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Supporting Energy Transition in the Urban Environment

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Abstract

In this research, a technology-oriented approach is adopted to investigate the urban energy transition. This analysis focuses on envisioning possible energy scenarios and the associated technology portfolio. In order to actually deploy such technologies, social, economic and politic factors are considered without forgetting the active role of final users. The methodology presented to develop scenarios and investigate the urban energy system transition have a strong potential to inform and transform energy strategy development. The attention is paid to the representation of energy and related resource systems to support policy, investment, environmental or development analytics, and preferably aspects of their interaction.

1 Introduction

Energy transition represents the energy sectors' shift from fossil fuels consumption, mainly oil, natural gas and coal, to renewable energy sources as wind and solar. This switch from nonrenewable to renewable energy sources is made possible by technological advancements and a societal push towards sustainability. Indeed, the energy transition advocates structural changes to supply, demand, and prices frameworks with the final aim to reduce energy-related greenhouse gas emissions. In this decarbonization context, energy markets are rapidly changing as renewable sources are replacing conventional ones.

Power production from renewable sources is only part of the energy transition. Energy efficiency measures have proven to be a viable solution to reduce the fossil fuel consumption. Indeed, increasing the energy savings is a top priority as there is no need to guarantee cleaner production for the energy that is not consumed [1]. Alongside from the environmental issues, energy saving has entered into the public debate driven by many concerns regarding the security of supply. Central in energy policies of all the industrialized countries, the security of supply is clearly linked to the geopolitical stability of the suppliers as it guarantees reliability of provision and continuous access to natural gas and other fuels [2].

Numerous European countries have engaged the energy transition process and have publicly set related targets among their priorities. In fact, emerging economies are trying to determine how to increase energy access and sustain development while also transitioning toward cleaner energy production. Worldwide there is growing political momentum around lower greenhouse gas-emitting power generation and a clean energy economy. In this sense, all countries with scarce fossil fuel resources and with a policy based on the import of energy are trying to enforce their weak position by employing innovative energy policies. In light of this, in the last years, the European Union elaborated several strategies to increase renewable energy share and diversify the primary energy mix in order to reduce the risk [3]. These actions resulted in binding agreements with all member states for decreasing the energy demand in parallel to the deployment of an electricity generation mix centred on renewable energy sources.

In this research contribution, a technology-oriented approach is adopted to investigate the urban energy transition. This analysis focuses on envisioning possible energy scenarios and the associated technology portfolio. In order to actually deploy such technologies, social, economic and politic factors are considered without forgetting the active role of final users. The methodologies presented to develop scenarios and investigate the urban energy system transition have a strong potential to inform and transform energy strategy development. The attention is paid to the representation of energy and related resource systems to support policy, investment, environmental or development analytics, and preferably aspects of their interaction. In addition to the urban energy system modeling, the building sector efficiency and the transport sector electrification are investigated in the following sections.

The increasing penetration of renewable energy into the energy supply mix, the onset of electrification and the energy efficiency are all key drivers of the energy transition.

2 Literature review

2.1 Energy efficiency in buildings

Retrofit measures can significantly reduce operational energy consumption for winter and summer climatization and improve the efficiency of existing buildings. Mirabella et al. propose a wide literature review [4] on research efforts to analyze the environmental impacts of strategies for improving energy efficiency. The review highlights the relevance of considering building materials and equipment during the entire life cycle of buildings. Their findings show how the impact of the renewable systems' embodied energy is neglected in most of the decision-making processes mainly for the difficulty in obtaining detailed information. In fact, since new materials require manufacturing and transportation, the retrofit process inherently leads to an increase of the embodied energy of the whole building and needs to be included in the life cycle assessment [5]. New building projects need an evaluation to be designed and materials selected to balance embodied energy with factors as climate, availability of materials and transport costs [6]. Whereas, in existing buildings, the new technological energy efficiency measures that reduce energy consumption have a relevant embodied energy contribution and need to be included in the life cycle assessment [7].

In this context, Hong et al. propose a multi-dimensional input-output framework to examine which provinces and supply chain stages contribute more to the embodied energy of the building sector [8]. In line with this, a multi-regional input-output analysis is applied by Liu et al. [9] to understand the global consumer countries and the sectorial interactions concerning the energy embodied in the production of construction goods and services. Besides, Stephan and Stephan [10] propose a cost structure of energy consumption in each of the phases of the life cycle including embodied, transportation and operational energy. In addition, Chau et al. [11] analyzed the "end of life" management strategies for a building and concluded that materials' recycling is the most convenient method from the energy point of view, as it allows to exploit the embodied energy contained in the re-used materials. In terms of building efficiency governance, Koezjakov et al. [12] questioned the climate and energy efficiency policies in the Dutch residential sector and suggested the need of considering the embodied energy by showing that embodied energy use in standard houses is about 10–12% of the total energy use. Furthermore, Cao et al. [13] focused on the Chinese context by modeling the turnover of the building stock and the related operational and embodied energy dynamics.

Table 2.1 Main findings of previous studies on the embodied energy (EE) impact on the LCA.

Methodology	Target	Region	Highlights
Systematic literature review	Analyze the strategies to improve the energy performance of building	-	The impact of the renewable systems' EE is neglected in most of the decision-making processes.
Multi-regional input-output (MRIO)	Investigate the EE use in the construction industry [5], in the regional exchanges [8], in the international trade of construction goods [9].	China [5], [8] World [9]	The construction sector has great potential for energy saving in relation to its intermediate input of EE.
Input–output-based hybrid analysis	Life cycle energy and cost analysis of embodied, operational and user-transport energy [10]	Lebanon [10]	There is a need for assessments with a broad scope and their potential to inform energy reduction strategies in the built environment.
Buildings energy simulation	Analyze the relationship between operational energy demand and embodied energy [7], [12], [14]; investigate the differences in the life cycle energy efficiency arising from the buildings characteristics [15], [16]; evaluate the relationship between embodied and thermal energy demands [17]	Italy [7], [14] Netherlands [12], Finland [15], Spain [17], Iran [16]	The relative importance of EE use is increasing. It is important to include embodied energy use in future policy objectives. It is important to adopt a life cycle perspective, especially for buildings with low-intensity use.
Parametric analysis	Assessment of the life cycle energy demand of passive houses [6]	Belgium [6]	Current building energy efficiency certifications might not ensure a lower energy demand as EE is not included.
Mathematical estimation	Investigate the end of life phase of construction materials [11]	China [11]	Recycling allows to exploit the EE contained in the re-used materials.
Top-down dynamic material flow analysis	A calibration and verification based on dynamic material flow analysis [13]	China [13]	Building lifetime is a crucial parameter for modelling building stock's turnovers.

Recent studies highlight the importance of analyzing operational and embodied energy in the study of buildings life cycle assessment. Takano et al. [15] assessed that in low-energy buildings, embodied energy contributes highly to the building life cycle energy with contributions up to 46% of total energy use . Accordingly, Rossellò-Batle [17] highlighted the relevance in the long term energy consumption analysis of the initial embodied energy required for facades refurbishments, roofs improvements, change of windows' frames and insulation of thermal bridges for a Mediterranean detached house. Similarly, Zomorodian and Tahsildoost [16] investigated the double skin façades embodied energy and assessed that when the operational energy is minimized, the embodied carbon emissions increase. In the Italian context, Paganin et al. analyzed the impact of energy efficiency measures on an exhibition hall in Milan and their results [14] show that the insulation interventions are not affordable in terms of payback because of the building's intended use. Indeed, energy payback would be reached in 57 years.

2.2 Urban energy system modelling

Cities play a key role in the climate change mitigation as they represent the place of main economic and social activities. Urban complexity is rising with an increasing number of buildings, infrastructure elements and relevant stakeholders. This complexity challenges planners in making decisions for urban and energy planning [1].

As cities are one of the main contributors to greenhouse gas emissions, they offer great potential for implementation of energy efficiency measures and emissions reduction [1]. Baitule and Sudhakar analyzed how the higher educational institutes with a lot of free areas can play a vital role in reducing the conventional energy consumption and carbon footprint proposing solar powered green campus as a large-scale deployment of the renewable energy system [3].

Thus, the question arises on how to support the implementation process. The main challenge is not only the implementation and use of technologies, but also the optimization of existing local instruments, processes, and frameworks to efficiently support the design and implementation of energy strategies in communities [1].

If the adoption of low-carbon, high-efficiency technologies and building renovations is shown to be both cost-optimal and at the same time effective in reducing emissions under national policy constraints, more cities could be motivated to adopt sustainable energy system strategies [7]. Further studies that focus on local scale energy planning are necessary to analyze these issues.

With this aim, Yazdanie et al. [7] published a study for the city of Basel. They take into account energy efficiency measures as well as the introduction of distributed renewable generation. They find that the utilization of a balanced mix of the most convenient options could exceed the national targets in terms of efficiency and de-carbonization. Similarly, Mostegla et al. [2] also highlight the importance of the public participation in the local energy planning process.

As suggested by Eicker et al. [8], to perform such studies, the availability of quantitative data on buildings dimension, shape and energy performance is strongly needed. To cope with this, they developed a tool which automatically extracts building's geometry and volume from urban plans and transfer the information to an energy simulation tool. In this way, it is possible to evaluate the potential for energy efficiency implementations or integration of renewable energy sources.

A multi criteria analysis was utilized by Tsoutsos et al. [9], who considered technological, environmental, economic and social variables in the formulation of the energy plan of the Crete island and suggested a set of alternative energy plans. Dondariya et al. simulated the performance of grid-connected rooftop solar PV system for small households in the Indian city of Ujjain [10].

Other researchers focused their attention on the importance of the strategic planning process. For example, Brandoni and Polonara [11] investigated on the role of the municipal energy planning in the regional energy-planning process. Their aim was to evaluate quantitatively the contribution that municipalities, through their plans, provided to the regional target. Similarly, Delponte et al. [12] propose an analysis of the impact of the Sustainable Energy Action Plan (SEAP). In particular, they identifie cost-benefit analysis, bankability, peer review and participatory level as key elements for obtaining an operative SEAP monitoring and for fostering an effective environmental energy policy. Likewise, Jank [13] discusses the implications of IEA Annex 51 related to energy efficient communities. Specifically, Jank [13] concentrates on the differences between the different planning fields of 'urban energy planning', which is addressing whole cities and communities, and 'local energy planning', oriented to neighborhoods or building clusters. The necessary link between both is emphasized considering a city as an interconnected energy system requiring a holistic approach rather than compartmented considerations. Analogous considerations were developed by

Lazarevic et al. [14], who focused on the concept of urban resilient design with specific application to the Serbian context. The aim of their work is to understand if Serbian cities are ready to acquire the global knowledge of urban resilient design.

Amado et al. [15] introduced the energy efficient city as a new model for energy planning. In contrast with the dominant approaches to energy efficiency at local scale, the energy efficient city reflects a cellular model of self-reliant city based on the redesign of existing urban areas and the planning of new urban expansions conducted with the effort to reduce electricity use and promote widespread integration of solar energy and smart grids. When such a kind of models are considered, the support of the stakeholders is relevant. For this reason, Ouhajjou et al. [16] present a stakeholder-oriented approach, implemented in a planning support system, to provide stakeholders with specific information from their points-of-view, regarding the impact of energy strategies on their interests in the built environment. The approach is based on semantic web technologies, where an ontology has been developed to provide targeted information for different stakeholders while developing urban energy strategies.

A systematic review of the literature related to integrated energy planning in cities and territories is reported by Mirakyan and De Guio [17]. Their paper first presents a generic integrated energy planning procedure in which the planning activities are divided into four main phases. Second, the methods and the tools that are used for these diverse planning tasks are mapped to the suggested generic planning procedure tasks.

In many areas of North Europe, local energy planning is implemented to a relevant extent, therefore, different authors focused on this area [18-20]. Damso et al. [18] discuss on the implementation of local climate action plans to develop, in order to make Copenhagen a carbon neutral capital. Similarly, Ottelin et al. [19] analyze how climate change mitigation policies and other events affect the consumption-based household carbon footprints in the Helsinki Metropolitan Area from 2006 until 2012. The Finnish context is also studied by Hukkalainen et al. [20]. They introduced a methodology, embedded to a tool called Kurke, that aims to support the planning of sustainable and energy efficient urban areas by analyzing the energy performance of city plans and the impacts of their energy design alternatives on carbon dioxide emissions during planning.

The Canadian context was considered by St. Denis and Parker [21], who evaluated the role of renewable energy in community energy planning. They concluded that smaller and more remote communities may be the most willing to lead in the planned introduction of renewable energy systems.

Different urban morphologies in the city of London were analyzed by Sarralde et al. [24], who highlighted that the optimization of up to eight parameters connected with urban forms allows to increase the amount of solar radiation captured by the roofs. They suggest the utilization of their methodology in the design of new districts which may exploit solar radiation in an optimal way.

Solar photovoltaics' advantages have been assessed by Kumar et al. that compared the performance of photovoltaics (PV) for building applications in two configurations: building applied photovoltaics (BAPV) and building integrated photovoltaics (BIPV) [4]. Debbar et al. propose a large review on applications of building-integrated photovoltaics (BIPV) and building integrated photovoltaic thermal (BIPV-T) technologies [5]. Shukla et al. assessed the advantages of a detailed design of a standalone rooftop solar PV system to provide uninterrupted power supply for a hostel building [6].

The problem of optimal installation of building integrated photovoltaic (BIPV) at district level are analyzed in [22], where a bottom-up approach is proposed. A demonstration of the proposed method is carried out for the buildings of Izmir University (Turkey) demonstrating that the BIPV can achieve an annual share of electricity production of 23%. A similar analysis is developed by Brito et al. [23] in two areas of the city of Lisbon. They concluded that the installation of BIPV can contribute to the 50%-75% of the yearly electricity demand.

A three dimensional solar model was proposed by Redweik et al. [25], in order to estimate the amount of solar energy potential of a district by considering the façade and roofs of buildings. The model provides information for the possible optimal installation of solar devices. The proposed approach allows to account for the interaction among the different buildings present in the district and to select the most convenient locations for solar devices installation.

The effect of urban compactness on solar energy potential in the city of Geneva (Switzerland) was analyzed by Mohajeri et al. [26]. They modelled all the city of Geneva by using the software CitySim and identified the districts within the city with the optimal potential for installation of solar devices.

As for the Italian context, the literature review shows that a limited amount of studies focuses on the local level and those available [11, 12] concentrate on conceptual issues rather than on quantitative estimations on renewable sources territorial potential. Some studies [27-29] are available at country level, but methodologies and approaches to tackle the issue at urban-municipal level are missing.

2.3 Megacities rising energy needs

The challenges of decarbonization become more relevant as the urban dimension increases. Megacities, i.e. cities with more than 10 million inhabitants [18], are facing substantial challenges that are forcing them to rapidly find solutions in order to guarantee energy access to all the urban population and to improve inhabitants' well-being [19]. The dimension of megacities poses massive sustainability challenges in terms of housing, infrastructure and basic services. Nonetheless, given the rapidity of development and the magnitude of impact, they can be a potential locus to make the urgent energy system shift towards decarbonization [20]. In line with this, worldwide initiatives and international agreements [21] urge them also to address GHG emissions mitigation and reduce energy demand through local-scale energy system planning and policies [22]. Indeed, the integration of renewables is fundamental to lower the oil dependency [23] and to achieve the decarbonization goals [24].

In this context, urban energy systems modelling is fundamental in helping cities to plan and program the steps to meet the sustainable development goals [25]. Urban energy systems are the combined processes of acquiring and using energy to meet the energy demands of cities inhabitants [26]. The technical literature is rich of studies that analyze national and regional energy systems and often rely on tools able to provide useful information to guide decision makers [27], but there is still a limited set of research papers addressing the energy transition of cities and megacities [28]. In particular, the dearth of studies analyzing the African megacities was highlighted by the SAMSET project [29] that developed and implemented LEAP simulation models for six sub-Saharan cities in South Africa, Ghana and Uganda aiming to support them in the sustainable energy transition process [29]. In fact, even if more than a hundred papers in the scientific literature propose models of megacities urban energy systems to provide relevant guidance to policy makers, most of them address developed economies countries or Chinese main cities. Very few studies focus on African countries [30] and they rarely consider the urban energy systems intra-sector interactions [29,31] despite the fact that megacities located in developing countries are expected to have higher relevance in terms of energy consumption in the near future [32].

Megacities face several challenges including management of rapid urbanization, rising populations, expanding informal settlements. Thus, improving the quality of life in informal settlements or moving inhabitants to proper housing means providing adequate water and energy service access. To this purpose, governments need to improve the cities climate change resilience.

Researchers assessed the importance of knowledge sharing and city-to-city learning at both national [33] and regional scale [34]. In this context, Butera et al. [19] presented a review on energy access and energy efficiency of the built environment in informal settlements in Latin America and Africa. This review revealed from one side that data on energy are either missing or out-dated, as well as the data and information on the interaction between energy distribution companies and slums' dwellers, therefore they highlighted the need for further investigations. In order to fill the gap, researchers investigated the main energy carriers used in slums. Ebenaezer identified the fuel types and energy carriers commonly used for lighting, cooking, space heating, water heating and operating household appliances in urban informal households [35]. Similarly, several works focused on electrification of informal settlements. Bercegol and Mondstadt investigated the implementation of the Kenya Slum Electrification Project in Kibera in terms of new socio-technical rules and practices in unplanned settlements [36]. Baptista examined the transition to prepaid electricity happening in Maputo, Mozambique, in order to reflect on the contemporary geographies of urban energy infrastructure and urbanization in sub-Saharan Africa and other cities of the South [37]. In addition, Butera et al. [38] investigated the energy access of two informal settlements in Rio De Janeiro: Reta Velha (Itaboraí) and Jardim Bom Retiro (São Gonçalo) and assessed that 50% of the households are in a status of energy poverty and when available the electricity consumption is very high compared to the service provided, and expenditures are generally disproportioned to the households' income.

In the scientific literature, there are numerous definitions attempting to describe the city concept. The United Nations identify three approaches [18]: the "city proper", focusing on an administrative boundary; the "urban agglomeration", considering the extent of the contiguous built-up area, and the "metropolitan area", drawing the boundaries according to the degree of economic and social interconnectedness of nearby areas, identified by interlinked commerce or commuting patterns. In this study, cities are defined as urban agglomerations. In line with this, megacities are urban agglomerations with more than ten million inhabitants [18].

Megacities are facing environmental, economic, social, and infrastructural problems as well as risks linked to the uncontrolled and unplanned urban sprawling and to the improvement of the poor living conditions in the informal settlement determining an increasing energy demand and carbon footprint. In the scientific literature, Sovacool and Brown [39] address the dearth of available data on carbon emissions and comparative analysis between metropolitan areas and provide a preliminary comparison of the carbon footprints of twelve large metropolitan areas by examining emissions related to vehicles, energy used in buildings, industry, agriculture, and waste. Compared to cities, the accelerated urban development, the high density, and the large number of inhabitants, let megacities run higher climate change risks. In line with these findings, Facchini et al. compare the energy metabolism in 27 of the world's megacities including energy sources and sectoral end use, focusing on electricity use and generation source, and they found a significant regionalization of energy metabolism with relevant implication for resilience, infrastructure planning, GHG emissions, and policies for infrastructure decarbonization [40]. Most studies addressing the urban energy system in the available scientific literature recur to two main analysis approaches: (1) simulation, to simulate the operation of a given energy system, and (2) optimization, to optimize the operation costs and the investments in given energy system [27].

A deep literature review is reported in Table 2.2 to analyze all precedent works proposing a model to investigate scenarios impact on the whole urban energy system of the biggest 20 megacities [41]. The search was led on the Scopus scientific database and it was based on the following keywords: "city name", "energy", "simulation"; or "city name", "energy", "optimization". Over 2000 papers were carefully analyzed and a lack of literature was assessed regarding the use of models to integrate energy system at the city level. Indeed, only few published studies analyze the whole urban energy system in an integrated approach. The selected papers use either simulation or optimization models to assess the actual real consumption or to make future scenarios mainly focusing on fossil fuel consumption or CO_2 emissions. These research works are modelling the energy consumption of one or more urban sectors and analyzing the impact on the whole urban energy system.

Tokyo and the Chinese megacities have a richer database of research studies aiming mainly to improve the energy consumption in urban public [42],[43], transport strategies [44], [43,45,46], residential sector [46] and power demand [47],[48–52]. The other Asian megacities have fewer papers available in literature and they address mainly transport strategy [53,54], energy related CO_2 emissions [55] and urban solid waste management. Regarding the South American cities, less studies were found in literature: only few papers address Sao Paulo's urban sustainable development [56–58], and transportation [59,60]. So far, there is no any study available in literature analyzing the energy system of any African megacity. In particular, there is no published work modelling the urban energy system of an African megacity using a simulation or optimization model, or addressing how rising demand can be satisfied in a sustainable way.

