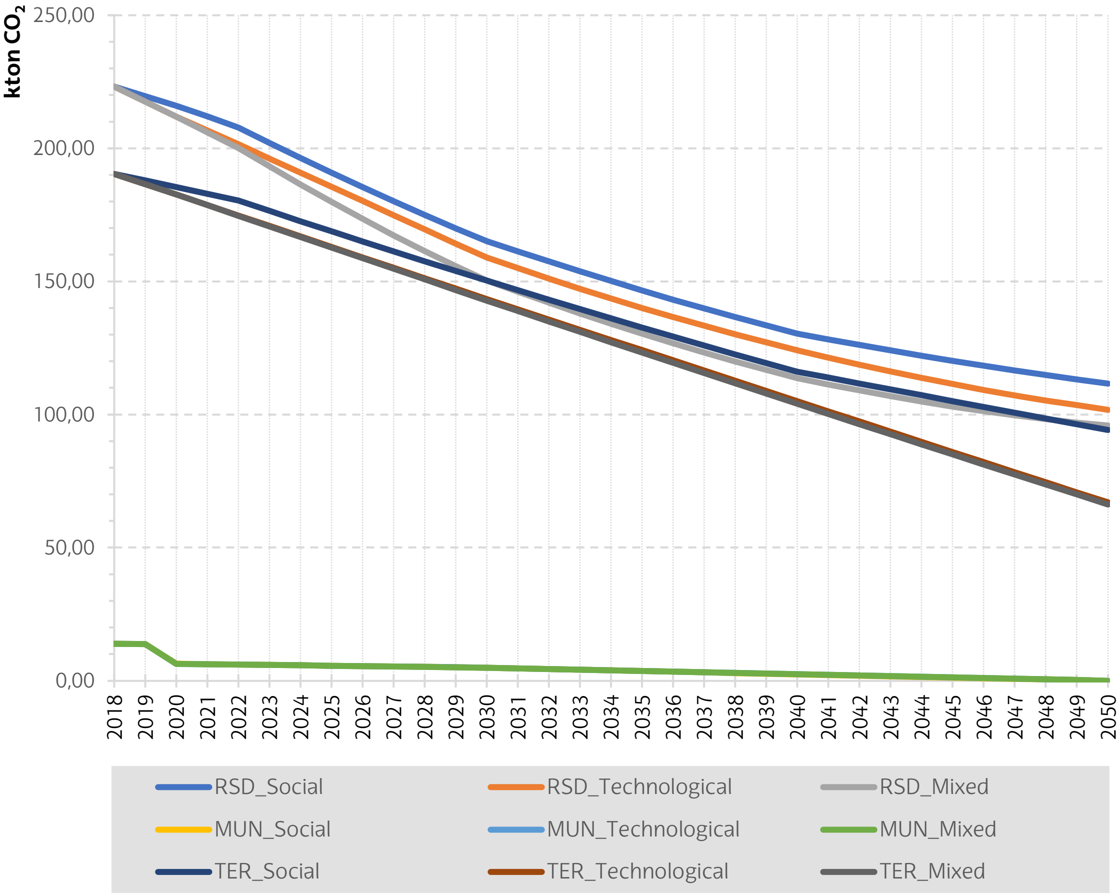

Figure 4.27. CO_2 emissions evolution by city strategy scenario in the different sectors. Constant EEF

Table 4.16 summarises the results of the different city strategy scenarios by sector. The same pattern is repeated in the residential, municipal and tertiary sectors. Mixed scenarios are the ones achieving the largest CFES, CCESC and CCESV, followed by technological, and then, social scenarios. Regarding the economic dimension, only the social, technological and mixed scenarios in the tertiary sector obtain economic benefits (i.e. a positive SNPV). This is mainly due to the great economic impact of the systems renovation scenarios (SR) (included in the technological and mixed scenarios) and the consumption patterns scenario (CPS) (included in the social and mixed scenarios) in this sector (see Table 4.13).

It should be noted however than a second economic analysis has been carried out (SNPV'), in order to give another future perspective regarding the economic outputs of the scenarios. Indeed, in this second assessment, the evolution of natural gas and electricity prices[52], the abatement costs of

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[52] Following the EU Reference Scenario (European Commission, 2016), natural gas price is expected to rapidly increase in the short term reflecting the impact of carbon taxes, and geopolitical and supply conflicts (e.g. Ukraine war) amongst others. Electricity price is also expected to rise in the short term, although in a far less rate, and then gradually stabilise.

specific technologies (i.e. heat pumps) issued from Joint Research Centre (2014) data, and the benefits of subsidies for building renovation have been considered[53]. Under these assumptions the overall economic performance of all scenarios is increased as investment costs are reduced and operational savings increased, although scenarios in the residential and municipal sectors still having a negative SNPV (i.e. investment costs still higher than operational savings).

Table 4.16. City strategy scenarios results by sector

Sector	Scenario	CFES (GWh)	CCESV (kton CO_2)	CCESC (kton CO_2)	SNPV (M€)	SNPV' (M€)
Residential	RSD_Social	9.710	4.933	2.176	-680	-404
	RSD_Technological	10.438	4.920	2.389	-600	-373
	RSD_Mixed	11.362	5.046	2.623	-623	-332
Municipal	MUN_Social	503	325	325	-35	-21
	MUN_Technological	601	325	325	-26	-13
	MUN_Mixed	603	325	325	-29	-14
Tertiary	TER_Social	7.386	4.224	1.701	351	593
	TER_Technological	8.606	4.236	2.052	17	187
	TER_Mixed	8.698	4.246	2.073	515	778

In light of the results, further energy savings are achieved when combining different ECMs. In the case of emissions reductions, this is particular noticeable when the national grid decarbonisation is not considered (i.e. CCESC indicator). In economic terms, the combination of measures help to compensate the costs of specific ECMs at the expenses of greater initial investments (e.g. mixed scenarios take advantage of the benefits from deep building and heating systems renovations by compensating their high costs with the profits from systems renovation). Overall, technological and mixed scenarios (which include the deep renovation and electrification of heat energy services scenario (HR3)) yield the best results in terms of final energy savings and CO_2 emissions abatements. These scenarios also include the ambitious systems renovation scenario (SR2) which achieves great savings at a relative low cost, especially in the tertiary and municipal sectors where lighting and appliances represent an important share of final energy use. Although not reaching such reductions, social scenarios including building renovations (BR) achieve other benefits hard to quantify such as the improvement of thermal comfort and mitigation of energy poverty situations, the improvement of the life quality of the dwellers, and the revaluation of the dwelling, amongst others.

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[53] A 30% price reduction has been considered in the €/m^2 cost for building renovation according to the current Spanish government subsidies (Instituto para la Diversificación y Ahorro de la Energía. IDAE, 2022).

4.5. Chapter conclusions

This chapter has proposed a methodology to simplify building stock energy modelling and to avoid recurring issues such as the lack of data at city level to feed the model or the prediction gap. Indeed, a preliminary analysis was carried out to show how certain models fail at capturing the actual energy use of the building stock, hence incurring in this gap. Using the Spanish city of Bilbao as case study, theoretical heating useful energy requirements issued from a bottom-up physics-based model, ENERKAD, were compared with actual ones. An average deviation of 28% was found between actual and theoretical values, being the latter greater than the former as a general rule. This deviation was further assessed against socioeconomic and building characteristics data to evaluate how these factors affect model outputs. Results have shown that income effects on the ability to satisfy thermal comfort are not correctly captured within the model. The model overestimates the useful energy demands of dwellings in energy poverty situation, i.e. it allocates a higher energy use than the actual one to buildings which do not reach comfort conditions due to economic constraints. This hinders the modelling of these conditions and impedes to properly deal with them. The effects of occupancy, and building age are also overestimated by the model, since obtained deviation increases for less occupied dwellings and older buildings. This means that hourly profiles do not match actual user habits and that aged buildings are not as inefficient as they are considered by the model. These factors cause a gap that prevents the model results from meeting current energy use. Additional data (e.g. hourly detailed actual consumption, updated thermal transmittance values, or available budget for energy expenditures) would be required to calibrate the model and reduce this gap. Unfortunately, this information is sometimes hard to obtain, is disperse, or even completely lacking at city level.

To overcome the lack of data and the performance gap, a method to model the energy use of the building stock at city level has been proposed, based on the integration of basic cadastral data and reported energy consumption. The method starts with the clustering of the whole building stock floor area by activity and heating system using cadastral data and the information included in EPCs. Combined with this floor area classification, reported energy consumption is used to define useful energy requirements (for every energy service in every activity) to match actual final energy use. As a result, the energy performance of the city building stock is characterised in detail, providing an accurate and disaggregated starting point for the generation of different energy scenarios. Conversely to other methods, no extensive building-related information (like in bottom-up physics-based models) nor large amounts of historical data (like in bottom-up statistical-based models) are needed to model the energy performance of the building stock. Additionally, no detailed modelling and scale-up of archetypes nor complex regression methods are required since the whole building stock is modelled at once with precision. Lastly, performance gap is reduced, since useful energy is directly obtained with actual data (thus implicitly including user behaviour and consumption patterns), instead of being calculated based on theoretical conditions and further calibrated.

The methodology was implemented using LEAP energy modelling tool for the Bilbao case study. The energy characterisation of the city building stock was carried out. Resulting from this first task, it has been observed that dwellings dating between 1960 and 1980 (HB1980) and commercial floor areas (TERCOMM) are the highest energy users in the residential and tertiary sectors respectively, being the first one the main consumer within the building stock. Regarding fuels, electricity and natural gas are the main energy sources within buildings. The former is predominantly used in lighting and appliances services, whereas the latter is mostly consumed in heating applications. Indeed, space heating is the most demanded energy service within the city building stock, followed by DHW and lighting. Space heating, DHW and appliances are the most required services in the residential sector, while lighting and then space heating are the most requested in the tertiary sector.

Based on this initial energy characterisation, 8 energy scenarios were modelled in every sector (residential, municipal, tertiary), each one of them assessing a particular ECM with a specific deployment depth: 3 building renovation scenarios (reducing useful energy requirements for space heating and cooling through envelope renovation); 3 heating systems renovation scenarios (focusing on the efficiency improvement of space heating and DHW systems); and 2 systems renovation scenarios (reducing energy use in cooling, lighting, and appliances services through the renovation of these specific systems). Additionally, a consumption patterns scenario was generated for each sector, representing a reduction in useful energy demands due to behavioural changes of users towards energy use. Finally, 3 city strategy scenarios were created as a combination of the previous ones.

The evaluation of the scenarios has returned the following results. Assessed separately, heating systems renovation scenarios achieve the greatest energy and emissions savings at the expenses of worse economic performances. Indeed, as heating useful energy demands are already low, investment costs (with two renovation cycles of heating systems) are still too high to compensate the operational savings from reduced energy use. Systems renovation scenarios are the best cost-effective scenarios as they reach significant reductions and large economic returns. Indeed these scenarios are particularly relevant in the tertiary sector, where lighting and appliances represent a large share in the final energy consumption (thus these ECMs having great impact). Building renovation scenarios are more effective on the residential sector than on the municipal and tertiary sectors, although still achieve less energy and emissions reductions than the ambitious heating systems renovation scenarios. On this concern it should be noted that these scenarios may fulfil other hardly-quantifiable goals such as the improvement of thermal comfort, the tackling of energy poverty situations and enhancement of dwellers quality of life, or the revaluation of the dwelling. Special attention should be given to the scenarios modelling a change in the consumption patterns of users, which yield important energy and emissions abatements at zero cost. The combination of ECMs increases the energy and emissions savings allowing to exploit the benefits from different ECMs while compensating the costs of the expensive ones. When developing integrated strategies it should be taken into account however that certain ECMs may fit better in some sectors than others (e.g. building renovations in residential rather than in municipal or tertiary sectors, or systems renovations in tertiary sector rather than in residential). Thus, to optimise the impact of the different ECMs, these should be deployed where they may have a greater effect, i.e. based on the use patterns of each floor area category. This remark is relevant between sectors but also between different floor area categories from the same sector (e.g. given a specific ECM, this may yield better, or worse, results in the commercial floor area category than in the education floor area category, both included in the tertiary sector). Furthermore it should be noted the impact of considering the decarbonisation of the national electricity grid, as additional abatements can be reached without the need for extra measures. Fuels price variation, abatement costs of some technologies, and the availability of financial grants for specific measures have also a relevant impact on the economic results of the scenarios, increasing the profitability and monetary returns of some of them.

Finally, some observations are worth to note. Treatment of available information was a time-consuming process (some of the data presented inconsistencies or was outdated and information contained in various EPCs had to be fixed and adjusted). Data collection at city level should therefore be improved and EPCs accurately carried out. On this concern, the definition of data standards and the automatisation of the gathering, processing, and update of the information feed to the model should be put forward. Regarding the energy characterisation of the tertiary sector, the clustering and definition of useful energy demands for the different floor area categories (i.e. offices, health, education, or commerce) have proven to be though tasks due to the high heterogeneity of consumption patterns within the sector. Indeed, great differences between the energy use of the different floor area categories have been observed, even within the same category (e.g. large variance on energy consumption amongst office buildings). The collection of additional data concerning tertiary buildings (through energy audits for example) could be helpful to refine their detailed energy modelling. Further improvements aside, the proposed methodology do not require large amounts of data to create building stock energy models and thus can be replicated in cities where data is not extensively available.

CHAPTER V: Methodology for integrated modelling and impact assessment of urban energy systems scenarios

Index CHAPTER V

5.1. Introduction

Cities ought to play a key role in the energy transition towards a low-carbon society. As reviewed in section 1.2.1, cities gather more than half of the world's population, being responsible of more than two thirds of global primary energy consumption and global GHG emissions. Because of their particular idiosyncrasy, urban areas are both cause and solution to climate change. Cities are taking action to reduce their emissions and to contribute to higher decarbonisation goals (see chapter III). To achieve agreed climate targets, efficient urban energy planning, supported by accurate urban energy modelling, is a must. Indeed, tools and methods have risen to model the urban energy system, which represents all the energy-related components included within the city metabolism (see sections 1.2.2 and 1.2.3). Nevertheless, addressing the complexity of the urban energy system is a great challenge and new integrated instruments and methodologies are still needed to assess the present and future energy performance of cities.

This chapter presents a methodology for integrated modelling and impact assessment of city energy scenarios. Starting from the energy characterisation of the whole urban energy system, the proposed method suggests a set of guidelines to formulate energy scenarios at urban scale, concluding with a procedure for their assessment. The aim is to allow city stakeholders to take decisions based on the results issued from the modelled futures.

The suggested methodology seeks to simplify the characterisation and scenarios modelling processes, while considering a holistic view of the city and integrating all the elements from both demand and supply sides. On the one hand, data deficiencies at urban scale are overcome by exclusively relying on simple and accessible data to characterise the current situation. Moreover, complexity in the projection of future energy use is reduced by using straightforward key parameters to model the future energy performance of the city. On the other hand, the methodology developed in chapter IV is used to model the energy use of the building stock, accompanied by the energy modelling of the transport sector, and other elements from the urban energy system such as outdoor lighting, industry sector, or supply side systems and infrastructures. The modelling of the urban energy system and simulation of future scenarios is completed by a multi-criteria assessment of the proposed alternatives, clearly identifying the benefits and costs of the different modelled futures and facilitating the decision-making process.

5.2. Chapter main contributions and objectives

Previously reviewed studies (see sections 2.3.3.2, 2.3.3.3, and 2.3.3.4) tend to focus on one specific city sector or energy vector (e.g. building or transport, electricity or heat), or on one specific aspect of urban energy systems analysis (i.e. characterisation, scenario modelling, or impact assessment). This chapter aims to integrate all city sectors and parts of urban energy systems analysis under one single methodology. All of this while achieving a high level of detail without requiring large amounts of data. Following the approach used in chapter IV, performed bottom-up modelling is calibrated with actual top-down data reported in cities inventories. On the one hand, modelled city energy use is matched with actual energy consumption within the city, thus overcoming the performance gap. On the other hand, the integration of aggregated top-down data (issued from city databases, SECAP inventories, or energy facilities) with bottom-up data (i.e. micro-level technical data such as buildings and vehicles stocks, building geometries, vehicles mileages and fuel economies, systems efficiencies, load profiles, or generation systems availability factors and installed capacities) allows the further disaggregation of the city energy model.

As a complex system where different sectors and energy vectors are interrelated, the modelling of the urban energy system should encompass all these elements simultaneously, while also represent all the energy flows occurring inside and crossing the city borders (i.e. imports and exports), and account for the energy produced locally. Hence, the main target of this chapter is to develop a methodology for the energy modelling of the city as a whole. The method proposed in chapter IV for the energy modelling of the building stock is used, while energy use in the transport sector is modelled combining vehicle stock data and other transport-related parameters (e.g. modal share, trips mileages, or fuel economies). Moreover, aspects to be considered and modelling guidelines are provided to characterise and to represent future energy consumption in other sectors such as industry, agriculture, or outdoor lighting. The modelling of energy generation systems and supply networks is also addressed. Concerning energy scenarios generation, the proposed methodology calculates future energy consumption by using accessible key parameters, thus avoiding complex projecting methods or models such as the ones used by Yu (2018), Dagoumas (2014), or Samsatli and Samsatli (2018). Furthermore, top-down and bottom-up approaches are again combined to model the multiple pathways the city can face[54]. On the one hand, a top-down approach may be used to determine the future evolution of these key parameters, while it can be also useful to shape urban (or sectoral) future energy use in an aggregated way based on the extrapolation of the identified trends of the system (including evidenced driver-energy use correlations in the past). On

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[54] See Table 2.1 to recall the main characteristics of both modelling approaches.

the other hand, the bottom-up perspective allows to capture in detail the effects of technological aspects (such as efficiency improvements, fuel switches, or changes in the stocks of buildings, vehicles, or energy devices) on energy consumption, through the accurate modelling of micro-level energy measures and policies.

Lastly, the urban energy system modelling and assessment processes are here integrated, while reducing complexity and data needs. This chapter completes the work carried out by Fichera et al. (2016) (where only a characterisation of the city end use sectors was performed) or Reiter and Marique (2012) (which did not include a multi-criteria assessment of the scenarios), and also simplifies the approaches suggested by G. Simoes et al. (2018) and Yazdanie et al. (2017). While these studies also included a holistic approach in the modelling and assessment of urban energy systems, considering all the energy-related sectors within the city and assessing the developed scenarios through different criteria, the data required for their models would be difficult to gather for many cities. The proposed approach for the characterisation and modelling of the different energy-related sectors within the city, along with the adoption of more flexible, easy-to-use, and less data-intensive methods for the modelling of energy scenarios are an important advantage for integrated urban energy modelling.

This chapter comes to integrate and complete the work carried out in previous chapters III and IV. Indeed, methods and approaches developed previously are here gathered to fully develop an integrated approach for urban energy modelling and prospective assessment supporting long-term urban energy planning (see Figure 1.6 and Table 1.1). The main objectives of this chapter can be summarised as follows:

- To develop a technique for city-wide energy modelling: from current energy characterisation to energy scenarios generation, considering all city end-use and supply sectors.
- To reduce the complexity of urban energy modelling, and especially the projection of future energy demands, by overcoming the data scarcity usually faced at urban level.
- To provide urban energy planners and policy makers with an integrated methodology for modelling and impact assessment of urban energy system scenarios.

5.3. Methodology

5.3.1. Urban energy characterisation

The proposed methodology starts with the modelling of the city energy baseline. That is, the energy characterisation of all the elements of the urban energy system. One of the major challenges faced in this task is data availability. To depict the energy performance of the city and represent all its processes accurately, detailed and disaggregated urban-level data is required. However, this information is generally hard to obtain, often dispersed or incomplete, and sometimes completely missing. Conversely, available data is highly aggregated or not precise enough. To bridge this common issue, this methodology proposes the combination of bottom-up and top-down approaches. Like for the energy modelling of the building stock in chapter IV, energy use of every end-use sector is estimated using bottom-up approaches and calibrated in order to match the sector current final energy consumption reported by the city energy inventory, or by energy utilities supplying the urban area. In other words, results from bottom-up approaches along with available low-level data are used to disaggregate this top-down, highly aggregated data. Moreover, the performance gap between actual and modelled data is tackled. A disaggregated and richly detailed energy baseline is required to model a broad spectrum of energy measures accurately. Indeed, the greater the granularity and depth of the baseline, the easier to model fine-tuned scenarios. Figure 5.1 resumes the proposed integration of bottom-up and top-down approaches for the energy characterisation of the city.

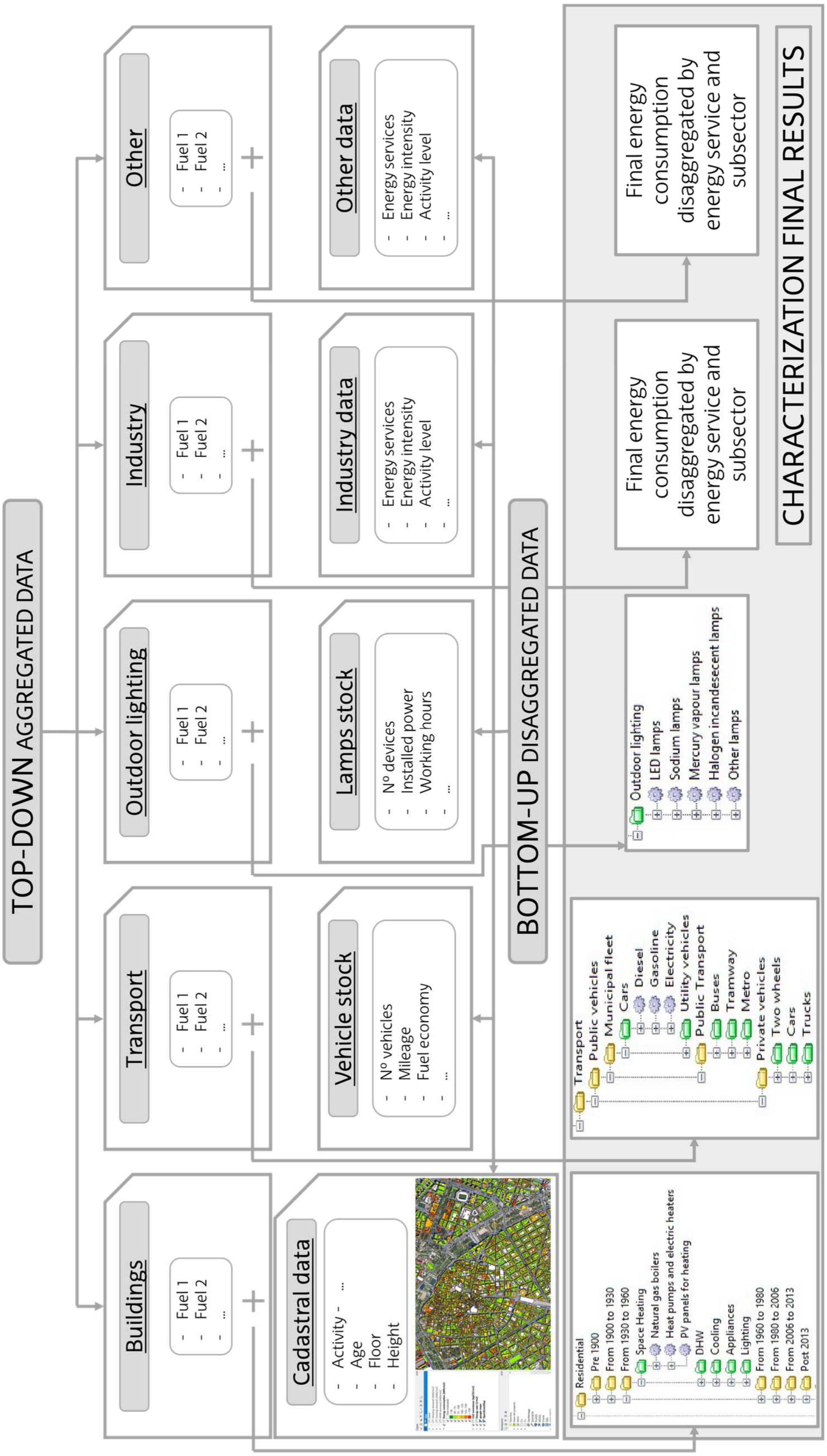

Figure 5.1. Urban energy characterisation approach

The methodology proposes a high level of detail in the modelling of the energy use of end-use sectors (e.g. building or transport sectors), since the most significant energy measures and policies at urban level are the ones directed to reduce energy consumption in the demand side (see sections 1.2.2 and 2.2.1). As an example of the relative influence of different end-use sectors on the total final energy consumption of urban areas, Figure 5.2 shows the total final energy use of a selection of cities participating within the EU MYSMARTLIFE project (2022) and MATCHUP project (2022).

