Energy Strategy Reviews 32 (2020) 100553

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: http://www.elsevier.com/locate/esr

Methodology for integrated modelling and impact assessment of city energy system scenarios

Iñigo Muñoz [a,c,*], Patxi Hernández [a], Estibaliz Pérez-Iribarren [b], Juan Pedrero [a], Eneko Arrizabalaga [a], Nekane Hermoso [a]

[a] *TECNALIA, Basque Research and Technology Alliance (BRTA), Astondo Bidea, Edificio 700, Derio, 48160, Spain*
[b] *ENEDI Research Group, Department of Thermal Engineering, Faculty of Engineering of Bilbao, University of the Basque Country UPV/EHU, Plaza Ingeniero Torres Quevedo 1, Bilbao, 48013, Spain*
[c] *University of the Basque Country UPV/EHU, Bilbao, Spain*

ABSTRACT

Cities are ought to play a key role in the energy transition to a low carbon society as they concentrate more than half of the world's population and are responsible for about 67% primary energy consumption and around 70% of the energy-related CO_2 emissions. To achieve the agreed climate targets, efficient urban planning is a must. Tools and methods have risen to model different aspects of the energy performance of urban areas. Nevertheless, addressing the complexity of a city energy system is a great challenge and new integrated tools and methods are still needed. This paper presents a methodology for integrated city energy modelling and assessment, from the characterization of the city's current energy performance to the development and assessment of future scenarios. Energy characterization is based on the combination of bottom-up approaches with top-down data to establish the city's energy baseline. This baseline integrates bottom-up results from a GIS based model which is used to characterize the city's building stock energy performance, while available information on the vehicle stock is used to model the mobility sector. Scenarios are developed from this baseline and assessed through a multi-criteria impact assessment model. A simplified case study is carried out for the city of Valencia (Spain) to demonstrate the suggested methodology, and results are shown for three different scenarios: one focused on the building sector, one on transport, and one combining measures in both sectors. The transport-focused scenario demonstrates to be the most favourable in terms of energy savings and emissions reductions. The application of the proposed method is intended to support the development of strategies and plans for energy transition at city level. The main challenges for its application in cities are data availability at urban level, the uncertainty related to modelling the transport sector, and the unavailability of adapted I/O tables at city scale to assess socioeconomic impacts.

1. Introduction

Gathering 55% of the world's population [1], cities are held responsible for 67% of the world's primary energy consumption and about 70% of the CO_2 energy-related emissions [2]. The expected raise of urban dwellers, reaching 70% of the global inhabitants in 2050 [1], will increase even more the cities' energy consumption. If actions were not taken, this would put more pressure on the environment, increasing resource scarcity, Greenhouse Gases (GHG) emissions and other effects related to the climate change, and increasing risks of social and economic crisis.

Urban areas should play then a pivotal role in the mitigation of climate change effects as they show huge potential for energy savings and pollutant emissions reduction. Cities concentrate a diverse amount of activities and sectors and can intervene in energy-related fields so varied as buildings, transport, industry, public lighting, waste management or energy generation. The aforementioned sectors, along with the socioeconomic situation of the city itself, form a so-called urban metabolism [3] which makes the city a complex energy system to evaluate but with wide possibilities of changes implementation. As innovation hubs and testing ground for the development of sustainable initiatives, cities should therefore act as leading characters in the transition towards a low-carbon society.

Transformation of urban areas into sustainable systems should be addressed through a long-term vision and the efficient management of available resources. While at national level, methodologies and tools for modelling energy scenarios have been used for decades, methods and approaches providing these inputs -energy scenarios-to energy plans and policies at city scale have been less studied. The reason for this is the intrinsic complexity of city energy modelling, with specific challenges regarding lack of data, boundaries definition, socioeconomic structure, infrastructure and decentralized energy systems modelling, amongst

---

* Corresponding author. TECNALIA, Basque Research and Technology Alliance (BRTA), Astondo Bidea, Edificio 700, Derio, 48160, Spain.
E-mail addresses: inigo.munoz@tecnalia.com (I. Muñoz), patxi.hernandez@tecnalia.com (P. Hernández), estibaliz.perezi@ehu.eus (E. Pérez-Iribarren), juan.pedrero@tecnalia.com (J. Pedrero), eneko.arrizabalaga@tecnalia.com (E. Arrizabalaga), nekane.hermoso@tecnalia.com (N. Hermoso).

https://doi.org/10.1016/j.esr.2020.100553
Received 22 October 2019; Received in revised form 6 June 2020; Accepted 27 August 2020

others. There is still a need for clear approaches and methodologies to develop urban energy models or to adapt existing national approaches to an urban level.

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

The presented methodology seeks to simplify the modelling and scenario generation process. On the one hand by overcoming the data deficiencies at urban scale by relying on accessible cadastre data to characterize the whole building sector through a GIS-based model and using simple vehicle stock data to outline the transport sector. Moreover, the characterization also intends to consider a holistic view of the city by integrating all the energy-intervening sectors in both demand and supply sides. On the other hand, the scenario generation process aims to reduce the complexity in the projection of future energy needs process by using straightforward key parameters to model future energy demands. The modelling of the city energy system and simulation of future scenarios is completed by an assessment of the proposed alternatives. By isolating the effects due to the system's natural trend, the impacts exclusively caused by the measures modelled in the alternative scenarios are identified. Therefore allowing to clearly identify the pros and cons of the different modelled futures and facilitating the decision-making process.

This paper is structured as follows: firstly, a critical review of the approaches for the modelling and assessment of the urban energy system is carried out. Secondly, the proposed methodology for modelling and impact assessment of city energy system scenarios is developed and explained. In order to illustrate the application of the method, a case study is presented. The article ends with a discussion and conclusion section where the main aspects of the proposed methodology are summarised, limitations identified, and future work outlined.

2. City energy system modelling and assessment review

The objective of city energy modelling is to represent the energy flows that occur inside and across the urban boundaries, through the evaluation of the performance of the different parts of the city energy system such as buildings, vehicles or energy generation systems. In the review by Abbasabadi and Ashayeri [4] 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. [5] which carried out a review of methods, and identified challenges and opportunities when modelling urban key areas like technology, building and systems design, urban climate, policy assessment, and transportation and land use.

Regarding the available tools for urban energy modelling and scenarios generation at city scale, reviews were carried out by Ferrari et al. [6] and by Beuzekom et al. [7]. Moreover Mirakyan and De Guio [8] reviewed a set of software resources for their proposed integrated energy planning methodology. Amongst the reviewed tools, Lind and Espegren [9] used the TIMES model [10] to compare the results of different energy measures implementation in Oslo, while low-carbon transition scenarios are evaluated in an International Energy Agency (IEA) report [11] for Helsinki and other Nordic cities. The same energy model was also used in the EU project InSmart [12,13] and by Yazdanie et al. [14]. In the former, outputs from specific transport and building models are used in TIMES to generate scenarios which are later assessed through a Multi-Criteria Decision Analysis (MCDA) process, whereas in the latter, policies such carbon taxes and measures like building refurbishments and decentralized generation and storage technologies deployment are evaluated in the Swiss city of Basel. Other models such as LEAP [15] or EnergyPlan [16] have also been used to generate energy scenarios at city level. Lin et al. [17] used LEAP to determine the GHG peak in a Chinese city in three different scenarios, while EnergyPlan was used by De Luca et al. [18] to identify the measures which make an Italian city a nearly zero carbon one.

The following sections provide a more detailed review of literature for three key steps of city energy modelling: characterization, scenarios, and assessment.

2.1. *City energy characterization*

The first step of a tool which seeks the assessment of urban energy performance is the energy characterization. That is, the elaboration of a city energy model 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 characterization of the city is the basis to build energy scenarios on which to evaluate the deployment of different strategies and actions. Martos et al. [19] reviewed a list of the energy-related aspects which should be considered for city energy characterization, and which included urban transport, buildings, Renewable Energy Sources (RES) integration, green areas, and water and waste management. Carreón and Worrell [20] revised the urban energy flows and services which shape the urban metabolism. Based on a GIS display, a method was developed by Fichera et al. [21] to characterize the energy demand of three main city end-use sectors: buildings, transport and street lighting. Chévez et al. [22] presented a methodology for the diagnosis of cities, i.e. the construction of the cities' baseline. Whereas Pérez et al. [23] proposed a methodology for the development of urban energy balances including the city's energy imports and energy generation, and the city's sectors -residential, commercial, institutional, industry, road transport, non-road transport, municipal solid waste treatment, and waste water treatment-final energy consumption.

Concerning the characterization of specific city end-use sectors, Swan and Ugursal [24] reviewed different top-down and bottom-up approaches to model end-use energy consumption in the residential sector -although the same methodologies could be used for the modelling of the energy demand in the buildings of the tertiary sector. Combining cadastral data -such building type, floor area, construction date, or envelope's characteristics-with regional or local surveys, energy demand in buildings was characterized in Ref. [13,21], and [25]. Chen et al. [26] used a GIS-based model to characterize the energy performance of different energy conservation measures in retrofitted office buildings in the city of San Francisco in the USA. Also from a bottom-up perspective and using a GIS methodology, García-Pérez et al. [27] developed a methodology for the characterization of the residential buildings stock in the Barcelona metropolitan area. In relation to urban building energy modelling too, Chen et al. [28] and Dall'O' [29] remarked the data dispersion issue to correctly support the modelling task, and developed methodologies to define databases for cities' buildings. Kim et al. [30] developed an urban building energy model integrating data of the HVAC system stock, thus reducing discrepancies between real and theorical final energy consumptions.

The characterization of the transport consumption is harder than the buildings' one due to a higher spatial and temporal variability. In Ref. [31], Letnik et al. reviewed urban freight transport models and modelling techniques, also pointing out transport policies and measures in European cities. Similar approaches were adopted in Ref. [13,21], and [32] where consumption is characterized based on the number of trips and on its characteristics (e.g. distance and fuel consumption per vehicle). All of them include the trip generation processes between urban areas. On the other hand, Strulak-Wójcikiewicz and Lemke [33] proposed a dynamic modular simulation framework of the urban transport considering social, economic, and environmental dimensions.

Regarding the characterization of the 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 stations are usually located within urban borders, thus cities are generally net importers of electricity and fossil fuels, coming to them through different distribution networks. However, small decentralized on-site generation systems can be present in some cases, fulfilling a share of the city's energy needs. At this concern the tools and methodological approaches reviewed by Allegrini et al. [34] could be helpful with regard to the modelling of district-scale energy systems such district heating systems, renewable energy generation processes or storage systems.

Some major difficulties which are faced in this first stage should be noted. First, the definition of the 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 boundaries' selection, modellers should also decide how to account and allocate energy consumption. Last but not least, one of the biggest issues when characterizing the urban energy usage is data collection. On a micro level such as the local scale, 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 treat the available information, sometimes using adapted 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.

2.2. *City energy scenarios*

Once the city energy model is set up, a range of pathways that the city can face is suggested, the so-called scenarios. As defined by Ghanadan and Koomey [35], scenarios "provide a set of alternative contexts for exploring different ways that the future may unfold". The authors also highlighted the differences between forecasts and scenarios, as in Ref. [36] where the terms of "forecast", "projection", and "scenario" are discussed. The EU Reference scenario 2016 [37] describes itself as based on "trend projections, not forecasts" and seeking to provide a "model-derived simulation of one of [the EU] possible future states given certain conditions". Going beyond, a classification of scenarios is established by Börjeson et al. [38]:

- close to conventional forecasts, predictive scenarios try to describe likely future situations ("What will happen?") based on past and present trends;
- explorative scenarios focus on the proposition of more alternative developments ("What can happen?");
- normative scenarios propose scenarios to fulfil determined targets ("How can a specific target be reached?").

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 forces. 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 in Ref. [39,40].

Energy scenarios at city level are modelled by a combination of socioeconomic parameters' evolution and 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.

Therefore, one of the major challenges faced by modellers in this step is to determine how the energy use will evolve. Based on historical data, energy use can unfold following past trends which in occasions can be explained by a causal relationship with certain parameter(s) called driver(s) that steer ("drive") the trajectory of the energy use. That is, the energy use is projected on the basis of an energy-driver link which has been evidenced in the past and is maintained in the future. Athanassiadis et al. [41] studied a set of drivers to explain the -aggregated- energy use of ten cities [20]. also highlighted environmental, technological, economic, and social drivers which explain the cities' energy use. Ürge--Vorsatz et al. [42] and Copiello and Gabrielli [43] assessed the influence of socioeconomic drivers in the building sector, although in these cases is applied at regional and national levels. Yu [44] introduced a methodology to forecast city buildings' energy demand. For the transport sector case, Zhao et al. [45] evaluated the influence of different drivers for the transport sector energy consumption in China's cities. All in all, a wide variety of methodologies and mathematical models exist in order to model future energy use based on drivers, historical trends, or other parameters. Some of them are listed in Ref. [46,47], and [48].

The establishment of these links can be difficult as both energy and socioeconomic historical data are rarely available at urban level. Also, as for the characterization step, driver-energy consumption connections found for country level may not be suitable for a city scale. Modellers should be aware of the studied city's characteristics in order to directly use or adapt data found at country level to the urban scale.

In any case, besides the downscaling of certain drivers and the consideration of city-specific characteristics, the approach for energy scenarios modelling at city scale does not differ from the generation of national-scale energy scenarios.

That said, modellers should be aware that the city's future energy uses will be ultimately influenced by:

- socioeconomic (e.g. city-specific GDP, sector GVA, household income, fuel prices), demographic and other (e.g. climate, urban structure, technological development: funding and learning curve rates) drivers;
- 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 well-being targets to be reached by the city;
- specific energy interventions to be shaped: modellers may analyse the city's proposed measures or even raise new ones.

Nevertheless, a question has to be made and that is whether at the time of an energy transition and even energy decoupling, it is justifiable to keep some relationships which have been proved in the past but may lose their significance in future times. The same issue was raised by García-Gusano et al. in Refs. [49]. Depending on the sought-after approach, scenarios could be based on past trends and driver-energy correlations if a more conservative situation wants to be projected; while if a more ground-breaking state of play wants to be portrayed other hypotheses should be considered in order to model the evolution of the energy consumption. The first case would correspond to "baseline scenarios" in which a conservative evolution of the system would be contemplated. This scenario type should serve as a benchmark for the analysis of alternative scenarios, thus the decision of "what" is included in it is crucial, since depending on the policies and measures to be analysed in a later stage some should be included and others not. That is, only the impacts of additional measures should be assessed when compared versus other scenarios [50]. As an example, the introduction of electric vehicles and building's refurbishments could be considered as processes that in the future will be developed naturally or by means of policies already approved, therefore these "trends" should be isolated from the more specific additional measures or policies to be evaluated in later scenarios. The analysis would remain to determine if the system's natural tendency will be to persist on past trends or conversely to evolve towards technological and consumption patterns changes [51,52]. discuss the need to create a scenario which does not contemplate any measure and keeps the system's natural trend ("Reference" scenario); and a scenario where the former's trend is maintained but measures already committed or adopted are included ("Business as Usual" or simply BaU scenario). "Alternative scenarios" correspond to the second case described previously and are generally based on BaU or reference scenarios. Hence they can inherit driver-energy correlations from the formers albeit including more explorative views. In these scenarios different futures can be then assumed and the impact of additional alternative measures and policies assessed. In order to consider city alternative energy scenarios -which may include changes in technological devices, in the inhabitants' behaviour, or in the city's socioeconomic structure, modellers should know the peculiarities of the city and the future's 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's future plans consist of, are there any preferences for a specific technology or policy, are structural changes expected in the city, amongst other questions. As noted in Ref. [40], a certain degree of uncertainty has to be dealt with in every scenario as modelling technological and behavioural changes is always difficult.