Table 2.2 Main studies addressing energy systems of megacities available in the scientific literature

Ranking [41]	**Megacity, Country**	**Population** [41]	**Focus of the modelling analysis**
1	Tokyo, Japan	37,393,129	- renewable energy source integration and implications on power market [47] - urban ecosystem sustainability [42] - electric vehicles impact on power demand [44]
2	Delhi, India	30,290,936	- transport strategies [53,54] - energy flow in the urban system [55] - solid waste management [61]
3	Shanghai, China	27,058,479	- transport strategies [43,45,46] - residential sector [46] - power demand [48–52] - fuel consumption [62,63] - environmental impact [64]
4	São Paulo, Brazil	22,043,028	- solid waste management [65] - electric mobility [59,60] - decarbonization pathways [56–58]
5	Mexico City, Mexico	21,782,378	- no studies available
6	Dhaka, Bangladesh	21,005,860	- residential energy use [66] - solid waste management [67,68]
7	Greater Cairo, Egypt	20,900,604	- no studies available
8	Beijing, China	20,462,610	- residential and transportation sectors [46] - transportation sector [69] - energy saving and emission reduction [64] - natural gas consumption [62] - energy-carbon nexus [39,70]
9	Mumbai, India	20,411,274	- transport strategies [53]

Ranking [41]	Megacity, Country	Population [41]	Focus of the modelling analysis
			- load forecasting [71]
10	Osaka, Japan	19,165,340	- commercial sector [72,73] - residential sector [74]
11	New York, USA	22,100,000	- plug-in hybrid vehicles impact on power system [75]
12	Karachi, Pakistan	16,093,786	- solid waste management [61]
13	Chongqing, China	15,872,179	- environmental impact [76]
14	Istanbul, Turkey	15,190,336	- no studies available
15	Buenos Aires, Argentina	15,153,729	- no studies available
16	Kolkata (Calcutta), India	14,850,066	- no studies available
17	Lagos, Nigeria	14,368,332	- no studies available
18	Kinshasa, Congo	14,342,439	- no studies available
19	Manila, Philippines	13,923,452	- no studies available
20	Tianjin, China	13,589,078	- transport strategies [77] - water-energy nexus [78]

2.4 Electrification of the transport sector

Electric mobility is a sustainable alternative to fossil fueled transportation. Electrification, i.e. the replacement of conventional vehicles with electric ones, is the key to road transport decarbonization and will have a strong impact on the energy systems [79]. In the scientific literature, researchers investigate possible pathways towards decarbonizing and electrifying the transport sector. A recent study on Southern Italian cities of Naples and Salerno highlights the advantages of the electric transport and provides guidelines for potential users and system designers with the support of a TRNSYS model [80]. Likewise, a scenario study on the use of utility controlled charging of vehicles in British Columbia analyzes the impact of electrifying the entire road vehicle fleet on the supply and demand balance [81]. Besides, an analysis on the decarbonization of the transport and residential sectors in the Madrid region shows a significant potential for the reduction in energy demand [82]. In line with this, Spangher et al. implement the US Green New Deal and study the transportation policies that might affect scrappage rates, vehicle types, and car sharing adoption and comparing them to different exogenous electric vehicle adoption scenarios [83].

The progressive electrification of the transport fleet will put a burden on the power system of several countries that will need to increase the share of renewables and decrease fossil fuel consumption [84]. However, the transport electrification represents an opportunity to achieve the sustainability goals thanks to the improvement of the electricity generation from hydropower maximizing the plants efficiency [85] without impacting the natural environment [86]. As a matter of fact, the generation mix is confirmed to highly affect electric vehicles sustainability [87]. Indeed, a study on the role of modal shift in decarbonizing the Scandinavian transport sector assesses the electric cars competitiveness in a power sector almost decarbonized [88]. In this context, Novosel et al. use a model of the hourly distribution of the electric vehicles energy consumption and analyze their impact on the Croatian energy system testing the load curves [89]. Indeed, stakeholders are required to strengthen the efforts for implementing clean energy storage technologies in order to maintain the sustainable development of the transport sector, otherwise the spread of electric cars will lead to more fossil fuel consumption [90]. To this purpose, Vilchez et al. elaborate a methodology to quantify key environmental impacts of electric vehicles deployment in the European Union [91]. Likewise, the emission performance of the electric vehicles in the UK is investigated also by Küfeoğlu et al. that assess how the user behavior of hybrid electric car owners have a significant impact and suggest the authorities to start discussing a hybrid car ban in the near future [92]. In this context, Upadhyayula et al. assess the life cycle impact of lightweighting and electrifying the Indian automotive sector to analyze the impact of the strict environmental policy [93]. Hence, transport electrification should be included in a system decarbonization framework [94].

However, even if the image of modernity and the reduced environmental and acoustic pollution let electric vehicles become a fashion product, the higher prices and few technical factors, such as the recharging infrastructure, make the market competitiveness of electric vehicles be far lower than the conventional ones. Indeed, the high selling price is one major obstacle to the sales, making support policies as incentives over the long-term be extremely important [95]. In line with this, Noel et al. assess that the current vehicle capital cost differences, a lack of willingness to pay for electric vehicles, and the consumer discount rates are substantial barriers to the electric vehicle deployment in Denmark in the near term [96]. Likewise, Deendarlianto et al. investigate the effect of the implementation of alternative fuels from the legal and macroeconomic points of views and the possible energy sources for the future road transportation in Indonesia [97]. Similarly, Nunes et al. analyze the effects of environmental transport policies on the environment, economy and employment in Portugal [98]. The Portuguese context is considered also in [99], where a TIMES model is used to assess the role of electric and hybrid vehicles in meeting Évora municipality (Portugal) 2030 greenhouse gases emissions reduction targets.

Furthermore, electric vehicles are zero-emission in the driving process and can reduce urban heat island intensity in cities. Electric vehicles can also decrease significantly the need for air conditioning in summer [69] and allow a better quality of life. Hence, the electrification of transport is fundamental to define decarbonization pathways for energy services in cities [56]. In addition, the share of renewable energy sources involved in the electricity generation process is increasing. Renewable sources can strongly improve the European energy system security and reduce the fossils dependency from extra EU countries [100]. This explains the plans to eliminate fossil fuel vehicles and the rapid growth of the European Union (EU) global stock of electric vehicles in recent years. EU countries are presenting fade-out schedules for liquid vehicles and energy models are fundamental for policy proposals. Cars' engines sold in Europe are subject to strict limits on the pollutants' emissions: the 'Euro' standards for cars' engine were introduced in 1991 and since then EU started encouraging industry to innovate and invest new transport technologies.

3 Research contribution

3.1 Life-cycle approach to the estimation of energy efficiency measures in the buildings sector

Energy efficiency measures are an effective solution that is encouraged in the energy saving strategies applied to the Italian residential sector. This research work assesses the embodied energy impact related to the envelope insulation and evaluates the energy and carbon payback of the efficiency measure. The proposed method consists of (1) an estimation of the baseline operational energy consumption, (2) the realistic retrofit solutions simulation and, (3) the assessment of the 'retrofitting' embodied energy and the energy and carbon payback time calculation. The payback is based on the comparison between the saved operational energy and the embodied energy of the selected materials for insulation. Ten Italian cities are analyzed, and the results show a deep dependence on the climate zone. In Northern Italian cities, envelope insulation gains relevance as the energy and carbon payback periods are shorter, about 3 years against the 84 years for the Southern city of Palermo. The optimal thickness is estimated for the city of Milan considering the buildings typology, the insulation materials and the energy payback. This study shows how the total energy saving can be used as a criterion to obtain design indications.

Based on of the reviewed literature summarized in Table 2.1, it appears fundamental to further investigate the relationship between operational and embodied energy in the assessment of energy retrofitting of existent buildings. In addition, the reviewed literature highlights the absence of studies devoted to the Italian context, despite the importance of the country at the European level. Furthermore, it is also important to underline that Italy is poor in primary energy sources, therefore it is fundamental for the country to implement effective energy policies. To do this, it is relevant to scrutinize the most performant energy efficiency interventions by considering all the life cycle energy balance.

In light of this, the authors aim to bridge this gap by presenting a specific methodology for the quantification of lifecycle energy savings of energy efficiency interventions and applied it to the Italian context, which is scarcely analyzed in the literature despite its importance.

To this aim, a specific methodology is developed and presented. The approach comprises the following steps:

- identification of the most common archetypes;

- definition of a detailed thermal model for dynamic simulation of the identified archetypes;
- evaluation of the embodied energy connected with the energy efficiency interventions;
- estimation of the embodied carbon associated with energy efficiency interventions.

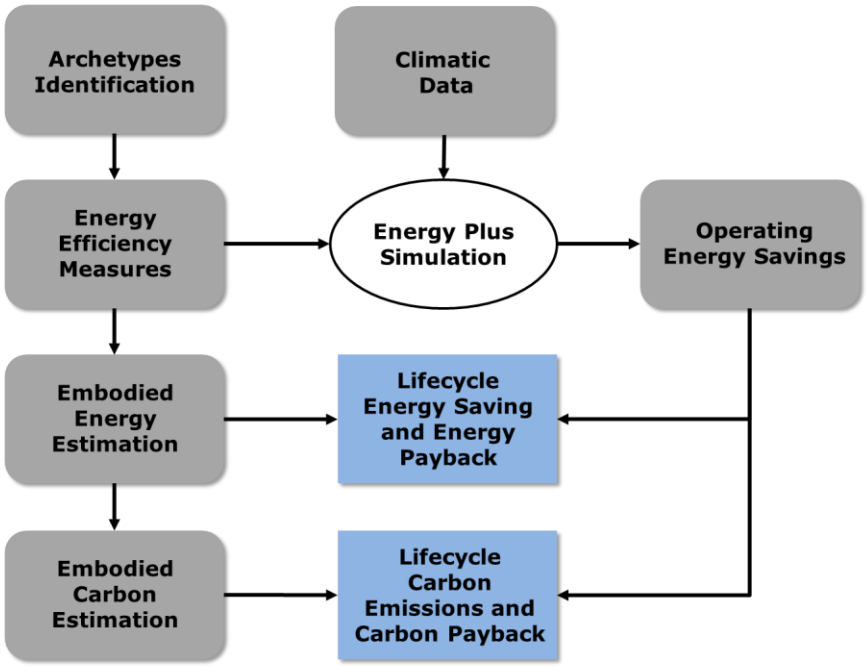

Figure 3.1 - Schematic of the proposed calculation procedure

Figure 3.1 reports a schematic of the presented calculation procedure. The analysis starts with the identification of the most common archetypes and the simulation of energy efficiency measure to assess the impact on the energy consumption. The simulations are run considering the climatic data of the different cities. Besides, the embodied energy of the efficiency measure and the related carbon emissions are estimated. Finally, the operating energy and carbon savings are compared to the embodied values in order to obtain the energy and carbon paybacks. In parallel, the authors propose a method to find the optimal insulator thickness to consider in order to maximize the lifecycle energy saving. To the best of authors' knowledge, this represents the first attempt in the literature to propose such an approach.

This work contains prominent novelty and contributions compared to the above listed literature. According to the given procedure, the energy payback period is introduced, and an innovative methodology is presented for the estimation of the carbon payback period.

This method is supposed to be a valid support for policy makers in selecting appropriate energy saving measures targeting the residential building sector and for buildings designers to derive more holistic considerations.

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3.1.1 Methodology

This research work analyzes building operational energy consumption and evaluates possible energy efficiency measures considering their embodied energy. Two building types are investigated: multifamily houses, namely small buildings characterized by a limited number of apartments, and apartment blocks, namely large buildings characterized by a high number of apartments. The analysis is performed for residential block types built in the period 1946-1990, as they represent the majority of the Italian household buildings, in fact they account for 61% of the total buildings as reported in [101]. It should be mentioned that buildings' insulation became compulsory in Italy only in 1977 with the introduction of energy efficiency regulations [102].

The input construction's data are provided by the National Scientific Report on Italian Building Typologies of the TABULA project. The Italian TABULA report was part of a European initiative aiming to assess the energy consumption of national building stocks adopting the UNI/TS 11300 norm for the calculations [103]. The report gives information on building-types, construction, system features and calculated energy performance [101]. The building energy simulation models used are firstly validated with the TABULA project values of operational energy for winter heating. The operational energy is calculated by means of dynamic energy simulations [104] and compared with the values calculated in the TABULA report for validation. This approach is demonstrated to be successful as shown in previously published works [105].

SketchUp Make is used to create the geometrical models and the energy requirements for winter heating are calculated with EnergyPlus software via two interfaces: Openstudio 2.4.0 and IDF-editor 8.9.0. EnergyPlus is an energy analysis and thermal load simulation program developed by the National Renewable Energy Laboratory (NREL) and it allows to calculate heating and cooling loads [106]. The software utilizes the transfer function methodology to solve thermal balances by considering radiation and convection effects at the same time on the internal and external surfaces.

Simulations are run in ten Italian cities covering all the national territory in order to provide a detailed analysis of the impact of the different climatic conditions [107]. The results are obtained by considering polyurethane insulation. Furthermore, for the cities of Milan, Rome and Palermo, representative of a large variety of climatic conditions, three types of insulation are proposed as retrofit interventions for the envelope: polyurethane foam; rock wool and resin-bonded fiberboard.

The proposed method compares the embodied energy to the operational energy decrease aiming to highlight the savings due to the retrofit solutions. Firstly, the embodied energy impact of the insulation materials is estimated and then compared to the energy savings in the use phase, allowing to calculate the energy payback time. Secondly, the carbon impact is calculated by accounting for the energy generation mix of the country.

Specifically, the operational energy savings (OE) in i years are calculated as per Eq. 3.1:

$$OE_i = \sum_i (E_{OP} - E_{OPS}) \qquad 3.1$$

where E_{OP} [MJ/m^2] is defined as the annual operational energy for heating of the non-refurbished building, and E_{OPS} [MJ/m^2] is the operational energy for heating of the refurbished building.

The energy pay-back time *n* is calculated in Eq. 3.2 when the embodied energy (*EE*) and the operational energy savings (*OE*) are compared:

$$EE - \sum_{i=1}^{n} OE_i = 0 \qquad 3.2$$

The energy pay-back time *n* represents namely the number of years of operational energy savings (*OE*) necessary to balance the embodied energy "investment" (*EE*).

In line with Eq. 3.2, the net saved operational energy *NSE* [MJ/m^2] in *f* years is estimated according to Eq. 3.3:

$$NSE_f = -EE + \sum_{i=1}^{f} OE_i \qquad 3.3$$

Besides, since the envelope insulation allows a reduction of primary energy consumption and consequently of related CO_2 emissions, the environmental impact is also assessed. The avoided CO_2 emissions per year, AE_{CO2}, are calculated per each building typology, per each insulation material and per city according to Eq. 3.4:

$$AE_{CO2} = NSE_f \times \alpha_j \qquad 3.4$$

where *NSE* is the net saved energy in *f* years [MJ/m^2] and *α* [kg/MJ] is the emission coefficient per the energy source *j* that would have been required to provide this amount of energy for the not refurbished building.

The carbon payback time can be calculated via the comparison of the avoided CO_2 emissions, AE_{CO2} to the embodied carbon emissions, EE_{co2} [kg]. It should be remarked that the embodied carbon emissions vary according to the energy mix of the considered. In line with this, the embodied carbon emissions EE_{CO2} are calculated as per Eq. 3.5:

$$EE_{CO2} = \sum_j \left(EE \times EMS_j \times \alpha_j \right) \qquad 3.5$$

where *EE* [MJ] is the initial embodied energy value, EMS_j [%] is the energy mix share per energy source *j,* and *α* [kg/MJ] is the emission coefficient per the energy source *j*.

Based on of this hypothesis and similarly to the energy payback time *n*, it is possible to estimate the carbon pay-back time *m* as in Eq. 3.6:

$$\sum_{i=1}^{m} EE_{CO2} - AE_{CO2,i} = 0 \qquad 3.6$$

A future development of the present work could be represented by the consideration of the degradation of the insulation layers during its operating life. This effect could be quantified by modifying Eq. 3.1 as follows in Eq. 3.7:

$$NSE = -EE + \sum_{i=1}^{n} \frac{OE_i}{(1+k)^i} \qquad 3.7$$

where k (e.g. degradation rate) represents a coefficient for the performance degradation of the insulator, which increases with the years i. In such a way a complete analogy can be provided with respect to financial indicators. In fact, *NSE* can be considered as the energy analogy of the Net Present Value (NPV), where *EE* represents the investment, OE_i is analogous of the cash flow and k has a role similar to that of the discount rate. The calculation of the degradation rate k will be the object of future research. Because of this analogy, it might be possible to define other energy performance indexes based on the financial ones, e.g. profitability index and others.

The economic payback time is calculated considering the prices of the insulation materials reported by the Regional Fare List that varies slightly according to the local markets. The initial investment required to refurbish the building is estimated and then compared to the saving in the bill corresponding to the decrease in natural gas and primary energy consumption for electricity. The economic payback time p is calculated as per Eq. 3.8:

$$I - \sum_{i=1}^{p} B_i = 0 \qquad 3.8$$

where I [€] is the initial economic investment for the refurbishment and B [€] is the bill savings in i years.

3.1.2 Models and simulations

3.1.2.1 Models

The 3D models' geometrical space characteristics are designed in SketchUp Make. EnergyPlus software allowed to insert the thermo-physical and construction data through the OpenStudio 2.4.0 platform. The input data regarding the building components materials, i.e. stratigraphy and transmittance, are provided on the basis of the TABULA report [101]. A representative week for an Italian family in winter is chosen to set the building occupancy schedule and, accordingly, the operating hours of the heating system. Occupancy and heating systems schedules were fixed considering building code and typical Italian family's habits. According to the buildings code, Italy is dived into climate zones and, per each zone, residential heating systems have a maximum number of working hours that varies from 6 to 14 (with the sole exception of the cities of Belluno, Trento and Cuneo that have no limitations) [108]. In particular, the heating maximum hours introduced in the models are the following: Milan, Bologna, Trieste, Turin 14h; Rome, Naples, Genoa, Cagliari, Bari 10h and Palermo 8h.

Table 3.1 - Construction data

	Multifamily House		**Apartment Block**	
Construction period	1946-1960 Fig. 1(a)	1961-1975 Fig. 1(b)	1961-1975 Fig. 1(c)	1976-1990 Fig. 1(d)
Floor-to-ceiling height	2.9 m	3.0 m	3.0 m	2.8 m
Volume	3076 m^3	3074 m^3	9438 m^3	12685 m^3
Conditioned area	880 m^2	799 m^2	2142 m^2	3831 m^2
Number of apartments	12	10	40	48
Number of floors	3	5	8	6
Insulation	No	No	No	Yes s=0.05m; λ=0.06 W/mK

Two profiles are created for the building occupancy schedule, one for the weekdays and the other for the weekends, and, respectively, two profiles for the heating system activity are added. It is assumed that the heating systems are not activated during the daily working hours as residents are supposed to leave and reach their jobs or schools. A minimum occupation of 10% is set to take into consideration elderly residents. The occupancy schedule varies in percentage of the maximum inhabitants of the building. In the morning hours, 8 a.m. -10 a.m., people start to leave and reach jobs or schools and they start coming back in the evening, 6 p.m-10 p.m. The full occupancy is reached in the night hours 10 p.m.-7 a.m. The construction data used in creating the models are summarized inTable 3.1.

As suggested by TABULA, in the four residential blocks, a single conditioned thermal zone is adopted, since in Italy it is very common to have all apartments connected by a central distribution characterized by horizontal strings in unheated rooms (e.g. cellar or soils) [101]. Therefore, a two zones model is considered, namely a heated zone for all the apartments and a non-heated zone for the staircase as shown in Figure 3.2.