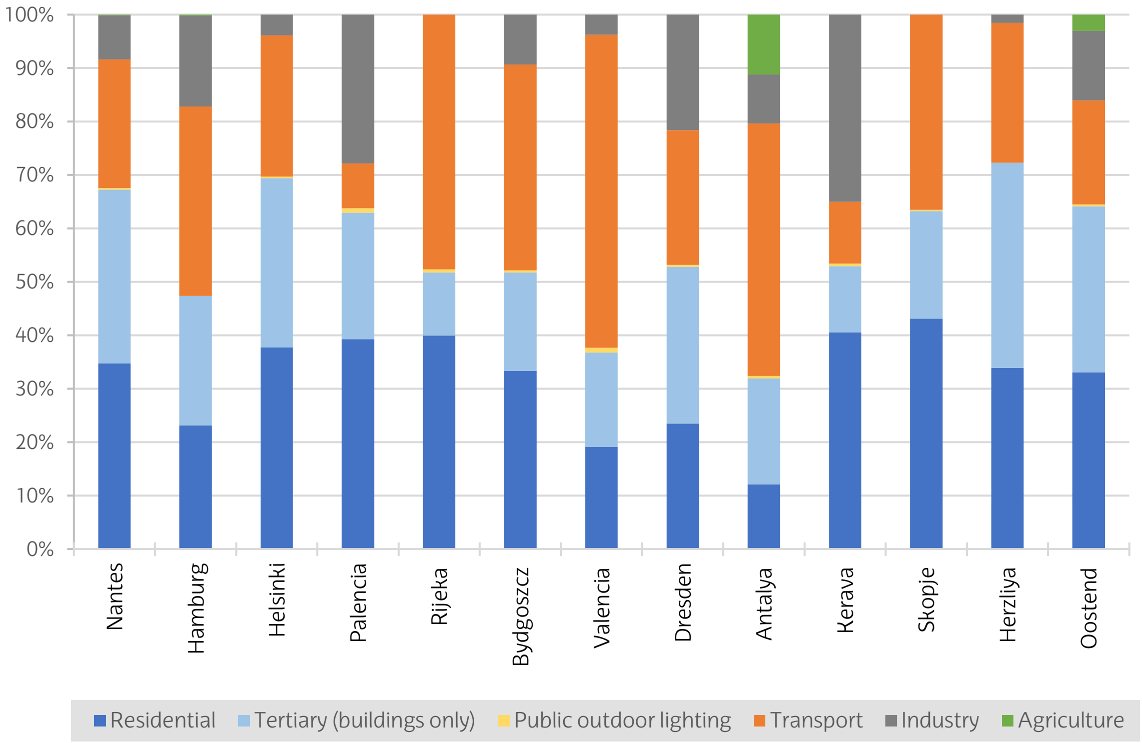

Figure 5.2. Energy consumption shares by sector of the cities within the EU projects Mysmartlife and Matchup (outdoor lighting included in tertiary sector for the cities of Hamburg and Herzliya)

The building sector (including residential and tertiary buildings) usually accounts for around 50%-70% of the total final energy consumption of the assessed cities, making the energy characterisation of this sector a relevant task. To perform it, this methodology considers the method developed in the previous chapter for building stock energy modelling (see section 4.3.2). City floor area is clustered by activity (i.e. residential, commercial, offices, health, or education), construction period, and heating system based on cadastral data, EPCs, and heating systems inventories. The floor space clustering is further combined with final energy use reported by the municipality in order to define useful energy demands that match the actual building energy use, and considering the city floor area classification (i.e. by activity or construction period), the different energy systems supplying the different energy services, and the efficiencies of these systems. With minimal data requirements, this approach disaggregates the final energy consumption of the building stock by floor area activity, energy service, and fuel. Hence establishing a highly detailed baseline which allows to model a wide range of energy measures with precision and to fine-tune energy scenarios in the building sector.

As shown in Figure 5.2, transport is, along with buildings, a major energy consumer in cities. As described by Bertoldi et al. (2018b) and Kennedy et al. (2010), cities can account for the transport final energy consumption within their borders following either a top-down or a bottom-up approach. On the one hand, the top-down approach is commonly based on the fuel sales method[55] where consumption is estimated by considering the quantity of fuel sold within the city boundaries. On the other hand, the bottom-up approach is founded on the use of higher detailed data such as registered vehicles, modal shares, travelled distances and fuel economies to estimate the energy consumption of the sector. As the proposed methodology seeks to preserve the original data supplied by the city, special attention must be taken regarding how the city reported the transport consumption in order to disaggregate it. If the city followed a bottom-up approach to account for the transport consumption, the same assumptions should be taken to disaggregate the reported information. Whereas, if the city used the fuel sales method, additional information will be required to breakdown the available energy data. A similar approach as in the case of buildings may be adopted. Provided that vehicle stock data is available, the vehicle fleet registered[56] within the city can be clustered by type and fuel (e.g. private gasoline cars, public transport electric buses, or freight diesel trucks)[57]. Different mileages and fuel economies are then allocated to each vehicle type and adjusted in order to match the aggregated transport sector energy data supplied by the city. Thus, a bottom-up approach is used to disaggregate the data from the sales method (top-down approach)[58].

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[55] Regarding the fuel sales method, Kennedy et al. (2010) remarked that this approach was appropriate for cities where in-boundary travels where predominant over cross-boundary journeys. While the bottom-up approach was more adequate for urban areas experiencing large cross-boundary commuter traffic. Altogether the authors stated that the application of one or another method in their case studies produced minimal differences, thus indicating that the use of the sales method or the bottom-up approach could be replicated in different cities regardless of the type of data available.

[56] This may however represent some inconsistencies. Indeed, the fuel sales method may account for the energy used by vehicles registered outside the city that travel within it, while conversely also account for the energy use of vehicles registered within the city but travelling outside it. In the absence of further data to differentiate the mileage travelled within the urban area by local and foreign vehicles, modellers will have to rely on stock data which is normally easier to access.

[57] It is worth to note that, as in the case of municipal buildings, it is interesting to identify the municipal and public transport vehicles so that specific actions can be modelled in municipal assets where direct actions can be undertaken by local authorities.

[58] It should be noted that activity data such as passenger-kms by vehicle type could be also used to breakdown data from the sales method, while also making easier the modelling of modal shifts. However, data regarding the characterisation of urban trips (e.g. journeys mileages or vehicles occupations) is usually inexistent. Conversely, cities keep track of the vehicles registered within their borders (for municipal tax purposes for example). Accordingly, the proposed methodology relies on vehicle stock data as a reliable and usually more available source of information at urban level.

Other energy-consuming sectors that are likely to be covered in the energy characterisation of the city are industry, agriculture, public lighting, and waste and water management. As long as data is available, industry and agriculture sectors should be included if their weight in the socioeconomic structure of the city is relevant, or if sector-specific energy and emissions savings goals are included in the city energy and climate targets. This is however unusual, as the capacity (and jurisdiction) to undertake effective and deep actions in these sectors usually falls under the competence of higher organisations and not under local stakeholders' capabilities. Thus, no further disaggregation is contemplated in the methodology proposed here as, in this case, the laborious work of data collection and treatment to breakdown the information supplied by the city would not be cost-effective.

Public lighting is indeed a service under the direct scope of local governments. Despite its low contribution to cities total final energy consumption (less than 1% in the cities presented in Figure 5.2) the renovation of old street lamps is a cost-effective and simple measure that local authorities can easily undertake. The available energy data may be disaggregated by lamp type. Municipalities usually have at their disposal information about the number and types of street lighting devices (e.g. LED lamps or sodium lamps) within the urban area. Thus, assuming an energy intensity for each device (or a consumption ratio between them), public lighting final energy consumption can be estimated following a bottom-up approach and adjusting the energy intensities if necessary in order to equal actual aggregated data.

The proposed methodology does not include a detailed approach for the characterisation and energy scenarios modelling regarding the energy use evolution of the city water and waste management services. It should be noted that these are usually handled by local authorities. Thus, it is of special interest to keep track of the energy consumption of these services as the city can directly act upon them to improve their energy performance. Moreover, waste management is a source of non-energy related emissions and should be included in the city emission inventory (Greenhouse Gas Protocol, 2014). Given that municipal sector data is available, this should be treated separately by asset (i.e. buildings, public lighting, vehicles, water and waste management, and other municipal services and facilities), as energy use in each one of them will be guided by different drivers.

Finally, regarding the energy characterisation of cities supply side, energy resources potential, energy transformation processes, and energy distribution networks must be considered. Large-scale transformation plants are not often present within urban areas and energy supply-side systems at local level normally consist of small decentralised on-site generation systems which are used for self-supply. Moreover, primary energy resources are not available in cities, and only specific local energy sources (usually renewable such as solar, biomass, or micro wind) can be harnessed.

Therefore, most cities base their supply on energy imports, and only a small share of their energy is generated within their borders. Fuels consumed by vehicles and buildings are brought to the city through extensive and complex distribution networks. Transmission losses affecting these infrastructures must be considered and quantified. Local district heating networks, power grids, or decentralised on-site generation systems such solar PV panels or micro-CHPs, must be also taken into account and modelled. In order to characterise the local production of energy, data about these systems must be collected (at least their installed capacity, working hours and efficiency). Locally-produced energy can be then calculated, and imports needed to cover the remaining city energy demand estimated.

5.3.2. Urban energy scenarios

Once the city is characterised a myriad of scenarios can be proposed. These can be modelled adopting a forecasting or a backcasting approach, aiming to explore and suggest different pathways and storylines (see section 2.1.3). A baseline unfolding of the city should be modelled. An analysis of its background as well as an evaluation of the already committed energy and climate actions and targets could be helpful in order to define a base storyline of the studied urban area, from which all other scenarios would be modelled. Moreover, this baseline scenario may further serve as a comparative benchmark to assess the achievements of alternative pathways (see section 2.3.3.3). Indeed, trends of the urban energy system and other endogenous elements should be identified so their impacts can be isolated from the ones achieved by additional measures modelled in the alternative scenarios. These could inherit those trends while adding extra effects from exogenous elements, or even suggest alternate tendencies in order to fulfil future objectives.

An analysis for the identification of potential urban energy drivers could be useful in order to advise modellers in the projection of future energy consumption patterns. However, energy drivers information and historical data are not widely available at city scale, making difficult to establish driver-energy correlations and modelling future urban energy use. In order to face this and other difficulties, the proposed methodology intends to provide a straightforward, less complex, and less data-dependent approach to generate energy scenarios at city level.

The proposed methodology focus on the modelling of future final energy consumption in the end-use sectors of the city demand side. Bottom-up approaches are used to perform this task, while top-down data is used to calibrate the results. Moreover, a top-down approach may be also integrated by including an econometric perspective in the prospective modelling of specific factors which ultimately influence final energy use. That is, if enough urban data is available, macroeconomic variables such as population, household income, GDP, or energy prices, may be used to determine the evolution of the key parameters employed by the proposed methodology (e.g. built floor area, vehicles stocks, the penetration of one energy technology or another, or the deployment rate of a specific energy measure) to model future energy use. Approaches to model future energy consumption in the different end-use sectors from the demand side of the urban energy system are suggested next. Regarding the city supply side, the method only considers its characterisation. Thus the evolution of its performance will depend on the tool and technique (simulation or optimisation) chosen by the modeller.

Building sector

The approach to model future energy consumption in the building sector has been developed in the previous chapter (see section 4.3.2) and it is based on the evolution of the building stock floor area. That is, the evolution of final energy consumption is modelled by shifting shares of floor area between non-renovated and renovated stocks, as well as by supplying shares of heated floor area with new and more efficient heating systems (see Figure 4.1). Indeed, improved useful energy demands and more efficient energy systems are defined for renovated and new buildings stocks[59]. Thus, when shifting a portion of floor area from the current stock of a specific building category to the renovated stock of the same building category (this shift representing the energy renovation of this floor area portion), a reduction in final energy consumption is achieved. Without considering the energy renovation of the building, savings can be also modelled in the current stock of a certain building category by increasing the share of floor area supplied by more efficient heating systems (e.g. considering that a certain amount of heated floor space will be supplied by a heat pump replacing the current gas boiler system), or by reducing the useful energy demands of specific energy services resulting from shifts in the consumption and lifestyle habits of final users. Scenarios can explore the impact of different renovation rates, penetration of diverse building energy technologies and solutions, or the effect of building-specific energy policies. To quantify the degree of implementation and the potential of these actions in the city, modellers might consult local stakeholders, revise land-use urban plans, and align the development of these actions with national energy and climate targets. Finally, scenarios can also model the effects of socioeconomic phenomena such demographic variations (e.g. establishing a relationship between the number of city inhabitants and the need of residential and tertiary floor areas), or economic impacts (e.g. establishing a relationship between useful energy demands and energy prices or households incomes).

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[59] National building codes and other building-related regulations may be useful in this task (e.g. setting envelope transmittance values requirements for the envelope of new and renovated buildings, or renewable shares in their final energy consumptions).

Transport sector

Transport future energy use will be determined by the evolution and changes in the vehicle stock and modal share of the city, as well as by technological improvements and changes in the characteristics of trips (e.g. journeys distances)[60]. On the one hand, old vehicles may be retired or replaced by new more efficient ones, the number of a certain type of vehicles can simply decline due to mobility policies (e.g. circulation bans for the most pollutant cars), or the use of a specific mode of transport increase because of changes in the modal split (e.g. increase of bus or rail journeys due to a shift from private towards public transport use)[61].On the other hand, energy use may be also affected as a result of the improvement of vehicles fuel economy or due to the decrease of their annual mileage, both achieving a reduction in energy consumption. As for the building sector, besides the technical drivers influencing final energy consumption, socioeconomic phenomena can be also considered to include a top-down perspective in the modelling of future transport energy use (e.g. fuel prices evolution influencing the city modal share).

Public lighting

The evolution of public lighting energy consumption will be determined by the changes in the stock of devices. Energy scenarios should consider new areas of the city equipped with public lighting, and the renovation of the old lamps by more efficient ones. Similarly to the approach adopted for the buildings and vehicles stock changes, the replacement of old devices with higher energy intensities by new efficient ones (i.e. with lesser energy intensities), achieve an abatement of the energy consumption.

Industry and agriculture sectors

Modelling of future energy consumption within these sectors is more diffuse as the energy drivers which explain it are usually macro-parameters which are not related to the city own performance. Therefore, this methodology does not contemplate a specific method to project the energy consumption of these end-use sectors. It is recommended to review national sector-specific trends, plans, and targets, as well as the past tendencies of the sectors, to get an idea of the expected

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[60] See Marique and Reiter (2012) who proposed a similar approach to model urban transport energy consumption.

[61] These kind of mobility measures have an impact on the distance travelled by vehicles (e.g. reduction in cars annual mileages and increase in mileages of buses) or in their occupation (e.g. increase of passenger-kms in buses). However, this methodology assumes that the result of the gradual decrease or increase in the use of specific vehicles results ultimately in a reduction or rise of the stock itself. Nevertheless, modellers should be aware that changes in the modal split do not imply one-to-one shifts in terms of vehicles. That is, for example, the decommission of a single private car in favour of the use of public transport would not result in the introduction of a new single bus, but the withdrawal of several cars would be equivalent to the introduction of a new bus.

evolution of these sectors and to align the development of industry and agriculture within the city (if present) with national trends.

5.3.3. Urban energy scenarios assessment

To assist urban energy planning, modelled scenarios are assessed and their impacts quantified. The proposed methodology evaluates the results from the generated scenarios under different perspectives Indeed, the energy, environmental, and economic performance of each scenario is assessed. That is, the achieved energy savings, emissions abatements, and economic returns of the different actions, measures, policies, strategies, and other exogenous and endogenous phenomena included in the scenarios are evaluated. Regarding the economic evaluation, the method developed by Arrizabalaga (2017) is followed. Economic evaluation, performed through Life Cycle Cost (LCC) analysis, serves as input for an extended IO model which is used to measure macroeconomic and social indicators such number of generated jobs, income increase, or GDP changes. However, it should be noted that IO tables are not usually available at city scale, hence intensive work would be needed to adapt available IO tables (usually national or regional) to a city level.

For each dimension (energy, environmental, economic) indicators are defined allowing to understand scenarios results with a wider perspective, as well as to prioritise them by weighting the different indices. The selection and definition of the aforementioned indicators should be done in collaboration with local stakeholders in order to correctly evaluate the needs and targets of the city. Indicators proposed by SCIS (2017) or Joint Research Centre (2016) could be used as a reference. Other measurable variables for the assessment of smart-cities are postulated in the EU STEEP project (2015), CITYkeys project (2017), and REPLICATE project (2017). Once indicators are selected, they are calculated for each scenario.

Finally, based on MCDA methods like the Analytical Hierarchy Process (AHP), indicators are weighted and compared, thus highlighting the relevance of one above the other based on the local stakeholders' preferences[62]. As the policies and measures implemented in the scenarios will have their own benefits and costs regarding the different dimensions to be assessed, this method allows city stakeholders to value which impacts are perceived to be more critical in the city. By weighting their impacts, scenarios are prioritised and the city can identify the one that best suits its long-term vision, being this the first step for the elaboration of an energy transition plan. Figure 5.3 illustrates the assessment procedure followed in the proposed methodology.

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[62] This develops and completes the scenarios assessment carried out in chapter IV.

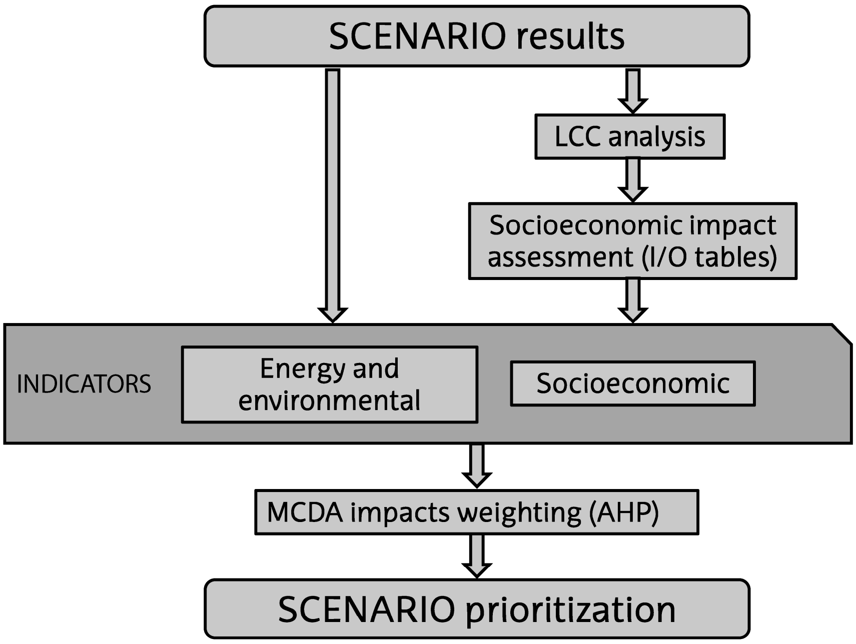

Figure 5.3. Urban energy scenarios assessment approach

5.4. Case study

Building on the work carried out in chapter III, the suggested methodology has been put into practice in the Spanish city of Valencia. Located in the Mediterranean Sea, Valencia is Spain's third biggest city with a population of 801.545 inhabitants (2020). LEAP energy modelling tool (see description and rationale in section 2.1.2) has been used for the energy characterisation of the city baseline and for the simulation of the energy scenarios. Only the municipality area (135 km^2) has been considered in the model, thus excluding the bigger metropolitan region. Concerning the time resolution, the model broadens the city SECAP time horizon (2030) and simulates the energy city performance until 2050. Results from the building and road transport sectors characterisation performed in chapter III have been completed with the description of other energy end-users such as public lighting, industry or rail transport, besides the integration of the city supply side systems and infrastructures. The modelled reference energy system is shown in Figure 5.4.

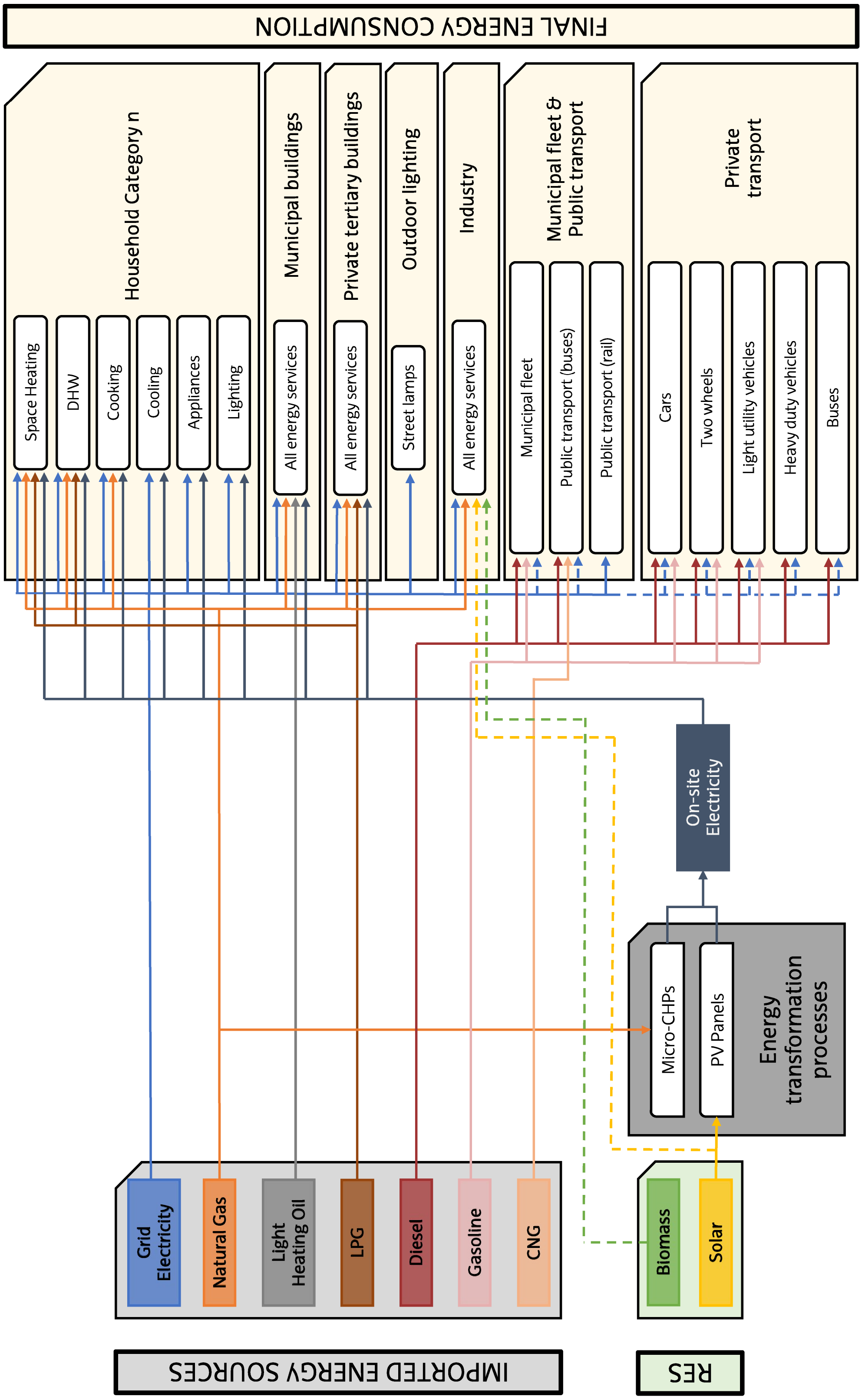

Figure 5.4. Reference Energy System of the case study (dotted lines represent additional fuels and connections modelled in the scenarios)

5.4.1. Urban energy characterisation

The characterisation of Valencia's residential and tertiary sectors was carried out in chapter III (see sections 3.4.2.1 and 3.4.2.2 respectively)[63]. Disaggregated residential and tertiary sectors final energy consumptions are shown in Table A.4 and Table A.6 in appendix A, while considered energy systems efficiencies and useful energy demands for every energy service in those sectors are detailed in Table A.3, Table A.2 and Table A.6 respectively in appendix A.

Regarding the transport sector, the energy characterisation of road transport was carried out in chapter III (see section 3.4.2.3) following a bottom-up approach. Results from this approach have been updated, further enlarged (including other road vehicles and rail transport) and disaggregated (between municipal[64], public transport and private fleets), and refined to match the latest data reported by the city[65] (Ajuntament de València, 2019, 2018). Indeed, the municipality used the fuel-sales method to account for the consumption of the transport sector within its borders. To fit with this data, mileages and fuel economies assumed in Table A.8 in appendix A, have been reworked to define an energy intensity for each vehicle (see Table C.1 in appendix C) in accordance with the reported final energy consumption of road transport. Thus, through the adjustment of the bottom-up approach, data obtained through the sales method (top-down approach) is disaggregated (see Figure 5.5).