Departing from models of future energy use for the cities, different authors proposed methods to develop energy scenarios at city level. Dagoumas [53] elaborated a set of scenarios for the city of London through a top-down approach using the MDM-E3 (Multisectoral Dynamic Model) macroeconomic model. On the other hand, following a bottom-up perspective, Reiter and Marique [54] modelled building and transport consumptions and compared eight scenarios for the Belgian city of Liège. Combining GIS and simulation and optimization models, Mohajeri et al. [55] 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 village's heat cooling and electricity demand, and the optimization of the integration of renewable energy systems to cover the former village's needs. Farzaneh et al. [56] elaborated two energy scenarios -baseline and optimal scenarios-for the Indian city of Delhi. Based on a bottom-up structure and using physical drivers, the authors projected the energy demand of the main city sectors -residential, commercial, and transport. The electricity demand and supply were subsequently economically optimized in the second scenario by using the General Algebraic Modelling System (GAMS). Jalil-Vega et al. [57] presented the COMET -Cities Optimization Model for Energy Technologies-model and implemented it in the city of Sao Paulo, Brazil. The authors modelled six scenarios seeking to supply the city's energy demand in the most cost-effective pathways under given constraints. Following the same optimization approach, Noorollahi et al. [58] modelled the supply side of a Japanese city seeking to diversify and maximize renewable share in the city's electricity supply. Samsatli and Samsatli [59] optimized the operation of integrated heat and electricity networks in an eco-town in England through the use of a Mixed-integer Lineal Programming (MILP) model. Alhamwi et al. [60] presented a GIS-based model seeking the optimization and flexibilization of the 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 [61] for two Pakistani cities, and by Li and Yu [62] for China's urban passenger transport sector. Both studies proposed different pathways to assess different transport policies and technological improvements. Meanwhile, Zhang et al. [63] developed a more complex Computable General Equilibrium (CGE) model to assess different transport scenarios.

2.3. *City energy assessment*

The assessment of city energy scenarios can support the development of urban strategies and plans. 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, optimization models provide the best system configuration but only for a single magnitude (e.g. TIMES gives the least-cost supply system under certain restrictions to meet the 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. [50] 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 [64] revised a set of indexes for benchmarking cities, also highlighting the importance of considerate multiple dimensions concurrently when assessing the sustainability of urban energy systems. Sharifi [65] reviewed different indicators and assessment methods for the evaluation of smart cities.

For each evaluated dimension clear indicators must be defined. Kuznecova et al. [66] 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 KPI Monitoring guide [67] which could be used as a reference. Indicators should plainly reflect if the city's 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 [68] advocated GPI (Genuine Progress Indicator) against GDP as an indicator for measuring well-being as it "accounts for a number of benefits and costs that normally escape market valuation".

Finally, when multiple impacts have been considered, weighting and prioritizing them is necessary to choose between the generated scenarios. Assessing the influence of one or another effect should be conducted by the city's own stakeholders who know best the urban needs. The selection of desirable scenarios through MCDA methods as employed by Gargiulo et al. [13] and by Arrizabalaga [69] can be the basis for the elaboration of city urban energy plans.

2.4. *Contribution to existing literature*

This section describes the contribution of this paper to the different aspects of urban energy modelling which have been reviewed.

Regarding overall scope of the modelling and assessment processes, most reviewed studies focus on one specific sector -building or transport- or one specific step -characterization, scenarios generation, assessment. This paper aims to integrate all these aspects in one single methodology -an approach already taken in few studies such as [12] or [69]- but completing the analysis by combining bottom-up calculations with real data. This is, the presented method in this paper does not exclusively relay on estimated or modelled consumptions, but exploits real energy use data, overcoming the historical gaps between theorical and measured data.

Integrating GIS methods as followed in Ref. [26,27] for the modelling of the building stock, and using a similar approach as in Ref. [32] for the transport sector modelling, the methodology seeks to include all the involved energy consuming areas in the city, along with other end-use sectors such industry, agriculture or public lighting. Unlike in Refs. [13] or [14] where predefined building models are used, the GIS-based building bottom-up model used in this methodology represents every single building of the city stock, providing a higher detail and resolution in the building stock modelling. It also manages to keep low and accessible data requirements. Transport sector modelling may lack some depth compared to specific models such [33] or [63] but relies on simple data which is easily available.

Concerning scenarios generation, this methodology models future energy consumptions by using accessible key parameters, thus avoiding complex projecting methods or models such in Ref. [44,53], or [59].

Lastly, as already mentioned, the methodology seeks to integrate all the steps of city energy modelling and assessment reducing complexity and the need of data. Thus, it completes the work carried out in Ref. [21] -where only a characterization of city's end use sectors was performed- or [54] -which didn't include a multi-criteria assessment of the scenarios. The methodology also tries to simplify the approaches suggested by Ref. [12,14]. These papers also included a holistic approach in the modelling and assessment of city energy systems, considering all the energy intervening sectors within the city and assessing the developed scenarios through different criteria. However, the data required for their simulation models would be difficult to gather for many cities. The building model used in the proposed methodology -which allows the characterization of the entire city's building stock with only cadastral data required-along with the adoption of more flexible, easy-to-use, and less data-intensive energy scenario simulation approaches are an important advantage for integrated city energy modelling.

3. Methodology

3.1. City characterization

Amongst the difficulties faced in the city's energy characterization, one of the most relevant is the availability of data. Detailed urban-level information is generally hard to obtain, often dispersed or incomplete and sometimes completely lacking. Conversely, available data is highly aggregated. To bridge this common issue, this methodology proposes the disaggregation of top-down real consumption data supplied by the city through integrating bottom-up approaches. The whole city real consumption data is generally calculated through data provided to the city by energy utilities, combined with monitoring strategies. Energy use bottom-up approaches are based on estimated energy demand for the different sectors. They are used to disaggregate top-down data or are calibrated with the former to match as accurately as possible the city's actual consumption, trying to overcome the performance gaps between real data and energy calculations. Fig. 1 resumes the bottom-up/top-down integration performed in this step.

The methodology proposes a high level of detail on the modelling of the energy end-use sectors (e.g. transport, buildings), as most important measures in urban energy plans are generally directed to reduce these sectoral energy demands.

An example of the relative influence of different end-use sectors on the city energy use is shown in Fig. 2 for a selection of cities for which data was analysed within the EU projects Mysmartlife [70] and Matchup [71].

The building sector -including residential and tertiary buildings- usually accounts for around 50%–70% of the studied cities' energy consumption, making the energy characterization of this sector a relevant task.

The methodology presented in this paper uses the ENERKAD [72] bottom-up GIS based model to disaggregate the top-down total energy use data provided by the city. ENERKAD performs an energy evaluation based on basic cartography, cadastral, and climatic information of the area under study, and calculates annual and hourly energy demand at building, district or city scale. To generate energy demand profiles ENERKAD bases its calculations on the heating degree hour method, considering different characteristics of each building inferred from available data like the building use and the construction year from the city cadastre. The georeferenced thermal energy -heating, cooling and Domestic Hot Water- and electricity -lighting and appliances-demands are therefore calculated for every building construction registered within the city. ENERKAD estimates the demand and final energy consumption of the city's building stock and disaggregates this data into the individual buildings. This approach is a way to attempt avoiding the prediction gap [73], and offers more detailed results than frequently used estimations based on reference buildings or national data for the building stock.

The final result of the calculations can be presented for different building clusters, which can be split by building age, use (e.g. residential, commercial, offices, public buildings, health, education, sports), or ownership (public or private). This disaggregation in clusters is made having in mind the detailed definition of energy measures which will be

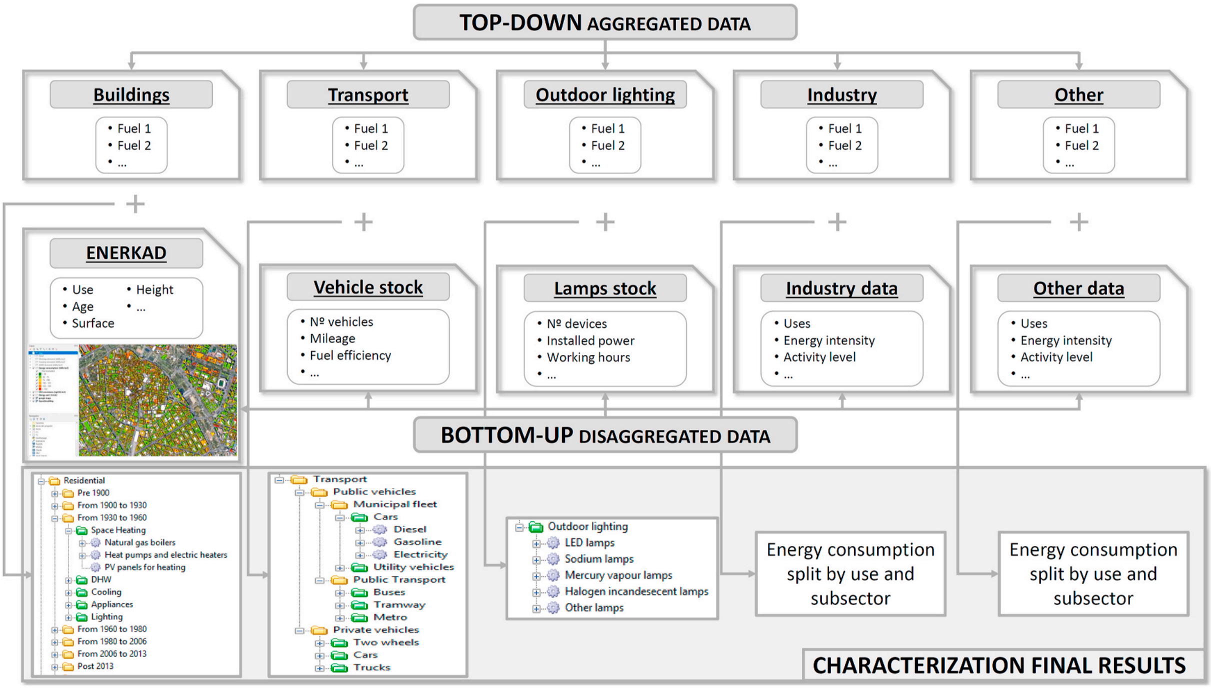

Fig. 1. City energy characterization approach.

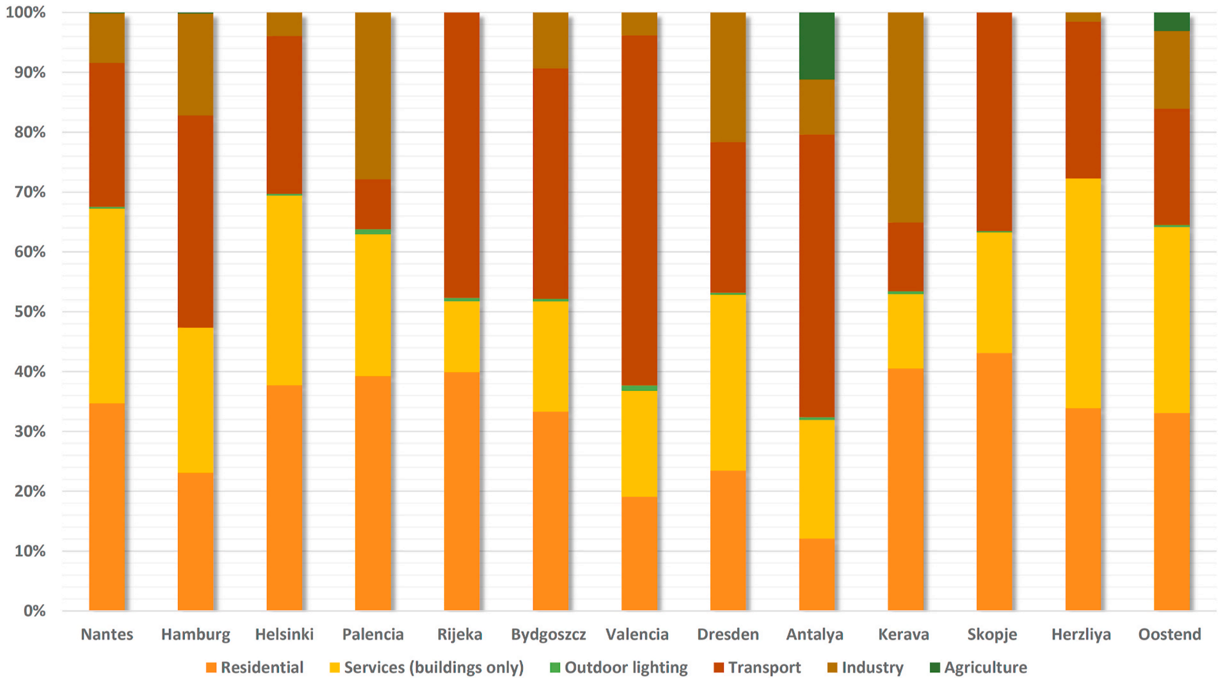

Fig. 2. Energy consumption shares by sector of the cities within the EU projects Mysmartlife and Matchup (outdoor lighting included in Services sector for the cities of Hamburg and Herzliya).

proposed later in energy transition scenarios.

As shown in Fig. 2, transport is together with buildings the key energy end-use sector in cities. The proposed methodology envisages the possibility of adopting either top-down or the bottom-up approach to characterize transport sector's energy usage as described in Ref. [74]. Top-down approach is commonly based on the fuel-sales method where consumption is estimated by taking the quantity of fuel sold within the city's boundaries as a basis. On the other hand, bottom-up approaches are founded on higher detailed data such as registered vehicles, modal shares, vehicle kilometre travelled and fuel efficiencies to estimate the transport sector energy consumption. As the methodology seeks to preserve the original data supplied by the city, special attention must be taken to how the city calculated its transport fleet consumption statistics. Thus, if the city followed a bottom-up approach the same assumptions should be taken to disaggregate supplied information. On the other hand, if the city used the fuel-sales method, modellers will be required to assume some hypotheses to breakdown the available data. If information is available, it is recommended to split the city's vehicle fleet into private and municipal/transport public fleets in order to identify on which vehicles local authorities can take direct action.

Other energy-consuming sectors that may be covered by the city's energy profile characterization include industry, agriculture, public lighting, and waste and water management. Provided that data is available, industry and agriculture sectors should be included if their share in the city's socioeconomic structure is relevant. However, no further disaggregation is contemplated in the methodology presented here as in-depth measures are not usually carried out in these sectors. The reason for this is that local authorities do not normally have the capacity to act upon them. Hence, the laborious work of data collection and processing to breakdown the information supplied by the city is not cost-effective.

Public outdoor lighting is indeed a service for which local governments have the power to carry out straightforward interventions. Despite its low contribution to the city's energy consumption -less than 1% in the cities presented in Fig. 2- the refurbishment of old lamps is a cost-effective and simple measure that local authorities can easily achieve. The natural process to disaggregate the available data is to separate the consumption due to each type of lamp. Municipalities usually have at their disposal information about the number and types of street lamps within the urban area. Assuming an energy intensity for each lamp or a consumption relation between them, top-down data can be broken down always trying to match the aggregates data supplied by the city with the estimated bottom-up consumption.

This paper does not include the detail approach for the characterization and energy scenarios of energy use in the city's water and waste management. However, it should be taken into account that these are services also handled by local authorities, and therefore the city administration can propose direct measure to improve energy performance in relation to them. If available, consumption from these services should be treated separately from the rest of the other public services, as its expected evolution and proposed scenarios could be very different. Moreover, modellers must be aware that waste management is a source of non-energy related emissions and should be included in the city's emission inventory and subsequent scenarios.

Finally, special consideration should be given to the energy generation sector. In cities, large-scale transformation plants are not often present and supply-side systems at local level normally consist of small decentralized on-site generation systems which are used for self-supply. Most cities therefore 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 or decentralized on-site generation systems such photovoltaic (PV) panels or micro-CHPs, must also be analysed and modelled. In order to characterize the local production of energy, data about these -and other-plants must be collected, at least their installed capacity, working hours and efficiency. With these data, the energy locally produced is calculated and imports needed to cover the remaining city's energy demand are estimated. Concerning electricity generated in decentralized on-site generation systems, this methodology considers the distinction between the on-site produced electricity and the one coming from the grid. Electricity produced in decentralized systems is directly allocated to the end-use sectors where the generation system is installed, and by extension where the electricity is consumed. This procedure allows the identification of self-supplied electricity rates for the sector under study.