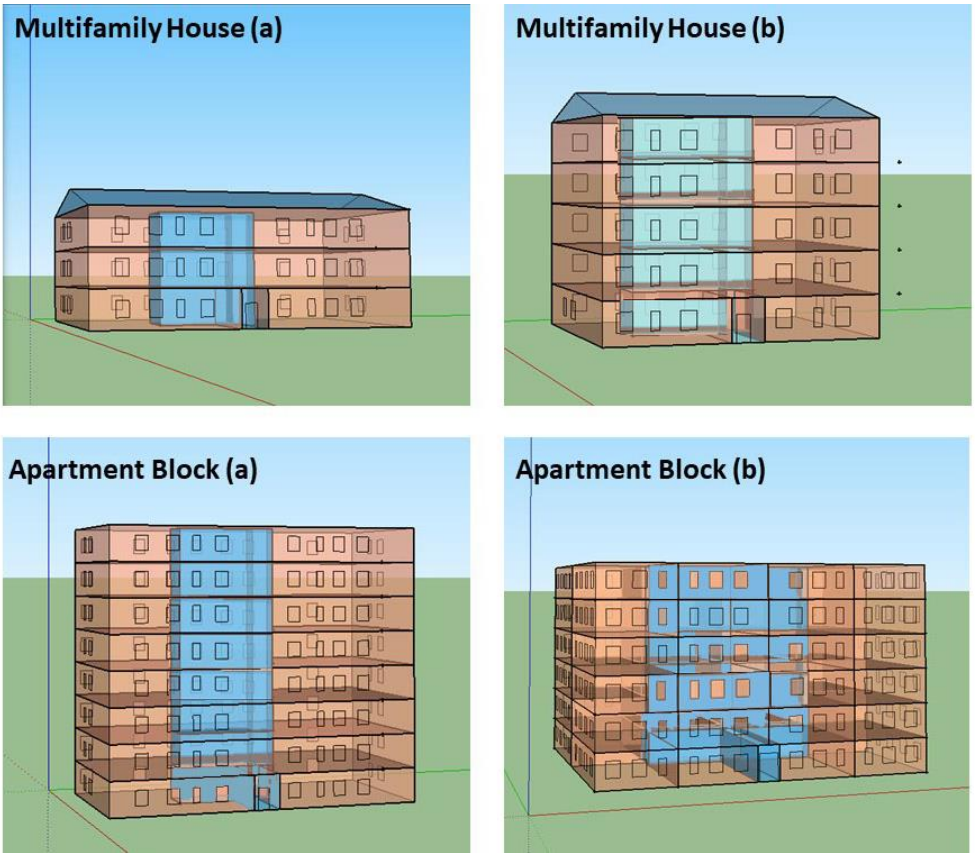

Figure 3.2 - Buildings typologies considered in the present analysis: (a) multifamily house of the period 1946-1960; (b) multifamily house of the period 1961-1975; (c) apartment block of the period 1961-1975; (d) apartment block of the period 1976-1990. The shaded central zone represents the volume of the stairs which is unheated.

The thermal loads are calculated on an hourly basis. Internal gains (people, lights, equipment, outside air infiltration, and ventilation) are provided in EnergyPlus as a design or peak level with a schedule that specifies a fraction of the peak for each hour of the day.

The HVAC systems are designed with the support of IDF-editor 8.9.0. In all the considered building archetypes it is assumed that the heating demand is completely satisfied by centralized natural gas boilers, which generates the hot water for each specific building block. The heat generator used is a non-condensing natural gas boiler, as suggested in TABULA, whose efficiency changes depending on the construction era:

- 0.70 - Multifamily House (1946-1960);
- 0.70 - Multifamily House (1961-1975);
- 0.70 - Apartment Block (1961-1975);
- 0.76 - Apartment Block (1976-1990).

3.1.2.2 Simulations

Dynamic simulations of a representative year are performed using IGDG meteorological annual weather data [109]. The simulations allow calculating the annual operational energy demand for heating. The main characteristics of the considered building components are summarized in Table 3.2.
The models' validation is accomplished by comparing the data resulting from the simulation with values provided by the TABULA project [101]. The comparison between the present calculation and TABULA data for the case without any intervention shows a reasonable agreement as highlighted in Table 3.3. Therefore, it can be concluded that the proposed model provides reliable estimations.

Considering the Italian context and history of incentives for energy efficiency measures, the envelope insulation is the most plausible intervention on already existing buildings. The insulation materials used for simulations are:

- polyurethane foam (for all the cities);
- rock wool (for Milan, Rome, and Palermo);
- resin-bonded fiberboard (for Milan, Rome, and Palermo).

A standard value of 10 cm thickness is assumed as it is commonly used for existing building refurbishment in Italy [110].

Table 3.2 - Main characteristics of the model building components

Building component	U [W/(m^{2}K)]	Material	λ [W/(mK)]
Roof	3.1	Bitumen	-
		Substratum	1.65
		Masonry	0.67
		Gypsum Plaster	0.7
Ground Floor	2.1	Ceramic	1.3
		Mortar	0.38
		Masonry	0.67
Foundation		Gravel	2.3
External Wall	1.3	Cement Plaster	0.9
		Brick I	0.52
		Brick II	0.52
		Gypsum Plaster	0.7
		Concrete	0.67
		Insulation (1976-1990)	0.06
Wooden Frame Window	4.9	Glass	0.9

The results of the dynamic simulations showed that the real efficiency of the insulation interventions depends on the climate zones. All the interventions are simulated per each city and the corresponding operational energy of the residential block is compared with the reference operational energy based on the present envelope and system conditions in [101]. All values represent the primary energy consumption.

The roof insulation is also simulated even if results show fewer interesting savings as this intervention decreased the operational energy demand of only 2% maximum of the total building because only the apartments on the top are concerned.

Table 3.3 - Operational energy requirements for heating. [MJ/m2]

			Proposed simulations		
	TABULA Project	**Without intervention**	**Polyurethane foam**	**Rock wool**	**Resin-bonded fibre board.**
			Multifamily House (1946-1960)		
Milan	630	644	485	492	487
Rome		303	228	236	234
Palermo		122	90	93	92
			Multifamily House (1961-1975)		
Milan	560	538	400	431	402
Rome		451	389	396	394
Palermo		242	216	219	219
			Apartment Block (1961-1975)		
Milan	558	538	418	434	430
Rome		190	134	142	140
Palermo		51	31	34	33
			Apartment Block (1976-1990)		
Milan	326	329	299	307	305
Rome		71	61	64	63
Palermo		16	12	13	13

3.1.2.3 Main assumptions and limitations

In this research, an implementation of the method is proposed by considering buildings archetypes and several assumptions for the simulations. The occupancy and heating system schedules are assumed following the Italian typical habits and norms that are not always representative of the reality. Thermal loads are assessed via dynamic simulations with EnergyPlus. The heating setpoint temperature is assumed as per the Italian decree [108] that suggests 20°C+2°C, but final users are not always following the guidelines. More precise results would be obtained if the real energy consumption were provided by the final users as measured on the bills. Similarly, the assumed habits change from one family to the other. Indeed, the thermal comfort is subjective and the heating setpoint may change.

Besides, the IGDG meteorological annual weather data [109] are based on a 1951-1970 period of record and do not take into account the global warming and climate change impacts. Measured up-to-date climatic data would allow more precise considerations.

In addition, the standard value of 10 cm thickness assumed is commonly used for existing building refurbishment in Italy [110], but it may vary in particular cases as there are no strict norms. On the other hand, all these assumptions are typical for energy simulations of buildings and calibration of the model parameters can be performed when a specific building is targeted.

Despite the above listed assumptions, the proposed method wants to include the embodied energy when considering the energy retrofitting of an existing building.

Results are providing clear indications on the magnitude of the embodied energy impact when the method is applied to archetypes, in the case of application to real buildings the data need to be based and calibrated on measured values.

In particular, authors want to emphasize that, differently from other works, they propose a criterion to consider embodied energy as a design parameter in order to determine the optimal thickness of insulation to install. Furthermore, this approach may also lead to energy policy initiatives as the certification of the embodied energy of construction materials. In this way designers know which is the embodied energy of the materials they are considering and they can use it as an input to improve buildings sustainability.

3.1.3 Results

In the following sections, the embodied energy of the insulation materials is calculated and compared to the operational energy to check the sustainability of the interventions. The embodied energy is, per definition, the total energy required for extracting, manufacturing, transporting and dismissing or eventually recycling an object [111]. In this study, the embodied energy considered is the initial energy required to produce the building materials. This amount of energy is strictly related to the manufacturing processes to produce the material (cradle-to-gate energy). The energy amount related to transport, dismissing or possible recycling is not considered as it may depend on specific choices by designers or architects. Indeed, the energy consumption due to the transport is difficult to foresee and calculate as it is not regulated by norms defining maximal distances. Hence, this research includes the values of the delivery to the manufacturing site and these might be increased with the values from the factory to the building' site.

The embodied energy coefficients (EE_I) considered in the present study are taken from the Inventory of Carbon and Energy [112]. These values are related to the United Kingdom and are widely used in literature for embodied energy studies in European countries. However, even if the embodied energy coefficient might be similar to materials produced in Italy, values should be very different if they are imported from China and other countries.

EE_I coefficients strictly depend on the production process and its level of efficiency and the lack of local EE_I values hardens the calculations of the embodied energy.

As mentioned earlier, how to collect the appropriate data (representative technologies, geographical context, energy mix, etc.) is a crucial dilemma in analyzing materials embodied energy [4] and, in fact, the results might change if another database is used for the EE_I values.

The embodied energy values per each type of insulation material and their impact on the building are reported in Table 3.4.

.

Table 3.4 - Main characteristics of the insulation materials

Material	Polyurethane foam	Rock wool	Resin-bonded fibre board
EE_I [MJ/kg]	110	16.8	16.6
ρ [kg/m^3]	30	92	240
s [cm]	10	10	10
λ [W/(mK)]	0.028	0.047	0.042
EE [MJ/m^2]			
Multifamily House (1946-1960)	351.2	164.5	424.0
Multifamily House (1961-1975)	535.6	250.8	646.6
Apartment Block (1961-1975)	435.4	203.9	525.7
Apartment Block (1976-1990)	206.6	96.8	249.4

3.1.3.1 Energy payback

The energy pay-back time is calculated according to Eq. 3.2 considering each typology of the insulator and the corresponding embodied energy. The results per city are reported in Table 3.5 (multifamily houses) and Table 3.6 (apartment blocks) where it can be remarked how the climatic conditions and building typology largely affect the energy pay-back period.

Table 3.5 - Effect of polyurethane foam insulation in multifamily houses. In the calculation of the carbon payback, it is assumed that the material is produced in China

City	Construction Period	Average HDDs	Energy Savings per Year (MJ/m2)	Energy Payback (Yrs.)	Carbon Payback (Yrs.)
Rome	1946-1960	1891	75	4.7	1.2
	1961-1975		62	8.7	2.9
Milan	1946-1960	2706	159	2.7	0.6
	1961-1975		138	3.9	1.3
Naples	1946-1960	1494	71	4.9	1.2
	1961-1975		61	8.7	2.9
Palermo	1946-1960	1122	22	11	2.8
	1961-1975		26	20.7	7.0
Bologna	1946-1960	2571	121	2.9	0.7
	1961-1975		102	5.2	1.2
Cagliari	1946-1960	1474	63	5.5	1.4
	1961-1975		54	9.9	2.3
Trieste	1946-1960	2459	102	3.4	0.9
	1961-1975		80	6.7	1.5
Turin	1946-1960	2933	122	2.9	0.7
	1961-1975		107	5.0	1.2
Bari	1946-1960	1582	75	4.7	1.2
	1961-1975		60	8.9	2.0
Genoa	1946-1960	1874	74	4.7	1.2
	1961-1975		59	9	3.0

Table 3.6 - Effect of polyurethane foam insulation in apartment blocks. In the calculation of the carbon payback, it is assumed that the material is produced in China

City	Construction Period	Average HDDs	Energy Savings per Year (MJ/m2)	Energy Payback (Yrs.)	Carbon Payback (Yrs.)
Rome	1961-1975	1891	51	8.5	7.7
	1976-1990		10	20.8	33.6
Milan	1961-1975	2706	121	3.6	3.3
	1976-1990		30	6.8	11.1
Naples	1961-1975	1494	50	8.6	7.8
	1976-1990		14	15.1	24.5
Palermo	1961-1975	1122	20	22.1	20.0
	1976-1990		4	50.0	80.9
Bologna	1961-1975	2571	108	4.0	2.5
	1976-1990		25	8.3	9.1
Cagliari	1961-1975	1474	57	7.6	4.7
	1976-1990		15	13.8	15.2
Trieste	1961-1975	2459	92	4.7	2.9
	1976-1990		20	10.3	11.4
Turin	1961-1975	2933	108	4.0	2.5
	1976-1990		22	9.4	10.3
Bari	1961-1975	1582	67	6.5	4.0
	1976-1990		17	12.2	13.4
Genoa	1961-1975	1874	54	8.1	7.4
	1976-1990		11	19.3	31.3

In the case of multifamily houses, the energy payback times range from 2.7 years in Milan and 11 years in Palermo for constructions built in the period 1946-1960, whereas for dwellings built in the period 1961-1975 the energy pay-back is comprised between 3.9 years in Milan and 20.7 years in Palermo. On this basis, the proposed analysis reveals that in Milan there is no doubt about the effectiveness of the thermal insulation, whereas in Palermo some concerns arise as the energy pay-back magnitude is comparable with the operating life of the insulator. Thus, in Palermo, from a life cycle perspective, if polyurethane foam is considered as an insulation it may result in a waste of energy rather than a saving.

Similar considerations can be obtained from the analysis of Table 3.6, where apartment blocks are considered. Namely, for buildings built in the period 1961-1975 the energy payback is comprised between 3.6 years in Milan and 22.1 years in Palermo. The difference is much ampler if dwellings built in the period 1976-1990 are considered. In fact, the energy payback period varies between 6.8 years in Milan and 50 years in Palermo. In this case, since the energy payback period is too long, it can be concluded that it is not convenient to install a polyurethane insulation layer in Palermo.

Based on the obtained results, more in-depth analyses are developed for Milan, Rome, and Palermo as shown in Figure 3.3, Figure 3.4, Figure 3.5, and Figure 3.6, where three insulation materials are compared, namely polyurethane foam, rock wool and resin-bonded fibre board. The cumulated energy savings are highlighted and compared to the first-year embodied energy, as reported in the next years' columns.

Results show that rock wool can be considered the most energy-efficient retrofit strategy. The rock wool insulation has the lower embodied energy value and, consequently, its energy payback time is shorter for all building typologies. Resin-bonded fibre board and polyurethane foam require longer payback time as they are characterized by a higher embodied energy. Hence, the embodied energy values have an important impact on the choice as the three of them show similar operational energy savings amounts.

Particular attention must be paid to Palermo where the payback times are very long for all the three insulation materials, especially in the case of apartment blocks built in the period 1961-1975 as it reaches 73.9 years with the resin-bonded fibre board.

Indeed, Palermo is a southern city characterized by a Mediterranean hot climate and its temperatures allow us to use less energy for winter heating. This result highlights the need to analyze the impact for each climate zone as the savings have to be compared to the actual "investment" in terms of embodied energy. Palermo proves that the installation of insulating material does not necessarily provide an energy saving when a life cycle analysis is taken into account. In this context, further considerations on the summer climatization may enrich the analysis.

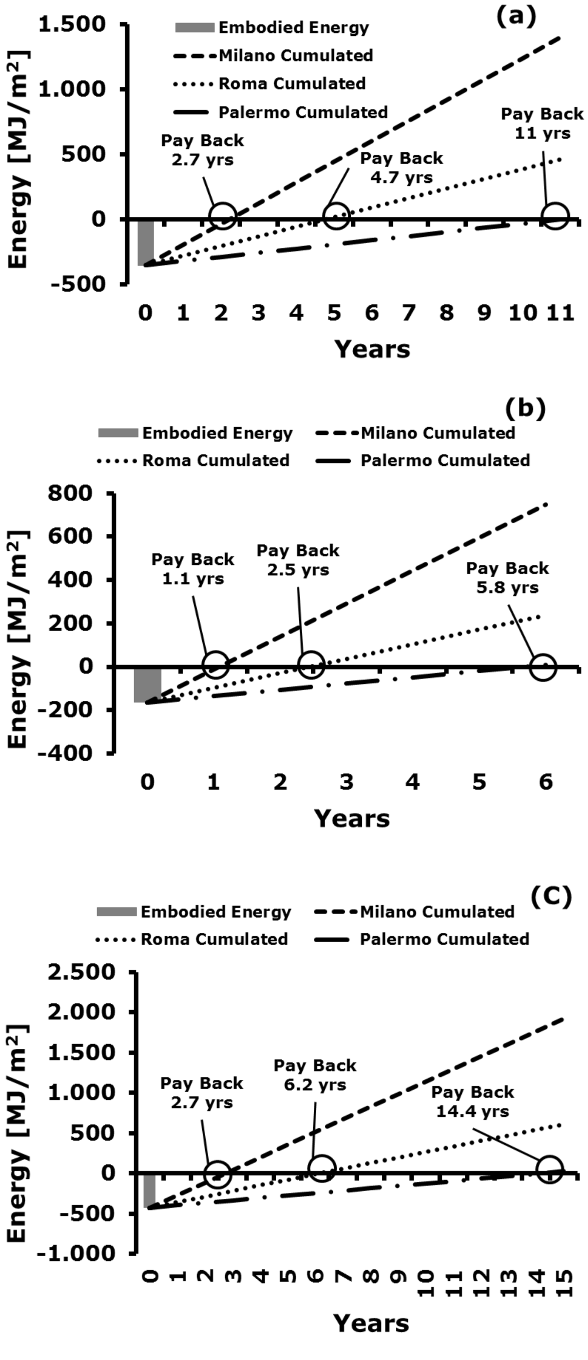

Figure 3.3 - Cumulated energy savings and embodied energy payback for an insulated multifamily house built in the period 1946-1960: (a) polyurethane foam; (b) rock wool; (c) resin-bonded fibre board. The energy efficiency investment is implemented in "Year 1", therefore the value is negative (i.e. "invested" embodied energy)

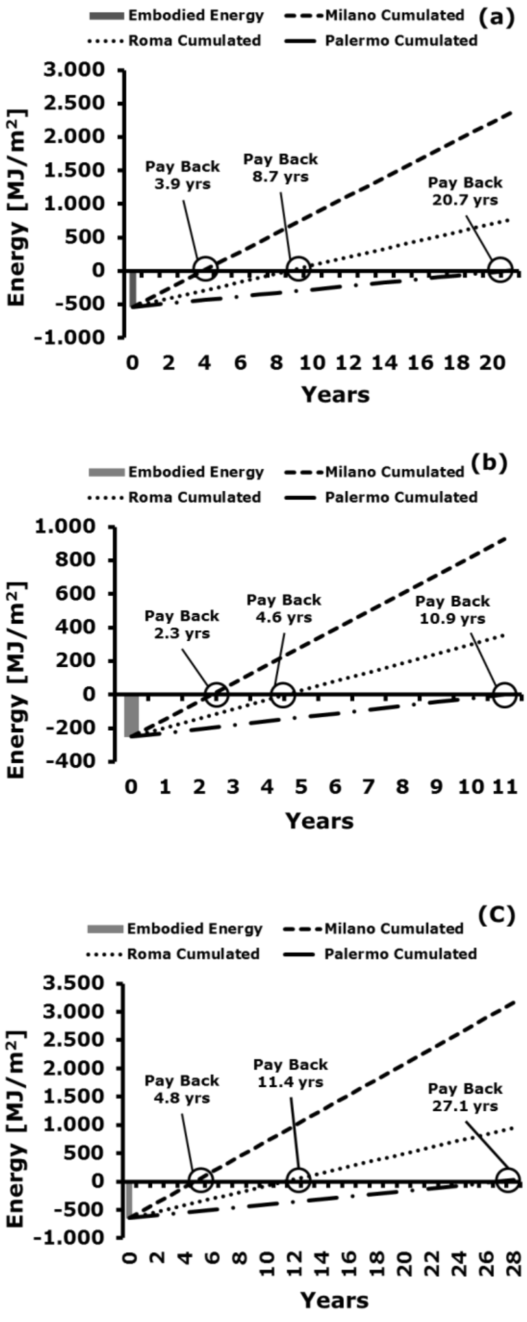

Figure 3.4 - Cumulated energy savings and embodied energy payback for an insulated multifamily house built in the period 1961-1975: (a) polyurethane foam; (b) rock wool; (c) resin-bonded fibre board. The energy efficiency investment is implemented in "Year 1", therefore the value is negative (i.e. "invested" embodied energy)

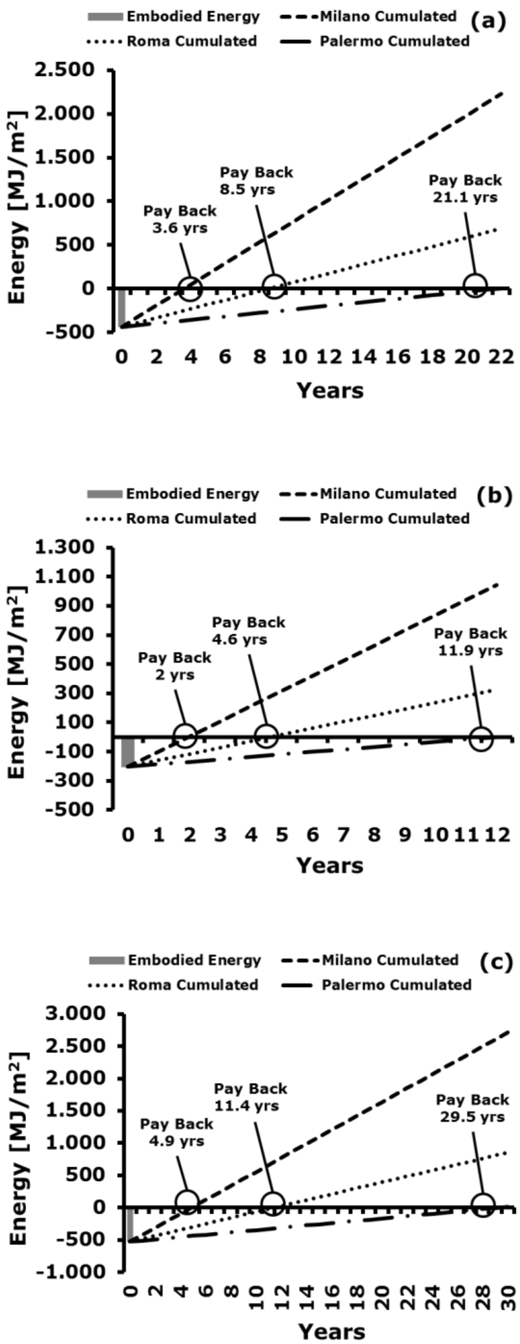

Figure 3.5 - Cumulated energy savings and embodied energy payback for an insulated apartment block built in the period 1961-1975: (a) polyurethane foam; (b) rock wool; (c) resin-bonded fibre board. The energy efficiency investment is implemented in "Year 1", therefore the value is negative (i.e. "invested" embodied energy)