Figure 5.6 shows total final energy consumption disaggregated by end-use sector and fuel in the city of Valencia in the base year. As it can be observed, transport is by far the most-consuming sector in the city representing 56% of total final energy consumption, while buildings in both residential and tertiary sectors represent 22% and 18% respectively. Regarding distribution of final energy use by energy carrier, diesel consumed in the transport sector represents the higher share (43%), followed by electricity (31%), and natural gas (11%).

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[63] Note that the approach followed in chapter III for the energy modelling of the building stock (Valencia case study) is indeed a less mature version of the methodology later developed in chapter IV (case study of Bilbao). Hence, results and energy characterisation of the building stock in the case study of this chapter are less detailed than the ones in the case study of chapter IV.

[64] Municipal fleet includes utility vehicles such as police cars or light utility vehicles. Public transport vehicles such as buses are accounted in the public transport sector.

[65] Note that in chapter III, integration of bottom-up with top-down data was only carried out for the building sector, whereas transport sector measures were modelled following a bottom-up approach without matching top-down data. In this chapter, the bottom-up modelling is adjusted with reported data. On this concern, 2016 final energy consumption was the latest data available for the transport sector. Hence, energy and vehicle stock data from 2016 have been used to define adjusted energy intensities. These have been further applied to the 2018 vehicle stock, thus updating the transport energy data (see Figure 5.5) and obtaining a full 2018 baseline situation for the city (see Figure 5.6).

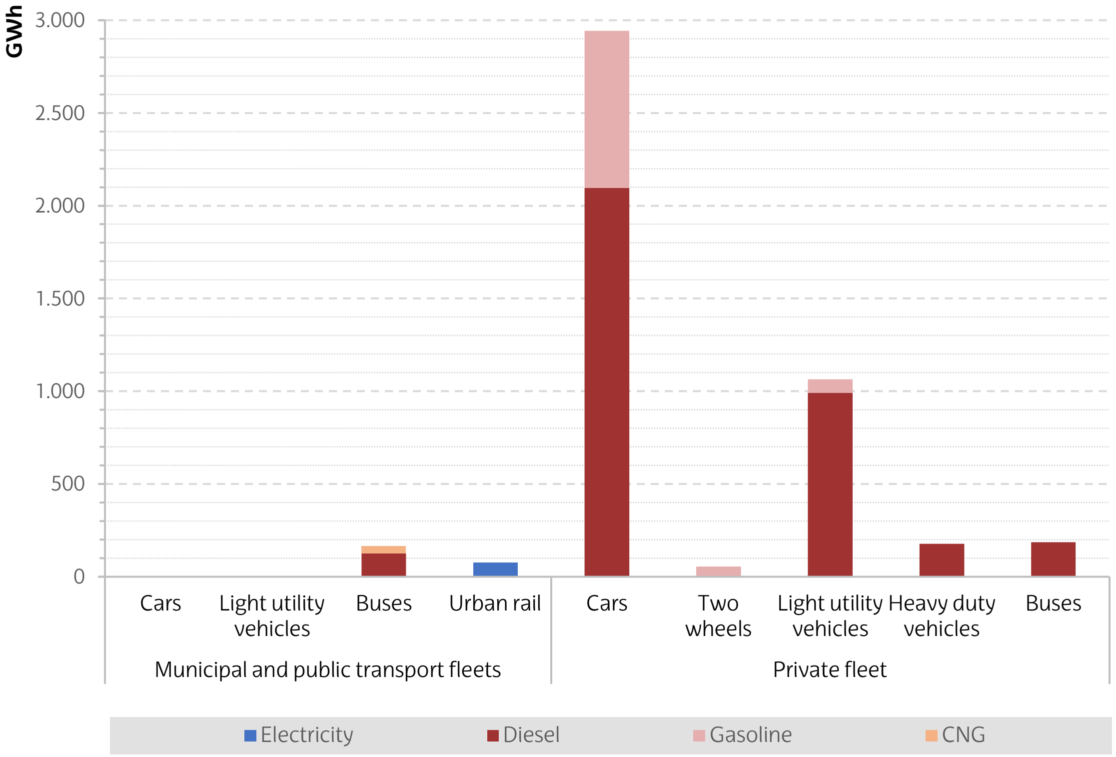

Figure 5.5. Public and private fleets final energy consumption by vehicle type in Valencia (2018)

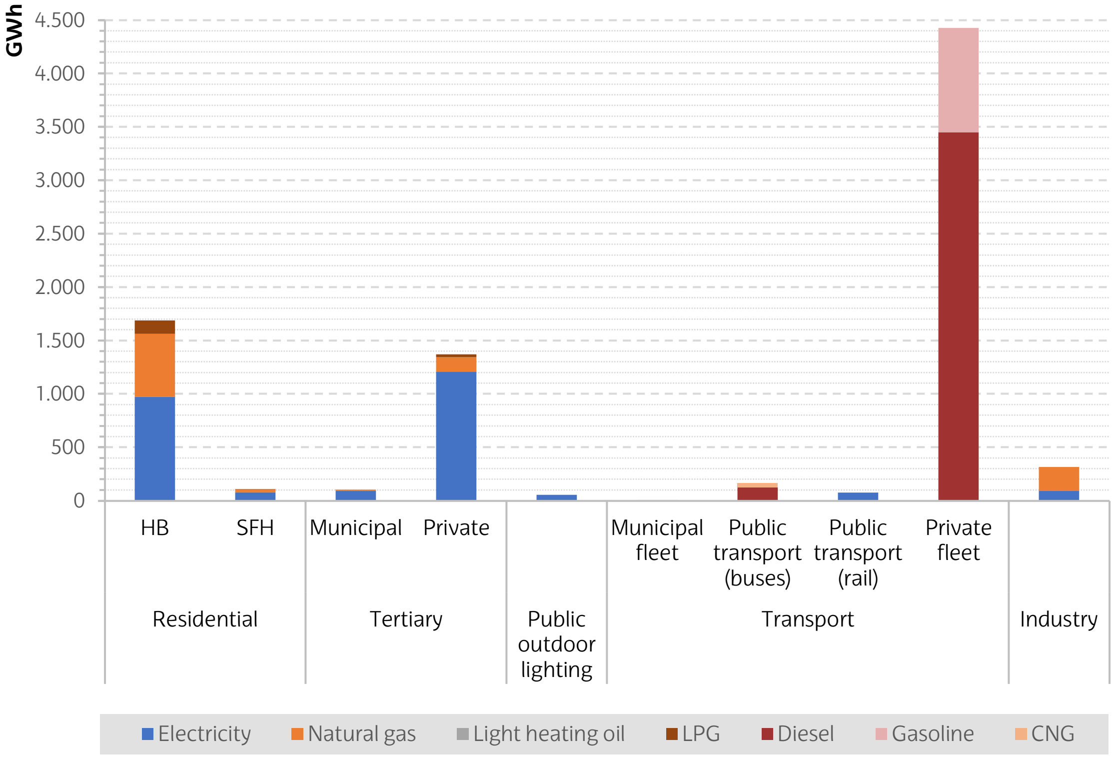

Figure 5.6. Total final energy consumption by end-use sector and fuel in Valencia (2018)

Concerning the city supply side, the only generation systems existing in Valencia are solar PV panels and micro-CHP installations. These on-site generation systems are used for self-consumption purposes, thus reducing the electricity demand from the grid. Electric installed capacity of these decentralised generation systems is displayed in Table 5.1. Produced electricity is then allocated to the sectors where the systems are themselves located and consequently where the electricity is consumed. Nevertheless, on-site electricity merely represents 0,6% of total electricity within the city. Hence, the former is mainly imported from the national grid. Remaining consumed fuels are also imported. With regard to the distribution networks, only electricity grid distribution losses have been taken into account and estimated on a 7% based on data from statistical data (The World Bank Group, 2018) and the MYSMARTLIFE project (2022). Electricity produced on on-site generation systems is considered to be losses-free.

Table 5.1. On-site electric generation capacity (in kW) by sector and technology in Valencia (2018)

	Residential	Municipal buildings	Private tertiary buildings
Solar PV panels	211	2.293	3.186
Micro-CHP	-	17.105	-

Sankey diagram in Figure 5.7 shows the link between supply and demand sides in the city of Valencia in the base year (2018).

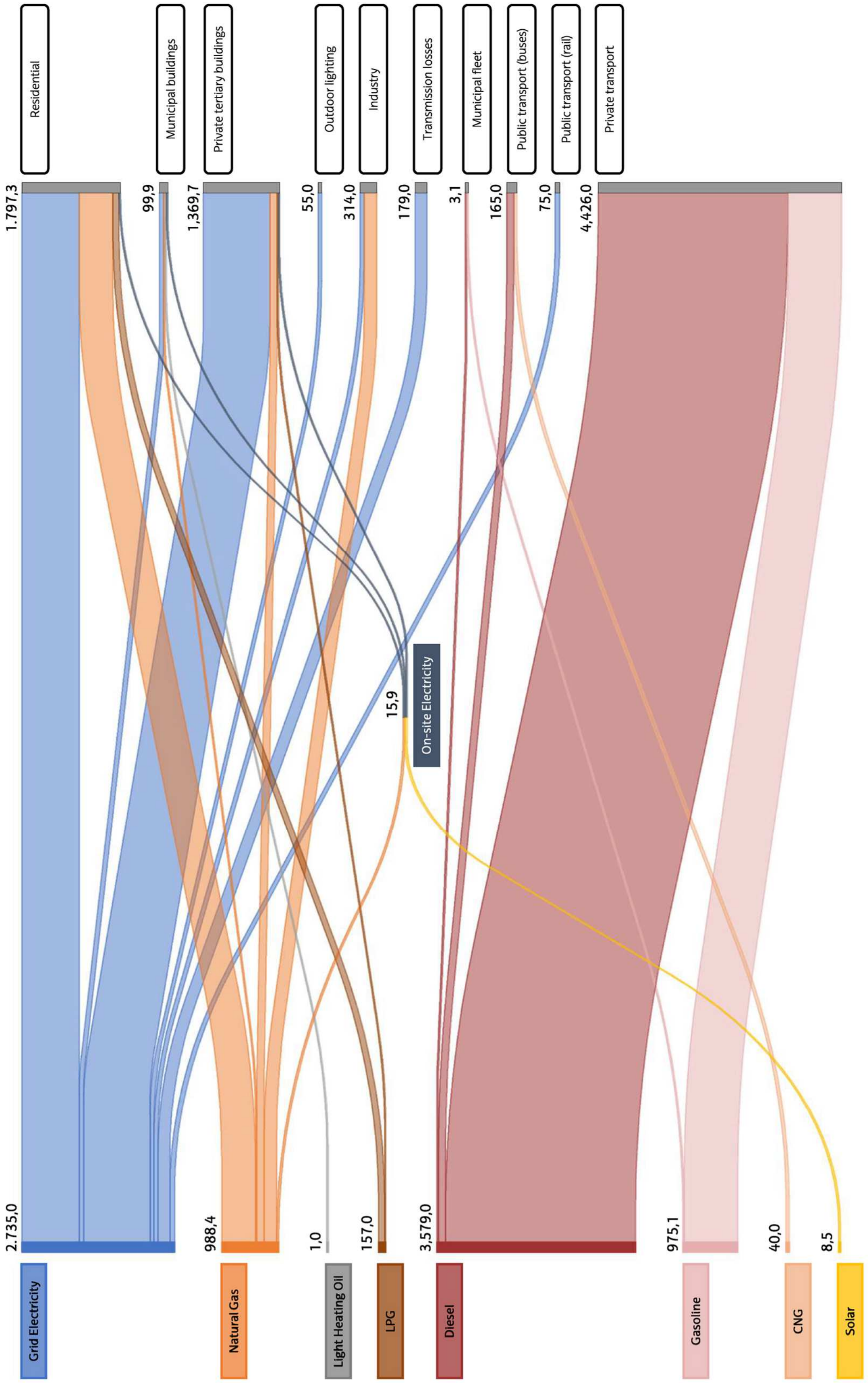

Figure 5.7. Sankey diagram. Valencia 2018

5.4.2. Urban energy scenarios

Once the energy characterisation of the city has been completed through the disaggregation of available data, four scenarios have been modelled: a BaU and three alternative scenarios[66].

- BaU scenario: this scenario models an upkeep of the natural energy trends of the city while slowly introducing new trends and low deployment of energy measures. It serves as a basis for the development of the three alternative scenarios, which inherit its trends and implemented measures.
- Building scenario: in this scenario the city concentrates its efforts and resources in the renovation of buildings in both residential and tertiary sectors. Energy measures in the transport sector are also carried out but at lower level.
- Mobility scenario: in this scenario the city focuses on the transport sector: measures to induce changes in the modal share are promoted and a high penetration of EVs is considered. Renovation of buildings is also contemplated but at slower pace.
- Mixed scenario: in this scenario the city acts in a balanced manner in both building and transport fields. This is an intermediate scenario where measures modelled in the previous alternative scenarios are combined at lower grades than the sector-specific scenarios.

As a summary, considered features and deployment level of modelled measures in the alternative scenarios are outlined in Table 5.2. Detailed considerations and hypotheses for the modelling of end-use sectors in each scenario are shown in Table C.2 in appendix C, while the modelling approaches followed to model the evolution of final energy consumption in the different urban energy systems elements are detailed next. In addition, for every end-use sector, potential drivers, trends, and historical data are discussed to contextualise the considered hypotheses for the BaU scenario (which serves as a reference for the rest).

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[66] Although sharing the same case study as chapter III, note that scenarios modelled in the present chapter do not include the impacts from the measures included in the SECAP (nor the adapted ones from the national plan calculated in the aforementioned chapter). This decision is motivated by three main reasons: (1) from chapter III discussion and conclusions sections 3.5 and 3.6, some impacts from the city SECAP measures are extremely ambitious and should be revised; (2) SECAP is not a legally binding document, thus its actions have not been included in the BaU scenario, (3) a more explorative perspective has been adopted without considering SECAP measures as a way to test the integrated methodology suggested in this chapter in a case study where no energy plan is active.

Table 5.2. Deployment level of modelled measures in the alternative scenarios

Sector	Modelled feature/measure	Alternative scenario		
		Building scenario	Mobility scenario	Mixed scenario
Residential	Renovation rate	+++	+	++
	New households*	=	=	=
Municipal buildings	Renovation rate	+++	+	++
Private tertiary buildings	Renovation rate	+++	+	++
Public lighting	LED lamps renovation*	=	=	=
Industry	ECM implementation*	=	=	=
Municipal fleet	Fleet evolution	=	=	=
	Fleet electrification	+	+++	++
Public transport	Public transport use (Buses)	+	+++	++
	Fleet electrification (Buses)	+	+++	++
	Urban rail use	=	+	=
Private transport	Private vehicle use reduction	+	+++	++
	Fleet electrification	+	+++	++

"=": same deployment level as the BaU; "+": medium deployment compared to the BaU; "++": high deployment compared to the BaU; "+++": very high deployment compared to the BaU

* Not evaluated in the final assessment

For the residential sector, methodology developed in section 4.3.2 for the modelling of future energy consumption in buildings has been applied. Energy use evolves according to the change in the residential floor area of the city. That is, the addition of new dwellings increases the overall final energy use, while the transfer of households from the current (non-renovated) to the renovated stock decreases it[67]. Considered characteristics of renovated and new dwellings are detailed in Table C.3 in appendix C. In the studied case, the rate of renovated households varies across the different scenarios, while the evolution of new dwellings remains unchanged with respect to the BaU scenario. On this concern, assumptions for the evolution of the renovation rate and the number of new households in this scenario are relevant decisions. Based on national reports (ESADE, 2022; Ministerio de Transportes Movilidad y Agenda Urbana, 2022b), a 0,1% yearly renovation rate has been assumed for the city of Valencia (this rate is further increased up to 0,5% from 2030 onwards, assuming a slight rise in the number of yearly renovated households). Regarding the number of new

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[67] Additional impacts can be considered and modelled besides the ones obtained by the addition of new dwellings or the renovation of buildings envelope or heating systems. Useful energy demands of the different stocks (current, renovated, and new households) may change due to other effects such as the impact of HDD or the effect of household income on the use of heating or other energy services, thus having an impact on the overall consumption of the sector. These effects however have not been considered in this case study.

households, according to municipal projections (Ajuntament de València, 2017) the city population will stagnate in the following years (when not even decrease). This effect may be compensated in part by the reduction in the number of dwellers per household, resulting on a nearly-zero increase in the need of new dwellings in the next years, followed by a later stagnation as see in Figure 5.8.

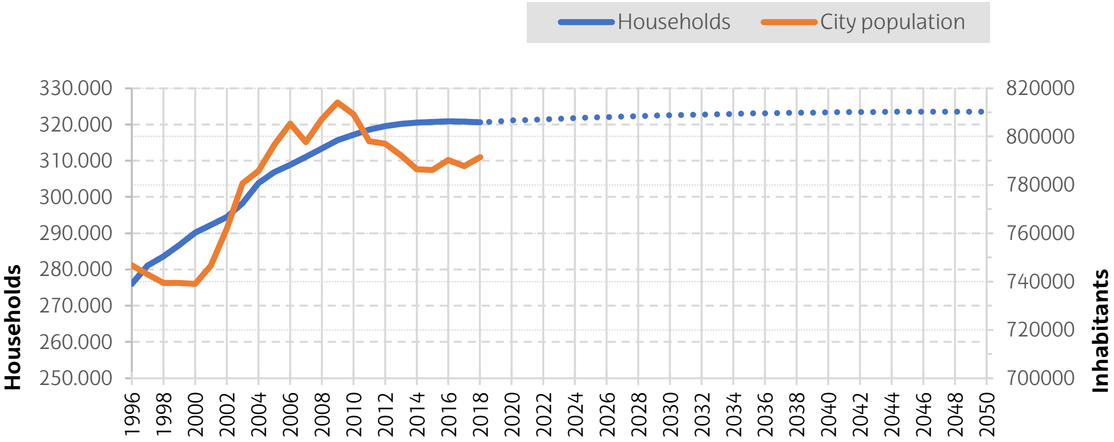

Figure 5.8. New households evolution in the city of Valencia. BaU and alternative scenarios

The modelling of future final energy use in municipal and private tertiary buildings follows a similar approach as for the residential sector. That is, municipal and private tertiary floor areas are shifted from the current (non-renovated) to the renovated stock, representing the energy impact from buildings renovation[68], while new floor area increases the overall final energy consumption of the sector. It should be noted however, that due to the difficulty of foreseeing new tertiary buildings in the city, no additional floor area is considered. Alternatively, to represent the impact of new or growing services, useful energy demands allocated to existing buildings are projected into the future (while keeping constant the total (existent plus new) tertiary floor area). On this concern, different urban drivers (such as population, GDP, or GVA) have been assessed to explain the energy performance of these sectors, although due to the lack of enough data, no solid correlations could be established. Henceforth, the projection of municipal and private tertiary buildings useful energy demands is assumed to follow the same trend as the extrapolation of last years final energy consumption. Concerning energy use in municipal buildings, although population in the city has dropped, energy use has been slightly increasing in the last decade. Based on this profile and considering a city aging population (demanding more public services) it is reasonable to assume a steady, though small, increase of energy demand in municipal buildings (see Figure 5.9). Regarding energy consumption in private tertiary buildings, the 2008 economic crisis meant a decrease in both

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[68] See Table A.7 in appendix A for considered savings achieved by envelope and lighting renovation. Additional savings are achieved considering that renovated buildings are equipped with more efficient heating and cooling energy systems.

private tertiary GVA[69] and final energy use. Although the former has resumed its growth path, the latter has stabilised. According to this context, it could be assumed a marginal increase in the energy consumption in private tertiary buildings in the following years, regardless of the economic development of the city (see Figure 5.10). Lastly, it should be noted that, since they are based on past developments, it is assumed that resulting projections from Figure 5.9 and Figure 5.10 do not contain the effects of any relevant deployment of ECM or energy policies (i.e. they can be considered WOM projections). Therefore, additionally to these evolutions, different renovation rates are assumed for each scenario: from a slow-paced renovation rate in the BaU scenario, to a high renovation rate in the building scenario (see Table C.2 in appendix C).

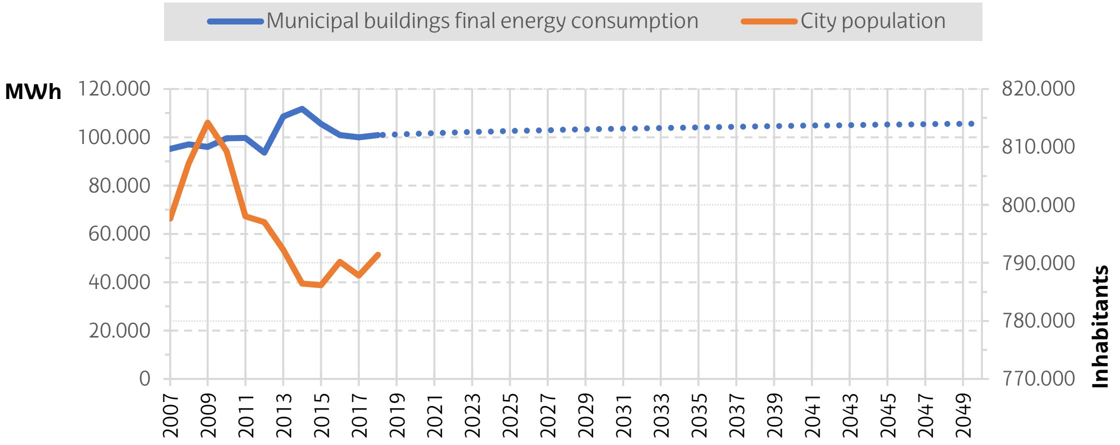

Figure 5.9. Municipal buildings final energy consumption. WOM projection

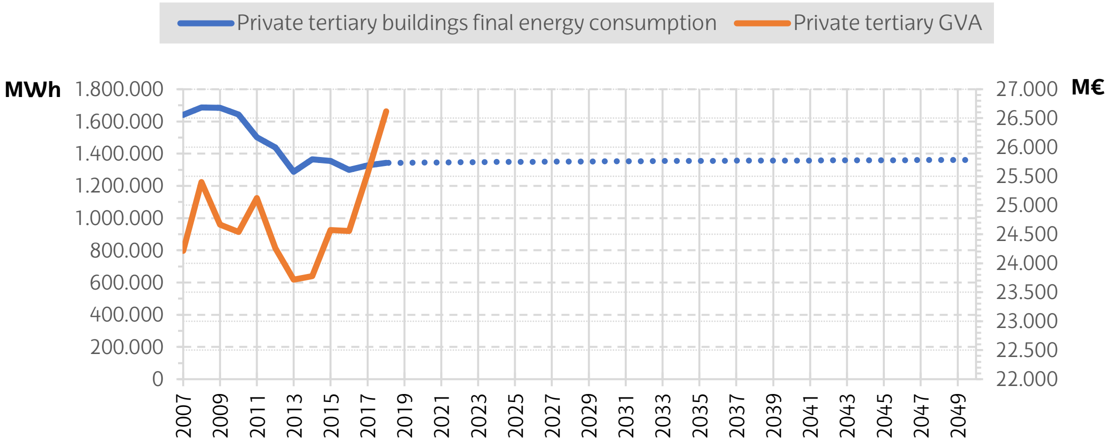

Figure 5.10. Private tertiary buildings final energy consumption. WOM projection

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[69] Due to the lack of data at urban level, provincial-level GVA is displayed. Valencia is however the capital city. It can be then assumed that the city has the greatest weight within the province GVA.

Public lighting final energy use is modelled through the variation in the number of total devices and the renovation of old devices by LED lamps. An energy intensity has been assigned to each type of lamp and an average 70% saving has been considered between old and LED devices based on monitored data (Instituto para la Diversificación y Ahorro de la Energía. IDAE, 2017). Total number of lamps is assumed to growth with the same rate as new households.

Concerning the industrial sector, a general approach has been adopted. The future energy performance of the industry within the city has been aligned with national trends. First, the recent development of Valencia's industrial sector has been assessed. Though sectoral GVA has recovered since the 2008 economic crisis, industrial final energy use has kept falling in general terms (see Figure 5.11). Based on that WOM projection, an additional final energy reduction of has been considered for the BaU and alternative scenarios, along with the sector partial electrification and a small penetration of renewable heat (from biomass and solar thermal collectors) based on national perspectives (Ministerio para la Transición Ecológica y el Reto Demográfico, 2020a, 2020b).