3.2. Scenarios generation

Once the city is characterized several scenarios can be proposed. A Business as Usual scenario -or a Reference scenario-should be modelled to contemplate the city's expected unfolding. An analysis of the city's historic development as well as an evaluation of the committed plans could be helpful in order to establish a base storyline of the studied urban area. On the one hand, naturally expected trends -both from natural tendencies or due to already pledged measures-might be identified and isolated from the rest of the interventions to be evaluated afterwards on the alternative scenarios. On the other hand, alternative scenarios could inherit the BaU trends while adding new interventions, and even suggest more ground-breaking tendencies in order to fulfil future objectives.

An analysis for the identification of potential drivers could be useful in order to advise modellers in the projection of future energy consumption patterns. However, drivers' information and historical data are not widely available at city scale. Therefore possible correlations are hard to establish and future consumption difficult to model at such scale. Modellers are often forced to rely on simple assumptions or interpolations from national data. In order to face these and other difficulties, the methodology presented here intends to provide a simpler approach when generating energy scenarios at city level by proposing the following considerations to model future energy consumption in the different city's end-use sectors.

- Buildings energy consumption: once the building stock has been characterized by use and age in the previous step of the methodology, each building category has an associated fuel(s) consumption: older buildings will generally have a higher energy usage while newer ones will be more efficient. The consumption in the building's sector will be determined by the evolution of the city's building stock, and this stock can be further classified in non-refurbished, refurbished and new buildings. This approach is resumed schematically in Fig. 3. The energy characteristics of the energy systems and building envelope for refurbished and new buildings, will depend on the scenarios taken for the application of the national building code, or other regional or city regulations. When a building of a given category is renovated and passes to the refurbished category, the integration of more modern equipment and a more efficient generation system is assumed. However, it may be the case that an existing energy system for a building is replaced and the building's envelope is not upgraded, and this situation should also be considered in the scenario modelling. For the quantification of all these specific actions, modellers can rely on the city's urban plans -to determine the number of new and refurbished planned buildings-, budgeted subsidies -to estimate a number of privately refurbished buildings and generation systems replaced-, or other data sources such as surveys, stakeholders' workshops, or the municipality's technical staff.
- Transport energy consumption: has been characterized in the former step -city characterization-by classifying the city's vehicle fleet by type of vehicle and fuel. As each vehicle has an associated energy intensity, the energy use scenarios in this sector will be determined by the evolution and changes in the vehicle stock of the city. Old vehicles can be removed from the streets and substituted by new 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 amount of public vehicles increase because of changes in the modal split (e.g. increase of the total number of buses due to a shift between the use of public transport instead of private one). Apart from the modelling of the vehicle stock's evolution, energy intensity assigned to each vehicle will change as a result of an improvement of the fuel efficiency due to stricter policies or by a decrease of the annual mileage. All this data for the evolving vehicle stock will be the basis for the transport sector's energy scenarios modelling.
- Industry/agriculture energy consumption: the modelling approach of these sectors' future consumption is more diffuse as the drivers which explain their energy use are usually macro parameters which are not related to the city's own functioning. 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 and energy plans to get an idea of the expected evolution of these sectors and to align the development of the city's industry and agriculture (if present) with national trends.

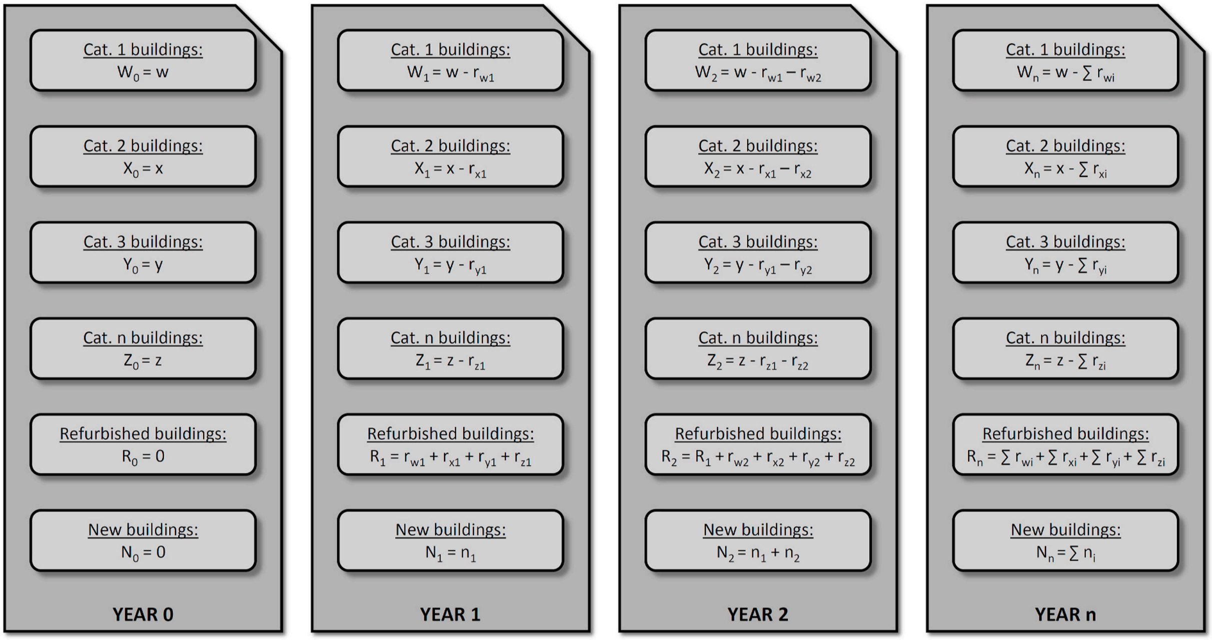

Fig. 3. Building stock evolution modelling approach.

- Public outdoor lighting energy consumption: has been characterized in the former step -city characterization-through disaggregation of the consumption by type of lamp. Each lamp has a specific energy consumption and the sum of them must match the consumption data indicated by the city. For this case the evolution of the energy consumed by the sector will be determined by the changes in the devices' stock and by the total number of lamps. The scenarios for energy consumption should take into account new areas of the city with public lighting, and the replacement of the old lamps.

3.3. Scenarios assessment

In this step scenarios are assessed under different perspectives -energy, environmental and socioeconomic- and compared. Scenarios' outcomes are the result of the combined action of the adopted measures. For each scenario, the energy, environmental, and economic performance of the implemented interventions are evaluated as proposed in the methodology developed by Arrizabalaga [69]. Economic evaluation, performed through Life Cycle Costing (LCC), serve as input for an extended Input-Output 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 Input-Output tables are not available at city scale, hence intensive work is needed to adapt available I/O tables -usually national or regional ones-to a city level.

After carrying out the energy and environmental performance analysis, and the LCC and I/O analysis, a set of socioeconomic, energy and environmental indicators -which must be previously defined-are quantified. It is recommended that the selection and definition of the aforementioned indicators should be done in collaboration with the city's stakeholders in order to correctly evaluate the city's needs and targets. Indicators proposed by the SCIS [67] or by the SEAP guidelines [75] could be used as a reference. Other measurable variables for the assessment of smart-cities are postulated in the EU projects STEEP [76], CITYkeys [77], and Replicate [78]. Once indicators are selected, they should be calculated for each intervention or proposed measure and results should be aggregated for each of the indicators for the modelled scenario.

The final step of the scenarios' assessment is the comparison of the performance between them. Based on MCDA such the Analytical Hierarchy Process (AHP), indicators can be grouped by fields (e.g. social, economic, environmental, energy, technical) and are compared and weighted, thus highlighting the relevance of one above the other. As the policies and actions implemented in the scenarios will have their own pros and cons regarding the different domains to be assessed, this method allows the city's stakeholders to value which impacts are more critical in the city. By weighting their impacts, the scenarios are prioritized and the city can identify the one that best suits its objectives, being this the first step for the elaboration of an energy action plan or energy transition plan. Fig. 4 illustrates the assessment procedure followed in the presented methodology.

4. Case study: Valencia

The suggested methodology has been put into practice in the city of Valencia, Spain. Located in the Mediterranean Sea, Valencia is Spain's third biggest city with a population of 794288 inhabitants (2019). Due to its flexibility and ability to work with limited data, LEAP tool was chosen to model city energy scenarios as in Refs. [17,79–83], and [84]. LEAP has been used for the city's energy baseline characterization and the dynamic simulation of the scenarios. Only the municipality area (134,65 km^2) has been considered in the model, thus excluding the bigger metropolitan region. Concerning the time resolution, the model broadens the city's SEAP time horizon (2030) and simulates the energy city performance until 2050. Top-down data has been collected from the consumption and emissions inventory for 2016 [85]. The reference energy system modelled in this case study is shown in Fig. 5.

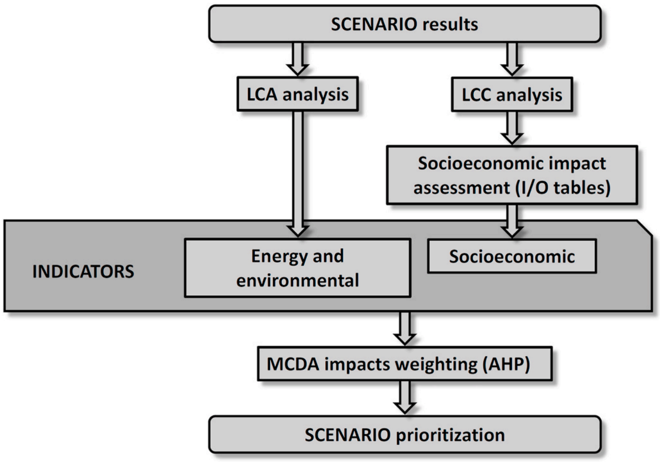

Fig. 4. City energy scenarios assessment approach.

For the residential building stock, bottom-up modelling using ENERKAD software has been carried out, using georeferenced cadastral data supplied by the city. Space heating, DHW, cooling, appliances and lighting energy demands for every household in the residential stock were calculated and then grouped by household age. Results from the EU project EPISCOPE-TABULA [86] have been used for a first calibration of the model. As little data concerning energy systems was available, it was assumed that 50% of the space heating and DHW demand was covered by natural gas boilers (85% seasonal efficiency), 25% by heat pumps (considered seasonal COP: 2,5), and 25% by electric heaters (100% efficiency). This distribution was estimated based on national and regional statistics from Ref. [87,88] and then polished in order to comply with real consumption data supplied by the city [85]. Although low, contribution of on-site PV panels to meet the energy needs has also been considered and distributed according to the available roof area in each household age category The output from the bottom-up model is the final energy use disaggregated by fuel and household age and is shown in Table 1.

This calculated output is used as a basis for the disaggregation of the real top-down energy data supplied by the city. ENERKAD model is recalibrated to match the top-down data, while maintaining each building characteristics and energy systems. Useful energy demand by service -space heating, DHW, cooling, appliances, lighting- and household age are then introduced in LEAP, as shown in Fig. 6.

In this case study, bottom-up modelling of the building stock has only been carried out for the residential buildings. Thus, for the tertiary sector, energy use provided within the 2016 inventory has been maintained in the city energy model as showed in Fig. 7.

Transport data supplied by the city was obtained through the fuel-sales method, and some assumptions have been made for the disaggregation of this total energy use. The city vehicle stock data has been taken from the national transport database [89]. A set of mileages and fuel efficiencies have been considered to determine the energy intensity for each vehicle. Resulting energy intensities are listed in Table A1in the appendix, while the final energy consumption of the transport sector is illustrated in Fig. 8.

As a representation of the energy characterization of the city, Fig. 9 shows the final energy consumption disaggregated by sector and fuel in the city of Valencia for the baseline year. As it can be observed, transport is by far the most-consuming sector in the city representing 58% of the total final energy consumption, while buildings in both residential and tertiary sectors represent 19% and 18% respectively. Regarding distribution of final energy use by energy carrier, diesel consumed in the transport sector represents the higher share (45%), followed by electricity (31%), gasoline (12%) and natural gas (11%). Electricity produced through solar PV panels only represents 0,2% of the total final

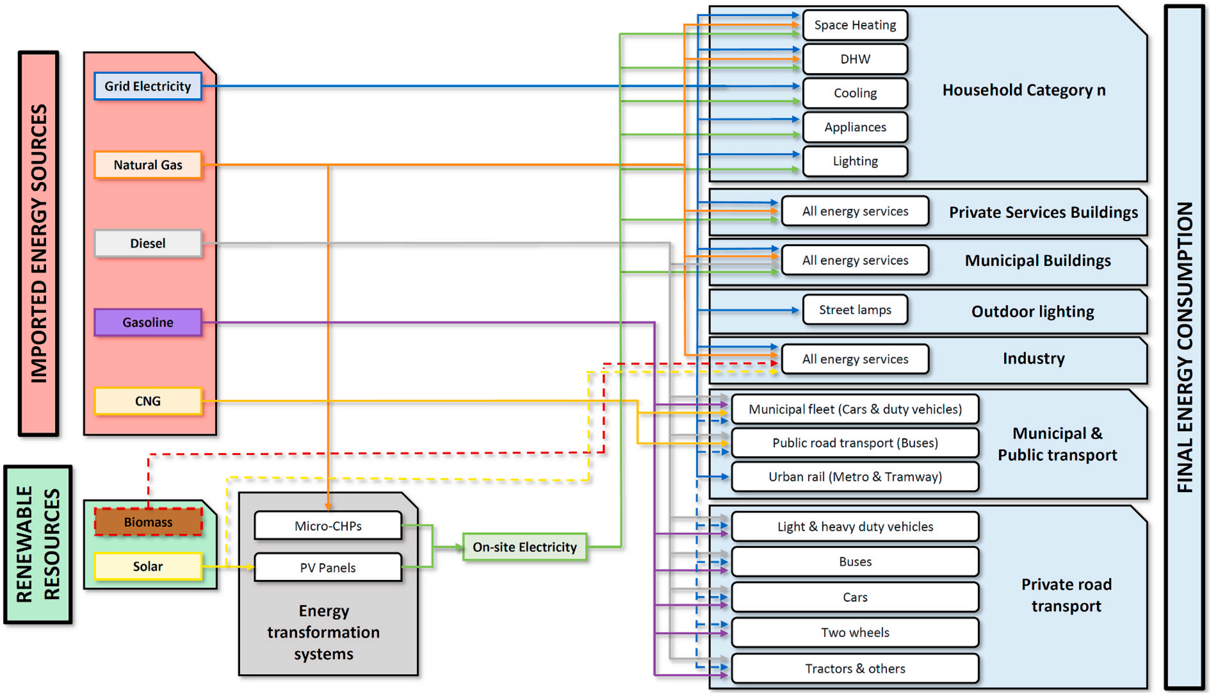

Fig. 5. Reference Energy System of the case study (dotted lines represent additional fuels and connections modelled in the scenarios).

Table 1
Residential sector final energy consumption (in GWh) by fuel and household age in 2016 in Valencia.

Fuels	Household category						
	Pre 1900	1900–1930	1930–1960	1960–1980	1980–2006	2006–2013	Post 2013
Electricity	10,42	31,86	111,96	421,36	368,38	40,11	0,66
Natural Gas	5,64	19,07	67,59	228,92	186,04	19,87	0,32
PV panels electricity	0,0024	0,0073	0,0258	0,1060	0,0955	0,0100	0,0002

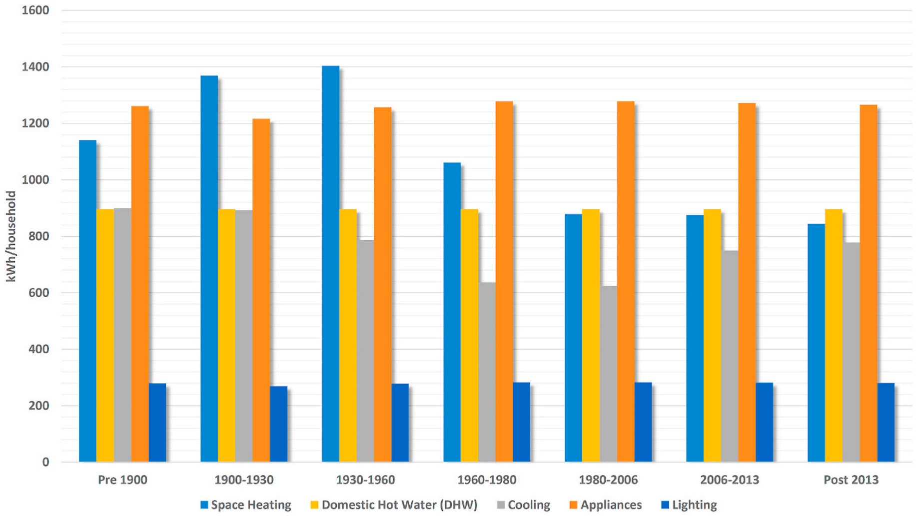

Fig. 6. Useful energy demand by energy service and household age in 2016 in Valencia.

energy consumption and is the only use of a local renewable resource within the city.