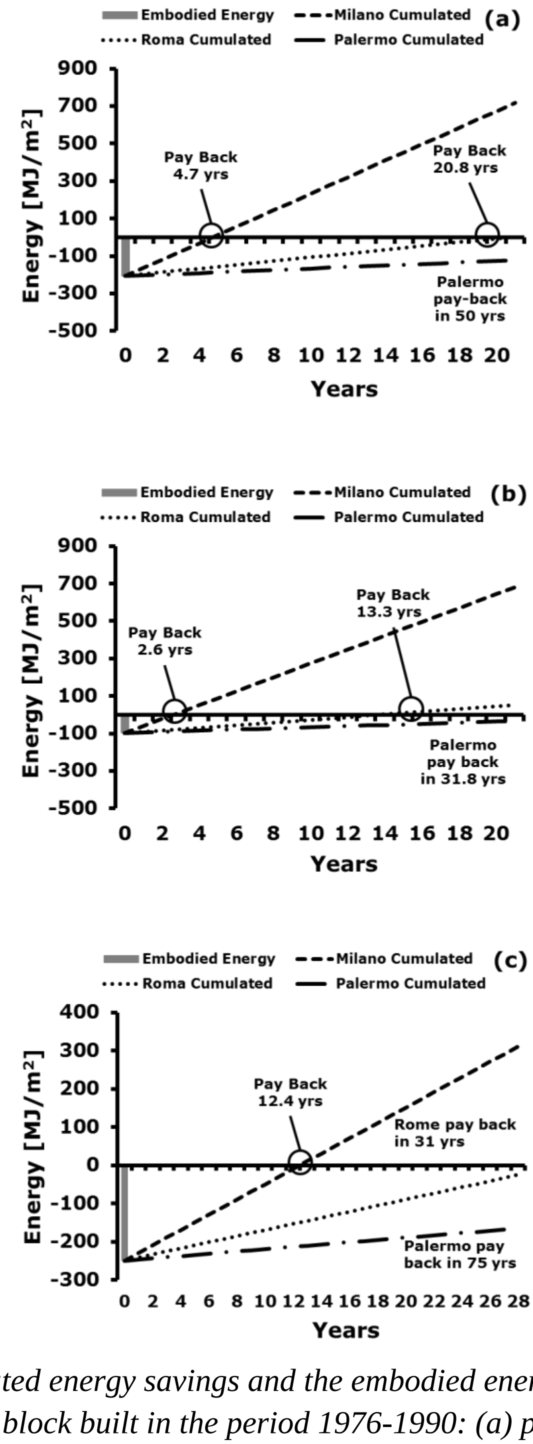

Figure 3.6 - Cumulated energy savings and the embodied energy payback for an insulated apartment block built in the period 1976-1990: (a) polyurethane foam; (b) rock wool; (c) resin-bonded fibre board. The energy efficiency investment is implemented in "Year 1", therefore the value is negative (i.e. "invested" embodied energy)

3.1.3.2 Carbon payback

The envelope insulation allows a reduction of natural gas or gasoil consumption for heating requirements and consequently of the related CO_2 emissions. If the avoided CO_2 emissions, AE_{CO2}, are compared to the embodied carbon emissions, the carbon payback time per each typology of insulation material can be calculated as per Eq. 3.6. The definition of the carbon pay-back is more difficult for the energy payback, since it is necessary to know how the energy utilized in the production process was generated to estimate its carbon intensity.
Besides, the carbon payback time strictly depends on the type of heating system and the energy generation mix of the country supplying the insulating material, as embodied emissions are calculated based on the energy mix per country, Table 3.7. A change of the producing country of the insulator corresponds to a different level of "embodied carbon emissions".

Table 3.7 - Carbon emissions coefficient per fuel and energy mix of the considered insulator producing countries [28,29]

	Biofuels/ waste	**Coal**	**Geothermal/solar/ wind**	**Hydro**	**Natural gas**	**Nuclear**	**Oil**
			Emissions Coefficients α [tCO_2/GWh_t]				
	45	888	55	26	500	28	735
Country			**Energy Mix Share (EMS) %**				
Australia	4.2	34.2	1.5	0.9	25.7	0.0	33.5
China	3.8	66.6	1.5	3.2	5.4	1.5	18.0
Italy	9.8	8.3	6.0	2.6	37.2	0.0	36.1
USA	4.5	17.1	1.4	1.0	29.6	9.9	36.5
Germany	9.6	25.5	3.5	0.5	20.9	7.7	32.3

In this study, the avoided CO_2 emissions per year, AE_{CO2}, are calculated considering that buildings heating in the Italian context is based on gasoil or natural gas boilers [113].

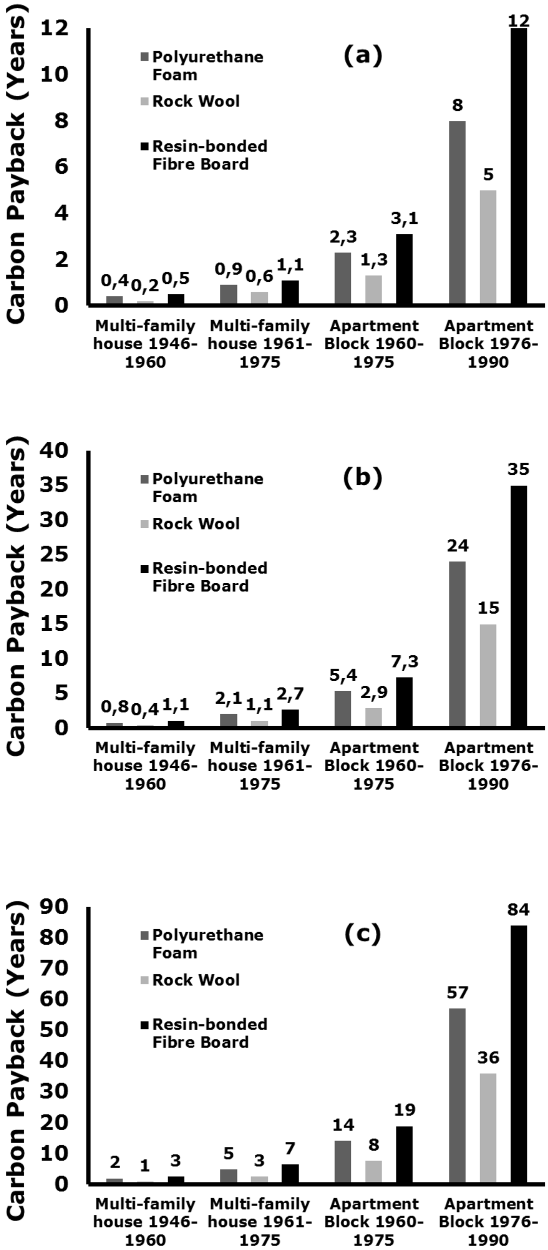

Figure 3.7 - Carbon payback for insulated buildings in the considered cities: (a) Milan; (b) Rome; (c) Palermo. It is hypothesized that the insulator material is manufactured in Italy, i.e. the Italian energy mix is considered to estimate the "embodied carbon emissions"

Table 3.5 and Table 3.6 report the carbon payback time for the ten considered Italian cities with the main assumption that the insulation material is manufactured in China. In analogy with the energy payback period, it can be observed that the index is largely affected by the climatic conditions and building archetype.
In a focus on the cities of Rome, Milan and Palermo, Figure 3.7 shows the carbon payback per building typology and insulator type in the hypothesis that the insulator is produced in Italy, i.e. based on the country's energy mix. The apartment blocks built in the period 1976-1990 have longer payback times as this building archetype was already insulated so the refurbishment has a lower impact on the heating energy consumption.

Assuming polyurethane insulation produced in different countries, Figure 3.8 shows the effect of the producing country of the insulator, namely the corresponding energy mix, on the carbon pay-back. The higher is the carbon intensity of the energy mix and the higher is the carbon pay-back. Thus, it can be noticed from Figure 3.8 that China provides the highest carbon pay-back value. This is because the Chinese energy mix is characterized by a large share of coal, 66.6%, with respect to the other countries considered in the study. Furthermore, it can be added that the impact is larger where the operating energy savings are lower (e.g. in Palermo). Therefore, in locations characterized by warm climate conditions, it is necessary to install an insulator with a low level of embodied carbon emissions if an acceptable carbon pay-back is to be achieved.

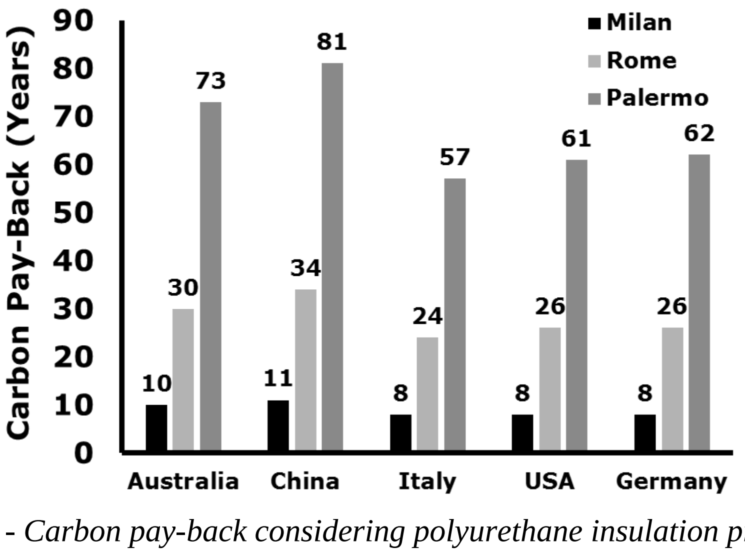

Figure 3.8 - Carbon pay-back considering polyurethane insulation produced in different countries

3.1.3.3 Thermal insulation thickness

The thermal insulation thickness defines the quantity of material required and consequently impacts energy and carbon payback. In the previously described simulations, the insulation panels' thickness is assumed to be 10 cm as it is an average value used nationwide in the retrofit of existing buildings.
However, interesting considerations can be made if the embodied energy payback is included in the definition of the materials' optimal thickness as the latter has a strong impact on the NSE, net saved energy [MJ/m^2], defined in Eq. 3.3.

In light of these considerations, parametric simulations are applied to the city of Milan to investigate the optimal thickness of the three insulation materials for each typology of building. The analysis considers the NSE achieved in 15 years. Figure 3.9(b) shows that for the case of polyurethane foam and resin-bonded fibre board, the optimal thickness results around 5 cm. Rock wool requires larger thicknesses as it is characterized by higher conductivity. These values maximize NSE. Furthermore Figure 3.9(d) highlights that thin values of insulator thickness provoke a waste of energy, since the operating energy saved does not pay back the *investment* in embodied energy.

Overall, when the three insulating materials resin fibre-board, polyurethane and rock wool are compared by city and building typologies, the latter is the most effective intervention at the envelope level with lower energy payback time. However, as Figure 3.9 shows, the rock wool insulation requires larger thickness and consequently, its carbon payback might increase significantly.

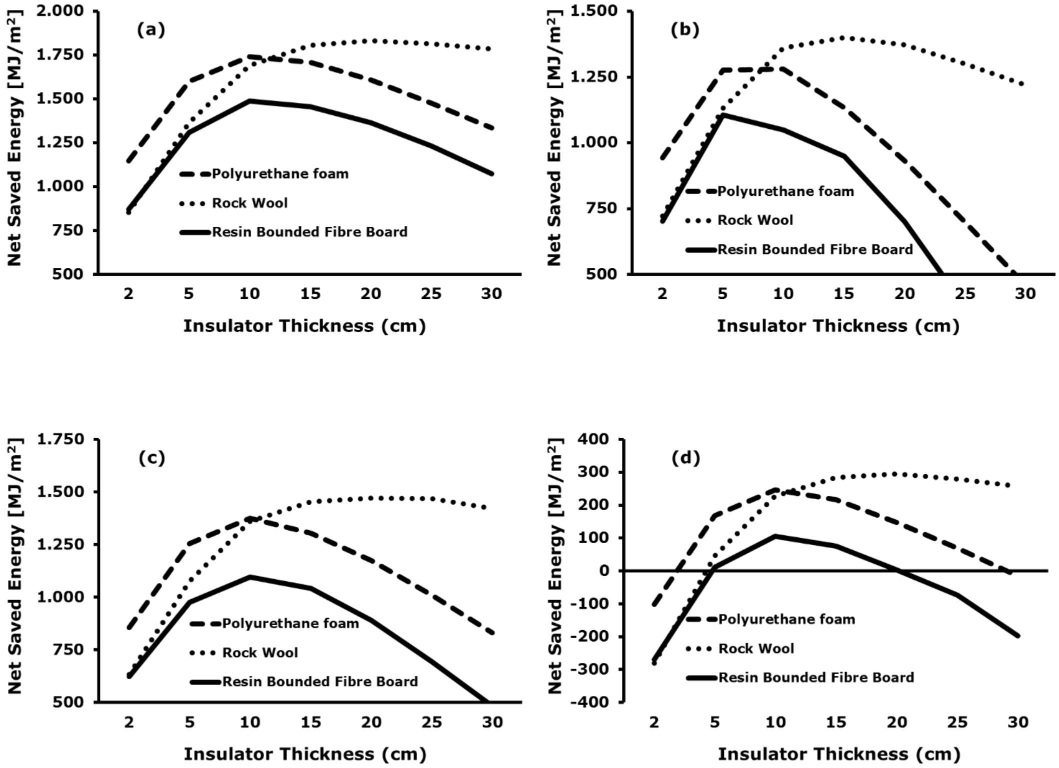

Figure 3.9 - The net saved energy in Milan in 15 years depending on the insulation thickness per typology of building: (a) Multifamily house built in the period 1946-1960; (b) Multifamily house built in the period 1961-1975; (c) Apartment block built in the period 1961-1975; (d) Apartment block built in the period 1976-1990

3.1.3.4 *Economic payback*

The economic payback of the initial investment is estimated considering the savings in the bills obtained by the refurbishments as per Eq. 3.8.

The savings in the bill are calculated for the Apartment block (a) and Apartment block (b) considering the cost of the natural gas for heating and the electricity for cooling. The natural gas (0.23 €/kWh) and electricity (0.07 €/kWh) prices are provided by the European Commission Database Eurostat [114].

The polyurethane foam, rock wool and resin bonded fibre-board prices considered are provided by the Regional Fare Lists that include materials, human labor, freight and transportation necessary for the realization of the insulation refurbishment. Prices also include safety costs and company base profit of 10% of the total expenses (Article 32 of Presidential Decree 207/10). All considered prices are VAT excluded. In addition, it is assumed that materials are bought locally so prices are taken respectively from the Regional Fare Lists of Lombardia (Milan) [115], Lazio (Rome) [116] and Sicily (Palermo) [117].

The economic payback values are reported in Table 3.8 and they start with the lowest value of 24 years for the apartment block (a) with rock wool insulation in Milan.

The apartment block (a) has values from 24 to 27 years for Milan and from 41 to 62 for Rome. Palermo has very high values starting from 105 years. The apartment block (b) has higher payback values starting from 58 years for the polyurethane foam insulation in Milan. The highest payback time estimated is 544 for the rock wool insulation in the city of Palermo.

On average, the economic payback values are very high and constitute a hard challenge for the private owners that consider refurbishing their apartment block. The investment can be more accessible if the owners could be granted with incentives for the retrofit measures.

Table 3.8 - Economic Payback

Apartment Block (a)			
	Initial investment, I [€]	**Annual bill savings, B [€]**	**Economic payback, p [years]**
		Milan	
Polyurethane foam	104 349	4 194	25
Rock wool	87 945	3 617	24
Resin bonded fibre-board	100 900	3 760	27
		Rome	
Polyurethane foam	123 559	3 040	41
Rock wool	163 026	2 638	62
Resin bonded fibre-board	130 248	2 736	48
		Palermo	
Polyurethane foam	159 918	1 234	130
Rock wool	190 650	1 068	179
Resin bonded fibre-board	116 161	1 108	105
Apartment Block (b)			
	Initial investment, I [€]	**Annual bill savings, B [€]**	**Economic payback, p [years]**
		Milan	
Polyurethane foam	85 017	1 475	58
Rock wool	71 652	600	119
Resin bonded fibre-board	82 207	491	168
		Rome	
Polyurethane foam	100 668	1 208	83
Rock wool	132 824	569	233
Resin bonded fibre-board	106 118	435	244
		Palermo	
Polyurethane foam	130 292	423	308
Rock wool	155 330	285	544
Resin bonded fibre-board	94 641	289	328

3.1.4 Conclusions

The insulation materials' embodied energy is analyzed to assess the relevance of the climate conditions and the production site on the choice of the retrofit measure. The proposed method proves that reducing embodied energy can significantly reduce the overall environmental impact of a building. In particular, the relationship between the energy spent on the production of the insulation material and the energy saved during their use as part of the building is investigated and the energy and carbon paybacks are calculated. The energy payback represents the period necessary to compensate for the embodied energy by the energy savings in the operating phase. Similarly, the carbon payback is the period in which the embodied carbon emissions are compensated by the avoided emissions in the operating phase.

The analysis is applied to ten Italian cities and shows how results deeply change in terms of energy and carbon payback depending on the climate zone. In Northern Italian cities, like Milan, Turin and Trieste, envelope insulation gains relevance as the energy and carbon payback periods are shorter, e.g. about 3 years in the case of apartment blocks built during the '60s. Whereas, the case of the Southern city of Palermo, where the carbon payback reaches 84 years, let the authors question the utility of insulating buildings in hot climates. In this context, it is assessed that not only the building location is relevant but also the country where the insulation material is produced has a strong impact on the life cycle assessment. Indeed, countries with a higher carbon intensity of the energy mix have higher carbon payback periods.

Nomenclature

AE_{CO2}	Avoided CO_2 emissions per year, tonnes
EE	Embodied energy, MJ/m^2
EE_{CO2}	Embodied carbon emissions, tonnes
EE_I	Embodied energy coefficient, MJ/m^2
EMS	Energy mix share per energy source, %
E_{OP}	Annual operational energy for heating of the non-insulated apartment block per floor area, MJ/m^2
E_{OPS}	Annual operational energy for heating of the insulated apartment block per floor area, MJ/m^2
$g_{gl,n}$	Solar factor or total solar energy transmittance of the window glass (UNI/TS 11300-1), -
NSE	Net saved operational energy per floor area, MJ/m^2
OE	Annual saved operational energy per floor area, MJ/m^2
s	Thickness, cm
U	Transmittance, W/m^2K
α	Emission coefficient, kg/MJ
λ	Conductivity, W/mK
ρ	Density, kg/m^3

3.2 Strategies for integrated solar energy planning

The solar energy potential and the local energy requirements of the city of Riva Trigoso are analyzed and two types of solar technologies are tested. An analytical methodology based on the exposition of the buildings present in the considered location is developed. The method allows to identify the areas where it is more convenient to invest and the specific technology to be used. The effectiveness of the optimization method is validated via comparison with random allocation of the same total surface of panels. The results presented as GIS maps where the municipality can identify the areas at best solar energy potential and the more suitable technology. The proposed approach can be used for any location and it allows to define detailed scenarios for local energy planning processes. This research aims at introducing an approach for improving the renewable sources technologies inclusion in the municipality planning process and calls to revisit the current governance to strengthen the implementation effectiveness.

The key contribution of this research is represented by the introduction of an innovative methodology to develop qualitative and quantitative local assessments at the micro scale (single building) in terms of solar energy exploitation potential. GIS maps are introduced to identify the areas at best solar energy potential and the corresponding optimal technology to take into account.