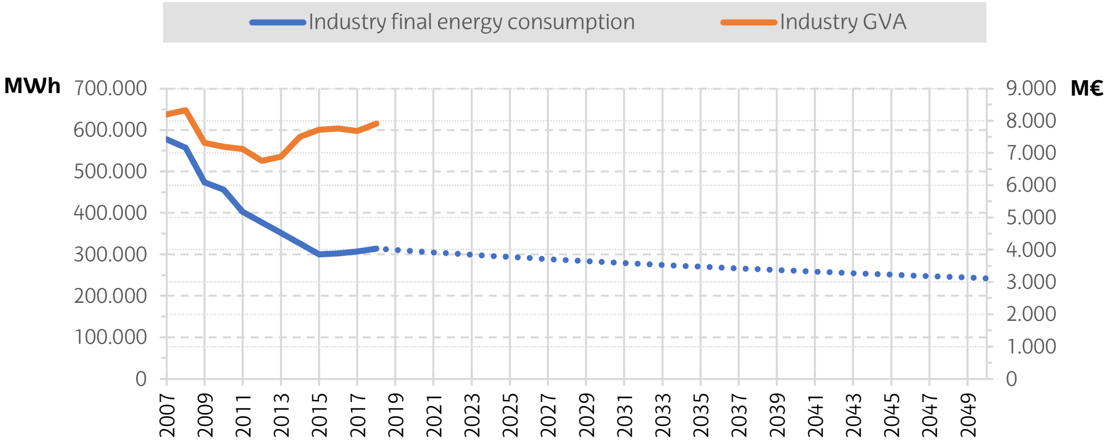

Figure 5.11. Industry final energy consumption. WOM projection

Transport sector final energy use has been modelled through the changes in the vehicle stock within the city, in terms of both modal share and fuel mix (i.e. considering the changes in the total number of vehicles of each type (cars, two wheels, buses, or utility vehicles) and in their powertrains (diesel cars, gasoline cars, electric cars)). A baseline evolution in the number of vehicles has been considered in the BaU scenario based on the city historical trend and considering future perspectives. For this scenario, the number of private cars is assumed to evolve as shown in Figure 5.12. Although the number of registered cars within the city dropped between 2007 and 2014, an increase has been observed since then. It has been found reasonable to assume that in the BaU scenario the number of private cars will rise again, though in a more controlled way due to recent trends such as traffic restrictions in urban centres, shift to public transport and active mobility, or high fuel prices. In the same way, following the historical path, private two wheels vehicles are assumed to grow in the BaU scenario. In the case of light utility vehicles, although the recent trend is in decline, a slight rebound (assuming the same growth rate as for private cars) has been considered due to the rise in urban deliveries (see Figure 5.13). The number of heavy duty vehicles is assumed to keep falling while buses remain steady (see Figure 5.14). Regarding the number of vehicles within the municipal and public transport fleets (the latter referring to the number of buses within the municipal public transport company), these are assumed to grow following the same growth rate as the one defined for municipal buildings (see Figure 5.9). Although not modelled through vehicle stock, evolution of urban rail in the BaU scenario is assumed to follow the passenger trend shown in Figure 5.15. Indeed, considering the population stagnation of the city it is reasonable to assume a similar stagnation in the number of rail transport users.

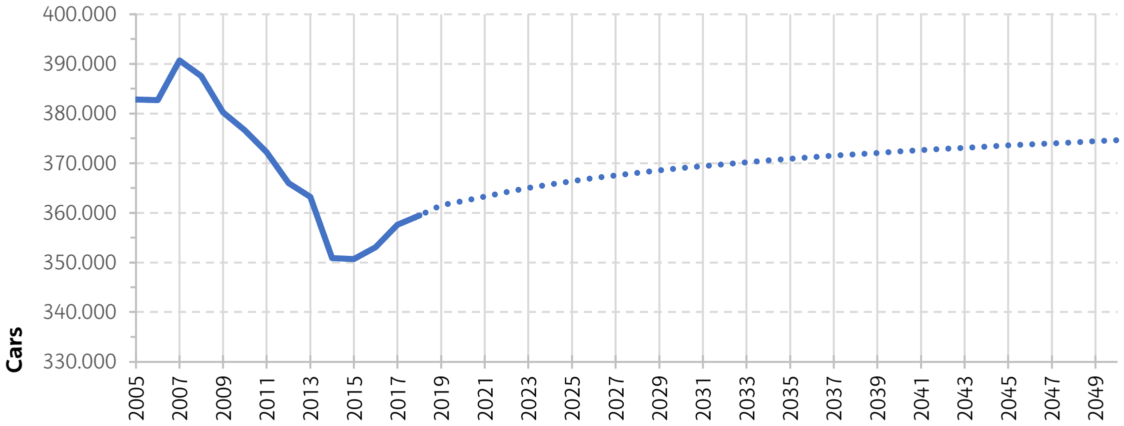

Figure 5.12. Private cars evolution. BaU scenario

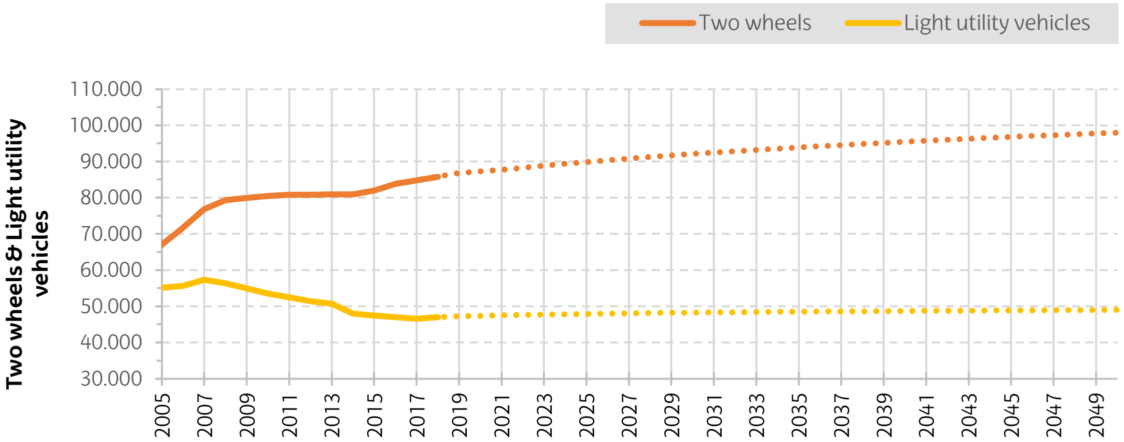

Figure 5.13. Private two wheels and light utility vehicles evolution. BaU scenario

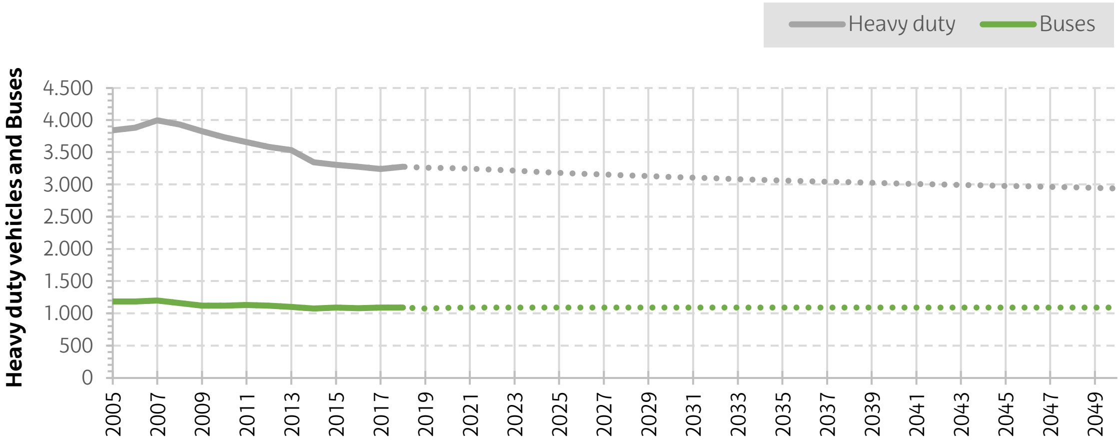

Figure 5.14. Private heavy duty vehicles and buses evolution. BaU scenario

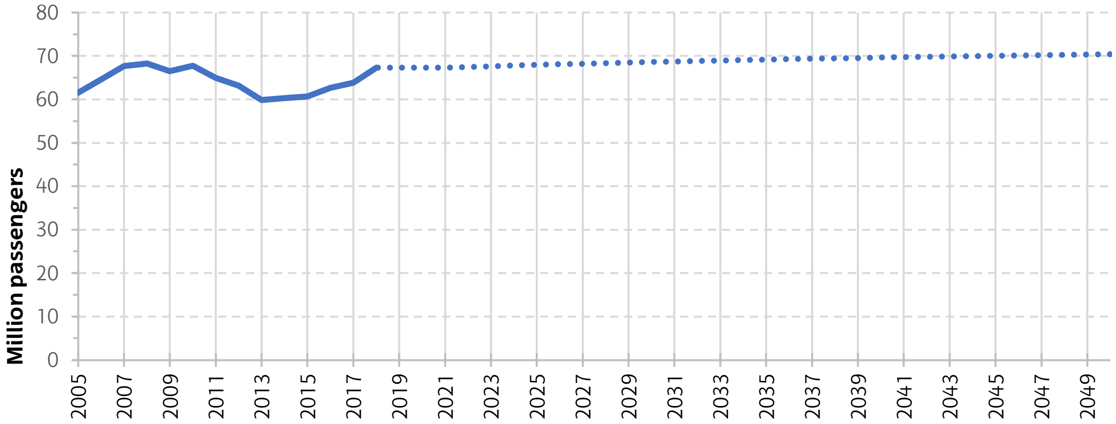

Figure 5.15. Urban rail passengers evolution. BaU scenario

It should be noted that these assumed evolutions take into account the renovation of the fleet (i.e. the balance between introduced and removed vehicles). Within this natural renovation of the fleet, the overtake of gasoline over diesel cars has been considered: annual mileage from the former has been increased (as gasoline cars are currently used for shorter journeys) while its fuel economy has been reduced (representing the penetration of hybrid engines). This achieves an overall reduction in the average energy intensity of ICE cars stock due to the natural renovation of the stock occurring in the BaU scenario. Regarding the modelling of measures in the alternative scenarios, starting from the baseline evolutions presented in the previous figures, the total number and share of the different types of vehicles may unfold differently depending on the measures modelled in each alternative scenario. That is, measures such as traffic restrictions (e.g. low emissions zones for example) or public transport promotion would discourage the use of certain vehicles, while stimulate other means of transport. This would ultimately result in the decrease or increase in the stocks of specific vehicles. Along with this stock evolution, changes in the fuel mix occur as alternative fuel-powered vehicles replace the old combustion-powered vehicles. Although other fuels are available for transport decarbonisation, this case study is focused on the electrification of the city fleet. EV vehicles also achieve energy reductions due to their higher efficiency. Indeed, fuel economy of a EV is assumed to be 70% lesser than a vehicle powered by an internal combustion engine (ICE) (LIPASTO, 2020). Evolutions of vehicles stocks and electrification rates in the different scenarios are detailed in Table C.2 in appendix C.

Regarding the city supply side, development of new energy generation capacity is associated with solar PV systems equipped in new and renovated households. This additional solar PV installed capacity is shown in Figure 5.16. No installation of other new energy generation systems nor decommissioning of the existent ones has been considered in the city in the different scenarios. Instead, the full decarbonisation of the Spanish national grid by 2050 proposed by the Spanish long-term decarbonisation strategy (Ministerio para la Transición Ecológica y el Reto Demográfico, 2020b) has been considered in all scenarios[70].

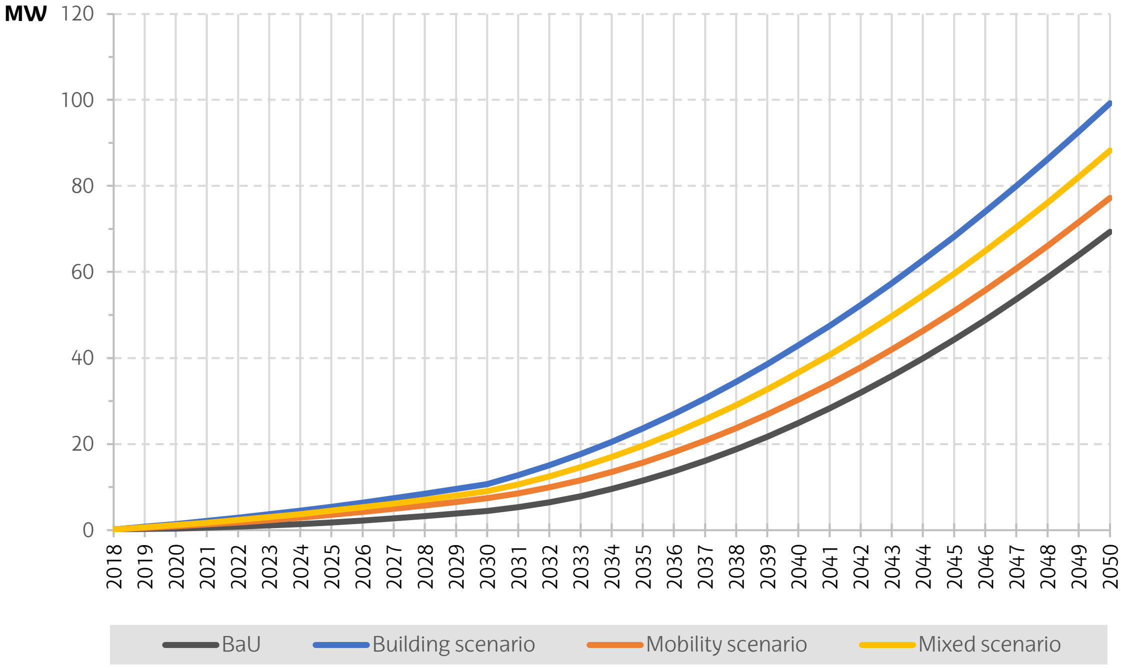

Figure 5.16. Additional PV capacity in new and renovated households in the different scenarios

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[70] It is assumed that the impact of increased local renewable generation is considered within the grid progressive decarbonisation. Considering this, the national EEF has been allocated to the electricity consumption of all sectors regardless of their renewable self-consumption capacity.

5.4.3. Urban energy scenarios assessment

Finally, the three alternative scenarios have been compared with each other, so local stakeholders can prioritise one of them based on different criteria. It is then necessary to calculate the specific energy, environmental and economic impacts for each alternative scenario.

All three alternative scenarios share their inheritance with the BaU. Thus, to properly assess them, trends and measures already implemented in the BaU scenario must be isolated from the ones which are exclusively modelled in the alternative scenarios, so that only the additional measures with regard to the BaU are assessed. In other words, by isolating the effects due to natural trends of the system and to already committed actions and policies, the impacts exclusively caused by additional measures modelled in the alternative scenarios are identified and evaluated. This is done by not considering the savings and costs due to actions already implemented in the BaU scenario (and which are therefore inherited and shared by all three alternative scenarios). Although modelled, measures which are identical in the four scenarios (i.e. same energy impacts and deployment rate) have no relative effect between them and hence do not provide further input to the comparative analysis. Therefore, they are avoided in the assessment process.

To assess the impacts of actions exclusively implemented in each one of the three alternative scenarios four indicators have been defined (see Table 5.3). These indicators have been established following a comparative approach to the BaU in order to identify the energy savings, emissions reductions, and economic costs exclusively due to additional measures with regard to the BaU[71].

CCES indicator evaluates the environmental performance of the scenario by showing the cumulative CO_2 emissions saving achieved in comparison to the BaU all along the scenario timeframe[72]. CTPES and CNRPES indicators assess the cumulative total and non-renewable primary energy saving achieved compared to the BaU all along the scenario period. Emission and primary energy factors considered to calculate these indicators are detailed in Table D.1 and Table D.2 in appendix D. SLCC indicator quantifies the economic performance of the scenario for the whole period at a specific discount rate. This indicator compares the LCC of the alternative scenarios (and their additional measures) against the LCC of the BaU scenario. A positive SLCC indicates that economic savings are achieved in the alternative scenario, hence implying an economic return of the investments. When assessing energy measures performed in buildings, the European Standard EN 16627 (European Committee for Standarization, 2013) has been followed. Construction process (phases A4 to A5) costs have been considered within the CAPEX, while use (phases B1 to B7) costs

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[71] Deployment of energy supply-side measures (i.e. solar PV panels installation) is considered negligible compared to the deployment of demand-side measures modelled in the scenarios. Therefore, they are not considered in the assessment.

[72] Only energy-related emissions have been considered.

have been assumed within the OPEX. Moreover, end of life (phases C1 to C4) expenses have been considered, along with a residual value (calculated as the proportional fraction of the CAPEX for the remaining years of life of the action after the end of the scenario), assumed as benefits from reuse and recovery potentials (phase D). Regarding vehicles, the purchase costs (CAPEX) and fuel and maintenance costs (OPEX) of vehicles have been considered. A residual value has been also assumed for the specific actions which are not fully used in the scenario period. Assumed CAPEX and OPEX costs, and evolution of fuel prices and technology costs are detailed in Table C.4 and Table C.5 in appendix C. Finally, for the sake of simplicity and due to lack of adapted IO tables for the city of Valencia, the IO analysis has not been carried out and thus no socioeconomic indicators have been defined.

Table 5.3. Defined indicators for the assessment of the alternative scenarios

Indicator	Formula	Definition
Cumulative CO_2 Emissions Saving (CCES)	$CCES = -\sum_{i=2019}^{2050}(CO_2\ emissions_{alternative_i} - CO_2\ emissions_{BaU_i})$	Sum of yearly CO_2 emissions savings (compared to the BaU) achieved all along the scenario period
Cumulative Total Primary Energy Saving (CTPES)	$CTPES = -\sum_{i=2019}^{2050}(Total\ Primary\ Enegy_{alternative_i} - Total\ Primary\ Energy_{BaU_i})$	Sum of yearly total primary energy savings (compared to the BaU) achieved all along the scenario period
Cumulative Non-Renewable Primary Energy Saving (CNRPES)	$CNRPES = -\sum_{i=2019}^{2050}(Total\ Non\ Renewable\ Primary\ Enegy_{alternative_i} - Total\ Non\ Renewable\ Primary\ Energy_{BaU_i})$	Sum of yearly non-renewable primary energy savings (compared to the BaU) achieved all along the scenario period
Scenario Life Cycle Cost (SLCC)	$SLCC = \sum_{i=2019}^{2050}\left(\frac{-CAPEX - OPEX + Operational\ savings + Residual\ value}{(1 + discount\ rate)^i}\right)_{alternative_i} - \sum_{i=2019}^{2050}\left(\frac{-CAPEX - OPEX + Operational\ savings + Residual\ value}{(1 + discount\ rate)^i}\right)_{BaU_i}$	LCC of the scenario compared to the LCC of the BaU

CAPEX: CAPital EXpenditures; OPEX: OPerational EXpenditures
Operational savings refer to net economic savings achieved by reductions in fuel consumption.

5.5. Results and discussion

Figure 5.17 shows the evolution of final energy consumption (including all city end-use sectors) for each scenario, resulting from LEAP simulation. The BaU scenario achieves a 12% final energy reduction by 2050. This baseline decrease is in line with the declining trend reported in the last years in the city (see Valencia's historical energy inventory (Ajuntament de València, 2019)) and can be explained by a stagnating population and low grow perspectives regarding new buildings and vehicles. This results in a situation where the slight growth assumed for the city is indeed offset by a very low deployment of measures[73]. However, this cannot justify the inaction of local authorities, which should play a leading role and aim for more ambitious goals. Regarding the alternative scenarios, the mobility scenario achieves the largest savings in terms of final energy consumption with a 35% reduction compared to 2018, while the building and mixed scenarios reach 30% and 28% energy savings respectively. These results are replicated in terms of CO_2 emissions (see Figure 5.18), with the mobility scenario achieving the highest reduction (81%) followed by the mixed (73%) and building (67%) scenarios. On this concern, the consideration of the gradual decarbonisation of the should be reminded since it influences the performance of all the scenarios (through the electrification of the energy demand). Regarding energy supply, Table 5.4 shows the share of on-site electricity produced locally. Since only PV panels in new and renovated households have been considered as additional energy generation systems, the degree of self-supply of the city remains poor. Deployment of additional solar PV and other energy generation systems (as well as the use of other RES locally available) could be considered to improve the energy independence of the city.

As a further remark, the mobility scenario would be the only scenario that achieves the city SECAP 2030 objectives (see Table 3.2) in terms of energy (7.079 GWh by 2030). Regarding the emissions target (1.610 kton CO_2 by 2030), the city plan did not consider the grid decarbonisation. Hence, obtained results cannot be considered, even though all the scenarios are below this level. Indeed, if this effect is omitted, no scenario would reach the 2030 emissions target. This situation is repeated when assessing the share of renewable sources in final energy consumption target (27% in 2030). That is, only the consideration of the grid decarbonisation (and its increased renewability) allows to achieve this target in the modelled scenarios.

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[73] Indeed, observed past energy trends in the different end-use sectors of the city may either confirm the degrowth drift of the city in both energy and socioeconomic terms, or indicate that energy measures and policies have already been implemented in the past.

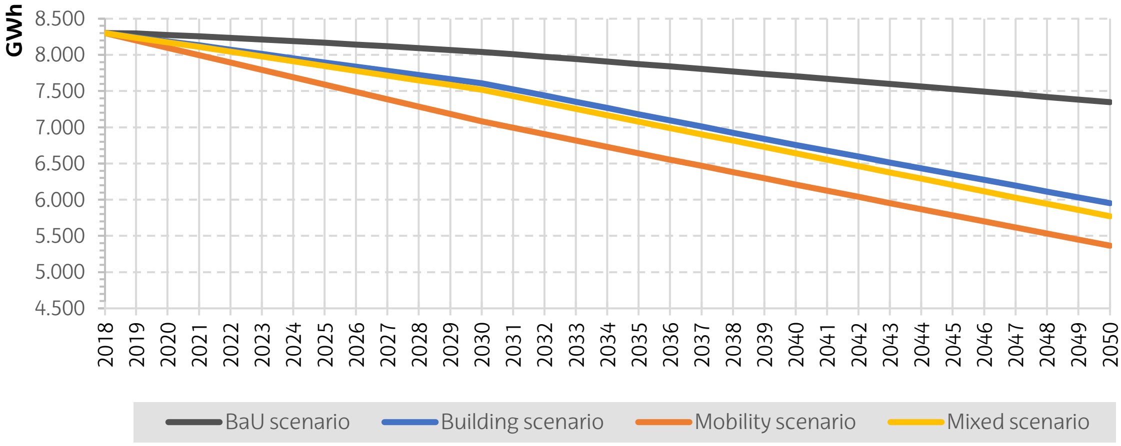

Figure 5.17. Evolution of total final energy consumption in the different scenarios

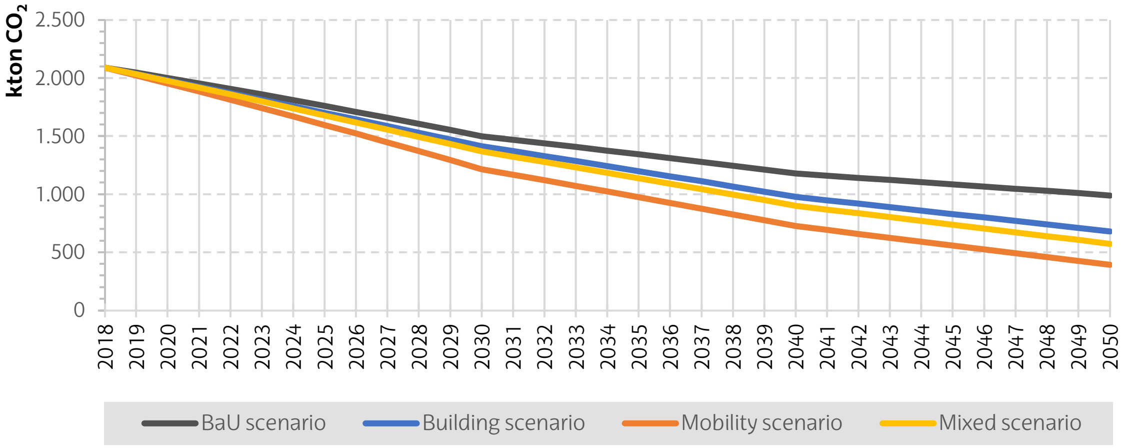

Figure 5.18. Evolution of CO_2 emissions in the different scenarios

Table 5.4. Share of locally produced electricity within the city by 2050

	Residential sector		**City**	
	% share with regard to electricity final energy consumption	% share with regard to total final energy consumption	% share with regard to electricity final energy consumption	% share with regard to total final energy consumption
BaU scenario	9,75%	6,02%	3,61%	1,62%
Building scenario	12,94%	11,67%	5,07%	2,74%
Mobility scenario	10,68%	7,32%	3,56%	2,43%
Mixed scenario	11,92%	9,38%	4,32%	2,55%

Next, results are broken down by fuel and sector, distinguishing those which fall under the direct competence of the municipality from those which not. Regarding municipal assets, scenario results in buildings and public transport fleet are shown in Figure 5.19. On the one hand, municipal buildings are fully decarbonised in the building scenario as they are fully electrified (and the grid is carbon free by 2050) in addition to achieving the greatest energy reduction (31% compared to 2018) by renovating the 100% of the stock. On the other hand, public transport fleet is fully electrified and decarbonised in the mobility scenario achieving a 47% final energy reduction compared to the base year. Diesel in public transport buses is removed in all scenarios, while CNG buses are still in use in the building and mixed scenarios by 2050, thus not reaching a full decarbonisation of the fleet. Although not represented in the figure[74], vehicles from the municipal fleet are also fully electrified in the mobility scenario, while a gasoline surplus (from hybrid vehicles) remains in the building and mixed scenarios.