Concerning the city's energy supply side, the only generation systems existing in Valencia are PV panels and micro-CHP installations. These on-site generation systems are used for self-supply purposes, thus reducing the electricity demand from the grid. Electric installed capacity of these decentralized generation systems is displayed in Fig. 10. Electricity generated in decentralized plants is then allocated to the sectors where the plants are themselves located and consequently where the electricity is consumed. Electricity used in the city, is therefore mainly imported from the grid, and is assumed as the average national electricity mix. The other consumed fuels in the city are also imported. With

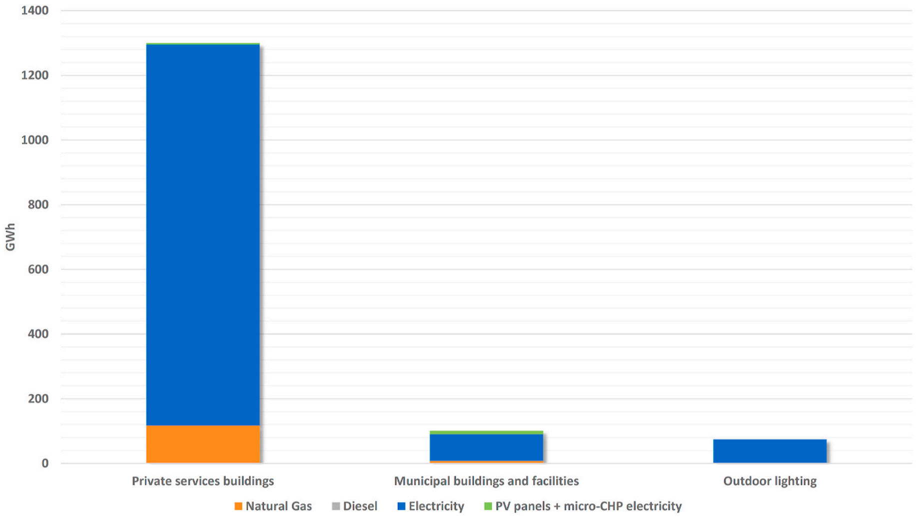

Fig. 7. Tertiary sector energy consumption by fuel and subsector in 2016 in Valencia.

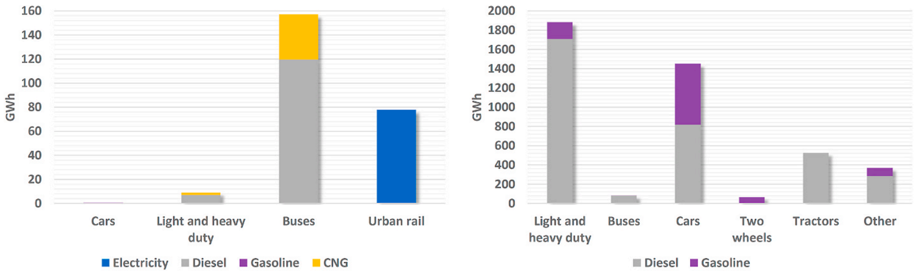

Fig. 8. Public (left) and private (right) transport sector consumption by type of vehicle in 2016 in Valencia.

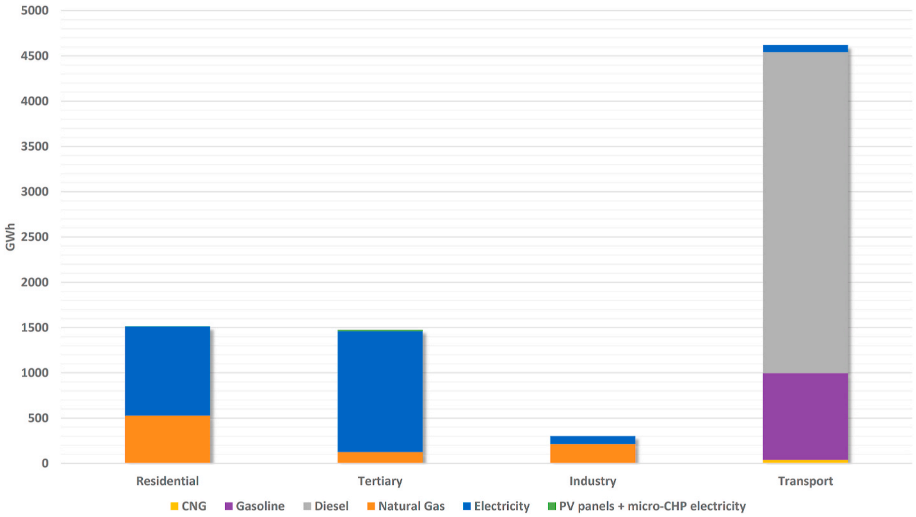

Fig. 9. Total final energy consumption by sector and fuel in 2016 in Valencia.

regard to the distribution networks, only electricity grid distribution losses have been taken into account. Considering that these losses are lower than the national average [90] -due to higher density and better grid quality-, a 7% has been estimated following data issued from the mysmartlife project [70]. Electricity produced on on-site generation plants is considered to be losses-free.

Sankey diagram in Fig. 11 shows the link between supply and demand in the city of Valencia in the baseline year.

Once the energy characterization has been completed through the disaggregation of the available data, a business as usual and three alternative scenarios are defined:

- Business as Usual scenario: this scenario models an upkeep of the natural energy trends of the city while introducing timid 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.

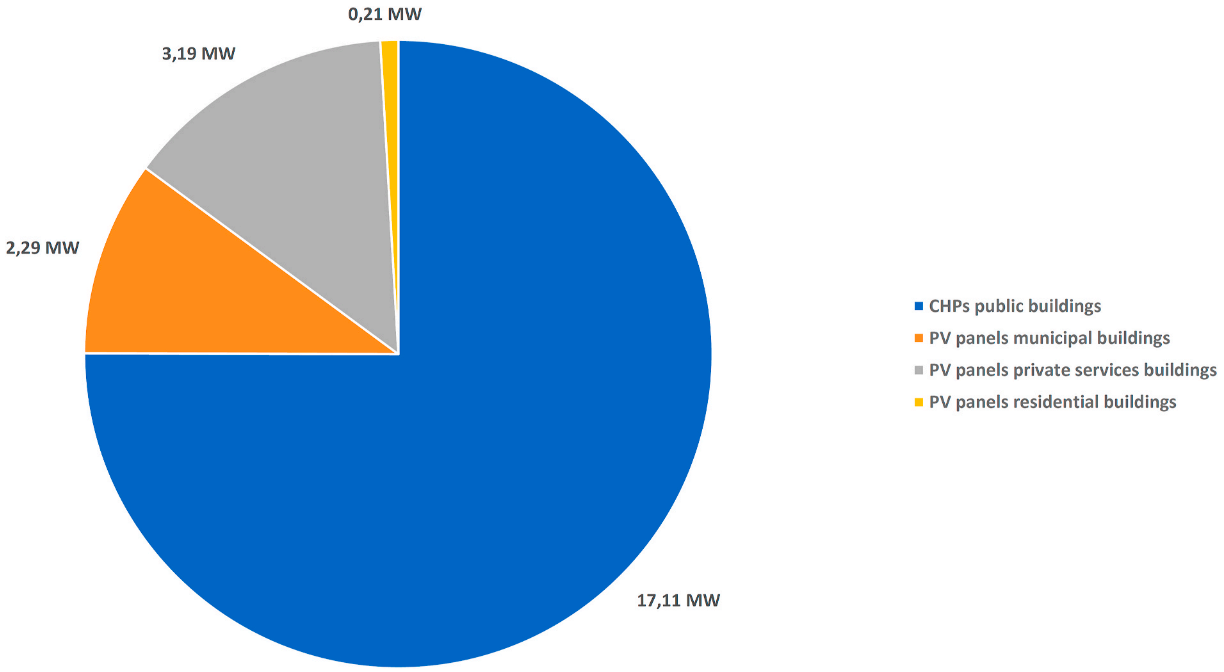

Fig. 10. On-site electric generation installed capacity by sector in 2016 in Valencia.

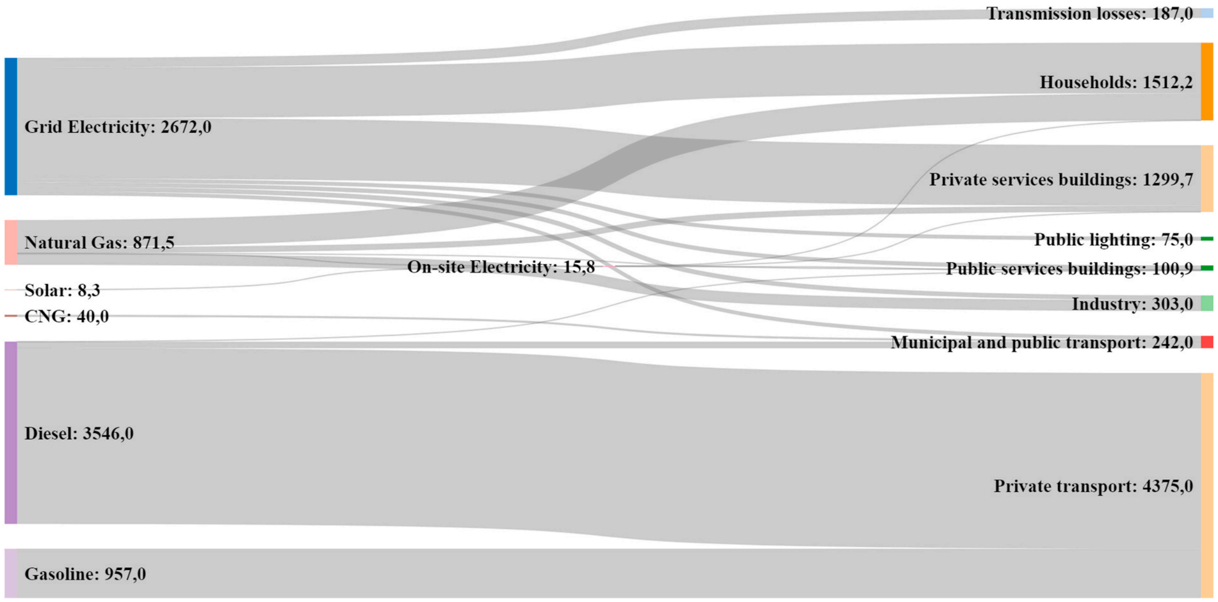

Fig. 11. Sankey diagram. Valencia. 2016.

- Building scenario (Alternative scenario 1): in this scenario the city concentrates its efforts and resources in the refurbishment of buildings in both residential and tertiary sectors. Energy measures in the transport sector are also carried out but at lower level.
- Mobility scenario (Alternative scenario 2): 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 electric vehicles is considered. Refurbishment of buildings is also contemplated but at slower pace.
- Mixed scenario (Alternative scenario 3): 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, modelled interventions and their roll-out level are outlined in Table 2.

Detailed modelling considerations and hypotheses for the end-use sectors in each scenario are shown in Table A2 in the appendix, while the approaches followed to model the different measures in every scenario -BaU and alternatives-are detailed next.

For the residential sector, energy consumption evolves according to the change in the city's household stock. The addition of new dwellings -extracted from Ref. [91]- increases the overall energy use, while the refurbishment of the existing dwellings decreases it. Depending on the construction rate of new households and their energy performance, and on the refurbishment characteristics and its rate, the sector's energy consumption evolves differently in each scenario. Considered characteristics of the refurbished and new households are detailed in Table A3

Table 2
Deployment differences of the modelled measures with respect to the BaU scenario ("-": less usage than in the BaU; " = ": 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).

Sector	Modelled intervention	Building scenario	Mobility scenario	Mixed scenario
Residential	Refurbishment rate	+++	+	++
	New buildings[a]	=	=	=
Tertiary buildings (private and public)	Refurbishment rate	+++	+	++
Public lighting	LED lamps substitution[a]	=	=	=
Industry	Efficiency measures[a]	=	=	=
Municipal fleet	Cars usage	=	=	=
	Cars electrification[a]	=	=	=
	Utility vehicles usage	=	=	=
	Utility vehicles electrification	=	+	=
Public transport	Buses usage	=	+	=
	Buses electrification	=	+	=
	Urban rail usage	=	+	=
Private transport	Freight vehicles, buses, cars, tractors and other vehicles usage	=	–	=
	Freight vehicles, buses, cars, tractors and other vehicles electrification	+	+++	++
	Motorcycles usage	=	–	=
	Motorcycles electrification	+	++	+

[a] Not evaluated in the final assessment.

in the appendix. As an example of the modelling approach followed for the residential sector's energy use, Fig. 12 shows the evolution of the household stock -disaggregated through the bottom-up GIS calculation with ENERKAD tool- and GHG emissions in the building scenario. Although total housing stock increases in the city by 2050, the oldest households with the highest associated energy use are refurbished. In the model, this is represented by a reduction of the number of existing households and an increase on the refurbished household categories. New buildings are added to the baseline's stock but, as they are more efficient, they only represent a small increase on final energy use and associated emissions. Larger energy savings from the refurbishing of existing buildings lead to a total reduction of energy use and CO_2 emissions on the residential sector.

As no bottom-up modelling approach has been used for tertiary sector buildings, the evolution of the energy consumption is assumed to follow the historical trend before the 2008 economic crisis, integrating different refurbishment rates and associated energy savings for each scenario. Because of the heterogeneity of the services sector's building stock, an average energy reduction has been considered according to a full tertiary building's renovation including different efficiency measures such thermal insulation, energy systems substitution, ventilation with heat recovery, LED lighting implementation, and energy management and control strategies. For each renovated building an average 40% energy saving is assumed in its overall consumption based on the results found in Ref. [92,93], and [94]. If a second renovation cycle is carried out on already renewed buildings, a 20% energy reduction is modelled. These yearly savings are applied to the sector's projected historical trend thus obtaining the consumption evolution in the different scenarios.

The evolution of the public lighting is modelled through the substitution of the 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 the old and the LED devices based on [95]. Total number of lamps is assumed to growth with the same rate as new households.

Concerning the industry sector, the sector's future energy consumption and mix share evolution has been considered taking an IEA report [96] as a reference. A yearly 2,1% energy use reduction due to efficiency measures implementation has been considered. Penetration of renewable heat -from biomass and solar collectors-has been modelled.