A set of novel operational tools is provided in order to optimize the utilization of renewable energy in the territorial planning process step by step: firstly, identify the case study and analyze its territorial context and the buildings stock; secondly, analyze the renewable sources of energy singularly and choose a set of possible technologies available on the market; afterwards calculate the technologies potential coverage of the heating/cooling/electricity requirement, and finally, create a map per each considered technology.

The proposed methodology can be considered valid for any location, provided that the necessary data are available, therefore it can be applied and improved by other researchers from all over the world.

As an example of application of the aforementioned methodology, the optimal utilization of solar energy for the city of Riva Trigoso is analyzed and the results show that a targeted placement, depending on orientation and availability of a certain panel surface, achieves a significantly better result than a random allocation. If the panel surface is installed in the optimal way, by taking into account the building typology and its exposition, it is possible to achieve substantially better results with respect to a random allocation of the same surface of solar panels allowing up to 13% of savings increase.

On the other hand, the savings in other locations may be much higher, as, in general, Riva Trigoso benefits from an average good solar exposition and, therefore, the improvements deriving from an optimal positioning of the panels are relatively small.

This research work is published in:

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3.2.1 Methodology

The purpose of this research is to optimize the energy planning method by taking into account the territorial potential and the technological availability and efficiency. To this aim an innovative methodology is introduced and presented. The elaboration of the method can be summarized in the following steps:

- Case study analysis: building stock characteristics and territorial context
- Renewable source of energy analysis: solar exposition, panels orientation and inclination
- Choice of technologies and identification of the best disposition in the territorial context and on the considered building stock
- Estimation of the buildings' heating requirement
- Calculation of the technologies' potential coverage of the heating requirement
- Creation of heating requirement coverage and avoided emissions maps as a communication tool for municipalities

The proposed methodology invites the planner to follow the above steps and iterate the same procedure for all the renewable energy sources available in the considered territory. The implementation of this analysis will help to better integrate the renewable energy efficient technologies in urban plans and optimize the results.

3.2.1.1 Case study analysis: building stock characteristics and territorial context

The large district of Riva Trigoso, shown in Figure 3.10, part of the municipality Sestri Levante, was chosen as a case study to implement and elaborate the energy planning method.

The Geographic Information System (GIS) territorial analysis was based on initial data from the Digital Land Model - DTM obtained from CTR 1:5000 of the 2007 Liguria Regional map [30]. GIS models can be defined as a data restitution system referring to an area in graphical and alphanumeric form. Layers in map are linked to data tables that can be exported and modified in spreadsheet software or other systems for data management.

Liguria regional map is a 3D topographic database consisting of 67 territorial layers (on the ground, roof, coastline, etc). In this research, four layers were used to build up the GIS model: buildings, quoted points, level curves and coastline. Buildings' height and area are obtained via the built and quoted points layers respectively.

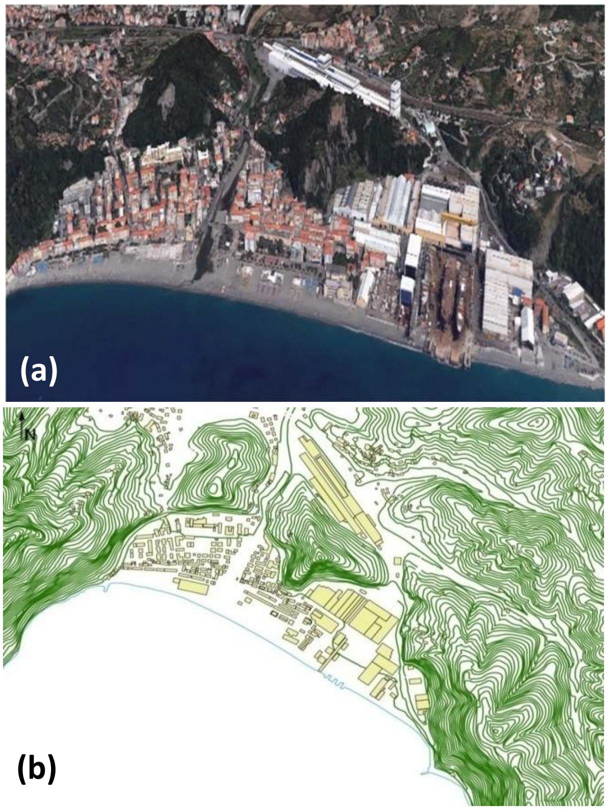


Figure 3.10 - Riva Trigoso: (a) Google Earth aerial view (b) Regione Liguria map

Thanks to the Google Earth platform, the types of roof coverage were analyzed for the 253 considered residential buildings. Depending on the structure of the roof, each building has the possibility to have a certain usable value of surface for panels, S_p.

$$S_p = \frac{A}{\cos\alpha} \cdot \frac{1}{\beta} \qquad 3.9$$

Where A is the roof area [m^2], α is its inclination angle and β the number of flaps (generally 2 or 4). Concerning sloped roofs, since the slope inclination coincides with that of the panel, surface is reduced by 5% for reciprocal shadings and plant requirements.

3.2.1.2 Renewable source of energy analysis: solar exposition, panels orientation and inclination

Comparing the Slope Exposure Chart (i.e. Carta dell'Esposizione dei Versanti) [31] and the Slope Steepness Chart (i.e. Carta dell’Acclività dei Versanti) [32] for the urban areas in Liguria region, it is possible to understand the slope exposition to the sun and its shadowing impact of the natural mountainous territory. This is the first step in order to define the best orientation of the solar panels.

The study of the slope exposure is a fundamental condition for the application of solar systems in the territory as it allows to determine its potential for solar energy capture. Compatibly with the flaps structure, solar panels are supposed to be positioned according to the orientation provided by the charts as the comparison defines the better exposed surface to the sunlight.

Extracts for the Riva Trigoso area charts are reported in Figure 3.11(a) and Figure 3.11(b). The two charts give information concerning the natural territorial conformation and the comparison among both in parallel with the Google Earth buildings images allowed to define a map of the best orientation of the roofs as in Figure 3.11(c).

The analysis is led for each single building. In the case of sloped roofs, the slope with the better exposition is identified: the panels orientation is defined by the charts and their inclination is calculated to maximize the solar radiation.

The total solar radiation in the winter months (from November to March), R_w, has been calculated on the Italian National Agency for Energy (ENEA) platform [33]. The input data were the geographic coordinates of the location, latitude and longitude; the azimuth and the soil reflection coefficient. The azimuth was varied according to the orientation identified thanks to Slope Exposure [31] and the Slope Steepness [32] charts. The soil reflection coefficient, or albedo, was always assumed equal to 0.20 as average value for asphalted streets. Varying the azimuth, radiation is calculated per each orientation and the optimal panel inclination is assessed as reported in Table 3.9.

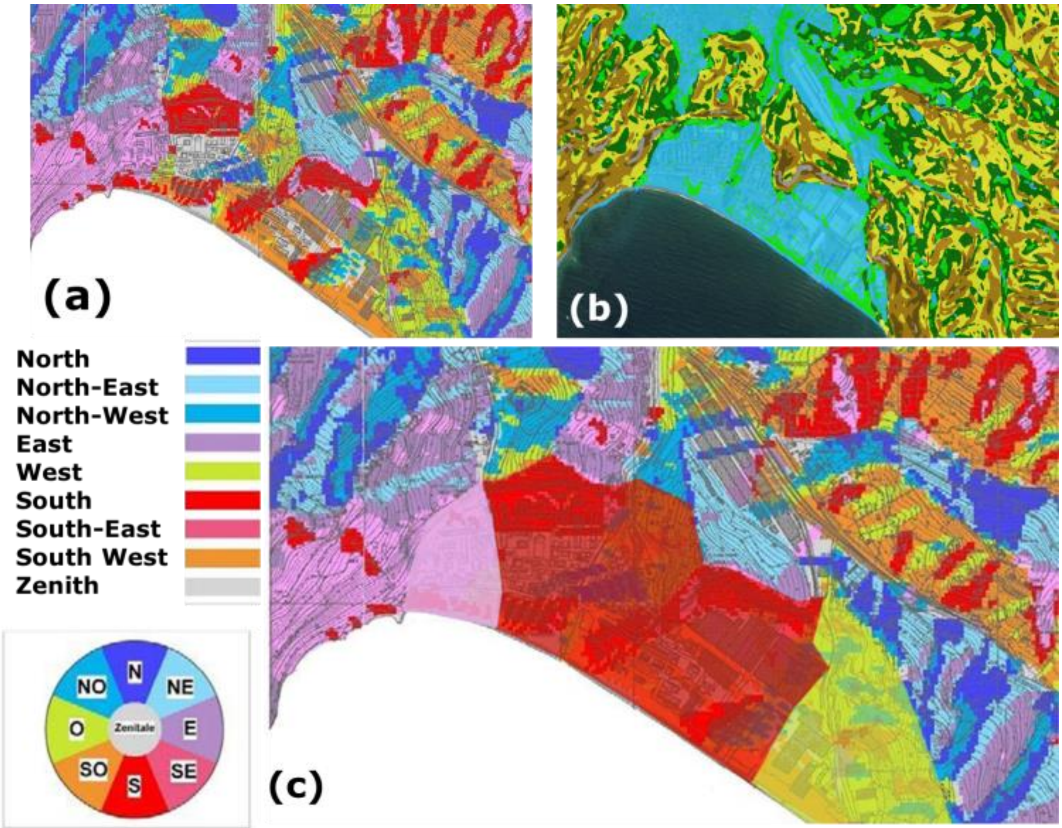


Figure 3.11 - Riva Trigoso territorial analysis: (a) Slope Exposure Chart [31] (b) Slope Steepness Chart [32] (c) Slope Exposure Chart taking into consideration the Steepness

Once calculated the solar radiation and identified the panels inclination and orientation, the total effective solar radiation, G, is estimated as per Eq. 3.10

$$G = R_w \cdot S_p \qquad 3.10$$

Where R_w [kWh/m^2] is the total solar radiation in the autumn/winter cold months and S_p is the panels' surface calculated per each building.

Table 3.9 - Orientation and optimal panel inclination

Orientation	Rw kWh/m²	Optimal Panel Inclination
N – NE - NW	321	0°
E-W	322	20°
SE-SW	436	55°
S	500	60°

3.2.1.3 Choice of technologies and identification of the best disposition in the territorial context and on the considered building stock

Two different technologies have been considered to assess the coverage of heating requirement: flat solar panels and vacuum solar panels. In order to have reliable results, two products available on the market are considered to run the analysis. The products considered are the flat solar panels CSP 21 A Kloben, thermal capacity 9.5 kJ/(m^2K), [34] and the vacuum solar panel Viessmann Vitosol 300-T as SP3B, thermal capacity 8.4 kJ/(m^2K) [35]. InTable 3.10, the technologies' performance efficiency, η_p, depending on the outside air temperature and the operating temperatures of the various components of the system, is also varied to take into consideration the panel's orientation, Eq. 3.11:

$$\eta_p = \rho - \frac{k_1(T_P - T_{EXT})}{G} - \frac{k_2(T_P - T_{EXT})^2}{G} \qquad 3.11$$

where ρ is the degree of optical efficiency, k_1 the primary heat loss coefficient, k_2 the secondary heat loss coefficient, T_p is the panel surface temperature and T_{EXT} the outside air temperature. (T_p - T_{EXT}) is assumed to always be 45 K [36]. Outside air data daily average values per month are obtained from the Eurometeo database [37].

Table 3.10 - Panels efficiency, ηp

Orientation	Flat solar panels CSP 21 A Kloben	Vacuum solar panel Viessmann Vitosol 300-T as SP3B
N – NE - NW	0.19	0.57
E-W	0.19	0.58
SE-SW	0.35	0.64
S	0.40	0.66

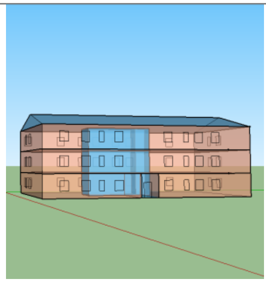
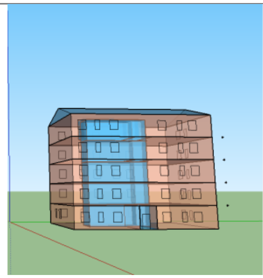
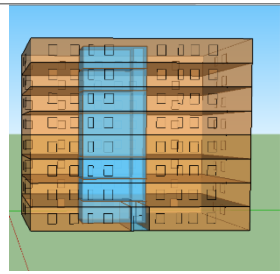
3.2.1.4 Estimation of the buildings' heating requirement

Riva Trigoso buildings present visibly common construction features so three building typologies are identified to describe the households. As reported in Table 3.11, two multifamily houses types and one apartment block type are analyzed. The multifamily houses are small buildings characterized by a limited number of apartments. The apartment block is a big building characterized by a high number of apartments. The three models are created with SketchUp Make (2017) and the buildings heating requirement is calculated with the support of Openstudio 2.4.0 – EnergyPlus program.

The heating requirement, R_q, is the annual amount of energy consumed or expected to be necessary for autumn/winter cold months in standard building use. The results are compared with the values calculated in the TABULA report [38] for validation.

TABULA is the National Scientific Report on Italian Building Typologies and gives information about building-types, construction and system features and calculated energy performance. In the apartment blocks and in Multifamily House (b), the heating demand is totally covered by a natural gas boiler centralized and connected to baseboards by water loops. Multifamily House (a) is characterized by a diesel boiler centralized and connected to baseboard by water loops too. The HVAC systems are designed with the support of IDF-editor 8.9.0.

Table 3.11 - Building typologies data [38] and Energy Plus Models

	Multifamily House (a)	Multifamily House (b)	Apartment Block (a)
Picture			
Energy Plus Model *The shaded central zones represent the volume of the stairs which is unheated.*			
Construction period	1946-1960	1961-1975	1961-1975
Floor-to-ceiling height	2.9 m	3 m	3 m
Volume	3076 m^3	943 m^3	9438 m^3
Conditioned area	880 m^2	799 m^2	2142 m^2
Number of apartments	12	10	40
Number of floors	4	5	8
Space heating system	non condensing boiler, oil burner	non condensing boiler, natural gas burner	non condensing boiler, natural gas burner
Heating requirement, R_q, kWh/m^2	123	181	126

	Multifamily House (a)	Multifamily House (b)	Apartment Block (a)
Transmittance, U, W/m²K:			
- **Roof**			
- **Wall**	1.80	2.20	2.20
- **Floor**	1.70	1.52	1.10
- **Window**	1.30	1.30	1.56
	4.90	4.90	4.90

3.2.1.5 Calculation of the technologies' potential coverage of the heating requirement and of the avoided CO_2 emissions

The buildings' heating requirement energy consumption values, r_q, are then compared to the maximum heat productivity values, P_{max}, calculated per each building in order to find the percentage of coverage as per Eq. 3.12.

$$R_q = \frac{P_{\max}}{r_q} \qquad 3.12$$

Where P_{max} is calculated according to Eq. 3.13:

$$P_{\max} = S_p \times G \times \eta_p \qquad 3.13$$

Considering that S_p is the usable surface, η_p is the panel efficiency and G is the total effective solar radiation per orientation.

An estimation of the avoided amount of CO_2 equivalent emissions, A_{CO2}, is made taking into account the emissions coefficients γ, 499 $\frac{tCO_2e}{GWh}$ and 735 $\frac{tCO_2e}{GWh}$ [39], respectively for natural gas and oil.

$$A_{CO2} = \gamma \times R_q \times \max(1; r_q) \qquad 3.14$$

3.2.1.6 Creation of heating requirement coverage and avoided emissions maps as a communication tool for municipalities

The optimization method results are translated into maps elaborated with the support of a GIS software. The maps are a graphic way to report results in a way easier to understand by urban planners even though they are not technicians. In fact, municipalities can check how the best solar panels allocation depends on the territorial context and the maps show the percentage of heating requirements coverage per each technology. The maps in Figure 3.12 show the heating requirement coverage percentage R_q and in Figure 3.13 the avoided CO_2 emissions per technology: (a) flat panels, (b) vacuum panels.

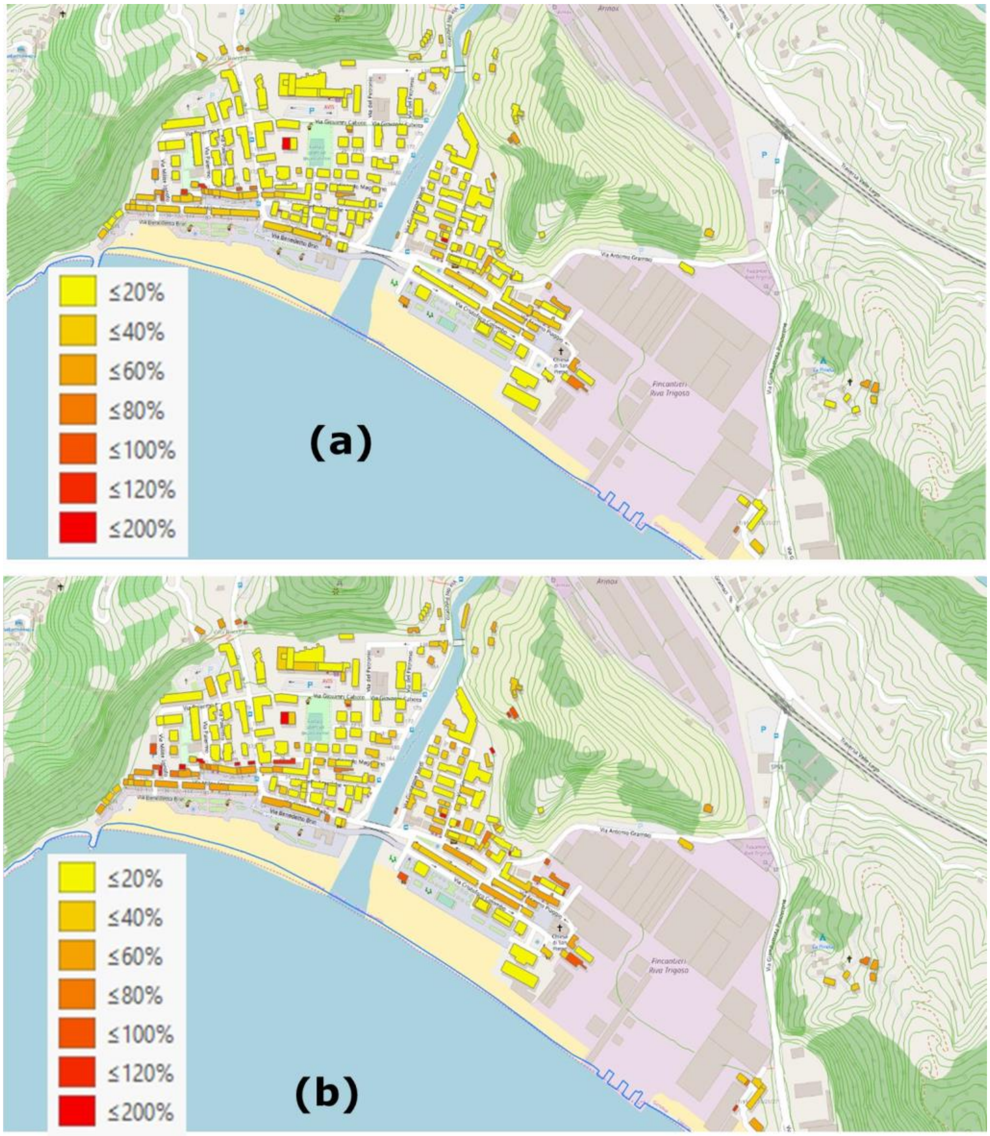


Figure 3.12 - Heating requirement coverage level, Rq, per technology: (a) flat panels; (b) vacuum panels

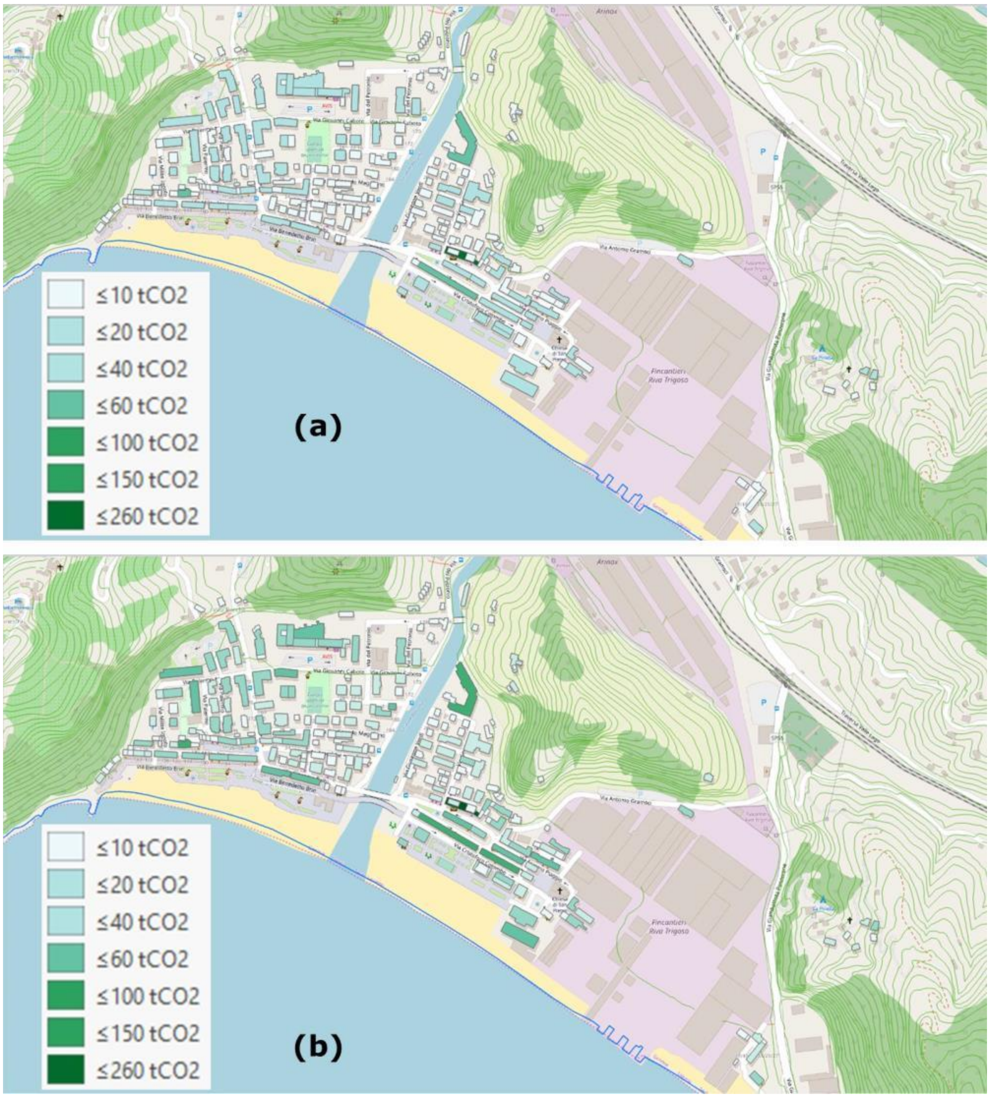


Figure 3.13 - Tons of CO2 emissions avoided per technology: (a) flat panels; (b) vacuum panels

3.2.2 Results and discussion

Results are analysed at the building and the city level in order to better understand the impact of a renewable technologies comprehensive allocation process.