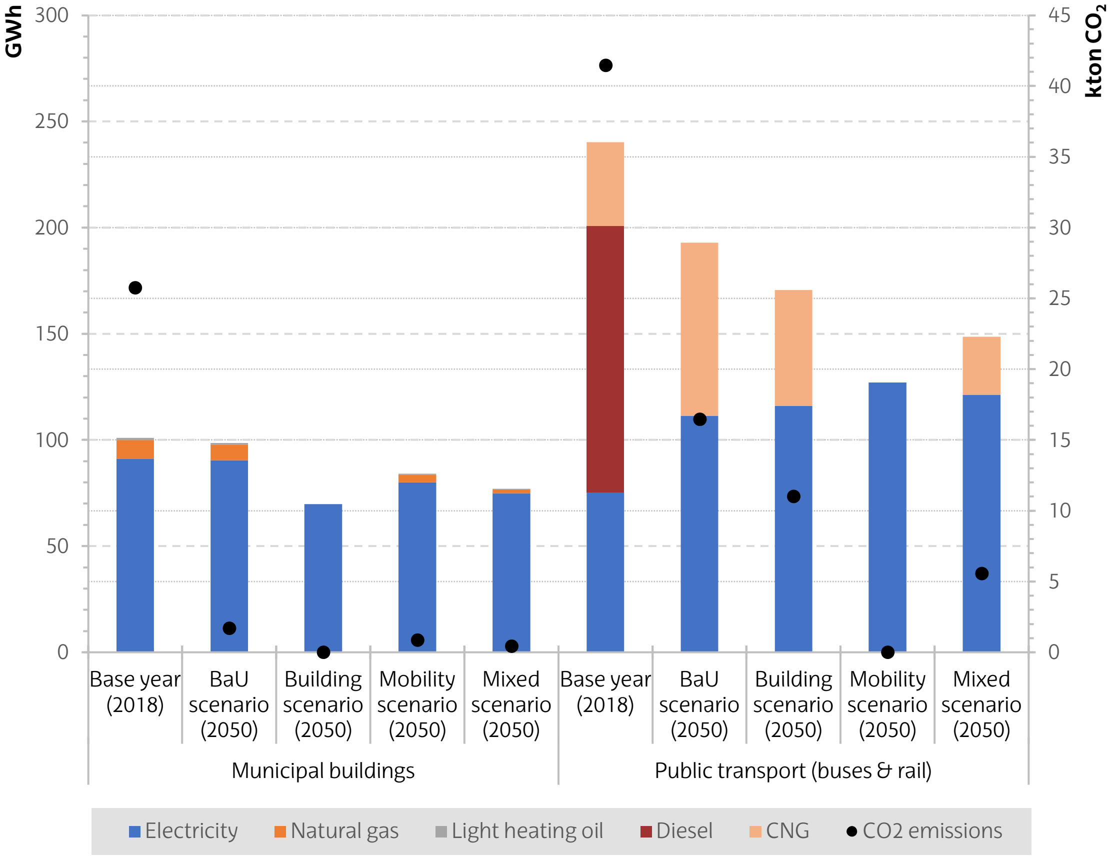

Figure 5.19. Municipal buildings and public transport CO_2 emissions and final energy consumption by fuel in the different scenarios

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[74] Municipal fleet accounts for only 3 GWh in the base year and achieves a 69% final energy reduction by 2050 in the mobility scenario.

Regarding private buildings (i.e. residential and private tertiary buildings, the high renovation rates in the building scenario, along with the electrification of the energy demand, achieve the greatest reductions both in terms of final energy consumption (30% in residential and 31% in private tertiary buildings compared to 2018) and CO_2 emissions (94% in residential and 99% in private tertiary buildings compared to 2018) as shown in Figure 5.20. While private tertiary buildings have a great electric share and are thus decarbonised in almost all scenarios, natural gas and LPG are still in use in the residential sector by 2050 in the mobility and mixed scenarios. Additional and cheaper measures (than the deep renovation of the household) could be implemented to completely phase out fossil fuels in the residential building stock. On this concern, the targeted renovation of remaining natural gas and LPG boilers in non-renovated households may serve this purpose. Other measures such as the renovation of lighting and appliances devices or the changes in consumption patterns could achieve cost-effective energy reductions (as seen in section 4.4.3.4).

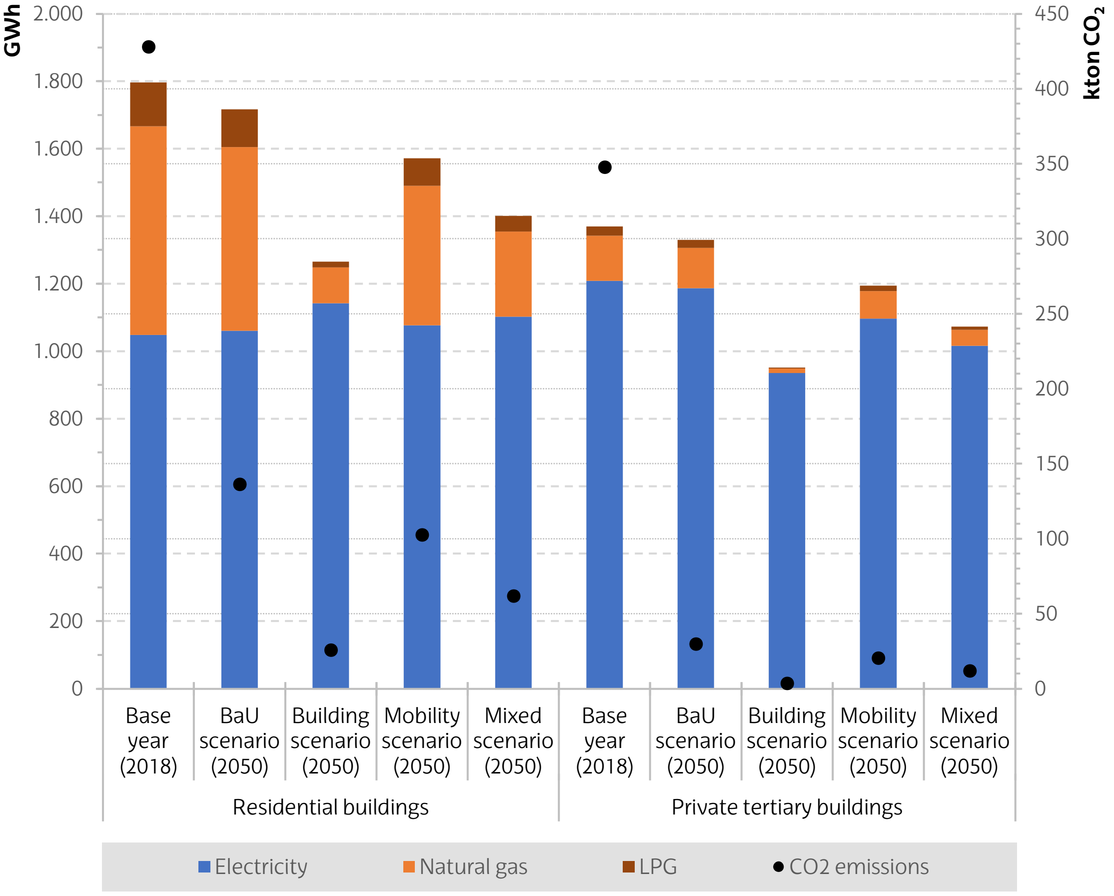

Figure 5.20. Residential and private tertiary buildings CO_2 emissions and final energy consumption by fuel in the different scenarios

Concerning private transport, the mobility scenario achieves a 51% final energy reduction by 2050 compared to 2018, and a 77% CO_2 emissions abatement by the same year (see Figure 5.21). Electricity represents in this scenario 52% of total final energy consumption by 2050. The remaining share is attributable to residual gasoline hybrid cars and mostly freight transport (light utility and heavy duty vehicles) whose further decarbonisation is more challenging. Other alternative fuels (such as hydrogen or biofuels) may be considered and modelled, along with increased options to further reduce the number of vehicles on the road (e.g more aggressive traffic limitations and increase in options for alternative forms of travel such as walking, cycling, or public transport) and therefore achieve further energy and emissions savings. This is especially relevant in the case of the building and mixed scenarios, where a further traffic reduction (i.e. in modelling terms, reducing the number of vehicles in the stock) would be needed to enable a greater (and technically feasible) electrification of the vehicle fleet.

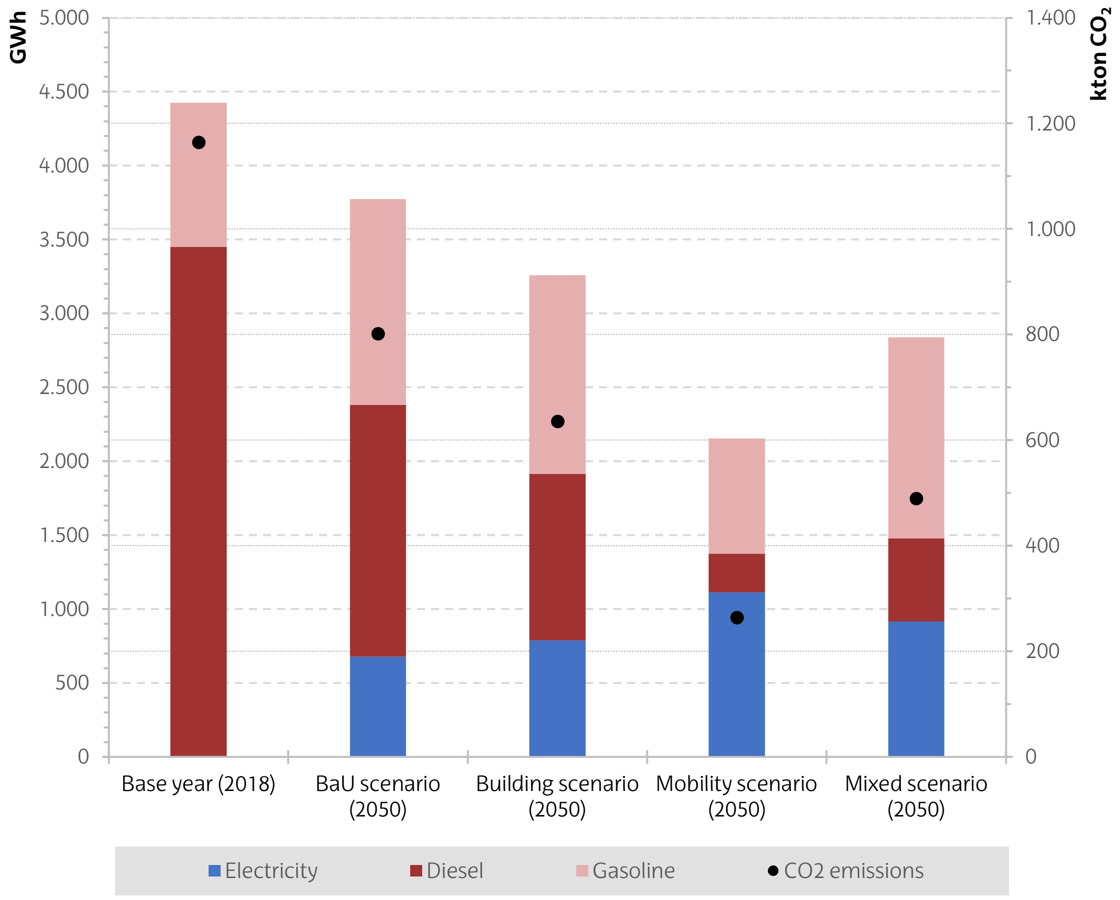

Figure 5.21. Private transport CO_2 emissions and final energy consumption by fuel in the different scenarios

Finally, alternative scenarios are compared amongst them and assessed based on the defined indicators. Table 5.5 summarises the environmental (CCES), energy (CTPES and CNRPES), and economic (SLCC) impacts of the modelled scenarios. Results are disaggregated by measure, so the effect of each one of them can be identified. As mentioned before and illustrated in Table 5.2 and Table C.2 in appendix C, only the additional impacts with regard to the BaU are assessed. That is, measures with the same deployment rate and characteristics in all the alternative and BaU scenarios (e.g. implementation of industry ECMs or public lighting) have no relative impact and have therefore been excluded from the evaluation.

Table 5.5. Environmental and energy impacts of the alternative scenarios

	Sector (modelled measure)	**Residential** (Household renovation)	**Municipal buildings** (Building renovation)	**Private tertiary buildings** (Building renovation)	**Municipal fleet** (Fleet electrification)	**Public transport** (Fleet electrification & Modal change)	**Private transport** (Fleet electrification & Modal change)	**TOTAL**
CCES (kton CO$_2$)	**Building scenario**	1.753	38	561	1	121	2.273	**4.747**
	Mobility scenario	631	19	201	3	347	9.739	**10.941**
	Mixed scenario	1.211	29	381	2	234	4.704	**6.561**
CTPES (GWh)	**Building scenario**	8.908	606	8.007	2	417	8.363	**26.303**
	Mobility scenario	3.297	303	2.874	8	1.163	31.820	**39.464**
	Mixed scenario	6.263	455	5.441	5	796	15.672	**28.632**
CNRPES (GWh)	**Building scenario**	9.783	313	4.409	2	518	9.355	**24.380**
	Mobility scenario	3.529	157	1.583	13	1.479	38.417	**45.178**
	Mixed scenario	6.768	235	2.996	8	1.001	18.676	**29.684**
SLCC (M€)	**Building scenario**	-5	-27	-248	-0,02	4	-26	**-302**
	Mobility scenario	-2	-14	-89	-0,47	13	-40	**-133**
	Mixed scenario	-4	-20	-168	-0,25	8	-68	**-252**

The mobility scenario achieves the best results in both environmental and energy terms, achieving the largest CCES, CTPES, and CNRPES. Private transport electrification (and reduction through modal changes) achieves the greatest CCES in all three alternative scenarios, also ranking first in CTPES and CNRPES in the mobility and mixed scenarios, second only to household renovation in the building scenario. Measures where large shares of fossil fuels are replaced by cleaner sources achieve a higher CNRPES than CTPES (e.g. household renovation or transport electrification). On this concern, both municipal and private tertiary buildings achieve less CNRPES, and also a relatively low CCES. This can be explained by the high electrified starting point of these sectors. Indeed, in the particular case of these buildings, since the grid decarbonisation is assumed in both BaU and alternative scenarios and no relevant fuel switches are carried out, no large relative savings are achieved in terms of emissions (CCES) and non-renewable primary energy (CNRPES), besides the ones obtained by the energy demand reduction (achieved by the buildings renovation itself) [75]. This comes to underline the differences discussed in previous chapters (see sections 3.5 and 4.4.3.4), on the issue of whether or not to consider the grid decarbonisation when estimating impacts and designing policies. While cities may rely on the national grid decarbonisation to reduce their emissions related to electricity consumption, they should not lose sight on the need for reducing the overall energy use and achieve greater primary (total and non-renewable) energy savings. Moreover, it would be advisable to also consider the diversification of the city energy supply by fostering a larger exploitation of local RES instead of committing the abatement of its environmental impact to the decarbonisation of the national grid.

Regarding economic performance, no scenario achieves a positive SLCC indicating that no economic return is reached as a whole in any of them. The sum of initial investments and further operational expenses of all the implemented measures exceed the potential economic savings from lesser energy demand or use of a cheaper fuel, thus no achieving a payback in the timeframe of the scenarios (see Table C.6 appendix C for further detail on CAPEX and OPEX costs and operational savings in each alternative scenario). On this concern, although having considered a high rise in fossil fuel prices, electricity cost is still higher at the end of the scenario than the cost of fuels that it replaces in residential and tertiary buildings, representing a cleaner and more efficient, though expensive option. Building energy systems and renovation costs should fall or be subsidised (especially in the case of envelope renovation) to improve the economic performance of the

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[75] The absolute impact of the grid decarbonisation in city emissions in every scenario can be noted in Figure 5.18. However, since it has been considered in all of them, its effect is cancelled in the comparative analysis (according to how the indicators have been defined). Nevertheless, it allows to identify the impacts of fuel switching. That is, sectors where fossil fuels are replaced by a progressively decarbonised electricity achieve larger emissions reductions than sectors heavily electrified from start. Indeed, while the former reflect the impacts of both energy demand reduction and switching to a cleaner fuel, the latter only account for the effects of energy demand reduction.

measures[76]. However, it should be noted that in the case of buildings renovation, economic performance has only considered the avoided costs from improving the energy performance of buildings, and these are not very large due to Valencia's mild climate. Other positive effects of buildings renovation like improvements on thermal comfort, liveability, or sanitation have not been considered in this case study but could be taken into account with additional indicators. Regarding transport-related measures, although considering the abatement of EV prices and the overtake of diesel price over electricity cost, only the electrification of public transport achieves operational savings that offset costs (CAPEX and OPEX). More aggressive reduction in EV costs (especially in OPEX and the battery replacement) could be considered, along with subsidies in the purchase of EV. Nevertheless, bolder modal changes policies and higher shifts towards public transport (revealed as a cost-effective solution), would ultimately reduce the need of electrification of the private transport fleet, hence reducing investment costs and improving the SLCC indicator.

In the practical demonstration of the methodology in Valencia's case study, scenarios results are conclusive. Mobility scenario obtains the best results in all four indicators CCES, CTPES, CNRPES, and SLCC. Hence, the AHP analysis has not been needed. The MCDA application proposed in the methodology would be more helpful in more complex applications. That is, if a larger number of scenarios and an extended set of indicators (including for example socioeconomic indicators) would be evaluated by the city, the use of these methodologies would be more useful[77]. On this concern, the modelling of additional scenarios considering the variation of critical parameters (e.g. energy prices, technology costs, renovation/electrification rates, buildings and vehicles stocks changes, amongst others) would strengthen the analysis in terms of sensitivity, besides widening the range of explored alternatives to face uncertainty.

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[76] Regarding economic results, a few notes can be added concerning the differences with regard to the results obtained in the Bilbao case study from chapter IV (see section 4.4.3.4). Indeed, household renovation costs are higher in Bilbao than in Valencia, whereas the renovation of private tertiary buildings are more economic in the former than in the latter. The difference in the costs of household renovation can be explained by the need of higher investments in electrification (household useful energy demand for heating in Bilbao's baseline is less electrified than in Valencia) and the consideration of a reduced increase in natural gas price (thus resulting in less operational savings) in the Bilbao case study. Regarding private tertiary buildings results, differences can be explained by much lower useful energy demands for heating in the case of Valencia, thus not compensating the investment costs. Deviations may be also due to differences in modelling assumptions and approaches and in the indicators definition and the way they are calculated.

[77] As a practical example, the AHP analysis has been carried considering each modelled measure in the building, mobility and mixed scenarios, as stand-alone scenarios. Three different cases have been assessed: a) emissions reduction priority, b) energy savings priority, c) least-cost option priority. Scores for every case are shown in Table C.7 in appendix C.

5.6. Chapter conclusions

This chapter has presented an integrated methodology to support urban energy planning through the prospective assessment of future pathways the city can face, aiming to allow city stakeholders to make decisions based on the impacts of diverse energy measures and policies implemented in different modelled energy transition scenarios. The suggested method begins combining bottom-up approaches with actual city energy data to perform the energy characterisation of the whole urban energy system. By matching bottom-up estimates with the city reported consumption, actual energy use is thoroughly disaggregated and performance gaps overcome. Only using available data, an accurate and detailed city energy baseline is shaped. Once this is achieved, energy transition scenarios can be set up in collaboration with local stakeholders and specific energy measures and policies modelled with precision and detail. Finally, scenarios outcomes are assessed under energy, environmental, and economic criteria, providing local stakeholders with insights on the performance of the modelled futures so they can prioritise them.

The proposed methodology was demonstrated in a case study for the city of Valencia, where the data supplied by the city was disaggregated and introduced in the LEAP energy modelling tool. Besides a BaU scenario, three alternative scenarios were considered and modelled: one focused on the building sector, one on the transport sector, and one combining measures in both sectors. For the specific case of Valencia, results have shown that the mobility-focused scenario obtains the most favourable results in terms of energy savings, emissions reductions, and costs. On this concern, no scenario achieves an economic return, but only the electrification and fostering of public transport incur in economic savings. Results from the different indicators provide insights to the municipality and local stakeholders regarding which are the scenarios (and measures) that have the greatest energy and emissions abatement potentials, and which are the ones where extra efforts would be needed. Moreover, results also show to what extent some measures should be funded to have an economic return. These results should help local government in the prioritisation, promotion, and funding allocation of different energy measures and policies. Besides actions focused on its own assets, local authorities should strive, as far as possible, in the fostering and subsidising of measures in sectors which are not under their direct scope of action such as residential and private tertiary buildings or private transport.

Finally, it is important to remark that this methodology has been conceived to be easily replicated. The energy characterisation and scenarios generation can be adapted according to the city, to its end-use sectors and energy supply-side systems, and to the available information. Thus, the same approach can be reproduced in other cities.

CHAPTER VI: Conclusions

Index CHAPTER VI

6.1. Summary

Cities face a major challenge in the near future. Under the current model of socioeconomic development, the need to accommodate an increasing urban population would lead to a rise in the energy and resources consumption of cities, with the consequent environmental, social, and economic impacts that this entails in a finite system such as the Earth. To avoid this unpromising future, while preserving the environment and ensuring the wellbeing of urban (and world) inhabitants, a transition towards low-carbon, sustainable and fair energy and economic systems must take place. In the particular case of cities, proper long-term energy planning is key to achieve this commitment at urban level.

To perform the task this Thesis has argued that the energy modelling and prospective assessment of urban energy systems are extremely valuable tools to support the development of integrated long-term urban energy plans. To this end, approaches and insights have been provided to develop energy models and energy scenarios at urban level, filling the gaps of knowledge in these fields (see need of energy modelling methodologies at urban level, unawareness when shaping future urban energy use, lack of data, and regarding urban energy planning: absence of coordination amongst decarbonisation actors). Results have proven that urban energy modelling can provide urban energy planners, policymakers and other relevant local stakeholders with useful information regarding the current and future energy use in cities. On this concern, the detailed energy characterisation of the urban energy system (and particularly building sector) and the straightforward modelling of future energy use of the most relevant end-use sectors within the urban energy system have been achieved. The disaggregation of the city energy use by end-use sector, energy service, and fuel has allowed to identify critical hotspots upon which to act, besides providing an exhaustive baseline from which a considerable number of events and actions can be modelled with ease and precision (e.g. energy measures at sector and even energy service level). Indeed, the modelling of different energy measures, policies, and other exogenous and endogenous phenomena has enabled to assess the multiple impacts (e.g. energy savings, emissions abatements, or economic costs) of the scenarios that comprise them. Moreover, the straightforward approach to shape the city future energy use (using key parameters and avoiding large data requirements and complex techniques) has made it possible to readily generate a set of diverse energy scenarios, offering a broader range of different possible futures amongst which decision makers can prioritise the one that best suits the city long-term vision. All these modelling outputs (e.g. achieved savings, abatement costs, deployment rates of measures, or the impact of the roll-out of a specific technology within the city) can be further integrated in urban energy planning as quantified goals, technological roadmaps, and decarbonisation paths. It is also important to note that the proposed approaches to characterise the energy performance of cities and to generate energy scenarios have reduced data needs and tackled the complexity when modelling (and further assessing) urban energy systems. Altogether, the methodological framework developed within this Thesis has addressed three particular fields of urban energy planning and modelling, proposing a specific approach for each one of them.

Chapter III has developed a method to effectively align local and national energy planning. Indeed, as remarked in the literature review and demonstrated in the applied case of the Spanish city of Valencia, urban energy plans and targets are not currently coordinated with upper energy and climate strategies and objectives. Thus, despite cities ambitions, there is a need for coordination in aligning local efforts to successfully contribute to the effective decarbonisation of national (and urban) energy systems. Moreover, the assessment of the case study urban energy plan showed that it lacked of detail when estimating the impacts from the planned measures, thus hindering the accuracy and reliability on how to achieve the committed energy and climate goals. By downscaling and adapting national targets and measures to the urban context, the proposed method has proven to be useful to quantify this discoordination, while also helpful to update or outline urban energy plans harmonised with national energy and climate strategies. In addition, just as national planning is supported by energy modelling, so must urban energy planning too.