Evolution of the transport sector energy use has been modelled through the changes on the vehicle stock for the city. Number of cars and motorcycles has been forecasted assuming the same evolution as [97], whereas for the rest of the vehicles the same activities (passenger-km and tonne-km) growth rates used in the EU Reference scenario 2016

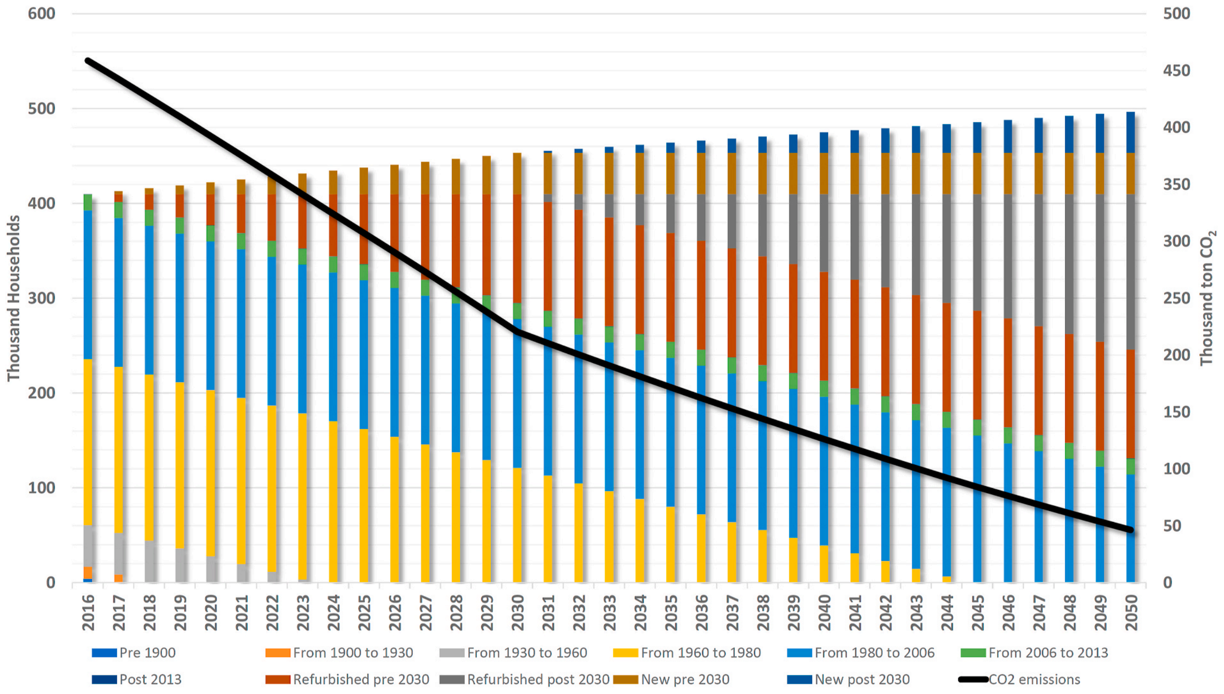

Fig. 12. Household stock evolution and residential CO_2 emissions reduction in the building scenario.

[37] have been considered. It should be noted that these assumed evolutions take into account the balance between introduced and removed vehicles.

Along with the vehicle stock evolution, changes in the fuel mix occur as alternative fuel powered vehicles replace the old combustion powered vehicles. Based on [98], average savings have been estimated. For cars and motorcycles a 70% reduction in final energy intensity is assumed between an electric vehicle and a vehicle powered by an internal combustion engine. Similarly, a 60% reduction is considered for the freight vehicles, buses, and other types of vehicles.

Regarding the city's supply side, development of new energy generation capacity is associated with solar PV systems equipped in the new and refurbished households. This additional PV installed capacity is shown in Fig. 13. No installation of other new energy generation systems nor decommissioning of the existent ones is considered in the city in the different scenarios. Instead, a full decarbonization of the Spanish electricity mix is considered by 2050 reducing the impact of the electricity consumed from the grid. This evolution is based on the scenarios from Linares et al. [99] and is shown in Fig. 14. Electric distribution losses are assumed to remain the same.

The evolution of the final energy consumption, including all the city end-use sectors for each scenario is shown in Fig. 15. Final energy consumption in the business as usual scenario increases 4% with respect to the baseline year (2016). The mobility scenario achieves the greatest savings with a 35% reduction compared to 2016, while the building and mixed scenarios achieve a 21% and 23% reduction respectively. These results are issued from the scenarios' simulation performed in the software LEAP's. They are subsequently considered in the definition of the indicators used in the assessment step.

Finally, in the assessment stage the three alternative scenarios are compared between them. The aim is that local stakeholders can prioritize one of the three proposed alternatives. It is then necessary to calculate the specific energy, environmental and economic impacts for each one of them. This is done by isolating and removing 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- and only by assessing the additional measures with respect to the former. Hence, although represented in the model, actions -or parts of them- which are identically modelled in the four scenarios (i.e. same energy impacts and deployment rate) have no relative effect between them and don't provide further input to the comparative analysis between the three alternative scenarios. Therefore, they are voided 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. These indicators have been established following a comparative approach to the BaU in order to identify the energy and environmental savings and economic costs due to these additional measures and excluding the ones due to shared measures with the BaU scenario. Indicators are shown in Table 3.

The first one, CCOES, assess the environmental performance of the scenario by showing the cumulate CO_2 savings achieved in comparison to the BaU all along the scenario's timeframe. CTPES and CNRPES evaluate the cumulate primary energy savings achieved compared to the BaU all along the scenario's period. Finally, the SLCC measures the economic performance of the scenario. This indicator evaluates the economic performance of the intervention for the whole period at a specific discount rate. It compares the lifecycle CAPEX and OPEX of the proposed measures against the costs that would be incurred by the equipment present in the BAU scenario. When assessing energy actions performed in buildings, the European Standard EN 16627 [100] has been followed. Product (phases A1 to A3) and construction process (phases A4 to A5) costs have been considered within the CAPEX, while use (phases B1 to B7) costs have been assumed within the OPEX. End of life (phases C1 to C4) expenses have been considered negligible. However, a return value -calculated as the proportional fraction of the CAPEX for the remaining action's years of life after the end of the scenario-has been considered as benefits from reuse and recovery potentials (phase D). Regarding vehicles, the purchase costs (CAPEX) and fuel costs (OPEX) have been considered. The same approach for the calculation of a return value has been also assumed in this case.

5. Results and discussion

In order to assess the performance of the alternative scenarios, yearly savings with regard the business as usual are obtained from LEAP. They are subsequently used for the calculation of the indicators in each scenario. As mentioned before and illustrated in Table 2 and Table A2, measures with the same deployment rate and characteristics in all the alternative and BaU scenarios (e.g. industry or public lighting) have no relative impact and are therefore excluded from the evaluation process.

Emission and primary energy factors issued from the Spanish IDAE

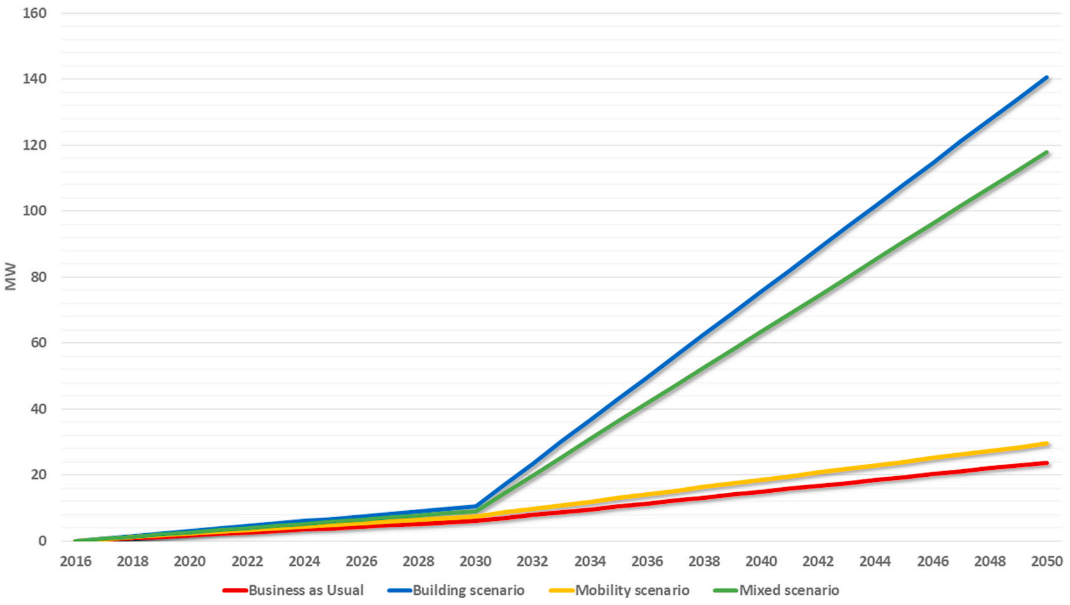

Fig. 13. Additional PV installed capacity in new and refurbished households in the different scenarios.

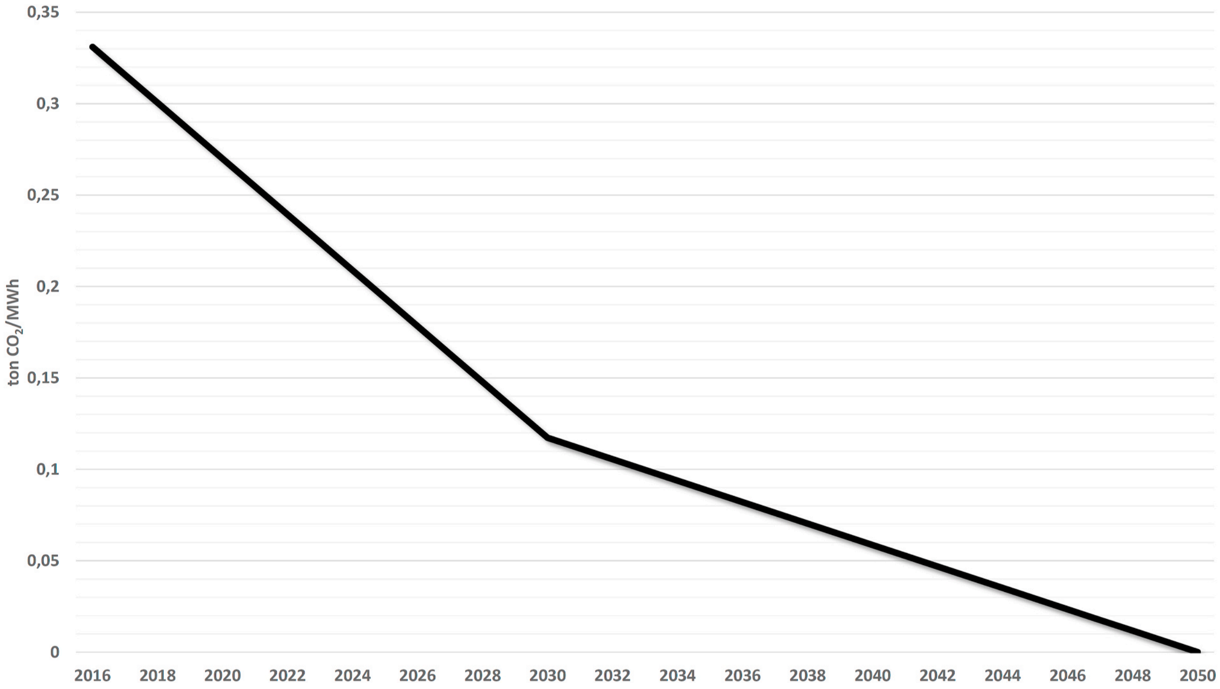

Fig. 14. Decarbonization of the Spanish electricity mix.

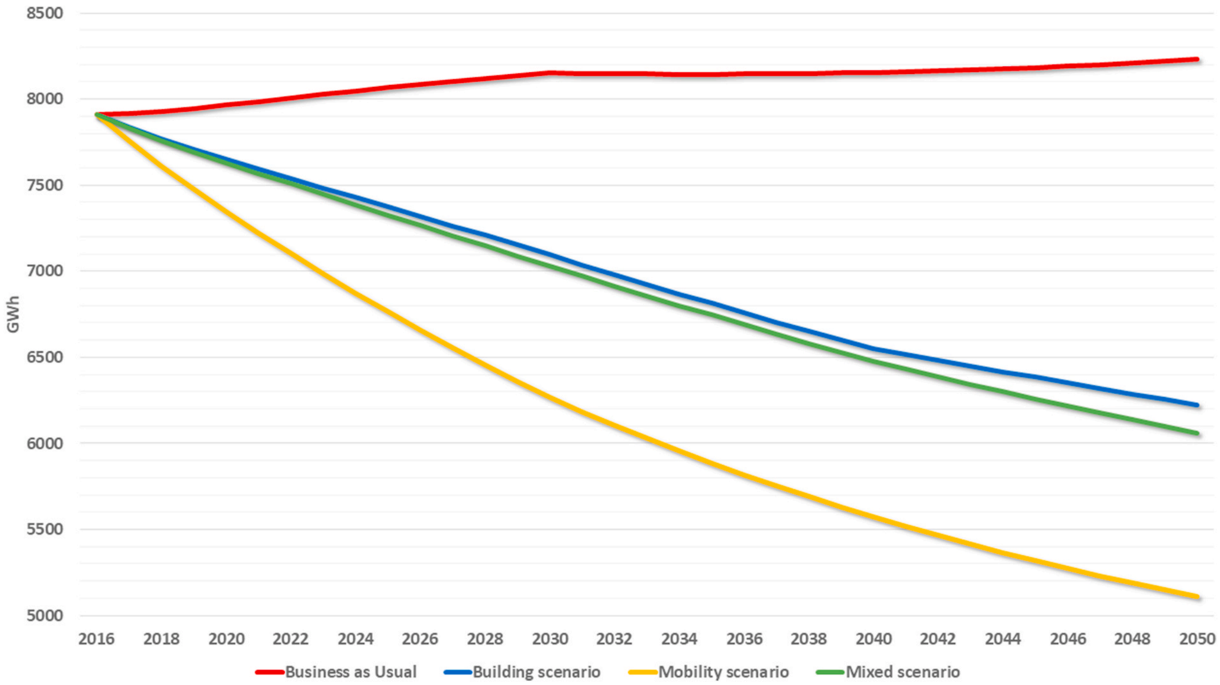

Fig. 15. Final energy consumption evolution in the different scenarios.

[101,102] are used to convert LEAP's final energy savings into equivalent CO_2 emissions, and total and non-renewable primary energy consumption. They are shown in Table 4.

The emissions and primary energy savings achieved by the assessed interventions in each alternative scenario are shown in Table 5.

Introduction of e-vehicles in the private transport sector achieves the greatest emissions and energy reductions in all three alternative scenarios with respect to the BaU. Even in the non-focused mobility scenarios this measure reaches higher savings than the refurbishment of households and tertiary buildings. Also, savings in non-renewable primary energy are greater than savings in primary energy in sectors where a higher share of fossil fuels are eliminated/substituted (e.g. residential and transport sectors). At this point it is important to note that these results are influenced by the assumed national grid decarbonization as the city is highly dependent on electricity imports. However, it would be advisable to the city to diversify its energy supply by fostering a larger deployment of local renewable energy sources instead of committing the electrification of the city's end-use sectors to a hypothetical decarbonization of the national grid.

For the economic indicators, a full LCC analysis of the additional

Table 3

Defined indicators for the assessment of the alternative scenarios.

Indicator	Abbreviation	Formula	Definition
Cumulative CO_2 Emission Savings	CCOES	$CCOES = \sum_{i=2017}^{2050} CO_2\ emissions_{alternative_i} - CO_2\ emissions_{BaU_i}$	Sum of the yearly reduction of CO_2 emissions-compared to the BaU- achieved all along the scenario's period
Cumulative Total Primary Energy Savings	CTPES	$CTPES = \sum_{i=2017}^{2050} Total\ Primary\ Enegy_{alternative_i} - Total\ Primary\ Energy_{BaU_i}$	Sum of the yearly savings of total primary energy -compared to the BaU- achieved all along the scenario's period
Cumulative Non-Renewable Primary Energy Savings	CNRPES	$CTPES = \sum_{i=2017}^{2050} Total\ Non\ Renewable\ Primary\ Enegy_{alternative_i} - Total\ Non\ Renewable\ Primary\ Energy_{BaU_i}$	Sum of the yearly savings of non-renewable primary energy -compared to the BaU- achieved all along the scenario's period
Scenario Life Cycle Cost	SLCC	$SLCC = \sum_{i=2017}^{2050} \left(\frac{CAPEX + OPEX - Return\ value}{(1 + discount\ rate)^i}\right)_{alternative_i} - \left(\frac{CAPEX + OPEX - Return\ value}{(1 + discount\ rate)^i}\right)_{BaU_i}$	Life Cycle Cost CAPEX and OPEX of the scenario compared to the BaU

Table 4

Considered emission and primary energy factors.

Fuel	CO_2 emission factor (kg CO2/ kWh final energy)	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)	0,331	2368	1954	[101]
Natural gas	0,252	1195	1190	[101]
Diesel (buildings)	0,311	1182	1179	[101]
Biomass	0,018	1037	0,034	[101]
Diesel (vehicles)	0,263	1,12	1,12	[102]
Gasoline	0,249	1,1	1,1	[102]
CNG	0,252	1195	1190	[101]

Table 5

Cumulative emissions and primary energy savings achieved in every alternative scenario disaggregated by modelled intervention.