Taller buildings have higher heating requirement, but proportionally lower roof dimensions and, consequently, lower solar energy contribution. Smaller buildings could have less inhabitants and consequently lower heating requirements. The building dimension strongly affects the heating requirements as the R_q values are calculated based on the conditioned floor area. It is assumed that bigger buildings could accommodate more inhabitants and consequently need higher heating requirements but have a limited dimension of roof and panels surface.

In the particular case of Riva Trigoso, the study reveals that flat solar panels, in Figure 3.12(a), can guarantee a thermal coverage of up to 50% for buildings over 2-3 floors, whereas for buildings with over 4-8 floors heating requirement coverage reaches 25%, even in cases of well-exposed areas. On the contrary, vacuum solar panels, in Figure 3.12(b), allow higher coverage values of around 70% for 2-3 floors buildings and up to 45% for 4-8 floors buildings. The increase is due to the effect of the higher collector efficiency characterizing vacuum solar panels with respect to the flat ones.

The thermal energy coverage is clearly affected by the panels orientation. In fact, buildings with panels oriented to the South have values almost doubled compared to the North ones. On the basis of this, it is important to observe that the availability of a visual tool, which immediately shows which are the most convenient locations for solar panels would support urban planners and policy makers in defining specific action plans. This would allow to optimize the installation of solar panels and reduce the visual impact [40], especially in areas with relevant landscaping value.

It is also assessed that heating requirement strongly depends on the buildings typology, since envelope features are noticeably different. According to the developed simulations, as reported in Table 3.11, the following energy consumption are estimated: multifamily house (a) 122 kWh/m^2, multifamily house (b) 181 kWh/m^2 and apartment block (a) 126 kWh/m^2. The apartment blocks have a higher compactness factor, that is why they need around 30% less thermal energy than multifamily houses (b). These archetypes are very common in the area considered for the investigation, therefore they can be considered as reference cases.

It can be said that all the typologies considered highlight relevant values of consumption and these consumption needs are currently satisfied by using fossil fuels, namely natural gas and gasoil, with the associated carbon and pollutant emissions. Therefore, a renewable integration would be beneficial for all the considered cases. Figure 3.14 and Figure 3.15 report two examples for multifamily houses and it shows that a solar integration would allow a coverage of the heating requirement between 35% and 55% depending on the typology of the considered solar thermal panel.

The proposed methodology has been validated comparing the suggested procedure for a targeted placement with a random allocation. In the case of Riva Trigoso, the targeted placement, depending on energy demand, building exposition and availability of a certain panel surface, achieves an increase of the solar integration of about 13% with respect to the random placement when considering standard collectors and of about 8.7% in case of evacuated collectors. This represent a substantial increase of saved energy that is an average further saving of ~ 0.5 GWh per year corresponding to a fuel saving of ~90 k€/year. Furthermore, it is important to consider that to the fuel saving also corresponds a decrease of pollutant and carbon emissions, as well as a decrease of the externality costs.

To conclude, the (fuel) heating needs of Riva Trigoso decreases from 38.6 GWh per year to 34.3 GWh per year in case of simple flat panels and to 31.1 GWh per year in case of vacuum tube collectors. The average fuel saving is near 6 GWh per year that is about 1M€/year.

The savings, in locations other than Riva Trigoso, may be much higher, as, in general, it can be said that Riva Trigoso benefits from an average good solar exposition and, therefore, the improvements deriving from an optimal positioning of the panels are relatively small.

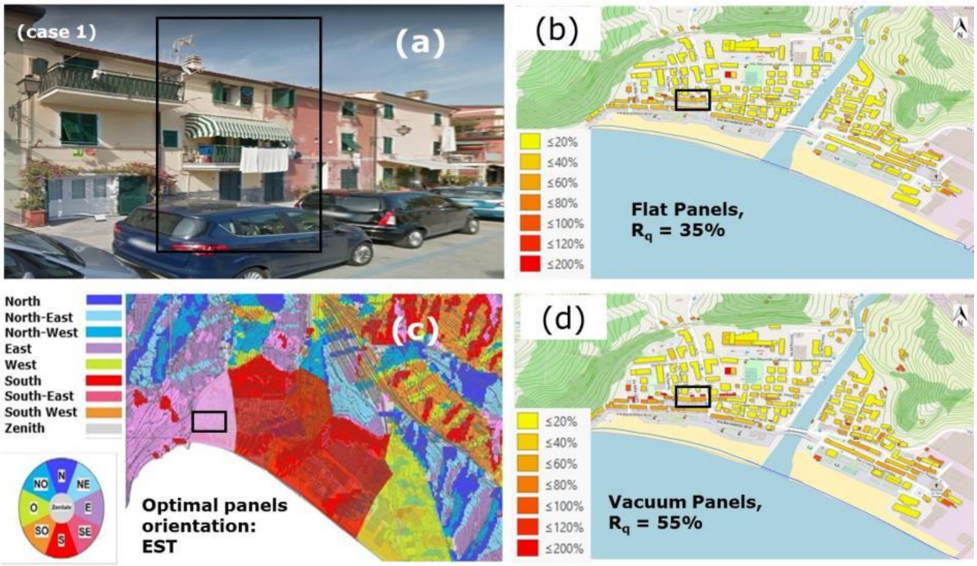


Figure 3.14 - Multifamily Houses (a) with East panels orientation (case 1): (a) picture of the considered buildings; (b) Rq in case of flat panels; (c) optimal panels orientation; (d) Rq in case of vacuum panels

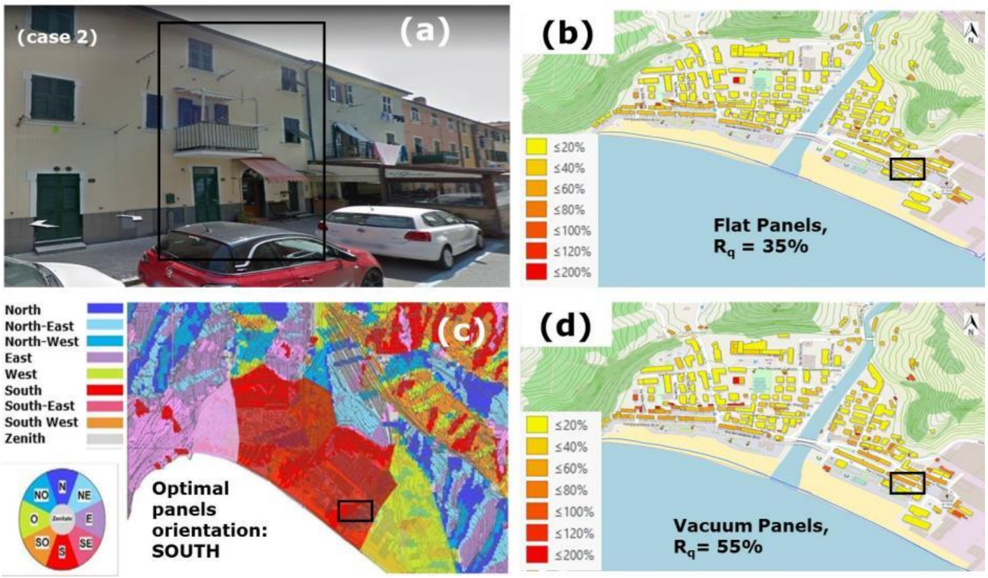


Figure 3.15 - Multifamily Houses (a) with South panels orientation (case 2): (a) picture of the considered buildings; (b) Rq in case of flat panels; (c) optimal panels orientation; (d) Rq in case of vacuum panels

3.2.3 Conclusions

This research contribution aims to provide a set of operational tools that could introduce the energy parameter in the design of territorial strategic plans and to revisit the current governance in order to achieve a more effective implementation of the planning tools and support the local administrations for the revision and innovation of its energy management policy. The study focuses on solar energy, but the approach can be applied to all energy sources by setting the proper criteria. This approach depends on the type of technology associated with the individual building characteristic and location.

The solicitation to invest on renewable sources is one of the reasons why the local administrations should foresee the development of a territorial energy management policy and the proposed methodology can be pivotal in this process. In order to do this, further research can be devoted to the development of a software capable to handle all the information related to the territory, buildings, climatic and technological data, etc. which allows to generate directly the GIS maps of optimal utilization. Such a tool might be easily utilized by local administrations all around the world, in order to include in their territorial planning process an optimal utilization of the available renewable energy sources. The analysis is relevant as it allows to determine the solar energy potential of a single building by taking into account also the surrounding urban context and its corresponding influences. This is of relevant importance in the design of urban level energy optimization or retrofitting interventions. Finally, the knowledge of these maps may also guide the allocation of incentives for the use of renewable sources targeted by area and by technology. Furthermore, the resulting GIS maps can help municipalities to identify the areas at best solar energy potential and the optimal technological system to consider.

Nomenclature

A	roof area, m^2
A_{CO2}	avoided tons of CO_2 equivalent emissions
G	total effective solar radiation, kWh
k_1	primary heat loss coefficient,
k_2	secondary heat loss coefficient
R_w	total solar radiation in the autumn/winter cold months, kWh/m^2
S_p	usable value of square meters for panels, m^2
Q	buildings' heating requirement, kWh
Q_{max}	maximum heat productivity values, kWh
T_p	panel surface temperature
T_{EXT}	outside air temperature
α	panels' inclination angle
β	number of roof flaps
γ	emissions coefficient
η_p	performance efficiency
ρ	degree of optical efficiency

3.3 Analysis of the Italian power market potential to accommodate heat pumps for space heating

The share of renewables in the electric power generation is rapidly increasing in Italy and shifting the buildings' heating demand to electricity represents a sustainable solution to decrease the natural gas dependency. In this research, the maximum share of heating demand that can be switched to electricity is estimated according to the Italian power market. By determining market price, plants generation and fuel consumption, the optimal share is calculated in terms of carbon emissions minimization. The methodology is developed with the support of a bid stack model (BISM) that performs an hourly simulation of the electricity market. Firstly, the analysis is led considering heat pumps' coefficient of performance COP values between 2 and 4. Then a focus is made on the COP calculation considering the local heating degree days. In addition, three different time schedule of heat pumps activity are modeled to simulate the final users' habits. This approach is based on the idea that the environmental and market conditions in Italy are particularly favorable for heat pump utilization. Indeed, the high coefficient of performance COP in terms of "electricity to heat" conversion can guarantee a global saving of primary energy. Results show that the Italian electricity market allows a penetration of the heat pumps for buildings heating in the range of 10%-56% for COP values between 2 and 4.

This research work is published in:

Abd Alla, S., Bianco, V., Marchitto, A., Scarpa, F., & Tagliafico, L. A. (2018). Impact of the utilization of heat pumps for buildings heating in the Italian power market. *International Conference on the European Energy Market, EEM, 2018-June*. https://doi.org/10.1109/EEM.2018.8469904

Abd Alla, S., Bianco, V., Tagliafico, L. A., & Scarpa, F. (2018). Effect on the energy market of the potential switching to heat pumps for space heating. *Modelling, Measurement and Control C*, *79*(3). https://doi.org/10.18280/mmc-c.790312

3.3.1 Methodology

In the Italian context, buildings heating relies mainly on natural gas consumption. In this research, it is assumed that buildings use heat pumps instead of natural gas boilers for ambient heating purposes. Firstly, the amount of natural gas consumed for buildings' heating is estimated. Then, the amount of electricity required to cover the heat demand is calculated. Indeed, the objective is to establish the optimal share of heat pumps accommodation that minimizes the carbon emissions related to electricity generation and natural gas combustion, as shown in Figure 3.16.

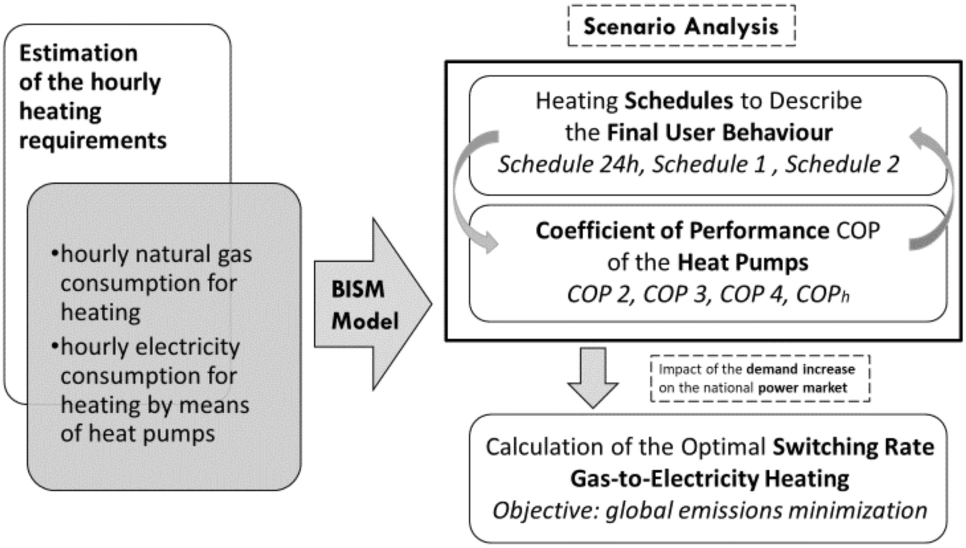


Figure 3.16-Schematic of the methodology

The procedure can be summarized in the following steps:

- calculation of the hourly natural gas consumption for heating,
- estimation of the heat pumps coefficient of performance COP,
- estimation of the hourly electricity consumption for heating by means of heat pumps,
- analysis of the demand increase impact on the national power market,
- calculation of the optimized switching rate from gas to electricity heating based on a global emissions minimization target.

The natural gas consumption is analyzed in order to estimate the share dedicated to heating. The data on natural gas is collected [118] on the daily basis. An increasing trend in cold months is observed due to the gas boiler wide deployment for heating in Italy. During the whole year, natural gas is used for cooking and domestic hot water almost constantly. The increased amount in the cold months is assumed to be share of natural gas used for heating purposes. Indeed, when the data is analyzed in descending order, it is possible to create a load duration curve and highlight the base-load value E_b. The base load E_b is the daily amount of natural gas constant all over the year that is dedicated to domestic hot water and cooking purposes.

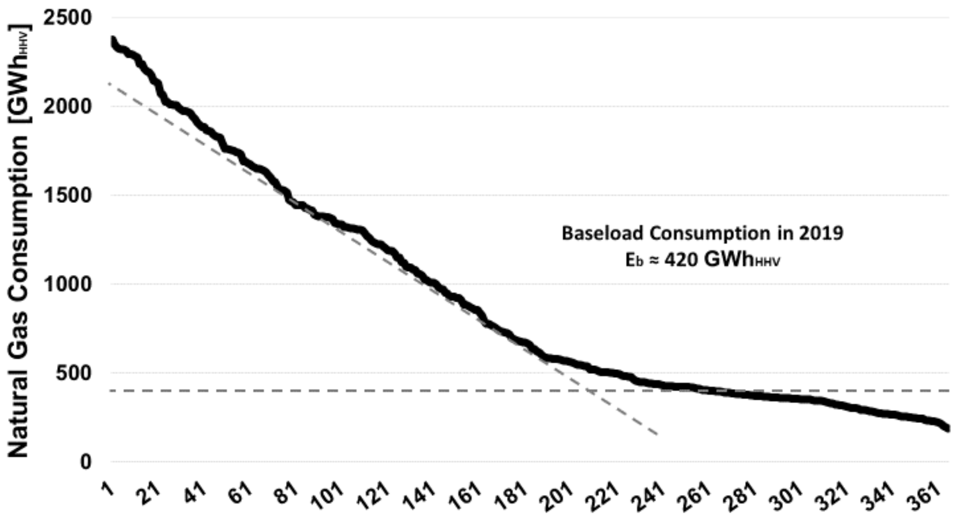


Figure 3.17-Load Duration Curve of daily natural gas consumption for the year 2019

As reported in Figure 3.17, when the daily gas consumption values are put in ascending order, they define the hyperboles-like load curve with an almost asymptotic end that allows to estimate E_b to determine the heating consumption in the winter months. In particular, for the year 2019, E_b is estimated to be ≈ 420 GWh per day. Once defined E_b, it is possible to calculate the daily amount of natural gas for heating E_h as reported in Eq. 3.15:

$$E_h = E - E_b \qquad 3.15$$

where E is the daily total amount of natural gas consumption.

The hourly consumption of natural gas is investigated in order to analyze the impact on the electricity hourly load if heating is provided via heat pumps. To do so, the national hourly degree day (HDD) values are defined as a weighted average of the hourly values [119] of three main Italian cities: Naples, Rome and Milan. The 21st day of every month is considered as a valid example for the thermo-behavior of the whole month. According to the Italian law [108], the heating systems are assumed to be operative only in the winter months of January, February, March, April, November and December.

Per each city, the hourly heating degree day for the hour "i" are calculated in Eq. 3.16:

$$HDD_i = T_{in} - T_{out,i} \qquad 3.16$$

where inside temperature of the buildings T_{in} is assumed to be 20℃ and $T_{out,i}$ is the outside environmental temperature for the hour "i" [119].

The daily heating degree day HDD_D represent the sum of the hourly degree day during the whole day, namely:

$$HDD_D = \sum_{i=1}^{24} HDD_i \qquad 3.17$$

In addition, the hourly weighted factor α_i is introduced in order to estimate the hourly natural gas consumption for heating for each hour:

$$\alpha_i = \frac{HDD_i}{HDD_D} \qquad 3.18$$

The heating requirements of the building sector, Q_h, is calculated considering the gas combustion by means of standard gas burners with average combustion efficiency η_b according to Eq. 5:

$$Q_h = E_h \frac{H_L}{H_H} \eta_b \qquad 3.19$$

where E_h is the daily amount of natural gas for heating, H_H is the high heating value and H_L is the low heating value of the natural gas. The average combustion efficiency η_b is assumed equal to 80% [113].