Chapter IV has put forward a method to develop detailed building stock energy models with minimal data requirements. Indeed, to tackle the lack of data at urban level and to avoid the performance gap, the proposed methodology has integrated available cadastral data with aggregated reported final energy consumption within cities building stocks. A first analysis was carried out to assess how some parameters caused the performance gap. Comparing actual data with the results from a GIS physical-based building energy model, results showed that theoretical-based calculations from the model failed at capturing actual energy use, which in turn was influenced by variables such as income or number of dwellers. This reinforced the need of integrating real consumption data to outline accurate energy baselines to prevent the estimation of skewed savings. Thus, a novel approach was proposed combining a bottom-up approach with top-down data, which allows to obtain a disaggregated building stock energy model for the whole city, overcoming the performance gap, and without requiring huge amounts of complex technical data. Furthermore, the modelling of future energy scenarios in the building sector is carried out without relying on intricate techniques. The application of the suggested approach in the case of the city of Bilbao (Spain), has demonstrated that the methodology provides helpful insights in terms of both the accurate and richly detailed characterisation of the current building stock energy performance, and also the modelling of diverse energy measures, policies and scenarios within the building stock. Hence assisting the decision-making and development of energy plans by local stakeholders.

Moreover, due to its low data requirements and straightforward way to model building stock energy scenarios, the suggested methodology is easily replicable in other cities.

Chapter V has integrated the analysis performed in the previous works, presenting a holistic approach to model urban energy systems. Indeed, the full urban energy system has been modelled considering all the end-use sectors and energy supply-side systems within the city. The proposed methodology has also included the method for the generation and evaluation of urban energy scenarios. Instead of relying on complex techniques and data-intensive methods for shaping the current urban energy performance and future energy use, the presented approach advocated for combining bottom-up approaches to separate and detail highly aggregated reported data in order to define an accurate energy baseline from which to model energy scenarios in a precise and understandable way. This approach revealed itself as an advantageous solution given the usual lack of information at urban level. The usefulness of the methodology and its contribution to urban energy planning was demonstrated in the case study of the city of Valencia, where an urban energy model was developed using only the available data within the city, and urban energy scenarios were generated and further assessed under different criteria.

Finally, some general final remarks can be noted:

- To obtain an accurate and detailed urban energy model, an intensive work of data treatment is required. Indeed, since urban data is scarce and highly aggregated, gathering and processing the available data in order to obtain a precise and disaggregated model becomes a time-consuming task. Moreover, the integration of bottom-up and top-down data must be performed carefully since their scopes may not always match. Modellers should be aware of that to avoid the definition of warped baselines. Sometimes forced to rely on assumptions, this hinders the energy characterisation and further future modelling of specific sectors like private tertiary buildings and urban mobility. Cities must make an effort bringing together more quality information in order to reduce modelling hypotheses and to enhance the particular modelling of the transport sector.

- Modelling assumptions have a great impact on the results of the model, and thus must be documented and updated if new data becomes available. Also hypotheses and considerations must be shared in order to guarantee the transparency of the model. Indeed, final users of results issued from the model (i.e. local stakeholders) must understand how the scenarios outcomes have been achieved. On this concern, engagement and participation of urban stakeholders in the development of the model and in the assumption of hypotheses improve model results while also making it easier for the involved agents to understand the outputs from the model.

- To develop a comprehensive urban energy model (including a detailed energy baseline and accurate energy scenarios) the following aspects are crucial:
    - Demand side of urban energy systems gather the most pivotal actors in terms of energy use and GHG emissions. Hence the disaggregation of energy use within the demand side of the city by end-use sector, energy service, and technology (e.g. heating system, lighting system, vehicle type and used fuel) provides wider options to accurately model the implementation of specific energy measures and policies at sector and even energy service scale.
    - A review of the city background is not only useful but necessary to contextualise the city. On the one hand, the historical development of the city supplies with valuable insights on urban trends, past energy performance, or the city behaviour, awareness, and commitment towards energy use (especially for the set-up of a BaU scenario). On the other hand, the identification of committed plans or targets sheds light on which may be the paths followed by the city or which may be its preferences (i.e. its desired future city vision), thus allowing to fine-tune the energy scenarios. Moreover, it is also important to understand the system in which the city is embedded. That is which are the external impacts which may affect its development (e.g. national or regional plans and commitments, national energy systems, or global energy prices).
    - The comprehensive definition of the urban energy system boundaries is key in order to correctly allocate the impacts to the city. Although there is not better approach than other, the urban energy model should clearly establish which are the elements and impacts that are considered within it (e.g. national grid impacts, or metropolitan mobility). These considerations are not only critical in the modelling process, but also when it comes to drawing holistic energy strategies, defining competences and assigning responsibilities.
- Results have shown the impact of whether considering or not the impact of the national grid decarbonisation. Indeed, if this effect is considered, municipalities can achieve higher emissions abatements without the need of reducing its energy demand. This can be misleading as municipalities would only require electrifying its demand to achieve specific climate targets without carrying out efficiency and energy reduction policies. Hence, energy use (and more specifically primary energy use) would not be decreased. To successfully transform urban energy systems into sustainable and low-carbon environments both electrification and energy savings policies must be put into effect.

- To effectively support urban energy planning, multiple and diverse scenarios must be created. Intended to assist decision-making, the generation of one single energy scenario is pointless as this neglects the actual value of the scenario approach: tackle uncertainty by exploring a range of possible futures.

6.2. Future work

As every work has its own scope and limitations, the work carried out in this Thesis is also subject to be expanded. Indeed, further research lines are needed to fulfil other specific gaps in the fields of urban energy planning and modelling that this work has left unexplored. Some are listed next:

- The modelling of the transport sector within urban energy systems must be enhanced and completed if more data becomes available. Approaches must be put forward to tackle the complexity of urban mobility and to comprehensively assess its impacts within the urban environment.

- To achieve a true urban energy transition, cities must decarbonise not only their direct energy use but also their energy use embodied in imported goods and services. Adapted urban IO tables should be developed to quantify this impact through Environmentally-Extended IO analysis. Circular economy indicators should be also integrated in urban assessment.

- If more urban data becomes available, the establishment of links between urban socioeconomic parameters and energy drivers may help to reinforce top-down urban energy modelling approach. That is, to better reflect the impact of external impacts such as energy prices variations, supply shortages, economic crises, and other socioeconomic and geopolitical events in the energy use of cities.

- Social dynamics and agent-based modelling approaches could be also included to account for the impacts of user behaviour, improving modelling results and widening the possible futures to be modelled. Within the proposed methodologies, the use of optimisation techniques may be also explored.

- Modelled results from the proposed methodologies are heavily based on the considered assumptions. Although the results have been proven to be useful towards the support of urban energy planning, it remains to refine scenarios outputs (within the impossibility of calibrating results occurring in a long-term future). To tackle uncertainty and strengthen modelling results and their usefulness, it would be advisable to assess the effects of the variance of critical parameters (e.g. energy prices, energy systems efficiencies, or technology costs) on the results. Carrying out sensitivity analysis upon these parameters would widen the range of explored uncertainty, turning from a current deterministic to a stochastic analysis.

- As a long-term work, the contrast between the results from modelled scenarios and future energy use would serve to validate and also improve the work of this Thesis.

Appendices

Scientific dissemination

Peer-reviewed journal publications

- Muñoz, I., Hernández, P., Pérez-Iribarren, E., Pedrero, J., Arrizabalaga, E., Hermoso, N., 2020. Methodology for integrated modelling and impact assessment of city energy system scenarios. Energy Strateg. Rev. 32, 100553. https://doi.org/10.1016/j.esr.2020.100553
- Urrutia-Azcona, K., Molina-Costa, P., Muñoz, I., Maya-Drysdale, D., Garcia-Madruga, C., Flores-Abascal, I., 2021. Towards an integrated approach to urban decarbonisation in practice: The case of Vitoria-Gasteiz. Sustainability 13, 1–20. https://doi.org/10.3390/su13168836

Conference publications

- Oregi, X., Hermoso, N., Arrizabalaga, E., Mabe, L., Munoz, I., 2018. Sensitivity assessment of a district energy assessment characterisation model based on cadastral data. Energy Procedia 147, 181–188. https://doi.org/10.1016/j.egypro.2018.07.053
- Pedrero, J., Hermoso, N., Hernández, P., Muñoz, I., 2019. Assessment of urban-scale potential for solar PV generation and consumption. IOP Conf. Ser. Earth Environ. Sci. 323. https://doi.org/10.1088/1755-1315/323/1/012066
- Arrizabalaga, E., Muñoz, I., Hermoso, N., Urcola, I., Izkara, J.L., Prieto, I., Pedrero, J., Hernandez, P., Mabe, L., 2019. Methodology for the Advanced Integrated Urban Energy Planning. Proceedings 20, 17. https://doi.org/10.3390/proceedings2019020017

Other dissemination works

- Muñoz, I.., Energy modelling process, with a double approach bottom-up and top-down. MatchUp Webinar. June 23rd 2021. Online
- Muñoz, I., ¿Cómo pueden las ciudades contribuir eficazmente al cumplimiento de objetivos de descarbonización? Metodología para coordinar las planificaciones energéticas nacionales y locales. Jornada Red Mentes. May 25th 2022. Alcalá de Henares (Madrid)

Appendix A: Chapter I

Table A.1. Valencia residential building stock disaggregation (number of households)

	HEATING SYSTEM	No heating	No heating	Natural gas boiler	Heat pump	Electric stove	LPG stove	Electric stove	Heat pump	TOTAL
	DHW SYSTEM	Electric heater	Natural gas heater	Natural gas boiler	Electric heater	Natural gas heater	LPG heater	Electric heater	Natural gas heater	
SFH	Pre 1900	174	9	462	81	165	83	331	248	**1.554**
	1901-1940	755	40	1.996	352	715	358	1.431	1.073	**6.719**
	1941-1960	358	19	948	167	340	170	679	510	**3.191**
	1961-1980	337	18	891	157	319	160	639	479	**2.999**
	1981-2007	522	27	1.382	244	495	248	990	743	**4.651**
	Post 2007	102	5	269	48	96	48	193	145	**906**
	TOTAL	**2.248**	**118**	**5.947**	**1.050**	**2.131**	**1.066**	**4.263**	**3.197**	**20.020**
HB	Pre 1900	43	385	1.200	63	757	435	347	385	**3.615**
	1901-1940	153	1.381	4.309	227	2.719	1.562	1.246	1.382	**12.978**
	1941-1960	304	2.738	8.545	450	5.393	3.097	2.470	2.740	**25.737**
	1961-1980	1.414	12.723	39.710	2.090	25.060	14.392	11.479	12.733	**119.600**
	1981-2007	1.347	12.125	37.845	1.992	23.883	13.716	10.940	12.135	**113.982**
	Post 2007	292	2.625	8.194	431	5.171	2.970	2.369	2.627	**24.680**
	TOTAL	**3.553**	**31.977**	**99.804**	**5.253**	**62.983**	**36.171**	**28.851**	**32.001**	**300.592**

Note: in order to combine Table A.1 and Table A.2, an average 98,41 m^2 floor area per household has been considered (Ajuntament de València, 2018).

Table A.2. Considered useful energy demands for residential energy services (kWh/m².year)

	Construction period	Space heating	DHW	Cooling	Cooking	Lighting	Appliances
SFH	Pre 1900	10,39	10	7,53	2,93	4,52	20,37
	1901-1940	24,10		6,83			
	1941-1960	12,59		7,07			
	1961-1980	13,33		7,40			
	1981-2007	7,79		7,57			
	Post 2007	5,23		7,94			
HB	Pre 1900	13,16	15	5,12	2,93	4,52	20,37
	1901-1940	11,76		4,25			
	1941-1960	14,34		4,23			
	1961-1980	9,20		3,62			
	1981-2007	3,63		3,57			
	Post 2007	3,15		4,12			

Table A.3. Considered efficiencies for buildings energy systems

Space heating		DHW		Cooling		Cooking	Lighting	Appliances
Natural gas boiler	85%	Natural gas boiler/heater	69%	Heat pump	300%	100%	100%	100%
Heat pump	290%	Electric heater	81%	New heat pump	400%			
Electric stove	100%	LPG heater	60%					
LPG stove	70%	New natural gas boiler/heater	85%					
New natural gas boiler	95%	New heat pump for DHW	250%					
New heat pump	300%							

Table A.4. Disaggregated residential sector final energy consumption in Valencia in 2018 (MWh)

Energy service		Space heating				DHW				Cooling	Cooking		Lighting	Appliances	TOTAL
Fuel		Electricity	Natural gas	Light heating oil	LPG	Electricity	Natural gas	Light heating oil	LPG	Electricity	Electricity	Natural gas	Electricity	Electricity	
HB	Pre 1900	1.631	1.829	0	805	830	5.862	0	1.070	405	800	242	1.608	7.247	**22.330**
	1901-1940	5.229	5.866	0	2.581	2.978	21.043	0	3.842	1.208	2.873	870	5.773	26.016	**78.279**
	1941-1960	12.650	14.189	0	6.244	5.907	41.731	0	7.619	2.384	5.697	1.725	11.449	51.593	**161.187**
	1961-1980	37.710	42.298	0	18.614	27.448	193.919	0	35.407	9.477	26.473	8.017	53.202	239.747	**692.312**
	1981-2007	14.183	15.909	0	7.001	26.159	184.810	0	33.744	8.905	25.230	7.640	50.703	228.486	**602.770**
	Post 2007	2.661	2.985	0	1.314	5.664	40.015	0	7.306	2.230	5.463	1.654	10.978	49.472	**129.743**
SFH	Pre 1900	624	555	0	121	717	1.267	0	136	269	344	104	691	3.114	**7.942**
	1901-1940	6.254	5.569	0	1.212	3.099	5.479	0	587	1.055	1.487	450	2.989	13.469	**41.651**
	1941-1960	1.552	1.381	0	301	1.472	2.602	0	279	519	706	214	1.419	6.396	**16.841**
	1961-1980	1.544	1.375	0	299	1.383	2.446	0	262	511	664	201	1.334	6.012	**16.031**
	1981-2007	1.399	1.245	0	271	2.145	3.792	0	406	810	1.029	312	2.069	9.322	**22.800**
	Post 2007	183	163	0	35	418	739	0	79	166	201	61	403	1.817	**4.265**
TOTAL		**85.620**	**93.365**	**0**	**38.798**	**78.220**	**503.706**	**0**	**90.736**	**27.938**	**70.967**	**21.491**	**142.618**	**642.692**	**1.796.151**

Table A.5. Assumed hypotheses for the modelling of measure 2.7

	Refrigerator	Freezer	Washing machine	Dishwasher	Dryer	Oven	Source
% of households equipped	100%	14,6%	99,5%	42%	21,5%	94,9%	*(Portal Estadístico de la Generalitat Valenciana, 2020)*
Devices in Valencia (devices to be replaced annually)	320.612 (12.287)	46.809 (1.794)	319.008 (12.226)	134.657 (5.161)	68.931 (2.642)	304.260 (11.661)	*(Portal Estadístico de la Generalitat Valenciana, 2020)*
Specific consumption per device in Valencia (kWh/device)	962	820	374	360	375	336	*Adjusted from (Instituto para la Diversificación y Ahorro de la Energía. IDAE, 2011)*
Achieved saving due to energy labelling improvement	52%	52%	31%	31%	47%	49%	*(Organización de Consumidores y Usuarios, 2020)*

Table A.6. Tertiary sector final energy consumption and useful energy demand disaggregated by energy service

Municipal buildings						
Final energy consumption (MWh)	Space heating	DHW	Cooling	Appliances	Lighting	TOTAL
Electricity	11.021	7.610	13.237	20.059	39.276	**91.203**
Natural gas	6.856	1.846	0	0	0	**8.702**
Light heating oil	796	224	0	0	0	**1.020**
TOTAL	**18.638**	**9.671**	**13.237**	**20.059**	**39.276**	100.880
Final energy consumption (kWh/m^2.year)	*13,23*	*6,86*	*9,40*	*14,24*	*27,88*	-
Useful energy demand (kWh/m^2.year)	*27,22*	*12,88*	*28,19*	*14,24*	*27,88*	-
Private tertiary buildings						
Final energy consumption (MWh)	Space heating	DHW	Cooling	Appliances	Lighting	TOTAL
Electricity	146.042	100.849	175.404	265.805	520.454	**1.208.554**
Natural gas	105.359	28.365	0	0	0	**133.724**
LPG	0	27.042	0	0	0	**27.042**
TOTAL	**251.401**	**156.255**	**175.404**	**265.805**	**520.454**	1.369.320
Final energy consumption (kWh/m2.year)	*17,61*	*10,94*	*12,29*	*18,62*	*36,46*	-
Useful energy demand (kWh/m^2.year)	*35,94*	*18,04*	*36,86*	*18,62*	*36,46*	-

Table A.7. Assumed savings for the modelling of measure 2.8 modelling (From (Ministerio de Transportes Movilidad y Agenda Urbana, 2020)*)*

Energy action	Energy service	Energy saving
Envelope renovation	Space heating	14%
	Cooling	13%
Energy systems renovation	Space heating	30%
	Cooling	0%
	DWH	15%
Lighting renovation	Lighting	50%

Table A.8. Valencia current vehicle stock disaggregation and considered modelling hypotheses

Vehicle type	Powertrain	Stock (number of vehicles)	Urban fuel economy (kWh/100 km)	Annual urban mileage (km)
Cars	Diesel	183.911	72	5.694
	Gasoline	173.414	75	5.694
	Electricity	123	17	5.694
	CNG	19	64	5.694
Two wheels	Gasoline	84.111	42	1.347
	Electricity	223	10	1.347
Light utility vehicles	Diesel	17.159	103	8.748
	Gasoline	5.646	107	8.748
	Electricity	28	24	8.748
	CNG	2	92	8.748
Buses	Diesel	1.040	438	23.449
	Electricity	0	103	23.449
	CNG	47	563	23.449

Appendix B: Chapter II

Table B.1. Residential floor area (m²) disaggregated by construction period and space heating system

Heating system	Conventional natural gas boiler		Condensing natural gas boiler		Light heating oil boiler		LPG boiler		Heat pump		Electric boiler		Biomass boiler		No space heating	TOTAL
Config.	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central		
RHB1900	560.221	16.185	24.350	1.596	0	12.182	1.381	0	0	0	241.017	0	0	0	20.619	**877.552**
RHB1940	915.038	111.678	71.744	3.097	0	53.698	1.887	0	0	0	256.174	0	2.255	0	26.498	**1.442.069**
RHB1960	1.424.544	382.175	141.281	15.383	0	182.250	3.866	0	0	1.608	469.929	0	0	0	39.255	**2.660.291**
RHB1980	2.422.103	1.068.154	292.461	43.497	0	1.313.254	2.461	0	0	0	925.042	0	0	0	47.272	**6.114.245**
RHB2007	1.307.440	565.011	162.194	9.314	0	400.680	4.665	0	0	0	116.015	0	0	0	13.770	**2.579.089**
RHB2018	86.540	429.734	0	0	0	5.880	0	0	0	2.785	8.318	0	0	10.102	0	**543.360**
RSF2018	208.552	0	2.845	0	10.633	0	2.515	0	0	0	31.118	0	203	0	1.858	**257.724**
TOTAL	**6.924.437**	**2.572.937**	**694.875**	**72.887**	**10.633**	**1.967.945**	**16.777**	**0**	**0**	**4.393**	**2.047.613**	**0**	**2.459**	**10.102**	**149.272**	**14.474.330**

Table B.2. Residential floor area (m²) disaggregated by construction period and DHW system

Heating system	Conventional natural gas boiler		Condensing natural gas boiler		Light heating oil boiler		LPG boiler		Heat pump		Electric boiler		Biomass boiler		No DHW	TOTAL
Config.	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central		
RHB1900	558.476	15.204	24.350	1.596	0	12.182	15.892	0	0	1.125	248.727	0	0	0	0	**877.552**
RHB1940	926.947	111.821	71.744	3.097	0	57.490	17.332	0	0	0	253.638	0	0	0	0	**1.442.069**
RHB1960	1.484.399	334.221	141.281	15.383	0	145.499	30.858	0	225	0	508.425	0	0	0	0	**2.660.291**
RHB1980	2.553.755	1015.281	292.461	43.497	0	1.275.816	47.241	0	6.518	0	879.677	0	0	0	0	**6.114.245**
RHB2007	1.316.631	568.603	162.194	9.314	0	403.029	8.239	0	0	0	108.948	0	2.131	0	0	**2.579.089**
RHB2018	86.131	427.662	0	0	0	5.880	0	0	409	3.190	9.986	0	0	10.102	0	**543.360**
RSF2018	211.565	0	1.448	0	10.121	0	4.669	0	0	0	29.718	0	203	0	0	**257.724**
TOTAL	**7.137.905**	**2.472.792**	**693.478**	**72.887**	**10.121**	**1.899.896**	**124.230**	**0**	**7.152**	**4.314**	**2.039.118**	**0**	**2.335**	**10.102**	**0**	**14.474.330**

Table B.3. Municipal floor area (m^2) disaggregated by activity and space heating system

Heating system	Conventional natural gas boiler		Condensing natural gas boiler		Light heating oil boiler		LPG boiler		Heat pump		Electric boiler		Biomass boiler		Natural gas microCHP	No space heating	TOTAL
Config.	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central			
MUNEDUC	0	217.042	0	599	0	0	0	0	0	157	0	1.040	0	0	0	0	**218.838**
MUNSPRT	0	5.206	0	0	0	0	0	1.466	0	762	0	0	0	0	84.567	765	**92.766**
MUNADMI	0	87.960	0	5.387	0	2.435	0	0	0	30.586	0	2.765	0	0	0	2.878	**132.012**
MUNOTHR	0	52.706	0	0	0	5.187	0	0	0	1.453	0	0	0	0	0	63.539	**122.885**
MUNAZKZ	0	40.368	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**40.368**
TOTAL	**0**	**403.283**	**0**	**5.987**	**0**	**7.622**	**0**	**1.466**	**0**	**32.959**	**0**	**3.805**	**0**	**0**	**84.567**	**3.984**	**606.869**

Table B.4. Municipal floor area (m^2) disaggregated by activity and DHW system

Heating system	Conventional natural gas boiler		Condensing natural gas boiler		Light heating oil boiler		LPG boiler		Heat pump		Electric boiler		Biomass boiler		Natural gas microCHP	No DHW	TOTAL
Config.	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central			
MUNEDUC	0	217.042	0	599	0	0	0	0	0	157	0	1.040	0	0	0	0	218.838
MUNSPRT	0	5.206	0	0	0	0	0	1.466	0	762	0	0	0	0	84.567	765	92.766
MUNADMI	0	94.150	0	2.036	0	2.435	0	0	0	29.809	0	3.581	0	0	0	0	132.012
MUNOTHR	0	52.944	0	0	0	5.187	0	0	0	1.453	0	103	0	0	0	63.197	122.885
MUNAZKZ	0	40.368	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40.368
TOTAL	**0**	**409.710**	**0**	**2.636**	**0**	**7.622**	**0**	**1.466**	**0**	**32.182**	**0**	**4.725**	**0**	**0**	**84.567**	**765**	**606.869**

Table B.5. Tertiary floor area (m^2) disaggregated by activity and space heating system

Heating system	Conventional natural gas boiler		Condensing natural gas boiler		Light heating oil boiler		LPG boiler		Heat pump		Electric boiler		Biomass boiler		Natural gas microC HP	No space heating	TOTAL
Config.	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central			
TERCOMM	690.875	443.883	53.011	10.677	0	98.664	0	0	354.472	67.927	773.487	0	0	0	0	235.357	**2.728.353**
TEROFFI	95.590	893.736	4.395	12.079	0	177.950	0	0	0	329.519	47.374	0	0	0	0	10.450	**1.571.093**
TEREDUC	11.692	702.705	0	18.509	0	168.972	0	0	0	6.881	1.603	0	0	0	0	61	**910.424**
TERLODG	37.772	308.061	4.805	9.575	0	24.202	0	0	0	24.047	8.274	0	0	0	0	19.170	**435.907**
TEROTHR	76.002	413.425	3.019	0	0	67.632	0	0	0	372.310	199.241	0	0	0	0	345.407	**1.477.036**
TERHLTH	0	26.934	0	0	0	0	0	0	0	0	0	0	0	0	93.652	0	**120.587**
TOTAL	**911.931**	**2.788.745**	**65.230**	**50.840**	**0**	**537.420**	**0**	**0**	**354.472**	**800.684**	**1.029.979**	**0**	**0**	**0**	**93.652**	**610.446**	**7.243.399**