Modelled intervention	CCOES (1000 ton CO_2)			CTPES (GWh)			CNRPES (GWh)		
	Building scenario	Mobility scenario	Mixed scenario	Building scenario	Mobility scenario	Mixed scenario	Building scenario	Mobility scenario	Mixed scenario
Household refurbishment	1267	413	871	5977	2040	4100	6065	1965	4177
Private tertiary buildings refurbishment	1101	632	800	14557	8616	10897	5791	3321	4201
Public tertiary buildings refurbishment	84	48	61	1130	669	846	442	253	320
Municipal fleet/public transport e-vehicles	232	611	438	597	1831	1268	955	2671	1873
Private transport e-vehicles	8177	19690	10654	22607	58296	29481	33644	81171	43851

measures modelled-compared to the BaU scenario-is carried out for each one of the alternative scenarios. As for the environmental indicators, the relative differences between the business as usual and alternative scenarios are taken into account. Derived costs from Refs. [69,93,103,104], and discount rates from Refs. [105] are detailed in Table A4 of the appendix. The inclusion of the socio-economic impacts of the scenarios using the Input/Output approach were not included in this case study as no adapted I/O tables were available for the city of Valencia.

Table 6

SLCC of each modelled intervention for every alternative scenario.

Modelled intervention	SLCC (M€)		
	Building scenario	Mobility scenario	Mixed scenario
Household refurbishment	409,16	124,92	262,52
Private tertiary buildings refurbishment	−356,21	−220,28	−278,60
Public tertiary buildings refurbishment	75,66	40,57	51,30
Municipal fleet/public transport e-vehicles	−0,68	0,46	−0,59
Private transport e-vehicles	2944,11	6711,39	3822,72

As shown in Table 6, all modelled interventions have a positive SLCC -except for the private tertiary buildings' refurbishment and municipal fleet and public transport e-vehicles substitution in building and mixed scenarios-, thus indicating that no net economic savings are achieved. Initial investments and further operational expenses of these interventions exceed the avoided costs and therefore no payback is achieved in the scenarios' timeframe. However, it should be noted that in the case of the buildings' refurbishment, economic performance has considered only the avoided costs of improving energy performance of the buildings, and these are not very large due to Valencia's mild climate. Other positive effects of building refurbishment due to improvements on thermal comfort, liveability, or sanitation, issues have not been considered in this case study but could be considered by additional indicators. In the case of vehicles, CAPEX includes charging infrastructure and battery, thus increasing the SLCC. There is a high uncertainty on the price evolution of e-vehicles, and more optimistic assumptions than those taken in this study (see Table A4) could result on a higher reduction of the CAPEX, improving the economic results.

In this practical application of the methodology to the Valencia case study, the scenarios considered have offered clear results. As it can be directly observed in Figs. 16–18, the mobility scenario achieves the largest savings in terms of energy and CO_2. However, total life cycle cost

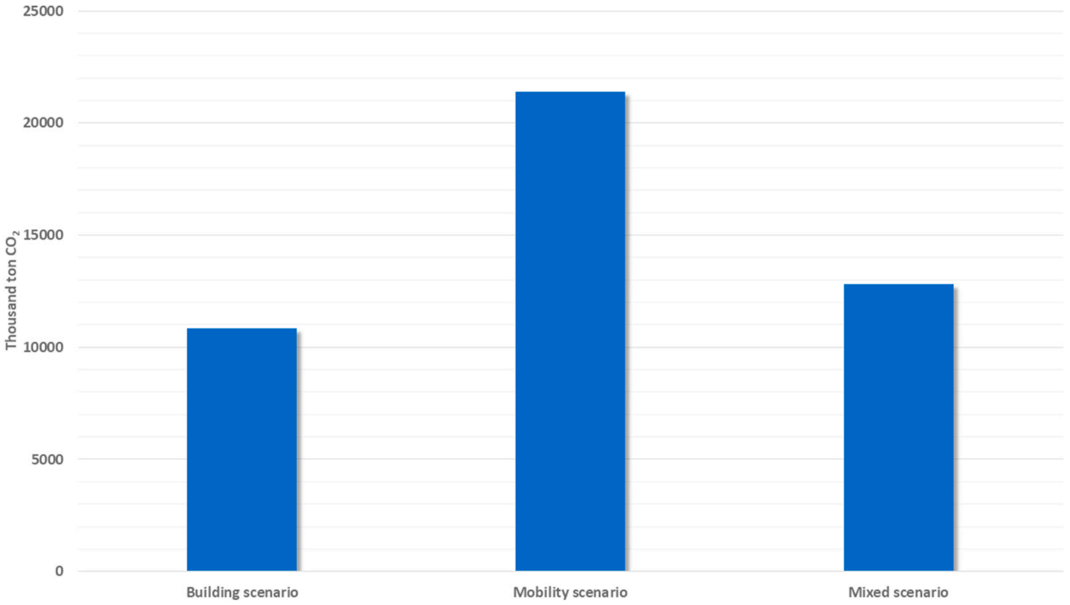

Fig. 16. Cumulative CO_2 Emission Savings achieved in the different alternative scenarios.

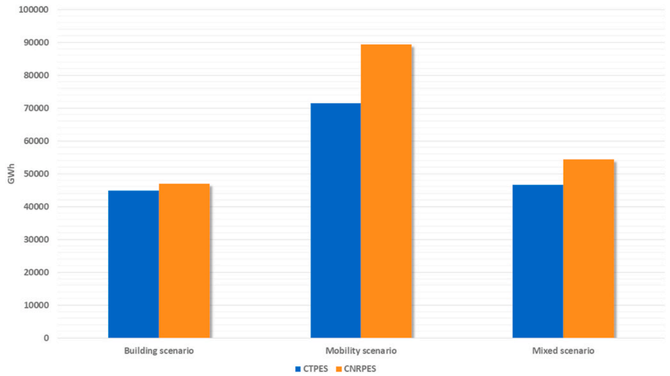

Fig. 17. Cumulative Total Primary Energy Savings (CTPES) and Cumulative Non-Renewable Primary Energy Savings (CNRPES) achieved in the different alternative scenarios.

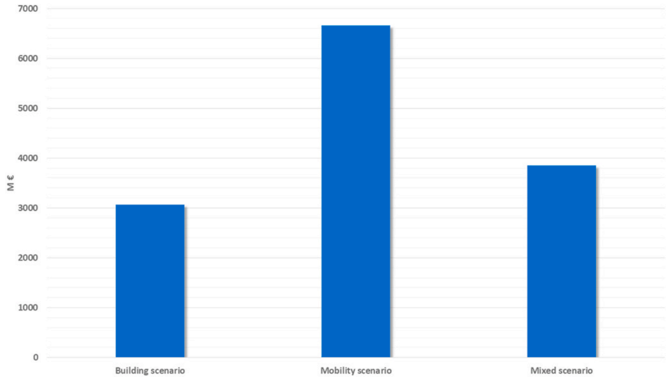

Fig. 18. Life Cycle Cost (SLCC) of the different alternative scenarios.

for this scenario is larger than for the rest. On the contrary, the building scenario involves the lowest life cycle cost from all the three scenarios.

An AHP process has been carried out considering three different cases: a) emissions reduction priority, b) energy savings priority, c) least-cost option priority. Scores for each scenario in every case are shown in Table A5table A5 of the appendix. As expected, due to the indicators' clear results, if the city focusses its efforts in reducing emissions and energy consumption (cases a) and b) respectively) the mobility scenario should be chosen. If the city's budget is constraint, then the building scenario should be selected. It should be noted that the MCDA application proposed in the methodology could 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.

After the application of the case study some limitations to the proposed methodology have been found:

- During the integration of bottom-up and top-down, problems related to the data gathering methods can be faced: scope of the top-down data may not always match with available bottom-up data (e.g. consumption of vehicles vs registered vehicles). This can lead to the assumption of establishment of overly high or low energy intensities in order to preserve the original top-down aggregated data supplied by the city. Modellers should be aware of that in order to adopt particular hypotheses to correct this fact. As an example, m^2 of the residential sector registered in ENERKAD GIS tool, taken from the cadastre database, had to be reduced in order to obtain a coherent area/household relation, in accordance with the listed households in the city of Valencia. This issue could be arranged through and effort from the cities in the collection of clear and accurate data.
- When modelling energy scenarios, only technical aspects (e.g. buildings refurbishment, energy generation systems substitution, or vehicle stock substitution) are taken into account to represent the evolution of energy consumption. Other energy use-related features like social and behavioural dimensions, which have impact in the future energy use, are not modelled in the proposed approach. This could be fixed by trying to integrate social dynamics or agent-based modelling into the methodology in order to account shifts in the energy usage due to changes other than technological. These approaches were considered respectively by Ref. [5,19] in their reviews.
- Transport sector modelling approach through vehicle stock data has some limitations regarding the modelling of mobility actions such modal changes or parking and pricing policies. These interventions must be implicitly introduced in the model trough changes in the

stocks of the different vehicles. Additional work is needed to precisely translate these mobility actions into increases or reductions of vehicles.

6. Conclusions

Cities will face a major challenge in the near future. The urge to satisfy the energy needs of the expected urban population increase, will cause resource consumption to rise if the current economic and energy model is preserved. Measures must be taken to avoid this future and to comply with the agreed climate targets. In order to accomplish this task, proper long-term energy planning is required at city level. It is therefore essential to develop tools at urban scale or to adapt the already national-scale existing ones in order to facilitate assessment and development of urban energy policies and plans.

Modelling the performance of urban areas is a difficult exercise as cities are complex energy systems with specific problematics. From the early characterization of the city to the final assessment of the proposed futures, modellers may meet a certain number of challenges such data scarcity at urban level or boundaries definition amongst others. Modellers should also be aware of the city's idiosyncrasy (i.e. the existing end-use sectors, the urban energy demand mix and supply systems, and its socioeconomic structure) in order to project future scenarios in accordance with the city's past and present. Special attention should be paid to the preservation of historical trends or, conversely, to the proposal of new ones when constructing baseline scenarios (i.e. Business as Usual/Reference). Finally, the assessment should not only focus on the energy performance of the different scenarios, but also consider the environmental, economic and social implications that future situations may have. Thus, the scenarios assessment should be carried out in a holistic way taking into account all the relevant indicators for the city.

This paper presents a methodology to support city planners and policymakers in the elaboration of urban energy plans. The aim is to allow the city's stakeholders to make decisions based on the results of different energy transition scenarios. In the first step top-down real consumption data supplied by the city is disaggregated through integrating bottom-up approaches in order to characterize the energy performance of the city. By matching bottom-up estimates with the city's actual measured consumption, real-theorical gaps can be overcome. For the building sector a GIS-based tool (ENERKAD) is used to disaggregate the energy consumed in the city's building stock. Once the city's energy baseline is portrayed, energy transition scenarios can be set up in collaboration with local stakeholders. Finally, scenarios are assessed through energy and environmental criteria, and LCC analysis.

The proposed methodology has been demonstrated in a case study for the city of Valencia, where the data supplied by the city was disaggregated and introduced in the LEAP tool. Three different scenarios were considered: one focused on the building sector, one on the transport, and one combining measures in both previous sectors, being the second the one with the most favourable results in terms of energy savings and emissions reductions.

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

Lastly, future work should address the identified flaws of the methodology:

- Cities should make a data-gathering effort in the next few years to reduce modelling assumptions.
- Transport characterization should be improved to easily implement mobility measures.
- For the characterization of the energy transition scenarios' socio-economic impacts, the use of I/O models is recommended. However, I/O tables are generally at national or regional level, and their adoption at city level is a challenging task.

CRediT authorship contribution statement

Iñigo Muñoz: Methodology, Formal analysis, Investigation, Writing - original draft. **Patxi Hernández:** Writing - review & editing, Supervision. **Estibaliz Pérez-Iribarren:** Writing - review & editing, Supervision. **Juan Pedrero:** Formal analysis. **Eneko Arrizabalaga:** Conceptualization. **Nekane Hermoso:** Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The work supporting this paper was funded by the EU projects MAtchUP and mySMARTLife, that received funding from the European Union's Horizon 2020 research and innovation programmes under grant agreement No. 774477 and No. 731297 respectively.

Appendix

Table A1
Resulting energy intensities of the city vehicle stock.

Vehicle	Private fleet		Public fleet	
	No.	Energy intensity (GWh/vehicle)	No.	Energy intensity (GWh/vehicle)
Gasoline trucks	6649	0,0263	0	–
Diesel trucks	43540	0,0392	49	0,1435
GNC trucks	0,00	–	8	0,2503
Gasoline buses	2	0,0527	0	–
Diesel buses	1032	0,0785	410	0,2885
GNC buses	0	–	75	0,5005
Hybrid buses	0	–	7	0,2019
Gasoline cars	169740	0,0037	27	0,0027
Diesel cars	183182	0,0045	29	0,0163
Gasoline motorcycles	60586	0,0011	0	–
Diesel motorcycles	34	0,0014	0	–
Diesel tractors	3263	0,1609	0	–

(*continued on next page*)

Table A1 (*continued*)

Vehicle	Private fleet		Public fleet	
	No.	Energy intensity (GWh/vehicle)	No.	Energy intensity (GWh/vehicle)
Gasoline others	774	0,1080	0	–
Diesel others	1773	0,1609	0	–

Table A2
Detailed modelling considerations and hypotheses for the end-use sectors in each scenario.

Sector	Modelled intervention	Business as usual scenario	Building scenario alternative scenario 1	Mobility scenario alternative scenario 2	Mixed scenario alternative scenario 3
Residential	Households refurbishment rate	0,5%/year	2%/year	1%/year	1,5%/year
	New households	*until 2030: 3102 households/year *from 2030: 2171 households/year			
Private tertiary buildings	Base energy consumption growth	*2016–2030: 0,44%/year *2030–2040: 0,42%/year *2040–2050: 0,40%/year			
	Refurbishment rate	No refurbishment contemplated	100% of the buildings are refurbished in 2040. After that year the same refurbishment rate is followed	80% of the buildings are refurbished in 2050	100% of the buildings are refurbished in 2050
Public tertiary buildings	Base energy consumption growth	0,19%/year			
	Refurbishment rate	No refurbishment contemplated	100% of the buildings are refurbished in 2040. After that year the same refurbishment rate is followed	80% of the buildings are refurbished in 2050	100% of the buildings are refurbished in 2050
Public lighting	LED devices	100% LED in 2030			
Industry	Base energy consumption growth	−2,1%/year			
	Fuel share	*electricity: 1% growth/year *biomass: 30% in 2030 *solar: 1% in 2030 *natural gas: remainding share			
Public transport/ municipal fleet	Cars stock evolution	2050: +4% with respect to the baseline's stock			
	% electric cars	100% (2030)			
	Bus stock evolution	2050: +4% with respect to the baseline's stock	2050: +4% with respect to the baseline's stock	2050: +21% with respect to the baseline's stock	2050: +4% with respect to the baseline's stock
	% electric buses	10% (2030); 70% (2050)	10% (2030); 70% (2050)	100% (2030)	10% (2030); 70% (2050)
	Utility vehicles stock evolution	2050: +4% with respect to the baseline's stock			
	% electric utility vehicles	42% (2030); 100% (2050)	42% (2030); 100% (2050)	100% (2030)	42% (2030); 100% (2050)
	Rail energy consumption evolution	0,79%/year	0,79%/year	0,95%/year	0,79%/year
Private transport	Freight vehicle stock evolution	*2016–2020: 0,8%/year *2020–2030: 1,3% *2030–2050: 0,8%/year	*2016–2020: 0,8%/year *2020–2030: 1,3% *2030–2050: 0,8%/year	*2016–2020: 0,4%/year *2020–2030: 0,65% *2030–2050: 0,4%/year	*2016–2020: 0,8%/year *2020–2030: 1,3% *2030–2050: 0,8%/year
	% electric freight vehicles in 2050	0%	40%	80%	50%
	Bus stock evolution	*2016–2020: 0,5%/year *2020–2030: 0,5% *2030–2050: 0,8%/year	*2016–2020: 0,5%/year *2020–2030: 0,5% *2030–2050: 0,8%/year	*2016–2020: 0,25%/year *2020–2030: 0,25% *2030–2050: 0,4%/year	*2016–2020: 0,5%/year *2020–2030: 0,5% *2030–2050: 0,8%/year
	% electric buses in 2050	0%	40%	80%	50%
	Cars stock evolution	2050: +5% with respect to the baseline's stock	2050: +5% with respect to the baseline's stock	2050: +2,5% with respect to the baseline's stock	2050: +5% with respect to the baseline's stock
	% electric cars in 2050	4% (2030); 37% (2050)	50%	80%	60%
	Motorcycles stock evolution	2050: +5% with respect to the baseline's stock	2050: +5% with respect to the baseline's stock	2050: +2,5% with respect to the baseline's stock	2050: +5% with respect to the baseline's stock
	% electric motorcycles in 2050	20% (2030); 50% (2050)	100%	100% (2040)	100%
	Tractors stock evolution	*2016–2020: 0,8%/year *2020–2030: 1,3% *2030–2050: 0,8%/year	*2016–2020: 0,8%/year *2020–2030: 1,3% *2030–2050: 0,8%/year	*2016–2020: 0,4%/year *2020–2030: 0,65% *2030–2050: 0,4%/year	*2016–2020: 0,8%/year *2020–2030: 1,3% *2030–2050: 0,8%/year
	% electric tractors in 2050	0%	40%	80%	50%
	Others stock evolution	*2016–2020: 0,8%/year *2020–2030: 1,3% *2030–2050: 0,8%/year	*2016–2020: 0,8%/year *2020–2030: 1,3% *2030–2050: 0,8%/year	*2016–2020: 0,4%/year *2020–2030: 0,65% *2030–2050: 0,4%/year	*2016–2020: 0,8%/year *2020–2030: 1,3% *2030–2050: 0,8%/year
	% electric others in 2050	0%	40%	80%	50%

Table A3
Considered characteristics of the refurbished and new households.