Besides, the hourly electricity consumption L_h is calculated considering the heating requirements and the hourly heat pumps Coefficient of Performance COP_h, as per Eq. 3.20:

$$L_h = \frac{Q_h}{COP_h} \qquad 3.20$$

When estimating the electricity increase for buildings' heating purpose, the heat pumps' COP_h is assumed equal to 2, 3 and 4 according to the technologies available on the market. In addition, a scenario case COP_h is a national value estimated considering the average external temperatures of the three main Italian cities: Naples, Rome and Milan. In particular, the COP is related to the working temperatures, T_{out} and T_{in}, and to the efficiency of the heat pump's components, η_{ex}, as per Eq. 3.21:

$$COP_h = \frac{T_{out} - \Delta T_{ev}}{(T_{in} + \Delta T_{cond}) - (T_{out} - \Delta T_{ev})} \eta_{ex} \qquad 3.21$$

where:

T_{out} is the outside temperature [119]

T_{in} is the temperature inside the building

ΔT_{ev} is the differential temperature at the extremes of the evaporator, assumed equal to 10 [°C]

ΔT_{cond} is the differential temperature at the extremes of the condenser, assumed equal to 15 [°C]

η_{ex} is the average efficiency of the components of the heat pumps, assumed equal to 0,4

As reported in Table 3.21 the values of the average COP_h of Naples, Rome and Milan vary between the lowest 2.7 and the highest 4.7 optimizing the technologies coefficient of performance according to the external temperature during the day.

Table 3.12 - Average National COPh

Hour/Months	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
January	2,8	2,7	2,8	2,8	2,8	2,7	2,7	2,8	2,9	3,0	3,1	3,2	3,2	3,3	3,2	3,2	3,1	3,0	2,9	2,9	2,8	2,8	2,8	2,8
February	2,8	2,7	2,7	2,6	2,6	2,6	2,7	2,7	2,9	3,1	3,2	3,2	3,3	3,3	3,2	3,2	3,1	3,0	3,0	2,9	2,9	2,9	2,9	2,8
March	3,0	3,0	2,9	2,9	2,9	2,9	3,1	3,3	3,5	3,6	3,7	3,9	3,8	3,8	3,8	3,8	3,7	3,5	3,4	3,4	3,2	3,2	3,1	3,1
April	3,3	3,3	3,2	3,1	3,1	3,3	3,4	3,7	4,0	4,0	4,1	4,3	4,2	4,3	4,2	4,1	4,0	3,8	3,7	3,6	3,5	3,4	3,4	3,3
October	3,6	3,6	3,6	3,6	3,6	3,6	3,8	3,9	4,3	4,5	4,6	4,6	4,7	4,7	4,6	4,5	4,2	4,1	4,0	3,9	3,9	3,9	3,7	3,7
November	3,0	3,1	3,1	3,0	3,1	3,0	3,0	3,2	3,3	3,5	3,6	3,6	3,7	3,6	3,6	3,5	3,3	3,3	3,3	3,2	3,2	3,1	3,1	3,1
December	2,8	2,7	2,7	2,7	2,7	2,7	2,6	2,8	2,9	3,0	3,2	3,2	3,2	3,4	3,2	3,0	3,1	2,9	2,9	2,9	2,8	2,8	2,8	2,8

Finally, a bid stack model (BISM) [100], created at University of Genoa, is used to analyze the power system behavior towards the higher electricity consumption due to the heat pumps' spread. Thanks to the hourly simulations, BISM provides data on the market price, the plants generation and the fuel consumption. The estimated values of power price, primary energy consumption and carbon emission result and are compared to the actual situation in year 2019. Year 2019 is the most recent year with available stable and complete energy consumption data [118]. Further analysis can be developed in order to investigate the future development of the energy system.

The heat pumps' hourly electricity consumption L_h values are added to real historical values of electricity hourly consumption E_b, as per Eq. 3.22:

$$E_n = E_b + L \qquad 3.22$$

where E_n is the new value of electricity demand per hour.

In Eq. 3.23, an objective function is introduced to avoid the presence of "unserved energy":

$$\min\{E_{CO2,Tot} = E_{CO2,h} + E_{CO2,PM}\} \text{ subject to:}$$

$$0 \leq \beta \leq 1 \qquad 3.23$$

$$UE = 0$$

where, $E_{CO2,Tot}$ represents the total carbon emissions, $E_{CO2,h}$ is the carbon emission related to the natural gas boilers and $E_{CO2,PM}$ is the carbon emissions deriving the power market, whereas β is the switching rate of heating systems from natural gas to electricity and UE is the "unserved energy" (i.e. the energy exceeding the generation capability of the power market). Indeed, the final objective is to find the optimal switching rate from natural gas to electricity market that minimize the carbon emissions but maintains, at the same time, the energy balance on the power market. $E_{CO2,PM}$ is provided by the BISM model, considering the increased electricity consumption due to the heat pumps, whereas $E_{CO2,h}$ is calculated on the basis of the natural gas consumption data.

3.3.2 The scenarios

The Italian law defines six local thermal zones and for each one concedes a limited number of hours of the day to turn on heating systems [108]. Even if the total number of hours is defined, the final user behavior determines the demand profiles and consequently the hourly peak values of the gas consumption. In this research, two representative final users' profiles are proposed to investigate the different peak loads, namely Schedule 1 and Schedule 2 as reported in Table 3.13. In addition, a less realistic case of heat pumps working all day, Schedule 24h, is proposed to compare the Schedule 1 and 2. Indeed, the final user can decide the distribution of these heating hours based on the personal habits and daily activities. Employees and workers do not stay at home during the day and prefer to use the heaters early in the morning and in the evening as in Schedule 1. Whereas the elderlies spend more time at home and might need to improve the thermal comfort also in the midday hours. The latter behavior is represented in Schedule 2. In the three schedules, it is assumed that the total number of hours for heating is equal to 10. It should be remarked that the number of operating hours of the heat pumps directly influences the peak values of electricity demand, L_h, increasing the risk of overloads in the national power grid.

Table 3.13 - Final Users Heating Schedules

	Hours of heating systems activity
Schedule 24h	0h-24h
Schedule 1	6h-9h; 17h-22h
Schedule 2	6h-7h; 11h-13h; 17-21h

Each one of the three schedules is simulated four times for each of the COP proposed (COP2, COP3, COP4 and COP_h).

3.3.3 Results

Considering the data availability, year 2019 is analyzed allowing to develop an ex-post investigation of the heat pumps potential in terms of energy savings. The optimization problem reported in Eq. 9 has been solved and optimal market shares of heating load to switch from natural gas to electricity market is determined. Results are presented in terms of primary energy consumption, carbon emissions and power prices according to the different COP and schedule scenarios. These values correspond to the shares which minimize carbon emissions, but at the same time they guarantee that power load does not exceed the available supply in each hour.

The gas-to-electricity switching rate represents the share of heating demand that the power market can accommodate according to the final users' schedules and the heat pumps technologies. In Table 3.14, the switching rates vary between 10% and 56%. The increasing value of COP allows a higher penetration of heat pumps as the systems are consuming less electricity for the heating they provide.

In particular, with COP equal to 2, 3, 4 and COP_h, in the Schedule 24h the penetration rate is higher compared to the other schedules since heating pumps are supposed to be working the whole day. Moreover, Schedules 1 and 2 show very little difference of 1% between them and this means that the midday heat pumps activity 11h-13h have a little impact on the hourly power demand in Italy.

Table 3.14 - Gas-to-electricity Switching Rate

	No Heat Pumps	**COP 2**	**COP 3**	**COP 4**	**COP h**
Schedule 24h		27%	42%	56%	41%
Schedule 1	0%	10%	19%	25%	18%
Schedule 2		10%	18%	24%	19%

In terms of total primary energy consumption, as given in Figure 3.18, it can be observed that heat pumps guarantee a lower level of consumption and, in particular, the higher is the COP and the larger is the energy saving. Between the No Heat Pumps and the COP2 scenarios there is almost no difference since the latter shows the result of technologies with a very low coefficient of performance.

In the case of the other scenarios the total primary energy decreases linearly with the increase of the COP. In addition, the COPh scenario shows the highest primary energy savings with all the schedules since the technologies are performing better.

It can be also said that most of the primary energy saving regards a decrease in the natural gas consumption for residential heating corresponding an increase in the power generation. Indeed, the power sector experience a change in the merit order due to the higher demand. In terms of coal consumption, the four scenarios show the almost the same behavior, as reported in Figure 3.19. Indeed, coal fired plants represents a baseload technology so they are the first to be deployed to supply the increase of power demand due to the higher amount of heat pumps.

Similarly, the increase of power demand is translated in a higher natural gas consumption for electricity generation. The impact is more relevant when the No Heat Pumps and COP 2 scenarios are considered, as highlighted in Figure 3.20. In the case of COP equal to 3, 4 and COPh, the natural gas consumption is almost constant for the three scenarios since they reach the maximum generation according to the different schedules. This is due to the fact that natural gas technologies, in particular CCGTs, are the marginal technologies of the market, therefore at the increase of the demand, they immediately experience an increase of the load factor, with a consequent increase of the fuel consumption. Hence, COP 3, COP 4 and COPh have the same behavior for the three scenarios because they achieve the highest thermal generation, including coal and gas, according to the schedules the heat pumps are active. The main difference is the higher switching rate to heat pumps. In fact, COP 4 allows a higher amount of heat pumps to enter in the market as they are performing better for the same power consumption as COP 3 and COPh. It should to be remarked that, for COP 3, COP 4 and COPh, the estimated market shares represent the maximum possible value in terms of load, in order to have UE=0, therefore the switching rate increase and the heat pumps load shows no changes.

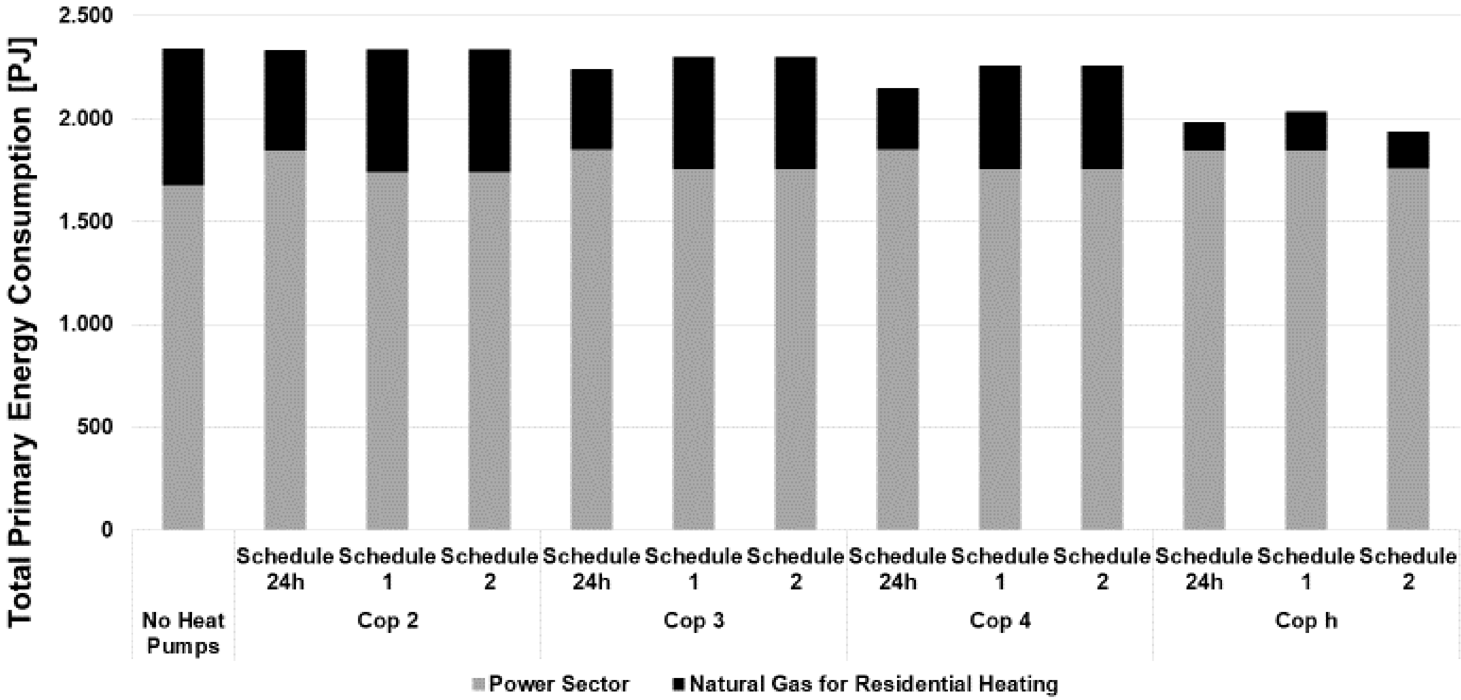


Figure 3.18 - Total primary energy consumption

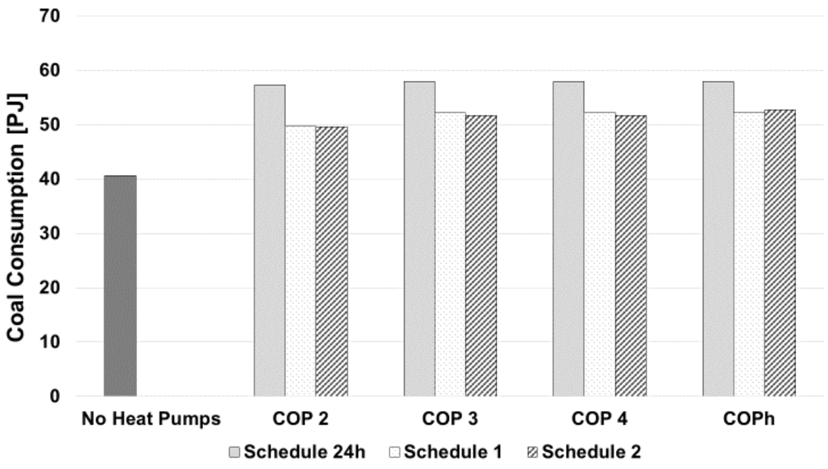


Figure 3.19 - Coal consumption in the power market

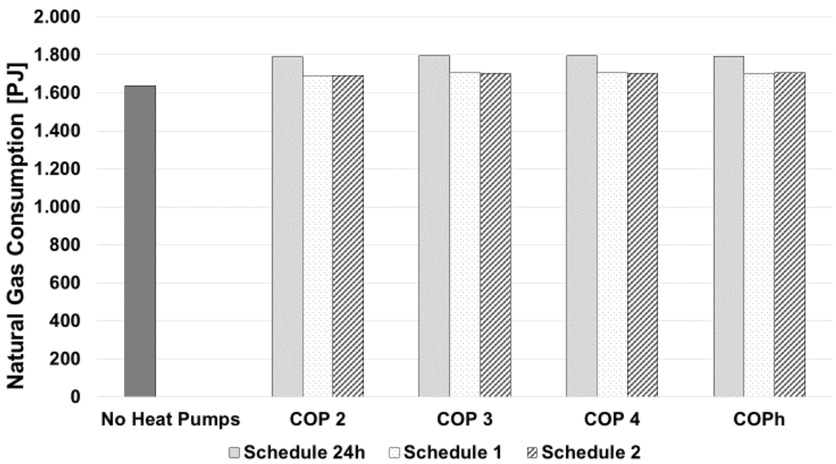


Figure 3.20 - Natural gas consumption in the power market

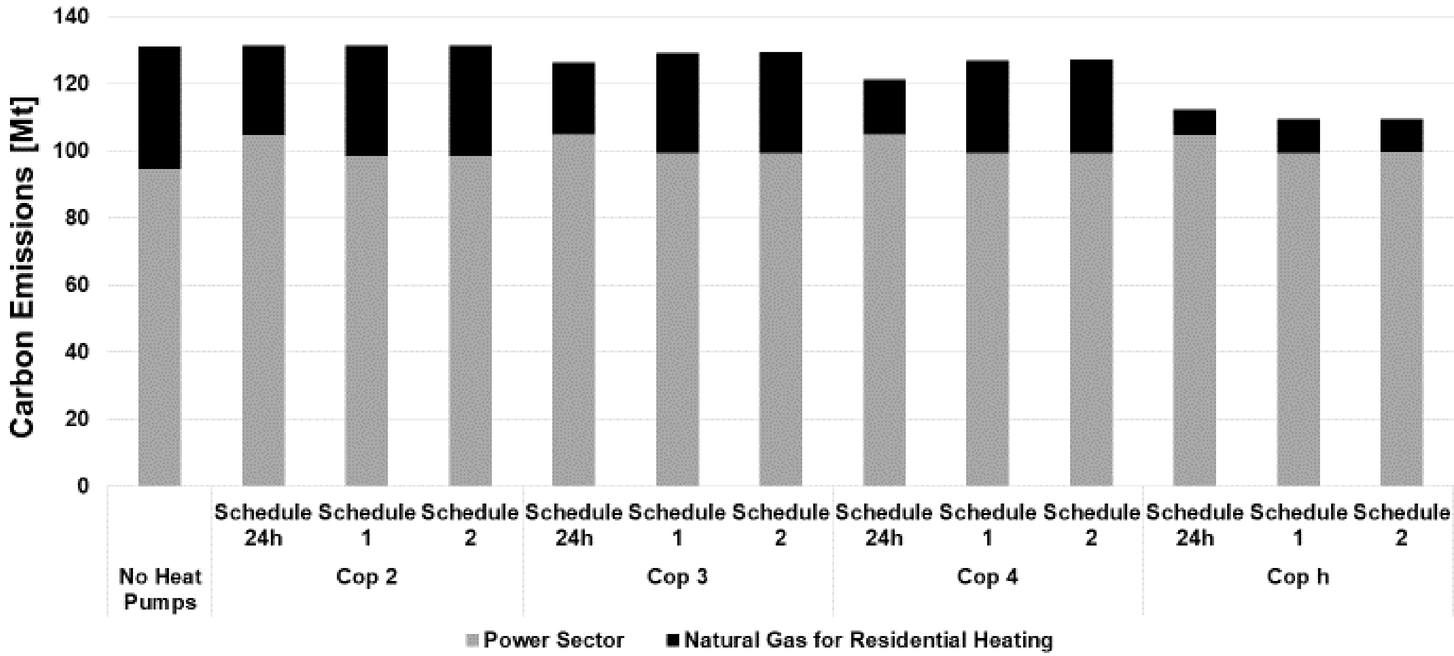


Figure 3.21 - Total carbon emissions

The environmental impact is analyzed in terms of total carbon emissions, namely those due to the power market and those due to the utilization of natural gas boilers. The higher is the share of heating demand switching to electricity, there will be an increase in the power sector emissions as the electricity demand grows. As reported in Figure 3.21, it can be observed a steady decrease of the emissions at the increase of the COP. The lowest emissions are related to the lowest energy consumption. The highest savings are obtained by the COPh scenarios that decrease the carbon emissions of almost 20 Mt. These values are strictly related to the Italian market since the reduction of the carbon emissions depends the power capacity mix of the considered country. In countries that can rely on a cleaner power production and higher renewables integration, the benefits of heat pumps heating are more relevant.

The increased power demand will bring consequent changes in the system merit order as it will require a new power supply mix. These changes are perceived also in the power price. However, as Figure 3.22 shows, the effect of the higher power demand is estimated around ~1 €/MWh and it does not change according to the considered COP, because, as previously mentioned, the power system structure is assumed not to change with the additional heat pumps load.

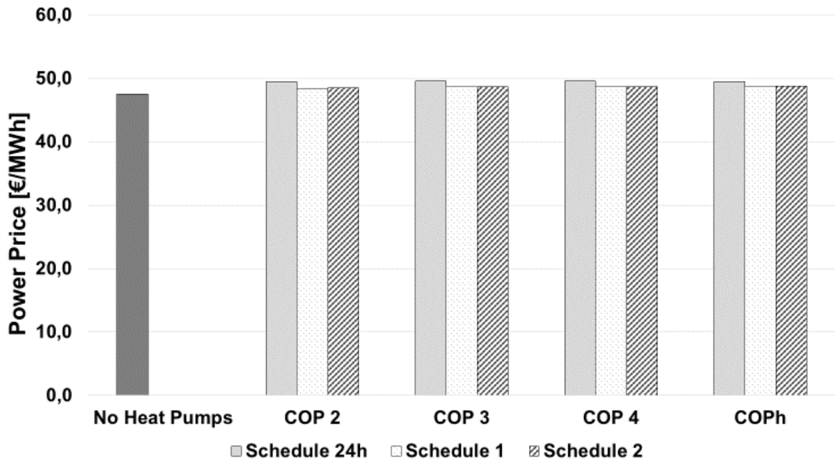


Figure 3.22 - Power Prices

3.3.4 Conclusions

The renewables share in the power system in Italy is increasing and heat pumps can reduce the emissions related to the buildings' heating demand that is up-to-today mainly satisfied by natural gas boilers. This research work aims to assess the optimal share of buildings heat demand that can be accommodated by the electricity market in order to minimize the total carbon emissions. The daily natural gas consumption for residential heating is estimated and the hourly pattern is analyzed in order to calculate the hourly increase in the power demand. The temperatures data are analyzed for the three main Italian cities of Naples, Rome and Milan and a national average is assumed. Several assumptions are made in terms of technology coefficient of performance COP varying from 2 to 4 and a hourly COPh is estimated according to the outside temperature during the day. Besides, three different time schedules for operating the heat pumps are considered to analyze the final users' behavior impact.