Table B.6. Tertiary floor area (m^2) disaggregated by activity and DHW system

Heating system	Conventional natural gas boiler		Condensing natural gas boiler		Light heating oil boiler		LPG boiler		Heat pump		Electric boiler		Biomass boiler		Natural gas microC HP	No DHW	TOTAL
Config.	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central	Individual	Central			
TERCOMM	748.784	409.550	54.829	8.410	0	86.823	0	0	6.367	51.852	990.978	0	0	0	0	370.759	**2.728.353**
TEROFFI	94.812	896.457	4.395	10.349	0	177.011	0	0	0	313.260	72.241	0	0	0	0	2.568	**1.571.093**
TEREDUC	11.753	717.764	0	4.368	0	150.741	0	0	0	6.881	16.371	0	0	0	0	2.545	**910.424**
TERLODG	37.817	321.923	4.805	9.575	0	23.935	0	0	0	24.047	13.805	0	0	0	0	0	**435.907**
TEROTHR	75.819	413.063	3.019	0	0	67.088	0	0	0	357.299	237.438	0	0	0	0	323.309	**1.477.036**
TERHLTH	0	26.934	0	0	0	0	0	0	0	0	0	0	0	0	93.652	0	**120.587**
TOTAL	**968.986**	**2.785.691**	**67.047**	**32.703**	**0**	**505.598**	**0**	**0**	**6.367**	**753.339**	**1.330.834**	**0**	**0**	**0**	**93.652**	**699.181**	**7.243.399**

Table B.7. Bilbo average monthly temperature considered in ENERKAD modelling

Month	Average temperature (°C)
January	9
February	10
March	12
April	11
May	15
June	18
July	21
August	20
September	20
October	17
November	12
December	11

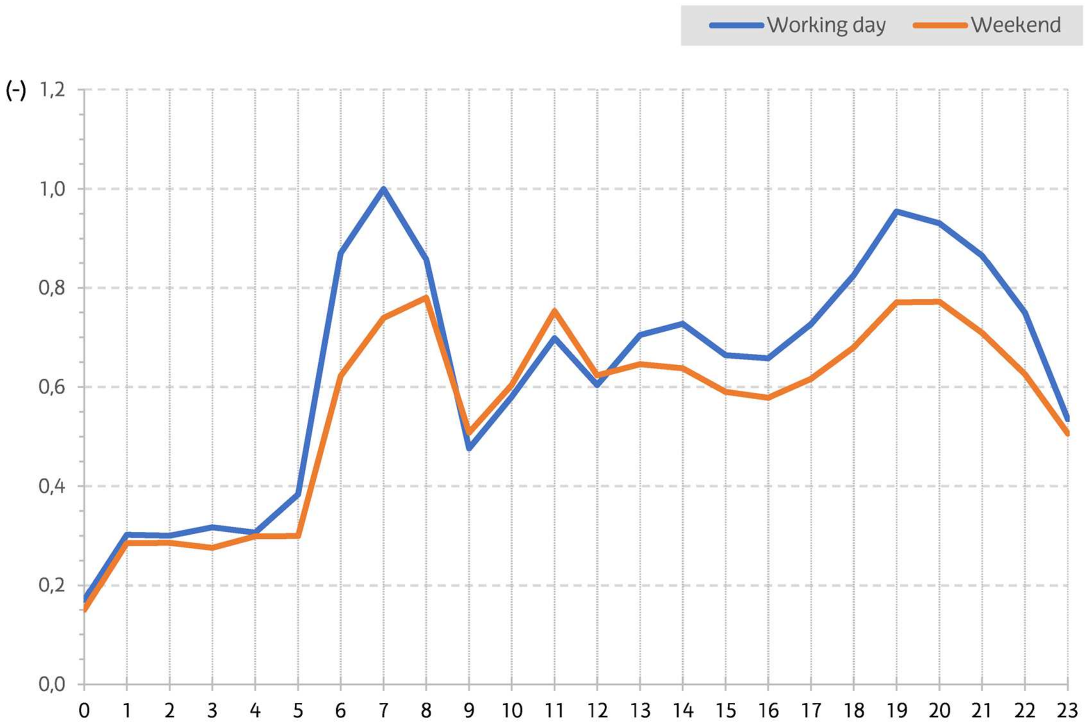
Table B.8. Residential buildings parameters considered in ENERKAD modelling

Construction period	Thermal transmittance (W/m².K)			Air leakage (h^{-1})	Renovation rate (h^{-1})	Glazing surface (%)
	Roof	Wall	Window (original/renovated)			
Pre 1944	1,8	2,5	5,7/2,65	0,9	0,63	27
1945 - 1969	1,4	2,1	5,7/2,65	0,84		
1970 - 1979	1,4	2,1	5,7/,265	0,84		
1980 - 2006	1,8	1,4	3,3	0,73		
2007 - 2013	0,53	0,95	3,3	0,73		
2014 - 2018	0,5	0,75	3,1	0,63		
Post 2019	0,4	0,49	2,1	0,63		

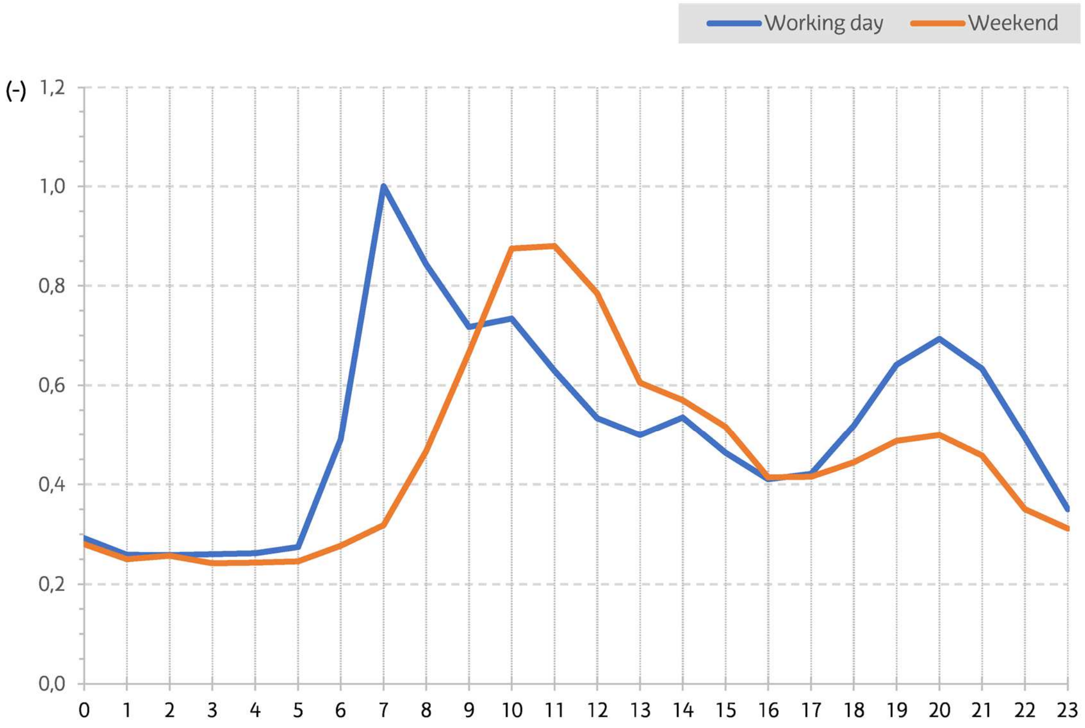
Note that construction periods differ from the ones considered in Table 4.1. Indeed, construction periods in ENERKAD are defined based on the Spanish building code (Ministerio de Transportes Movilidad y Agenda Urbana, 2022a), while the ones defined for the case study follow the disaggregation used by the Spanish building renovation strategy (Ministerio de Transportes Movilidad y Agenda Urbana, 2020). As ENERKAD provides results at building level, these are further aggregated based on the construction period defined in Table 4.1.

Table B.9. Hourly profiles considered in ENERKAD modelling

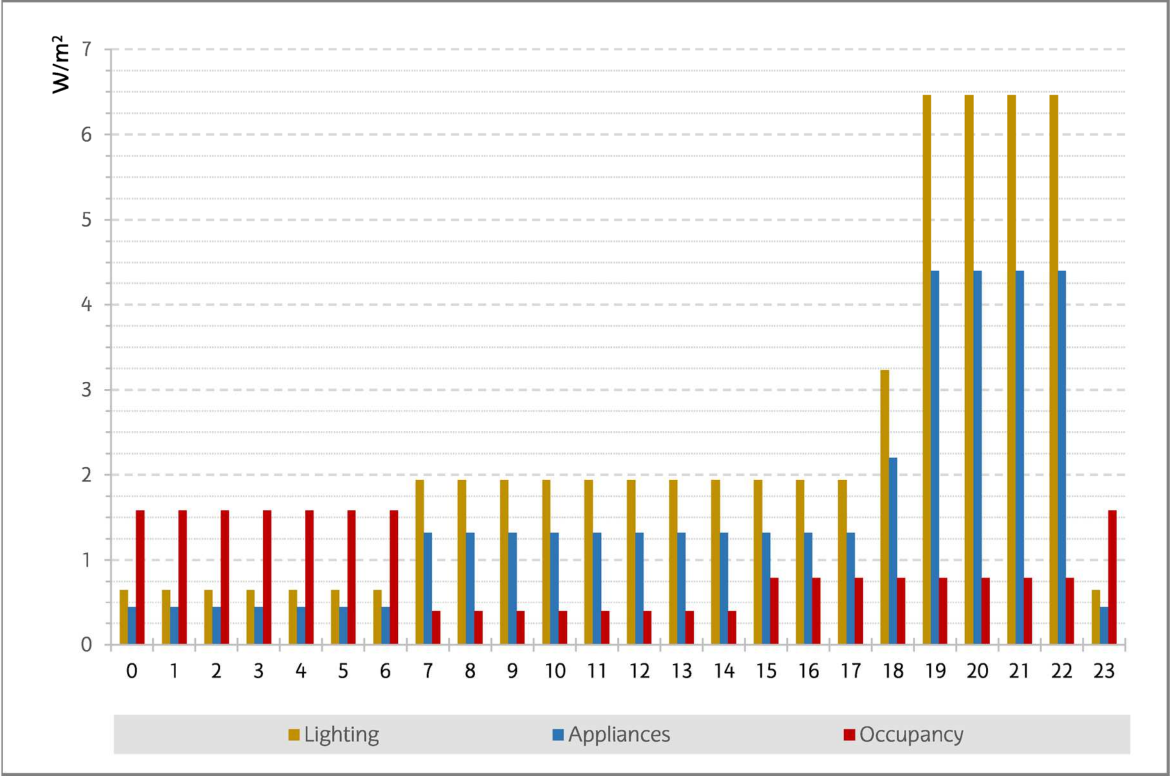
SPACE HEATING



DHW



INTERNAL GAINS (typical day)



SOLAR GAINS (annual)

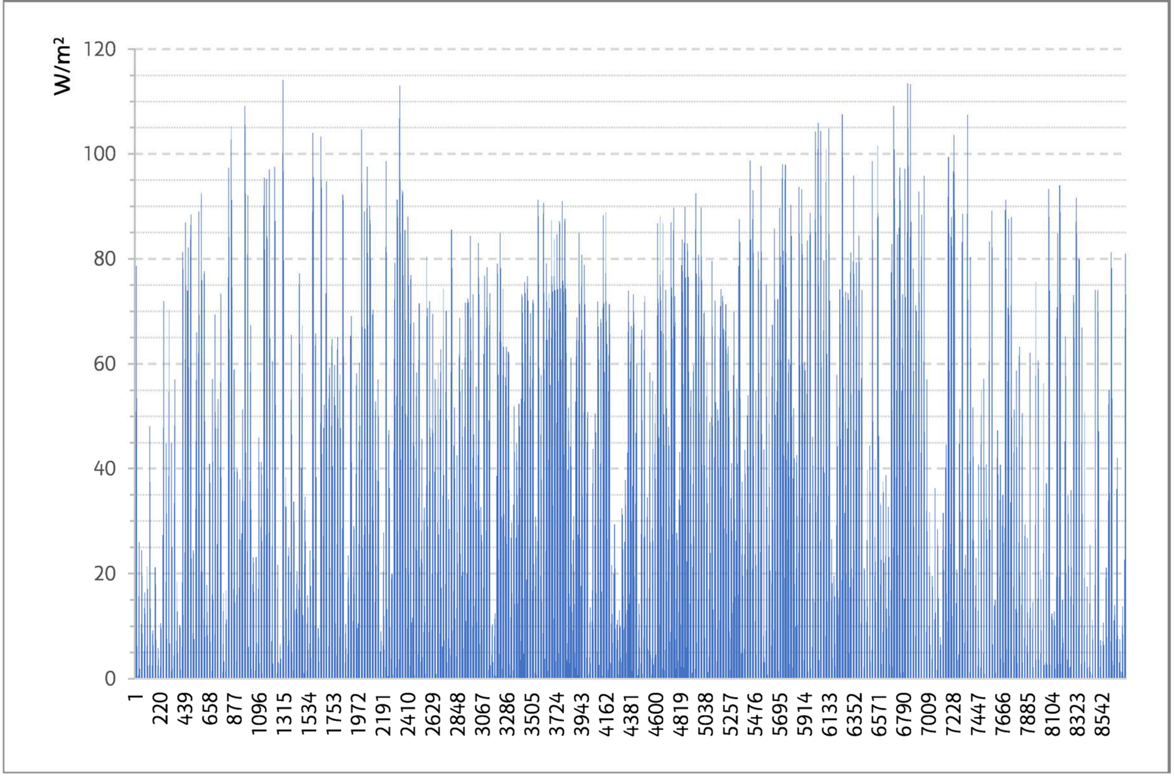


Table B.10. Socioeconomic and buildings characteristics data

ZIP Code	48001	48002	48003	48004	48005	48006	48007	48008	48009	48010	48011	48012	48013	48014	48015
Average household income (€)	79.545	30.837	36.204	33.572	45.361	37.123	38.439	80.449	84.149	59.362	100.451	41.720	45.352	45.768	40.866
Share of inhabitants aged 0-19 (%)	16	16	19	15	15	16	15	16	17	15	17	15	19	15	16
Share of inhabitants aged 20-64 (%)	60	62	64	59	68	59	57	59	56	59	56	61	60	58	59
Share of inhabitants aged more than 65 (%)	24	21	17	26	16	25	28	25	27	26	27	24	22	27	25
Share of working population (%)	43	40	43	39	49	41	40	40	40	40	38	41	40	40	40
Share of foreigners (%)	6	13	15	8	12	11	10	9	5	8	4	14	6	9	9
Share of population with higher education (%)	40	9	14	11	33	17	16	38	41	32	40	20	20	22	16
Average number of dwellers per household (dwellers)	2,30	2,37	2,43	2,32	2,18	2,29	2,25	2,40	2,45	2,28	2,48	2,37	2,33	2,33	2,41
Share of empty dwellings and secondary residences (%)	21	10	8	7	21	10	10	19	16	13	14	10	11	11	9
Average residential building stock age (years)	59	49	48	47	86	58	56	76	70	69	66	54	54	52	50
Average useful floor area of dwellings (m^2)	109	68	80	72	94	79	77	127	124	94	122	82	85	83	83
Average number of dwellings per building (rooms)	8	9	12	17	4	12	11	8	9	8	8	14	11	12	15
Average number of rooms per dwelling (rooms)	5,08	4,25	4,54	4,56	4,59	4,62	4,51	5,28	5,24	4,94	5,49	4,74	4,70	4,74	4,78
Efficiency index (-)[i]	2,58	1,97	2,22	2,07	2,26	2,18	2,03	2,49	2,41	2,24	2,53	2,24	2,21	2,28	2,27
Floor area with available info (%)	93	90	90	92	90	94	92	97	96	96	99	96	91	94	94

[i] Efficiency index measures the average efficiency of the building stock from 7 (highly efficient) to 1 (poorly efficient).

Table B.11. Descriptive statistics

	Mean	Standard Deviation	Minimum	Maximum
Deviation (%)	29	12,16	15	56
Average household income (€)	53280	21257	30837	100451
Share of inhabitants aged 0-19 (%)	16	1,34	15	19
Share of inhabitants aged 20-64 (%)	60	3,09	56	68
Share of inhabitants aged more than 65 (%)	24	3,44	16	28
Share of working population (%)	41	2,46	38	49
Share of foreigners (%)	9	3,19	4	15
Share of population with higher education (%)	25	11,04	9	41
Average number of dwellers per household (dwellers)	2,34	0,08	2,18	2,48
Share of empty dwellings and secondary residences (%)	13	4,57	7	21
Average residential building stock age (years)	60	11,07	47	86
Average useful floor area of dwellings (m^2)	92	18,83	68	127
Average number of dwellings per building (rooms)	11	3,24	4	17
Average number of rooms per dwelling (rooms)	4,80	0,33	4,25	5,49
Efficiency index (-)	2,27	0,17	1,97	2,58
Floor area with available info (%)	94	2,60	90	99

Table B.12. Correlations matrix

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Deviation (%)	1															
2	Average household income (€)	-0,57	1														
3	Share of inhabitants aged 0-19 (%)	-0,41	0,20	1													
4	Share of inhabitants aged 20-64 (%)	0,60	-0,44	0,06	1												
5	Share of inhabitants aged more than 65 (%)	-0,38	0,31	-0,44	-0,92	1											
6	Share of working population (%)	0,50	-0,19	-0,06	0,87	-0,76	1										
7	Share of foreigners (%)	0,59	-0,71	-0,11	0,67	-0,56	0,42	1									
8	Share of population with higher education (%)	-0,35	0,92	0,06	-0,18	0,14	0,15	-0,60	1								
9	Average number of dwellers per household (dwellers)	-0,48	0,43	0,59	-0,43	0,16	-0,53	-0,21	0,13	1							
10	Share of empty dwellings and secondary residences (%)	-0,06	0,68	-0,06	0,19	-0,15	0,49	-0,35	0,87	-0,18	1						
11	Average residential building stock age (years)	0,08	0,56	-0,13	0,21	-0,14	0,46	-0,21	0,78	-0,24	0,82	1					
12	Average useful floor area of dwellings (m2)	-0,49	0,96	0,21	-0,32	0,21	-0,04	-0,60	0,94	0,39	0,75	0,69	1				
13	Average number of dwellings per building (rooms)	-0,10	-0,55	-0,06	-0,29	0,29	-0,44	0,18	-0,72	0,21	-0,82	-0,80	-0,58	1			
14	Average number of rooms per dwelling (rooms)	-0,59	0,96	0,16	-0,52	0,40	-0,26	-0,71	0,87	0,48	0,57	0,51	0,94	-0,37	1		
15	Efficiency index (-)	-0,46	0,88	0,21	-0,23	0,13	0,06	-0,56	0,88	0,37	0,72	0,49	0,88	-0,44	0,90	1	
16	Floor area with available info (%)	-0,38	0,70	-0,17	-0,68	0,68	-0,53	-0,49	0,57	0,45	0,19	0,28	0,64	-0,06	0,81	0,58	1

Table B.13. Solar thermal collectors installed within the city

Floor area category	Installed capacity (m²)	Share of DHW useful energy demand supplied by solar thermal collectors
RHB1900	257	0,76%
RHB1940	278	0,49%
RHB1960	292	0,28%
RHB1980	1.357	0,53%
RHB2007	1.181	1,09%
RHB2018	3.603	16,26%
RSF2018	230	2,26%
MUNEDUC	0	0%
MUNSPRT	178	0,61%
MUNADMI	49	10,10%
MUNOTHR	30	0,76%
MUNAZKN	0	0%
TERCOMM	0	0%
TEROFFI	164	2,71%
TEREDUC	83	1,41%
TERLODG	0	0%
TEROTHR	91	0,15%
TERHLTH	0	0%

Table B.14. Efficiencies for new heating and other systems in the modelled scenarios (From (Ministerio de Transportes Movilidad y Agenda Urbana, 2020) & (DEEDS EU project, 2022))

Heating system	Individual configuration		Central configuration	
	Space heating	DHW	Space Heating	DHW
New Air heat pump	332%	298%	298%	269%
Anergy ring heat pump[i]	500%	450%	450%	405%
New Biomass boiler	86%	77%	77%	70%
Other energy systems	Efficiency improvement			
Cooling devices	25%			
Lighting devices[ii]	233%			
Appliances	67%			

[i] Heat pumps connected to a low-temperature heat network. This configuration improves heat pumps efficiency (Buffa et al., 2019).

[ii] Conventional light bulbs replaced by highly efficient LED lamps.

Table B.15. Characteristics of renovated and new dwellings (kWh/m²)

	Space heating[i]	DHW	Cooking	Cooling	Lighting	Appliances
RNV2030 (Renovated dwellings 2019-2030)	8,51	17,12	6,67	5,90	3,29	19,11
RNV2050 (Renovated dwellings 2030-2050	6,81			4,72		
NEW2030 (New dwellings 2019-2030)	5,96			4,13		
NEW2050 (New dwellings 2030-2050)	4,25			2,95		

[i] Space heating useful energy demands for renovated and new buildings are set according to the requirements of the Spanish building code (Ministerio de Transportes Movilidad y Agenda Urbana, 2022a).

See Table B.18 for equipped heating systems in renovated and new dwellings.

See Table A.7 for the considered savings in the space heating and cooling useful energy demands achieved through envelope renovation in the municipal and tertiary sectors.

Table B.16. Yearly renovation rates (in parentheses total floor area renovated for the given year)

	Building renovation scenario	2020	2030	2050
Residential	R_BR1	0,5% (0,5%)	0,5% (5%)	2% (30%)
	R_BR2	1% (1%)	1,7% (7%)	2,2% (50%)
	R_BR3	1% (1%)	3% (21%)	3,5% (84%)
	R_BR3’	1% (1%)	1,8% (15%)	3,5% (67%)
Municipal	M_BR1	2% (1%)	2% (1%)	2% (1%)
	M_BR2	3% (2%)	3% (30%)	3% (90%)
	M_BR3	4% (3%)	4% (40%)	4% (100% in 2045)
	M_BR3’	3,5% (2%)	3,5% (35%)	3,5% (100% in 2049)
Tertiary	T_BR1	0,5% (0,5%)	0,5% (5%)	2% (31%)
	T_BR2	1% (1%)	1% (1%)	3% (51%)
	T_BR3	1% (1%)	3% (22%)	3,5% (87%)
	T_BR3’	1% (1%)	2,6% (20%)	3,5% (82%)

Table B.17. Evolution of residential floor area shares (in %) supplied by specific heating (space and water) systems in every floor category and heating system renovation scenario (2030/2050)

		RHB1900			RHB1940			RHB1960			RHB1980			RHB2007			RHB2018			RSF2018		
		HR1	HR2	HR3	HR1	HR2	HR3	HR1	HR2	HR3	HR1	HR2	HR3	HR1	HR2	HR3	HR1	HR2	HR3	HR1	HR2	HR3
Condensing natural gas boiler	Individual	64/54	55/0	55/0	69/59	60/0	60/0	59/49	50/0	50/0	48/38	35/0	35/0	58/43	45/0	45/0	18/5	5/0	5/0	81/71	70/0	70/0
	Central	2/2	1/0	1/0	7/7	4/0	4/0	18/18	10/0	10/0	33/33	15/0	15/0	34/34	17/0	17/0	76/76	50/0	50/0	0/0	0/0	0/0
Electric boiler	Individual	25/15	20/35	10/3	14/4	10/20	5/2	14/4	10/20	10/3	11/1	10/20	5/2	0/0	5/10	2/1	0/0	0/0	0/0	11/1	5/5	2/1
	Central	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
New Air heat pump	Individual	8/23	23/63	29/79	9/24	20/70	23/79	8/23	20/60	16/61	7/22	17/42	20/51	7/17	13/53	15/58	4/12	14/19	14/19	7/27	20/90	22/92
	Central	1/9	1/2	1/1	1/6	6/10	6/8	1/6	10/20	10/15	1/6	23/38	23/30	1/6	20/37	20/28	1/6	30/80	30/55	0/0	0/0	0/0
Anergy ring heat pump	Individual	0/0	0/0	4/16	0/0	0/0	2/9	0/0	0/0	2/9	0/0	0/0	2/9	0/0	0/0	1/4	0/0	0/0	0/0	0/0	0/0	1/2
	Central	0/0	0/0	0/1	0/0	0/0	0/2	0/0	0/0	0/5	0/0	0/0	0/8	0/0	0/0	0/9	0/0	0/0	0/25	0/0	0/0	0/0
New Biomass boiler	Individual	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/1	1/1	0/0	5/5	5/5
	Central	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0

Table B.18. Evolution of floor area shares (in %) supplied by specific heating (space and water) systems in every new and renovated residential floor categories and scenario (2030/2050)