Energy use	Fuel	Refurbished household pre 2030			Refurbished household post 2030			New household pre 2030			New household post 2030		
		Useful energy demand (kWh/m2)	Efficiency	Share	Useful energy demand (kWh/m2)	Efficiency	Share	Useful energy demand (kWh/m2)	Efficiency	Share	Useful energy demand (kWh/m2)	Efficiency	Share
Space Heating	Natural Gas	5,86	98,5%	10%	2,93	98,5%	5%	2,93	98,5%	5%	1,47	98,5%	0%
	Electricity (grid)		187,5%	85%		280%	85%		250%	85%		350%	70%
	Electricity (pv panels)		187,5%	5%		280%	10%		250%	10%		350%	30%
DHW	Natural Gas	10,48	98,5%	10%	10,48	98,5%	5%	10,48	98,5%	5%	10,48	98,5%	0%
	Electricity (grid)		187,5%	85%		280%	85%		250%	85%		350%	70%
	Electricity (pv panels)		187,5%	5%		280%	10%		250%	10%		350%	30%
Cooling	Electricity (grid)	9,11	300%	95%	9,11	350%	90%	9,11	300%	90%	9,11	350%	70%
	Electricity (pv panels)		300%	5%		350%	10%		300%	10%		350%	30%
Appliances	Electricity (grid)	14,75	100%	95%	14,75	100%	90%	14,75	100%	90%	14,75	100%	70%
	Electricity (pv panels)		100%	5%		100%	10%		100%	10%		100%	30%
Lighting	Electricity (grid)	3,27	100%	95%	3,27	100%	90%	3,27	100%	90%	3,27	100%	70%
	Electricity (pv panels)		100%	5%		100%	10%		100%	10%		100%	30%
Seasonal COP heat pump			3			3,5			3			3,5	
Heat pump fraction			70%			90%			90%			100%	
Electric heaters fraction			30%			10%			10%			0%	

Table A4
Assumed costs for the modelled interventions.

Modelled intervention	Description	Reference unit	Assumed costs[a,b,c,d]			Source
Household refurbishment	A full refurbishment of the household is carried out. The household's envelope is rehabilitated and the energy systems substituted by more efficient ones.	Additional surface (m^2) of refurbished floor area in the alternative scenario compared to the BaU	CAPEX	Insulation, mortar, construction services, and energy sytems	91,07 €/m^2	[69]
			OPEX	Maintenance	0,15 €/m^2. year	
Tertiary building refurbishment (private and public)	A full renovation of the building is considered including envelope refurbishment, systems substitution, LED lighting installation, and energy management and control strategies implementation.	Additional surface (m^2) of refurbished floor area in the alternative scenario compared to the BaU	CAPEX	Insulation, mortar, construction services, energy systems and other efficiency measures	116,58 €/m^2	[69, 93]
			OPEX	Maintenance	0,20 €/m^2. year	
Municipal light utility e-vehicles	Electric vehicles added to the stock	Additional electric vehicles introduced in the alternative scenario compared to the BaU[e]	CAPEX	E-vehicle over cost, battery, charger, taxes and insurance	10000 €/vehicle	[103]
			OPEX	Maintenance (includes as savings (negative costs) the maintenance expenses avoided compared to an ICE engine)	6,46 €/vehicle. year	[104]
Municipal e-buses	Electric vehicles added to the stock	Additional electric vehicles introduced in the alternative scenario compared to the BaU	CAPEX	E-vehicle over cost, battery, charger, taxes and insurance	200000 €/vehicle	[103]
			OPEX	Maintenance (includes as savings (negative costs) the maintenance expenses avoided compared to an ICE engine)	129,19 €/vehicle. year	[104]
Private e-motorcycles	Electric vehicles added to the stock	Additional electric vehicles introduced in the alternative scenario compared to the BaU	CAPEX	E-vehicle over cost, battery, charger, taxes and insurance	3500 €/vehicle	[103]
			OPEX	Maintenance (includes as savings (negative costs) the maintenance expenses avoided compared to an ICE engine)	2,26 €/vehicle. year	[104]
Private e-cars	Electric vehicles added to the stock	Additional electric vehicles introduced in the alternative scenario compared to the BaU	CAPEX	E-vehicle over cost, battery, charger, taxes and insurance	10000 €/vehicle	[103]
			OPEX	Maintenance (includes as savings (negative costs) the maintenance expenses avoided compared to an ICE engine)	6,46 €/vehicle. year	[104]
Other private e-vehicles (freight vehicles, buses, tractors and other vehicles)	Electric vehicles added to the stock	Additional electric vehicles introduced in the alternative scenario compared to the BaU	CAPEX	E-vehicle over cost, battery, charger, taxes and insurance	200000 €/vehicle	[103]
			OPEX	Maintenance (includes as savings (negative costs) the		[104]

(*continued on next page*)

Table A4 (*continued*)

Modelled intervention	Description	Reference unit	Assumed costs[a,b,c,d]		Source
			maintenance expenses avoided compared to an ICE engine)	129,19 €/vehicle. year	

[a] A discount rate of 4% has been considered for all interventions following [105].

[b] Costs for vehicles represent the extra expense in the purchase of an electric vehicle compared to an ICE (Internal Combustion Engine) one. On the other hand, avoided costs with regard to an ICE engine are also considered. The analysis is then focused in the introduction of electric vehicles instead of ICE vehicles.

[c] OPEX don't include fuel costs derived from energy consumption. Those are nevertheless considered afterwards in the calculation of the indicators and calculated depending on the actual consumption after the intervention is carried out. On the other hand, fuel prices are assumed to growth 0,8% per year starting from these baseline values:

- Grid electricity: 0,21 €/kWh
- Natural gas: 0,0642 €/kWh
- Diesel: 0,123 €/kWh
- Gasoline: 0,148 €/kWh

[d] For all the vehicles a yearly reduction of 4% until 2030 and 2% until 2050 in the CAPEX has been considered, simulating the decline in the price of e-vehicles.

[e] The increase in the total number of vehicles in both alternative and BaU scenarios is considered equal. However, penetration of e-vehicles is higher in the alternative one. As an example, considering x new vehicles in both scenarios in a particular year. y e-vehicles (and x-y ICE vehicles) are added in the BaU, while z e-vehicles (and x-z ICE vehicles) are introduced in the alternative scenario. The additional z-y e-vehicles introduced in the alternative scenario are compared against the same number of vehicles added in the BaU -which in the BaU case are ICE vehicles. This is the analysed difference.

Table A5

Resulting scores of the AHP process.

	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)
	CCOES	CTPES	A	9	CCOES	CTPES	B	7	CCOES	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
RESULTS												
Building scenario	0,04				0,04				0,70			
Mobility scenario	0,96				0,96				0,31			
Mixed scenario	0,19				0,17				0,60			

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

References

[1] UN Population Division, World Urbanization Prospects 2018, 2018. https://population.un.org/wup/DataQuery/.

[2] IEA, Energy Technology Perspectives, Towards Sustainable Urban Energy Systems, 2016, p. 2016.

[3] A. Facchini, C. Kennedy, I. Stewart, R. Mele, The energy metabolism of megacities, Appl. Energy 186 (2017) 86–95, https://doi.org/10.1016/j.apenergy.2016.09.025.

[4] N. Abbasabadi, J.K. Mehdi Ashayeri, Urban energy use modeling methods and tools: a review and an outlook, Build. Environ. 161 (2019) 106270, https://doi.org/10.1016/j.buildenv.2019.106270.

[5] J. Keirstead, M. Jennings, A. Sivakumar, A review of urban energy system models: approaches, challenges and opportunities, Renew. Sustain. Energy Rev. 16 (2012) 3847–3866, https://doi.org/10.1016/j.rser.2012.02.047.

[6] S. Ferrari, F. Zagarella, P. Caputo, M. Bonomolo, Assessment of tools for urban energy planning, Energy 176 (2019) 544–551, https://doi.org/10.1016/j.energy.2019.04.054.

[7] I. Van Beuzekom, M. Gibescu, J.G. Slootweg, A Review of Multi-Energy System Planning and Optimization Tools for Sustainable Urban Development, IEEE Eindhoven PowerTech, 2015, p. 2015, https://doi.org/10.1109/PTC.2015.7232360.

[8] A. Mirakyan, R. De Guio, Integrated energy planning in cities and territories: a review of methods and tools, Renew. Sustain. Energy Rev. 22 (2013) 289–297, https://doi.org/10.1016/j.rser.2013.01.033.

[9] A. Lind, K. Espegren, The use of energy system models for analysing the transition to low-carbon cities – the case of Oslo, Energy Strateg. Rev. 15 (2017) 44–56, https://doi.org/10.1016/j.esr.2017.01.001.

[10] (n.d.), https://iea-etsap.org/index.php/etsap-tools/model-generators/times.

[11] IEA, Nordic Energy Technology Perspectives, 2016, p. 2016, https://doi.org/10.1787/9789264257665-en.

[12] S.G. Simoes, L. Dias, J.P. Gouveia, J. Seixas, R. De Miglio, A. Chiodi, M. Gargiulo, G. Long, G. Giannakidis, Insmart – insights on integrated modelling of EU cities energy system transition, Energy Strateg. Rev. 20 (2018) 150–155, https://doi.org/10.1016/j.esr.2018.02.003.

[13] M. Gargiulo, A. Chiodi, R. De Miglio, S. Simoes, G. Long, M. Pollard, J.P. Gouveia, G. Giannakidis, An integrated planning framework for the development of sustainable and resilient cities - the case of the InSMART project, Procedia Eng 198 (2017) 444–453, https://doi.org/10.1016/j.proeng.2017.07.099.

[14] M. Yazdanie, M. Densing, A. Wokaun, Cost optimal urban energy systems planning in the context of national energy policies: a case study for the city of Basel, Energy Pol. 110 (2017) 176–190, https://doi.org/10.1016/j.enpol.2017.08.009.

[15] C.G. Heaps, Long-range Energy Alternatives Planning (LEAP) System. [Software Version: 2018.1.27], Stockholm Environment Institute, Somerville, MA, USA, 2016 (n.d.), https://www.energycommunity.org, https://www.energycommunity.org/.

[16] (n.d.), https://www.energyplan.eu.

[17] J. Lin, J. Kang, N. Khanna, L. Shi, X. Zhao, J. Liao, Scenario analysis of urban GHG peak and mitigation co-benefits: a case study of Xiamen City, China, J. Clean. Prod. 171 (2018) 972–983, https://doi.org/10.1016/j.jclepro.2017.10.040.

[18] G. De Luca, S. Fabozzi, N. Massarotti, L. Vanoli, A renewable energy system for a nearly zero greenhouse city: case study of a small city in southern Italy, Energy 143 (2018) 347–362, https://doi.org/10.1016/j.energy.2017.07.004.

[19] A. Martos, R. Pacheco-Torres, J. Ordóñez, E. Jadraque-Gago, Towards successful environmental performance of sustainable cities: intervening sectors. A review, Renew. Sustain. Energy Rev. 57 (2016) 479–495, https://doi.org/10.1016/j.rser.2015.12.095.

[20] J.R. Carreón, E. Worrell, Resources , Conservation & Recycling Urban energy systems within the transition to sustainable development . A research agenda for urban metabolism, Resour. Conserv. Recycl. 132 (2018) 258–266, https://doi.org/10.1016/j.resconrec.2017.08.004.

[21] A. Fichera, G. Inturri, P. La Greca, V. Palermo, A model for mapping the energy consumption of buildings, transport and outdoor lighting of neighbourhoods, Cities 55 (2016) 49–60, https://doi.org/10.1016/j.cities.2016.03.011.

[22] P.J. Chévez, I. Martini, C. Discoli, Methodology developed for the construction of an urban-energy diagnosis aimed to assess alternative scenarios: an intra-urban approach to foster cities' sustainability, Appl. Energy 237 (2019) 751–778, https://doi.org/10.1016/j.apenergy.2019.01.037.

[23] J. Pérez, S. Lázaro, J. Lumbreras, E. Rodríguez, A methodology for the development of urban energy balances: ten years of application to the city of Madrid, Cities 91 (2019) 126–136, https://doi.org/10.1016/j.cities.2018.11.012.

[24] L.G. Swan, V.I. Ugursal, Modeling of end-use energy consumption in the residential sector: a review of modeling techniques, Renew. Sustain. Energy Rev. 13 (2009) 1819–1835, https://doi.org/10.1016/j.rser.2008.09.033.

[25] A.F. Marique, T. De Meester, A. De Herde, S. Reiter, An online interactive tool to assess energy consumption in residential buildings and for daily mobility, Energy Build. 78 (2014) 50–58, https://doi.org/10.1016/j.enbuild.2014.04.016.

[26] Y. Chen, T. Hong, M.A. Piette, Automatic generation and simulation of urban building energy models based on city datasets for city-scale building retrofit analysis, Appl. Energy 205 (2017) 323–335, https://doi.org/10.1016/j.apenergy.2017.07.128.

[27] S. García-Pérez, J. Sierra-Pérez, J. Boschmonart-Rives, Environmental assessment at the urban level combining LCA-GIS methodologies: a case study of energy retrofits in the Barcelona metropolitan area, Build. Environ. 134 (2018) 191–204, https://doi.org/10.1016/j.buildenv.2018.01.041.

[28] Y. Chen, T. Hong, X. Luo, B. Hooper, Development of city buildings dataset for urban building energy modeling, Energy Build. 183 (2019) 252–265, https://doi.org/10.1016/j.enbuild.2018.11.008.

[29] G. Dall'o', A. Galante, M. Torri, A methodology for the energy performance classification of residential building stock on an urban scale, Energy Build. 48 (2012) 211–219, https://doi.org/10.1016/j.enbuild.2012.01.034.

[30] B. Kim, Y. Yamaguchi, S. Kimura, Y. Ko, K. Ikeda, Y. Shimoda, Urban building energy modeling considering the heterogeneity of HVAC system stock: a case study on Japanese office building stock, Energy Build. 199 (2019) 547–561, https://doi.org/10.1016/j.enbuild.2019.07.022.

[31] T. Letnik, M. Marksel, G. Luppino, A. Bardi, S. Božičnik, Review of policies and measures for sustainable and energy efficient urban transport, Energy 163 (2018) 245–257, https://doi.org/10.1016/j.energy.2018.08.096.

[32] A.F. Marique, S. Reiter, A method for evaluating transport energy consumption in suburban areas, Environ. Impact Assess. Rev. 33 (2012) 1–6, https://doi.org/10.1016/j.eiar.2011.09.001.