		RNV2030			RNV2050			NEW2030			NEW2050		
		Baseline and rest of scenarios	HR2	HR3	Baseline and rest of scenarios	HR2	HR3	Baseline and rest of scenarios	HR2	HR3	Baseline and rest of scenarios	HR2	HR3
Condensing natural gas boiler	Individual	40/40	25/0	25/0	30/30	0/0	0/0	25/25	15/0	15/0	15/15	0/0	0/0
	Central	40/40	25/0	25/0	40/40	0/0	0/0	40/40	25/0	25/0	40/40	0/0	0/0
Electric boiler	Individual	10/10	10/10	5/5	5/5	15/15	0/0	20/20	25/25	5/5	15/15	15/15	0/0
	Central	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
New Air heat pump	Individual	5/5	10/35	15/40	10/10	30/30	30/30	5/5	10/25	5/20	10/10	30/30	10/10
	Central	5/5	30/55	15/40	15/15	55/55	35/35	10/10	25/50	30/55	20/20	55/55	30/30
Anergy ring heat pump	Individual	0/0	0/0	10/10	0/0	0/0	20/20	0/0	0/0	10/10	0/0	0/0	20/20
	Central	0/0	0/0	5/5	0/0	0/0	15/15	0/0	0/0	10/10	0/0	0/0	40/40

Table B.19. Evolution of municipal floor area shares (in %) supplied by specific heating (space and water) systems in every floor category and heating system renovation scenario (2030/2050)

		MUNEDUC			MUNSPRT			MUNADMI			MUNOTHR			MUNAZKN		
		HR1	HR2	HR3	HR1	HR2	HR3	HR1	HR2	HR3	HR1	HR2	HR3	HR1	HR2	HR3
Condensing natural gas boiler	Individual	88/75	0/0	0/0	5/5	0/0	0/0	70/65	0/0	0/0	88/75	0/0	0/0	90/80	0/0	0/0
	Central	0/0	60/0	60/0	0/0	5/0	5/0	0/0	58/0	58/0	0/0	75/0	75/0	0/0	60/0	60/0
Electric boiler	Individual	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Central	0/0	0/0	0/0	0/0	0/0	0/0	2/2	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
New Air heat pump	Individual	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0//0	0/0	0/0	0/0	0/0	0/0
	Central	12/25	40/100	40/70	1/1	5/100	5/80	28/33	42/100	42/71	12/25	25/100	25/62	10/20	40/100	40/70
Anergy ring heat pump	Individual	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Central	0/0	0/0	0/30	0/0	0/0	0/20	0/0	0/0	0/29	0/0	0/0	0/38	0/0	0/0	0/30
New Biomass boiler	Individual	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Central	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
Micro CHP (natural gas)	Central	0/0	0/0	0/0	94/94	90/0	90/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0

Table B.20. Evolution of tertiary floor area shares (in %) supplied by specific heating (space and water) systems in every floor category and heating system renovation scenario (2030/2050)

		TERCOMM			TEROFFI			TEREDUC			TERLODG			TEROTHR			TERHLTH		
		HR1	HR2	HR3	HR1	HR2	HR3	HR1	HR2	HR3	HR1	HR2	HR3	HR1	HR2	HR3	HR1	HR2	HR3
Condensing natural gas boiler	Individual	5/4	5/0	5/0	4/4	4/0	4/0	0/0	0/0	0/0	2/2	2/0	2/0	3/3	0/0	0/0	0/0	0/0	0/0
	Central	15/12	15/0	15/0	49/39	50/0	50/0	86/68	85/0	85/0	96/77	80/0	80/0	43/38	40/0	40/0	20/20	20/0	20/0
Electric boiler	Individual	33/17	35/35	17/3	4/2	5/5	2/1	2/1	0/0	0/0	0/0	2/2	1/0	18/18	18/10	9/1	0/0	0/0	0/0
	Central	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
New Air heat pump	Individual	43/59	40/45	51/61	24/26	22/26	24/28	2/3	5/5	5/5	1/1	6/8	7/9	0/0	0/0	5/4	0/0	0/0	0/0
	Central	4/8	5/20	5/12	19/29	19/69	19/44	10/28	10/95	10/52	1/20	10/90	10/50	36/41	42/90	42/70	0/0	10/90	10/80
Anergy ring heat pump	Individual	0/0	0/0	7/16	0/0	0/0	1/2	0/0	0/0	0/0	0/0	0/0	0/1	0/0	0/0	4/5	0/0	0/0	0/0
	Central	0/0	0/0	0/8	0/0	0/0	0/25	0/0	0/0	0/43	0/0	0/0	0/40	0/0	0/0	0/20	0/0	0/10	0/20
New Biomass boiler	Individual	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
	Central	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
Micro CHP (natural gas)	Central	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	80/80	70/0	70/0

Table B.21. New energy savings and energy efficiency measures enacted by the Spanish government (BOE, 2022)

Energy service	Lighting	Space heating	Cooling
MEASURE	*Storefronts lighting switched off at night (22:00-06:00)*	*Set-point temperature is limited to 19°C (from previous standard 22°C)*	*Set-point temperature limited to 27°C (from previous standard 24°C)*
Floor area category	Achieved savings in useful energy demand		
MUNADMI	-	21%	21%
MUNOTHR	-	21%	21%
MUNAZKN	-	21%	21%
TERCOMM	33%	21%	21%
TEROFFI	-	21%	21%
TERHORE	-	21%	21%
TEROTHR	-	21%	21%

Table B.22. Fuel prices (From (Instituto para la Diversificación y Ahorro de la Energía. IDAE, 2020; Ministerio para la Transición Ecológica y el Reto Demográfico, 2018))

Fuel	€/kWh (2018)
Electricity	0,24
Natural gas	0,07
Light heating oil	0,06
LPG	0,09
Biomass	0,03

Table B.23. ECM investment costs (From (CYPE, 2022))

ECM	Investment costs	Unit
Building envelope renovation	153	€/m² (floor)
Condensing natural gas boiler	116	€/kW
Electric boiler	71	€/kW
NEW Air heat pump	894	€/kW
Anergy ring heat pump	1341	€/kW
NEW Biomass boiler	206	€/kW
Lighting renovation (residential)	0,4	€/m²
Appliances renovation (residential)	13	€/m²
Lighting renovation (tertiary)	0,8	€/m²
Appliances renovation (tertiary)	27	€/m²

Table B.24. Additional economic indicators

	Investment costs Present Value (M€)	Operational savings Present Value (M€)	SNPV (M€)	GWh saved/M€ invested	kton CO2 saved/M€ invested (variable EEF)	kton CO2 saved/M€ invested (constant EEF)
RSD_BR1	-171	25	-146	5	18	2
RSD_BR2	-309	44	-265	6	11	2
RSD_BR3	-610	84	-526	6	6	2
RSD_HR1	-469	46	-424	5	7	1
RSD_HR2	-529	69	-460	12	9	2
RSD_HR3	-578	106	-472	14	8	3
RSD_SR1	-45	114	69	19	67	7
RSD_SR2	-90	227	138	21	34	7
RSD_CPS	0	95	95	-	-	-
MUN_BR1	-15	0	-14	1	16	16
MUN_BR2	-22	1	-22	1	10	10
MUN_BR3	-30	1	-29	1	8	8
MUN_HR1	-16	1	-15	6	16	16
MUN_HR2	-20	3	-17	19	16	16
MUN_HR3	-21	3	-18	18	16	16
MUN_SR1	-4	10	7	31	65	65
MUN_SR2	-7	21	14	31	33	33
MUN_CPS	0	1	1	-	-	-
TER_BR1	-66	5	-61	6	50	2
TER_BR2	-114	9	-105	4	29	1
TER_BR3	-238	18	-220	3	14	1
TER_HR1	-260	25	-236	8	14	2
TER_HR2	-268	55	-213	13	15	3
TER_HR3	-307	86	-221	13	13	3
TER_SR1	-45	216	171	57	75	15
TER_SR2	-90	433	343	54	38	14
TER_CPS	0	595	595	-	-	-
RSD_BR3'	-446	62	-384	6	8	2
MUN_BR3'	-27	1	-26	1	9	9
TER_BR3'	-218	16	-202	3	15	1

Appendix C: Chapter III

Table C.1. Valencia vehicle stock characteristics

Sector	Vehicle type	Powertrain	Stock (number of vehicles) (2018)	Urban fuel economy (kWh/100 km)	Annual urban mileage (km)	Energy intensity (MWh/vehicle)
Municipal fleet	*Cars*	Diesel	189	72	5.293	3,81
		Gasoline (hybrid)	0	53	5.293	2,78
		Electricity	0	17	5.293	1,14
	Two wheels	Gasoline	131	42	1.323	0,55
		Electricity	0	13	1.323	0,17
	Light utility vehicles	Diesel	284	103	7.939	8,19
		Gasoline (hybrid)	0	75	7.939	5,97
		Electricity	0	31	7.939	2,46
Public transport	*Buses*	Diesel	417	485	61.999	300,60
		CNG	75	850	61.999	527,24
		Electricity	0	146	61.999	98,18
Private transport	*Cars*	Diesel	186.305	72	15.619	11,25
		Gasoline	172.989	75	6.540	4,90
		Gasoline (hybrid)	0	53	15.619	8,20
		Electricity	0	17	15.619	3,37
	Two wheels	Gasoline	85.822	42	1.547	0,64
		Electricity	0	13	1.547	0,19
	Light utility vehicles	Diesel	40.067	103	23.996	24,75
		Gasoline	6.668	107	10.048	10,79
		Gasoline (hybrid)	0	75	23.996	18,04
		Electricity	0	31	23.996	7,43
	Heavy duty vehicles	Diesel	3.257	227	23.996	54,52
		Electricity	0	68	23.996	16,35
	Buses	Diesel	597	485	64.323	311,87
		Electricity	0	146	64.323	93,56

Table C.2. Scenarios modelling assumptions

Sector	Modelled feature	Bau scenario	Building scenario	Mobility scenario	Mixed scenario
Residential	2018-2030 /2030-2050 yearly households renovation rate (total households renovated by 2050)	0,1% / 0,5% (11%)	2% / 3% (84%)	1% / %1% (32%)	1,5% / 2% (58%)
	New households evolution (2018-2050 variation)	y = 1022,76*ln(x) - 617,46 (0,90%)			
Municipal buildings	Reference energy evolution (2018-2050 variation)	y = 142,24*x + 101340 (4,74%)			
	Renovated floor area by 2050	20%	100%	60%	80%
Private tertiary buildings	Reference energy evolution (2018-2050 variation)	y = 551,91*x + 1344066 (1,38%)			
	Renovated floor area by 2050	12%	90%	40%	65%
Public lighting	LED devices	100% LED in 2030			
Industry	Reference energy evolution (2018-2050 variation)	y = -2950,94*x + 311447 (-30,44%)			
	Fuel share (2018/2050)	Electricity		30% /70%	
		Natural gas		70% / 10%	
		Biomass		0% / 15%	
		Solar heat		0% / 5%	
Municipal fleet	Car stock evolution (2018-2050 variation)	y = 0,27*x + 180 (4,74%)			
	% electric cars (2030/2050)	30% / 70%	30% / 80%	50% / 100%	40% / 90%
	Two wheels stock evolution (2018-2050 variation)	y = 0,18*x + 132 (4,74%)			
	% electric two wheels (2030/2050)	50% / 100%	50% / 100%	70% / 100%	60% / 100%
	Light utility vehicles stock evolution (2018-2050 variation)	y = 0,40*x + 285 (4,74%)			
	% electric light utility vehicles (2030/2050)	30% / 70%	30% / 80%	50% / 100%	40% / 90%
Public transport	Bus stock evolution (2018-2050 variation)	Reference evolution	2050 compared to BaU	2050 compared to BaU	2050 compared to BaU
		y = 0,69*x + 494 (4,74%)	0,25% (5%)	3,11% (8%)	1,20% (6%)
	% electric buses (2030/2050)	10% /70%	20% / 80%	40% / 100%	30% / 90%
	Urban rail passengers evolution	Reference evolution	Same as BaU	2050 compared to BaU	Same as BaU
		y = 106277*x + + 67113650 (4,67%)	-	0,32% (5%)	-

Sector	Modelled feature	Bau scenario	Building scenario	Mobility scenario	Mixed scenario
Private transport	Car stock evolution (2018-2050 variation)	Reference evolution	2050 compared to BaU	2050 compared to BaU	2050 compared to BaU
		y = 4751,43*ln(x) + 357083 (4,21%)	-2,12% (2%)	-8,83% (-5%)	-3,08% (1%)
	% electric cars (2030/2050)	5% / 30%	5% / 50%	20% / 80%	10% / 60%
	Two wheels stock evolution (2018-2050 variation)	Reference evolution	2050 compared to BaU	2050 compared to BaU	2050 compared to BaU
		y = 365,2*x + + 86776 (14,14%)	-3,63% (10%)	-10,64% (2%)	-8,01% (5%)
	% electric two wheels (2030/2050)	20% / 50%	50% / 80%	70% / 100%	70% / 90%
	Light utility vehicles stock evolution (2018-2050 variation)	Reference evolution	2050 compared to BaU	2050 compared to BaU	2050 compared to BaU
		y = 53,96*x + +47129 (4,21%)	-8,83% (-5%)	-13,63% (-10%)	-8,83% (-5%)
	% electric light utility vehicles (2030/2050)	5% / 20%	5% / 40%	20% / 70%	5% / 50%
	Heavy duty vehicles stock evolution	Reference evolution	2050 compared to BaU	2050 compared to BaU	2050 compared to BaU
		y = -10,53*x + + 2489 (-10,22%)	-5,33% (-15%)	-22,04% (-30%)	-10,90% (-20%)
	% electric heavy duty vehicles (2030/2050)	2% / 20%	2% / 30%	10% / 60%	2% / 40%
	Bus stock evolution (2018-2050 variation)	y = -0,01*x + 597 (-0,16%)			
	% electric buses (2030/2050)	10% / 30%	10% / 40%	30% / 70%	10% / 50%

Table C.3. Renovated and new households characteristics

	Space heating[i]		DHW		Cooking	Cooling	Lighting	Appliances
	Useful energy demand (kWh/m²)	Heating systems share (%) (heat pump/ electric heater/ natural gas boiler)	Useful energy demand (kWh/m²)	Heating systems share (%) (heat pump/ electric heater/ natural gas boiler)	Useful energy demand (kWh/m²)	Useful energy demand (kWh/m²)	Useful energy demand (kWh/m²)	Useful energy demand (kWh/m²)
Renovated SFH 2019-2030	5,23	70/20/10	10	70/20/10	2,93	7,94	4,52	20,37
Renovated SFH 2030-2050	4,19	90/10/0		90/10/0		6,35		
New SFH 2019-2030	3,66	90/5/5		90/5/5		5,56		
NewSFH 2030-2050	2,62	100/0/0		100/0/0		3,97		
Renovated HB 2019-2030	3,15	70/20/10	15	70/20/10	2,93	4,12	4,52	20,37
Renovated HB 2030-2050	2,52	90/10/0		90/10/0		3,30		
New HB 2019-2030	2,5	90/5/5		90/5/5		2,89		
New HB 2030-2050	1,57	100/0/0		100/0/0		2,06		

[i] Space heating useful energy demands for renovated and new buildings are set according to the requirements of the Spanish building code (Ministerio de Transportes Movilidad y Agenda Urbana, 2022a).

See Table A.2 for current stock characteristics.

All new and renovated dwellings are equipped with new energy systems. See Table A.3 for considered efficiencies.

100% electric cooking in all new and renovated dwellings categories.

Table C.4. SLCC assumptions

Modelled measure	Description	Reference unit	Assumed costs and life cycle			Source
Residential (Household renovation)	A full household renovation is carried out. Both envelope and heating and cooling systems are renovated	Renovated floor area (m²)	Discount rate		12%	(European Commission, 2021)
			CAPEX	Insulation, mortar, construction services, and energy systems	162 €/m² (2018-2030) 157 €/m² (2030-2050)	Adapted from Table B.23
			OPEX	Maintenance	0,35 €/m².year (2018-2030) 0,29 €/m².year (2030-2050)	
			Life cycle		Envelope renovation: 50 years Energy systems renovation: 20 years	
Tertiary building renovation (Municipal and private buildings)	A full building renovation is considered including envelope renovation, heating and cooling systems renovation, LED lighting installation, and implementation of energy management and control strategies	Renovated floor area (m²)	Discount rate		11%	(European Commission, 2021)
			CAPEX	Insulation, mortar, construction services, energy systems and other efficiency measures	173 €/m²	Adapted from Table B.23
			OPEX	Maintenance	0,36 €/m².year	
			Life cycle		Envelope renovation: 50 years Energy systems renovation: 20 years	
Municipal fleet (Fleet electrification)	EV introduction	ICE vehicle replaced by EV	Discount rate		7,5%	(European Commission, 2021)
			CAPEX	EV over cost	9.014 €/car 3.426 €/two wheel 9.298 €/light utility vehicle	(European Commission, 2021)
			OPEX	Maintenance	320 €/car.year 79 €/two wheels.year 476 €/light utility vehicle.year	(Gössling and Choi, 2015)
			Life cycle		EV: 14 years EV battery: 7 years	

Modelled measure	Description	Reference unit	Assumed costs and life cycle			Source
Public transport (Fleet electrification)	EV introduction	ICE vehicle replaced by EV	Discount rate		7,5%	(European Commission, 2021)
			CAPEX	EV over cost	150.196 €/bus	(European Commission, 2021)
			OPEX	Maintenance	3720 €/bus.year	(Gössling and Choi, 2015)
			Life cycle		EV: 14 years EV battery: 7 years	
Private transport (Fleet electrification)	EV introduction	ICE vehicle replaced by EV	Discount rate		11% (cars, two wheels, light utility vehicle) 10% (heavy duty vehicle) 7,5% (bus)	(European Commission, 2021)
			CAPEX	EV over cost	9.014 €/car 3.426 €/two wheel 9.298 €/light utility vehicle 120.671 €/heavy duty vehicle 177.254 €/bus	(European Commission, 2021)
			OPEX	Maintenance	375 €/car.year 139 €/two wheels.year 432 €/light utility vehicle.year 5.759 €/heavy duty vehicle.year 7.719 €/bus.year	(Gössling and Choi, 2015)
			Life cycle		EV: 14 years EV battery: 7 years	

Decommission costs (phases c1 to c4) are assumed as 2% CAPEX.

OPEX do not include costs derived from fuel consumption. These are calculated based on the data in Table B.22 and Table C.5.

Presented costs represent the extra expense of replacing a given technology/component at its end of life (e.g. building, energy system, vehicle) by an upgraded/cleaner version of this technology/component (i.e. the extra cost of renovating a building versus not renovating it, the extra cost of replacing a gas boiler by a heat pump instead of replacing it by an equivalent boiler, or the cost of replacing a ICE vehicle by a EV instead of replacing it by an equivalent ICE).

Table C.5. Evolution of fuel prices and technology costs (From (European Commission, 2021)*)*

	2018-2030 variation	2030-2050 variation
Fuels prices		
Electricity	4,43%	1,86%
Natural gas	50,83%	29,30%
Light heating oil	50,42%	32,08%
LPG	50,42%	32,08%
Diesel	50,42%	32,08%
Technology CAPEX		
Building systems	-9,04%	-6,84%
EV car	-37,75%	-7,43%
EV two wheels	-57,41%	-19,06%
EV LUV	-35,46%	-11,85%
EV heavy duty vehicle	-44,09%	-17,62%
EV bus public / EV bus private	-36,76% / -33,87%	-8,58% / -12,77%

Considered 2018 fuel prices are described in Table B.22 in appendix B. Considered 2018 diesel price: 0,11 €/kWh from (Ministerio para la Transición Ecológica y el Reto Demográfico, 2018).
Technologies CAPEX described in Table C.4.

Table C.6. Detailed CAPEX and OPEX costs and operational savings and residual values by scenario and modelled measure

	Sector (modelled measure)	CAPEX & OPEX	Operational savings & Residual value	SLCC
		M€		
Building scenario	Residential (Household renovation)	-6	1	-5
	Municipal buildings (Building renovation)	-44	17	-27
	Private tertiary buildings (Building renovation)	-437	190	-248
	Municipal fleet (Fleet electrification)	-0,12	0,09	-0,02
	Public transport (Fleet electrification & Modal change)	-13	17	4
	Private transport (Fleet electrification & Modal change)	-167	141	-26
Mobility scenario	Residential (Household renovation)	-3	1	-2
	Municipal buildings (Building renovation)	-22	8	-14
	Private tertiary buildings (Building renovation)	-157	68	-89
	Municipal fleet (Fleet electrification)	-1,29	0,82	-0,47
	Public transport (Fleet electrification & Modal change)	-40	52	13
	Private transport (Fleet electrification & Modal change)	-1011	970	-40
Mixed scenario	Residential (Household renovation)	-5	1	-4
	Municipal buildings (Building renovation)	-33	12	-20
	Private tertiary buildings (Building renovation)	-297	129	-168
	Municipal fleet (Fleet electrification)	-0,71	0,46	-0,25
	Public transport (Fleet electrification & Modal change)	-26	34	8
	Private transport (Fleet electrification & Modal change)	-390	322	-68

Table C.7. MCDA cases

CASE A Emissions reduction priority				CASE B Energy savings priority				CASE C Least-cost option priority			
A	B	More important (A/B)	Intensity (1-9)	A	B	More important (A/B)	Intensity (1-9)	A	B	More important (A/B)	Intensity (1-9)
CCES	CTPES	A	9	CCES	CTPES	B	7	CCES	CTPES	A	3
	CNRPES	A	9		CNRPES	B	9		CNRPES	A	3
	SLCC	A	9		SLCC	A	5		SLCC	B	9
CTPES	CNRPES	B	5	CTPES	CNRPES	B	7	CTPES	CNRPES	B	5
	SLCC	A	7		SLCC	A	9		SLCC	B	9
CNRPES	SLCC	A	7	CNRPES	SLCC	A	9	CNRPES	SLCC	B	9

Note: Intensity measures the importance of one indicator versus another, ranging from "1" for same importance to "9" for extremely important.

	Sector (modelled measure)	CASE A Emissions reduction priority	CASE B Energy savings priority	CASE C Least-cost option priority
		RESULTS		
Building scenario	Residential (Household renovation)	0,2343	0,2793	0,7159
	Municipal buildings (Building renovation)	0,0377	0,0415	0,5902
	Private tertiary buildings (Building renovation)	0,0892	0,1397	0,0333
	Municipal fleet (Fleet electrification)	0,0353	0,0353	0,6605
	Public transport (Fleet electrification & Modal change)	0,0480	0,0486	0,6751
	Private transport (Fleet electrification & Modal change)	0,2616	0,2699	0,6642
Mobility scenario	Residential (Household renovation)	0,1073	0,1239	0,6799
	Municipal buildings (Building renovation)	0,0365	0,0384	0,6253
	Private tertiary buildings (Building renovation)	0,0546	0,0727	0,4354
	Municipal fleet (Fleet electrification)	0,0355	0,0354	0,6594
	Public transport (Fleet electrification & Modal change)	0,0720	0,0733	0,7052
	Private transport (Fleet electrification & Modal change)	0,9925	0,9925	0,8595
Mixed scenario	Residential (Household renovation)	0,1732	0,2048	0,6985
	Municipal buildings (Building renovation)	0,0371	0,0399	0,6077
	Private tertiary buildings (Building renovation)	0,0719	0,1062	0,2343
	Municipal fleet (Fleet electrification)	0,0354	0,0353	0,6599
	Public transport (Fleet electrification & Modal change)	0,0600	0,0610	0,6898
	Private transport (Fleet electrification & Modal change)	0,4924	0,4950	0,6281

Appendix D: Emission and primary energy factors

Table D.1. Emission factors

Fuel	ton CO_2/MWh	Source
Electricity (Valencia 2007) (Chapter III)[i]	0,301	(Ajuntament de València, 2019)
Electricity (Bilbao 2018) (Chapter IV)[ii]	0,260	(REE, 2018)
Electricity (Valencia 2018) (Chapter V)[ii]	0,260	(REE, 2018)
Natural gas	0,202	(IPCC, 2006)
Light heating oil	0,263	(IPCC, 2006)
LPG	0,234	(IPCC, 2006)
Biomass	0,018	(Industria/IDAE, 2016)
Diesel	0,267	(IPCC, 2006)
Gasoline	0,249	(IPCC, 2006)
CNG	0,202	(IPCC, 2006)

i Assumed local electricity emission factor (2007) considered in the city SECAP for the estimation of impacts.
ii Assumed the national electricity emission factor.

Table D.2. Primary energy emission factors

Fuel	Total primary energy factor (kWh total primary energy/ kWh final energy)	Non-renewable primary energy factor (kWh non-renewable primary energy/ kWh final energy)	Source
Electricity (national grid)	2,368	1,954	(Industria/IDAE, 2016)
Natural gas	1,195	1,190	(Industria/IDAE, 2016)
Light heating oil	1,182	1,179	(Industria/IDAE, 2016)
LPG	1,204	1,201	(Industria/IDAE, 2016)
Biomass	1,113	0,085	(Industria/IDAE, 2016)
Diesel	1,12	1,117	(Industria/IDAE, 2010)
Gasoline	1,1	1,097	(Industria/IDAE, 2010)
CNG	1,07	1,066	(Industria/IDAE, 2010)

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