[33] R. Strulak-Wójcikiewicz, J. Lemke, Concept of a simulation model for assessing the sustainable development of urban transport, Transp. Res. Procedia. 39 (2019) 502–513, https://doi.org/10.1016/j.trpro.2019.06.052.

[34] J. Allegrini, K. Orehounig, G. Mavromatidis, F. Ruesch, V. Dorer, R. Evins, A review of modelling approaches and tools for the simulation of district-scale energy systems, Renew. Sustain. Energy Rev. 52 (2015) 1391–1404, https://doi.org/10.1016/j.rser.2015.07.123.

[35] R. Ghanadan, J.G. Koomey, Using energy scenarios to explore alternative energy pathways in California, Energy Pol. 33 (2005) 1117–1142, https://doi.org/10.1016/j.enpol.2003.11.011.

[36] E. Trutnevyte, W. McDowall, J. Tomei, I. Keppo, Energy scenario choices: insights from a retrospective review of UK energy futures, Renew. Sustain. Energy Rev. 55 (2016) 326–337, https://doi.org/10.1016/j.rser.2015.10.067.

[37] European Commission, EU Reference Scenario (2016) 2016.

[38] L. Börjeson, M. Höjer, K.H. Dreborg, T. Ekvall, G. Finnveden, Scenario types and techniques: towards a user's guide, Futures 38 (2006) 723–739, https://doi.org/10.1016/j.futures.2005.12.002.

[39] J.B. Robinson, Energy backcasting A proposed method of policy analysis, Energy Pol. 10 (1982) 337–344, https://doi.org/10.1016/0301-4215(82)90048-9.

[40] Z. Wang, Q. Wang, R. Wennersten, Q. Sun, Transitions to sustainable energy and material systems-outline of principles for scenarios, Energy Procedia 75 (2015) 2683–2693, https://doi.org/10.1016/j.egypro.2015.07.671.

[41] A. Athanassiadis, G. Fernandez, J. Meirelles, F. Meinherz, P. Hoekman, Y.B. Cari, Exploring the energy use drivers of 10 cities at microscale level, Energy Procedia 122 (2017) 709–714, https://doi.org/10.1016/j.egypro.2017.07.374.

[42] D. Ürge-Vorsatz, L.F. Cabeza, S. Serrano, C. Barreneche, K. Petrichenko, Heating and cooling energy trends and drivers in buildings, Renew. Sustain. Energy Rev. 41 (2015) 85–98, https://doi.org/10.1016/j.rser.2014.08.039.

[43] S. Copiello, L. Gabrielli, Analysis of building energy consumption through panel data: the role played by the economic drivers, Energy Build. 145 (2017) 130–143, https://doi.org/10.1016/j.enbuild.2017.03.053.

[44] D. Yu, A two-step approach to forecasting city-wide building energy demand, Energy Build. 160 (2018) 1–9, https://doi.org/10.1016/j.enbuild.2017.11.063.

[45] P. Zhao, J. Diao, S. Li, The influence of urban structure on individual transport energy consumption in China's growing cities, Habitat Int. 66 (2017) 95–105, https://doi.org/10.1016/j.habitatint.2017.06.001.

[46] L. Suganthi, A.A. Samuel, Energy models for demand forecasting - a review, Renew. Sustain. Energy Rev. 16 (2012) 1223–1240, https://doi.org/10.1016/j.rser.2011.08.014.

[47] W. Schellong, Energy Demand Analysis and Forecast, Energy Manag. Syst., 2011, https://doi.org/10.5772/21022.

[48] S.C. Bhattacharyya, G.R. Timilsina, Energy Demand Models for Policy Formulation: A Comparative Study of Energy Demand Models, 2009, https://doi.org/10.1596/1813-9450-4866.

[49] D. García-Gusano, J. Suárez-Botero, J. Dufour, Long-term modelling and assessment of the energy-economy decoupling in Spain, Energy 151 (2018) 455–466, https://doi.org/10.1016/j.energy.2018.03.102.

[50] D. Ürge-Vorsatz, A. Kelemen, S. Tirado-Herrero, S. Thomas, J. Thema, N. Mzavanadze, D. Hauptstock, F. Suerkemper, J. Teubler, M. Gupta, S. Chatterjee, Measuring multiple impacts of low-carbon energy options in a green economy context, Appl. Energy 179 (2016) 1409–1426, https://doi.org/10.1016/j.apenergy.2016.07.027.

[51] EEA, Projections in hindsight, 2015 papers2://publication/uuid/539922F4-7DEA-4EBE-BD5E-CC1B0C16A4CC.

[52] N. Strachan, Business-as-Unusual: existing policies in energy model baselines, Energy Econ. 33 (2011) 153–160, https://doi.org/10.1016/j.eneco.2010.10.009.

[53] A. Dagoumas, Modelling socio-economic and energy aspects of urban systems, Sustain. Cities Soc. 13 (2014) 192–206, https://doi.org/10.1016/j.scs.2013.11.003.

[54] S. Reiter, A.F. Marique, Toward low energy cities: a case study of the urban area of Liège, J. Ind. Ecol. 16 (2012) 829–838.

[55] N. Mohajeri, A.T.D. Perera, S. Coccolo, L. Mosca, M. Le Guen, J.L. Scartezzini, Integrating urban form and distributed energy systems: assessment of sustainable development scenarios for a Swiss village to 2050, Renew. Energy 143 (2019) 810–826, https://doi.org/10.1016/j.renene.2019.05.033.

[56] H. Farzaneh, C.N.H. Doll, J.A. Puppim De Oliveira, An integrated supply-demand model for the optimization of energy flow in the urban system, J. Clean. Prod. 114 (2016) 269–285, https://doi.org/10.1016/j.jclepro.2015.05.098.

[57] F. Jalil-Vega, I. García Kerdan, A.D. Hawkes, Spatially-resolved urban energy systems model to study decarbonisation pathways for energy services in cities, Appl. Energy 262 (2020) 114445, https://doi.org/10.1016/j.apenergy.2019.114445.

[58] Y. Noorollahi, R. Itoi, H. Yousefi, M. Mohammadi, A. Farhadi, Modeling for diversifying electricity supply by maximizing renewable energy use in Ebino city southern Japan, Sustain. Cities Soc. 34 (2017) 371–384, https://doi.org/10.1016/j.scs.2017.06.022.

[59] S. Samsatli, N.J. Samsatli, A general mixed integer linear programming model for the design and operation of integrated urban energy systems, J. Clean. Prod. 191 (2018) 458–479, https://doi.org/10.1016/j.jclepro.2018.04.198.

[60] A. Alhamwi, W. Medjroubi, T. Vogt, C. Agert, GIS-based urban energy systems models and tools: introducing a model for the optimisation of flexibilisation technologies in urban areas, Appl. Energy 191 (2017) 1–9, https://doi.org/10.1016/j.apenergy.2017.01.048.

[61] R. Shabbir, S.S. Ahmad, Monitoring urban transport air pollution and energy demand in Rawalpindi and Islamabad using leap model, Energy 35 (2010) 2323–2332, https://doi.org/10.1016/j.energy.2010.02.025.

[62] X. Li, B. Yu, Peaking CO2 emissions for China's urban passenger transport sector, Energy Pol. 133 (2019), https://doi.org/10.1016/j.enpol.2019.110913.

[63] R. Zhang, Y. Long, W. Wu, G. Li, How do transport policies contribute to a low carbon city? An integrated assessment using an urban computable general equilibrium model, Energy Procedia 152 (2018) 606–611, https://doi.org/10.1016/j.egypro.2018.09.218.

[64] Ş. Kılkış, Benchmarking the sustainability of urban energy, water and environment systems and envisioning a cross-sectoral scenario for the future, Renew. Sustain. Energy Rev. 103 (2019) 529–545, https://doi.org/10.1016/j.rser.2018.11.006.

[65] A. Sharifi, A typology of smart city assessment tools and indicator sets, Sustain. Cities Soc. 53 (2020) 1–3, https://doi.org/10.1016/j.scs.2019.101936.

[66] T. Kuznecova, F. Romagnoli, C. Rochas, Energy metabolism for resilient urban environment: a methodological approach, Procedia Econ. Financ. 18 (2014) 780–788, https://doi.org/10.1016/s2212-5671(14)01002-8.

[67] SCIS, Monitoring Kpi Guide, 2017. https://smartcities-infosystem.eu/sites/www.smartcities-infosystem.eu/files/document/scis-monitoring_kpi_guide-november_2018.pdf.

[68] P. Lawn, M. Clarke, The end of economic growth? A contracting threshold hypothesis, Ecol. Econ. 69 (2010) 2213–2223, https://doi.org/10.1016/j.ecolecon.2010.06.007.

[69] E. Arrizabalaga Uriarte, Multi-criteria Methodology for the Prioritisation of Alternative Energy Transition Scenarios of Cities, Ph.D. Thesis, University of the Basque Country, Bilbao, Spain, 2017.

[70] (n.d.), https://www.mysmartlife.eu/mysmartlife/.

[71] (n.d.), https://www.matchup-project.eu/.

[72] Tecnalia Research & Innovation, Enerkad. https://www.enerkad.net/, 2019.

[73] D. Majcen, L. Itard, H. Visscher, Statistical model of the heating prediction gap in Dutch dwellings: relative importance of building, household and behavioural characteristics, Energy Build. 105 (2015) 43–59, https://doi.org/10.1016/j.enbuild.2015.07.009.

[74] Joint Research Centre, Guidebook "How to Develop a Sustainable Energy and Climate Action Plan (SECAP)". PART 2 – Baseline Emission Inventory (BEI) and Risk and Vulnerability Assessment, RVA), 2018, https://doi.org/10.2760/118857.

[75] European Commission, The Covenant of Mayors for Climate & Energy, Reporting Guidelines, 2008, https://doi.org/10.2790/986666.

[76] STEEP project, D4.3 List of Possible Key Performance Indicators, 2015. http://www.smartsteep.eu/deilverables/.

[77] CITYkeys project, CITYkeys Indicators for Smart City Projects and Smart Cities, 2017. http://www.citykeys-project.eu/citykeys/home.

[78] Replicate project, D10.2 Report on Indicators for Monitoring at City Level, 2017. https://replicate-project.eu/.

[79] G. Hu, X. Ma, J. Ji, Scenarios and policies for sustainable urban energy development based on LEAP model – a case study of a postindustrial city: shenzhen China, Appl. Energy 238 (2019) 876–886, https://doi.org/10.1016/j.apenergy.2019.01.162.

[80] D. Zhang, G. Liu, C. Chen, Y. Zhang, Y. Hao, M. Casazza, Medium-to-long-term coupled strategies for energy efficiency and greenhouse gas emissions reduction in Beijing (China), Energy Pol. 127 (2019) 350–360, https://doi.org/10.1016/j.enpol.2018.12.030.

[81] D. Yang, B. Liu, W. Ma, Q. Guo, F. Li, D. Yang, Sectoral energy-carbon nexus and low-carbon policy alternatives: a case study of Ningbo, China, J. Clean. Prod. 156 (2017) 480–490, https://doi.org/10.1016/j.jclepro.2017.04.068.

[82] F.M. de A. Collaço, L.P. Dias, S.G. Simoes, T. Pukšec, J. Seixas, C. Bermann, What if São Paulo (Brazil) would like to become a renewable and endogenous energy -based megacity? Renew. Energy 138 (2019) 416–433, https://doi.org/10.1016/j.renene.2019.01.073.

[83] R. Chen, Z. Rao, G. Liu, Y. Chen, S. Liao, The long-term forecast of energy demand and uncertainty evaluation with limited data for energy-imported cities in China: a case study in Hunan, Energy Procedia 160 (2019) 396–403, https://doi.org/10.1016/j.egypro.2019.02.173.

[84] M. Zivkovic, K. Pereverza, O. Pasichnyi, A. Madzarevic, D. Ivezic, O. Kordas, Exploring scenarios for more sustainable heating: the case of Niš, Serbia, Energy 115 (2016) 1758–1770, https://doi.org/10.1016/j.energy.2016.06.034.

[85] Ajuntament de València, Plan de Acción para el Clima y la Energía Sostenible de la ciudad de València - Diagnóstico de la situación actual de la ciudad de València, 2018. http://www.valencia.es/ayuntamiento/energias.nsf/0/FB97C75EE481E93DC125840200442A22/$FILE/190415_AYTO_VALENCIA_PACES_Actualizado_.pdf?OpenElement.

[86] (n.d.), https://episcope.eu/welcome/.

[87] Instituto para la Diversificación y Ahorro de la Energía IDAE, Proyecto Sech-Spahousec, Análisis del consumo energético del sector residencial en España, 2016. www.idae.es.

[88] Instituto para la Diversificación y Ahorro de la Energía, IDAE, Síntesis del Estudio Parque de Bombas de Calor en España, 2016, p. 42. http://www.idae.es/uploads/documentos/documentos_Bombas-de-calor_FINAL_04ee7f42.pdf.

[89] (n.d.), https://sedeapl.dgt.gob.es/WEB_IEST_CONSULTA/.

[90] (n.d.) The World Bank Group, Electric power transmission and distribution losses, https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?end=2014&locations=ES&start=1997.

[91] Ayuntamiento de Valencia, Plan de Movilidad urbana sostenible de Valencia, Ayunt. Val. (2013) 511, https://doi.org/10.1007/s13398-014-0173-7.2.

[92] L. Belussi, B. Barozzi, A. Bellazzi, L. Danza, A. Devitofrancesco, C. Fanciulli, M. Ghellere, G. Guazzi, I. Meroni, F. Salamone, F. Scamoni, C. Scrosati, A review of performance of zero energy buildings and energy efficiency solutions, J. Build. Eng. 25 (2019) 100772, https://doi.org/10.1016/j.jobe.2019.100772.

[93] F. Patiño-Cambeiro, J. Armesto, G. Bastos, J.I. Prieto-López, F. Patiño-Barbeito, Economic appraisal of energy efficiency renovations in tertiary buildings, Sustain. Cities Soc. 47 (2019) 101503, https://doi.org/10.1016/j.scs.2019.101503.

[94] I. Çakmanus, Renovation of existing office buildings in regard to energy economy: an example from Ankara, Turkey, Build, Environ. Times 42 (2007) 1348–1357, https://doi.org/10.1016/j.buildenv.2005.11.007.

[95] Instituto para la Diversificación y Ahorro de la Energía, IDAE, Inventario, consumo de energía y potential de ahorro del alumbrado exterior municipal en España, 2017, p. 2017.

[96] (n.d.), https://www.iea.org/tcep/industry/.

[97] E.C. Foundation, Low-carbon Cars in Europe : A Socio- Economic Assessment, 2018.

[98] (n.d.), http://lipasto.vtt.fi/yksikkopaastot/indexe.htm.

[99] P. Linares, D. Declercq, Escenarios para el sector energético en España, 2018.

[100] European Committee for Standarization, Sustainability of construction works, Assessment of economic performance of buildings. Calculation method. EN 16627 (2013).

[101] S. General de Planificación Energética Seguimiento, Factores de emisión de CO2 y coeficientes de paso a energía primaria de diferentes fuentes de energía final consumidas en el sector de edificios en España, 2014, p. 31. http://www.minetad.gob.es/energia/desarrollo/EficienciaEnergetica/RITE/Reconocidos/Reconocidos/Otros documentos/Factores_emision_CO2.pdf.

[102] S. General de Planificación Energética Seguimiento, Factores De Conversión, 2011. http://www.idae.es/uploads/documentos/documentos_Factores_de_Conversion_Energia_y_CO2_(2010)_931cce1e.pdf%0Ahttp://www.cre.gob.mx/articulo.aspx?id=172.

[103] S. Bubeck, J. Tomaschek, U. Fahl, Perspectives of electric mobility: total cost of ownership of electric vehicles in Germany, Transport Pol. 50 (2016) 63–77, https://doi.org/10.1016/j.tranpol.2016.05.012.

[104] S. Gössling, A.S. Choi, Transport transitions in Copenhagen: comparing the cost of cars and bicycles, Ecol. Econ. 113 (2015) 106–113, https://doi.org/10.1016/j.ecolecon.2015.03.006.

[105] J. Steinbach, D. Staniaszek, Discount Rates in Energy System Analysis, 2015. http://bpie.eu/publication/discount-rates-in-energy-system-analysis/.