The results show that the use of heat pumps for building heating is a real option that allows a decrease of carbon emissions of up to 20Mt. The Italian power system is able to accommodate from 10% to 56% of the heating demand. The higher is the COP considered the higher is the share that can switch from natural gas boilers to heat pumps. Whereas, the user habits has a little impact on optimal share of switching from gas to heat pumps as the midday load on the power system is lower than the peak hours. However, since all the scenarios maintain the power market structure, even if the merit order changes, the power price is change is limited to 1€/MWh.

In light of this, it can be said that heat pumps can be considered as a valid option to reduce carbon emissions for heating purposes and also can save primary energy and to increase the overall efficiency of the Italian energy system. It can be observed that in renewables dominated power markets, the beneficial effects of heat pumps utilization increase, as larger share of renewable energy can be used for buildings heating purposes. Since the share of renewable sources in the electricity generation mix in Italy is rapidly increasing, this study introduces an energy policy instrument to estimate the maximum share of heat pumps use for buildings' heating purposes. In addition, the saving of natural gas in a country with scarce indigenous resources as Italy is of fundamental importance as it decreases the energy dependence of the country and enhances the energy security.

3.4 Tackling rising energy needs of megacities in developing countries[1]

Urban energy system modelling allows megacities to assess their future development and to draw sustainable pathways to meet the rapidly increasing energy needs. This research work elaborates three different scenarios for energy transition in Greater Cairo (GC) with a particular focus on the role of the informal settlements in the energy transition up to 2050.

In the past 40 years, informal settlements quality of life has been a core challenge to sustainable development policies. GC is promoting informal settlements inhabitants relocation and clearance that are conventional solutions adopted almost universally in developing countries' informal settlements [120]. This approach is often hiding the will of building high-rise complexes to replace them as the slum relocation is been pushed to the outskirts of cities, where economic facilities and social services are barely available [30]. This study assesses different pathways to cope with rising energy needs (supply and demand) deriving from informal settlements' inhabitants' relocation to outskirts dwellings with improved access to energy and a higher transport demand. To do so, a city-specific TIMES energy system model is used to investigate how energy supply and demand will evolve between 2015-2050.

The impacts in final energy consumption and CO_2 emissions are investigated considering different socio-economic pathways. The scenarios show that the long-term cost-efficiency optimization leads to the decarbonization of the power sector even in the absence of climate constraints. Climate policies are modeled to achieve by 2050 a carbon emissions reduction of 50% below the 2015 baseline. The results indicate that the implementation of current urban plans will double the carbon emissions per capita if no mitigation policies are adopted. The urban expansion programs need to take into consideration the energy-environment-economic nexus and to be coupled with climate mitigation policies to contain the rising carbon emissions.

The scientific literature review reported in Table 2.2 shows that previous works do not address the nexus between informal settlements and urban energy systems. The

[1] This research contribution was developed under the supervision of Prof. Sofia Simoes during the author's Erasmus activities at the CENSE Center for Environmental and Sustainability Research, NOVA School for Science and Technology, NOVA University in Lisbon, Caparica, Portugal.

dearth of data available prevents researchers from addressing properly the energy needs of the informal settlements, therefore they have been underrepresented in previous studies. Therefore, to the best of authors knowledge this is the first attempt to analyze the informal settlements' development impact on the energy system of a megacity.

This research work is published in:

Abd Alla, S., Simoes, S. G., & Bianco, V. (2021) Addressing rising energy needs of megacities – case study of Greater Cairo. *Energy & Buildings*, 236, 110789 https://doi.org/10.1016/j.enbuild.2021.110789

Abd Alla, S., Bianco, V., & Simoes, S. G. (2020) The Importance of Renewable Energy Systems in Meeting Rising Energy Needs of Megacities in a Sustainable Way: Case Study of Greater Cairo. *Proceedings of the ASME 2020 14th International Conference on Energy Sustainability*. *ASME 2020 14th International Conference on Energy Sustainability*. V001T10A003. ASME. https://doi.org/10.1115/ES2020-1629

3.4.1 Overview of the Greater Cairo energy system and informal settlements

The Egyptian energy system relies mainly on fossil fuels. Egypt’s energy demand is satisfied by natural gas and oil for almost 91%; with a contribution of 8% from hydropower and 1% from wind and solar electricity [121]. The national energy system is confronted with several challenges, such as covering the summer electricity shortages and meeting the increasing demand especially for cooling. As the evolution of the Egyptian power sector is a core topic in the national policy-making, researchers are investigating pathways to allow the country to comply with the increasing demand [122] and to meet the sustainable development strategy goals Egypt 2030 [123]. For instance, Mondal et al. [124] proposed a TIMES energy model system analysis of Egypt supply strategy to examine the energy policy goals as reflected in Egypt’s Vision 2030. The long-term optimization results showed a need of renewables penetration to interrupt the predominantly natural gas dependency in order to improve energy security and reduce carbon emissions.

Greater Cairo is the 7th largest city in the world with a population around 21 million urban inhabitants and the first one in Africa [41]. The evolution of urban growth, transport demand, energy supply, in the Greater Cairo will have a strong impact on the national strategy and requires a specific analysis [125]. With around 21 million inhabitants, Greater Cairo (GC) represents the core center of energy consumption in Egypt as it encompasses 22% of overall population of Egypt and 43% of overall urban population [126]. The energy transition challenges will be more relevant for GC as the government is currently enlarging the urban boundaries and creating several satellite cities. Nowadays, nearly 54% [127] of GC's population is living in informal urban settlements and the number is expected to continuously increase. The Strategic Development Plan for Greater Cairo Region 2050 [126], Cairo Vision 2050, considers the implementation of the Project of Containment (Tahzeem) of unplanned areas in Greater Cairo and the creation of new residential areas to host 10-12 million persons respectively in 6th October (Giza) and Helwan (Cairo). In addition, Cairo Vision 2050 plans to build alternative housing units for current inhabitants of cemeteries (2000 families) and to turn the Cairo Cemeteries into the Cairo Central Park. GC will be facing several issues such as overpopulation, buildings shortage, land shortage, traffic, lack of adequate infrastructures, and environmental challenges. Nonetheless, the urbanization process is still ongoing and GC will be requiring more energy to cover the needs of the new cities which are being built and will attract also population from other governorates. So far, the increased access to energy and the environmental effects of this relevant urbanization process are not assessed or mentioned in any plan.

In light of these considerations, there is nonetheless a need of addressing the transition of informal settlements when studying rising energy needs of megacities [128]. In the case of Greater Cairo, nearly two thirds [129] of the population are living in informal urban settlements, and the number is expected to continuously increase with consequences as overpopulation, land shortage, high unemployment rate, lack of adequate infrastructures, and environmental challenges. In the Cairo Vision 2050 [126], the government highlighted the urgency to address the informal settlements poor living conditions focusing on providing new adequate residential areas compatible with government plans to limit informal zones in order to create good and health society. To this purpose, the government is promoting informal settlements inhabitants' relocation and clearance. Even if relocation is a conventional solution adopted almost universally in developing countries' informal settlements [120]. From an energy efficiency perspective it seems to be preferable to keep the informal dwellings, making it easier to achieve GHG emissions targets [129], but from the social point of view the existence of these urban agglomerates, developed without any urban planning rational and any necessary service (e.g. sewer plants, water distribution, etc.), is not acceptable. Furthermore, the slum relocation approach is often hiding the will of building high-rise complexes and increase the land value income. The Cairo 2050 neighborhoods that will accommodate the informal settlements are in the outskirts of the city where economic facilities and social services are barely available [30]. However, the Cairo 2050 policy plans to create jobs opportunities for these citizens in parallel with the informal settlements relocation in order to increase their income. In addition, the government will subsidize the inhabitants asking for very low rents.

In this study, the optimization model considers 2015 as the base-year. In 2015, the total energy consumption in Greater Cairo was 254 PJ [130]. Transport had the highest value and it was responsible for the 70% (177 PJ) of the energy consumption, followed by the residential sector with 20.5%. Public lighting, municipal and commercial sectors represented respectively the 4%, 0.5% and 5%. Gasoline was the main energy carrier in transport (97,7 % - 173 PJ) and it was mainly deployed for cars, busses and motorcycles. Gas, used for urban busses, represented 2% of the energy consumption. Finally, diesel and LPG were responsible for 0.15% each. In the residential sector, electricity was the main energy carrier (43.5% - 22 PJ) and it was deployed mainly for cooling and home appliances. LPG and gas, used for cooking purposes and heating, represented respectively the 33% and 11% of the energy consumption. Energy savings due to insulation and renewables deployment were around the 12.5%. In 2015, GC was responsible for 22.9 ktons CO_2 emissions for energy services (89% transport – 10.5% residential – 0.1% municipal and 0.4 commercial sectors) and the share per capita was 1.04 kg CO_2/inhabitant.

3.4.2 The TIMES-Greater Cairo energy system model

With the aim to investigate how to address the Greater Cairo megacity rising energy needs in a sustainable way, a MARKAL-EFOM System (TIMES) model was developed and implemented to the Greater Cairo region. TIMES is a bottom-up technology rich energy system model generator developed by the IEA-ETSAP collaboration platform [131]. The ultimate objective of a TIMES model is the identification of the cost-effective optimum mix of technologies to supply the exogenous energy services demand for the whole energy system modelled (including energy supply and demand) [131]. TIMES models have been implemented at global [132], national [133] and city level [134], [135], [136]. The TIMES-GC model was based on the model structure developed by [137], with several adaptations made by the authors as detailed in the following sections.

The TIMES-GC model represents the megacity from the base year of 2015 till 2050 in five-year-time steps. It is disaggregated spatially for each one of the three regions corresponding to the three governorates of Cairo, Giza and Qalyubeya. Each region or zone considers the following energy end-use sectors: commercial (COM), municipal or municipality owned buildings (MUN), residential (RSD), and public lighting (PLIG) as in sectors. The tourism sector is included in the commercial one. Besides the end-use demand sectors, the model also considers primary energy supply possibilities available within the city, energy conversion technologies that can also be deployed within the city and transmission and distribution technologies. The structure of the model is represented in Figure 3.23.

For each buildings sector (municipal, residential and commercial) the following energy-services demands are detailed for each type of buildings considered: space heating, space cooling, water heating, cooking, lighting, other electric uses and other energy uses. In the transport sector, it is considered both passenger and freight transportation for several modes as shown in Figure 3.23. Also as depicted in Figure 3.23, the most relevant TIMES-GC model outputs are the primary and final energy flows and consumption, energy technology deployment, energy commodity prices, GHG emissions and energy costs (investment, operation & maintenance and fuels). These outputs are available for each sector and region considered in the model. Each year is subdivided into 12 time slices representing the day, night and peak of the four seasons of the year. This allows considering variability in energy demand and energy supply options throughout the year.

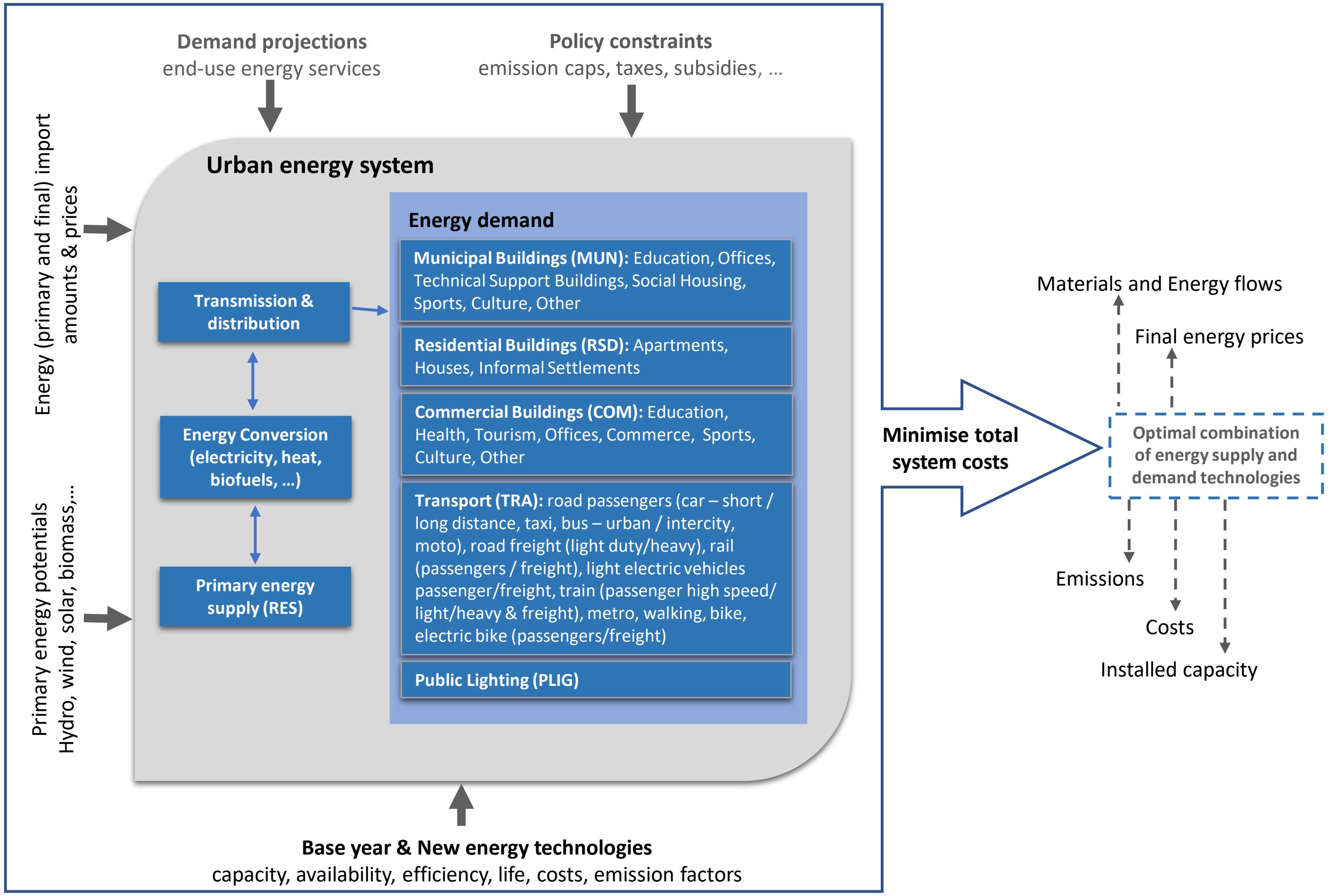


Figure 3.23 - Overview of the TIMES-GC model structure (adapted from [80])

Data collection was necessary in order to implement the TIMES-GC model but developing countries lack of online reliable databases. To comply with this lack of information, international databases and field experience have been used to complete the urban energy system background. More details about the data used in the model can be found below in Table 3.15.

The Statistical Yearbook 2015 [130] published by the national statistics authority CAMPAS provides most of the stock data for all sectors. The OntarioTech University Database on Megacities [138] contains the energy consumption data and the shares of energy carrier are calculated based on the IEA Statistics per sector [139]. In particular, the Greater Cairo consumption values are split into sectors considering the national percentage by IEA and then per each sector they are separated per carrier type considering the OntarioTech University Database on Megacities [138]. To this regard, for commercial and municipal sectors, IEA provides only the share of electricity consumption so the data have been integrated with the natural gas and LPG values in the Statistical Yearbook 2015 [130]. This was necessary as the commercial and municipal sectors includes restaurants and canteens that require natural gas and LPG.

In this model, several assumptions were necessary to provide a closer similarity with the real energy system. The public lighting energy consumption has been set according to the national values of the Statistical Yearbook 2015 [130]: a GC value is calculated as a weighted average of the national value on the population. An optimal number of lamps has been assumed to reach the LPG consumption calculated. A future use of hydrogen is not considered as it is not mentioned by national policies yet. The planned nuclear plant was not implemented as it seems to the authors to be no more going to be realized after the discovery of Zohr gas field. The gas price is decreased starting from 2020 as it is assumed that the recently discovered Zohr field is exploited [140]. Besides, according to the Wind and Solar Atlas, it is assumed that the maximum possible capacity of RES is around 31,150 MW from wind and 52,300 MW from solar [141]. In the residential sector, it is assumed that there is no space heating or space cooling for the informal settlements buildings.

Table 3.15 - Main data inputs in TIMES-GC

	Data	Source	Reference
Socio-economic	*GDP (*2.372 kEUR/capita)	World Bank data (GDP per capita in 2015 (constant 2010 US$)	[142]
Residential	*Stock*	Statistical Yearbook 2015	[130]
	Energy consumption	OntarioTech University Database on Megacities	[138]
	Shares of energy carrier	IEA	[139]
	Growth rate of inhabitated buildings	Statistical Yearbook 2015	[130]
	Growth rate	Statistical Yearbook 2015	[130]
Transportation	*Stock*	Statistical Yearbook 2015	[130]
	Energy consumption	OntarioTech University Database on Megacities	[138]
	Shares of energy carrier	IEA	[139]
	Modal Share split	World Bank Cairo Traffic Congestion study	[143]
	Shares of vehicles type per zone	Statistical Yearbook 2015	[130]
	*Trips per day (*25 million)	National Authority for Tunnels	[144]
Commercial	*Stock*	Statistical Yearbook 2015	[130]
	Energy consumption	OntarioTech University Database on Megacities	[138]
	Shares of energy carrier	IEA & Statistical Yearbook 2015	[130]
Municipal	*Stock*	Statistical Yearbook 2015	[130]
	Energy consumption	OntarioTech University Database on Megacities	[138]
	Shares of energy carrier	IEA & Statistical Yearbook 2015	[130]
Public Lighting	*Energy consumption*	Statistical Yearbook 2015	[130]
	Growth rate	Statistical Yearbook 2015	[130]
Electricity	*Electricity demand and generation plants*	Annual Report, Ministry of Electricity, 2016/2017	[121]

The main challenges in modelling a developing country megacity are access to data and developing robust scenarios on demography, economic growth and lifestyle changes. In this research work, the results have several limitations that authors plan to face in future works. In particular, the freedom of access to firewood allows an increasing biomass deployment without considering the preference for modern energy technologies that have a relatively higher infrastructure cost. Thus, the use of biomass for cooking should probably be reassessed.

3.4.3 Modelled scenarios

This study assesses different pathways to cope with rising energy needs (supply and demand) deriving from informal settlements' inhabitants' relocation in outskirts dwellings with improved access to energy and a higher transport demand. The MARKAL-EFOM System (TIMES) model is applied to the Greater Cairo region to investigate how energy supply and demand will evolve till 2050, and what are the impacts in terms of final energy consumption, technology deployment and CO_2 emissions investment. While performing the analysis, the feasibility of the Cairo Vision 2050 is investigated in terms of impact on the energy supply strategy.

Six scenarios are modeled. Firstly, the Business As Usual (BAU) scenario is built assuming that the GC urban energy system will have no important changes in the future and no policies will address the informal neighborhoods (Table 3). The other two scenarios address INFormal settlements inhabitants at two different paces. One scenario considers the strong and rapid innovations proposed in Cairo Vision 2050 [126] policy framework (INFA), whereas the second informal settlement relocation scenario considers an author-based potential average solution, less ambitious than the Cairo Vision 2050 (INFB). Table 3.16 details all characteristics of the modelled scenarios regarding population evolution.

Besides these 3 socio-economic scenarios addressing relocation of inhabitants of informal settlements, other 3 scenarios are considered by modelling a 2050 CO_2 emissions mitigation cap of less 50% emissions from 2015 values, for each of BAU, INFA and INFB (BAUc, INFAc and INFBc).

In INFA all the informal settlement population is assumed to gradually move to apartments starting from 2020, with a total of 7.9 million inhabitants relocated between 2020 and 2030 (50% of the persons estimated to be living in informal settlements in 2030, corresponding to 27% of GC total population) and 38.2 million inhabitants relocated between 2030 and 2050. In INFB, only 50% of the informal settlement population is assumed to move to apartments by 2050. As in INFA the relocation starts from 2020, but at a slower pace, with a total of 7.9 million inhabitants relocated between 2020 and 2030 and 19.1 million inhabitants relocated between 2030 and 2050 in this scenario. The visualization of the differences between inhabitants of informal settlements is depicted in Figure 3.24 and further detailed in Table 3.16.

Table 3.16 - Overview of the modelled scenarios

Parameters / Scenario	BAU - Business as Usual	INFA - Cairo Vision 2050 [126]	INFB – "Less Ambitious Relocation"
Informal sett. Population moving to residential areas	2030: None 2040: None 2050: None	All the informal settlement population is assumed to gradually move to apartments [126] , as follows: 2015: 54% of total population lives in informal settlements, 2030: 27%, 2050: 0%	Half of the informal settlement population is assumed to gradually move to apartments, as follows: 2015: 54% of total population lives in informal settlements, 2030: 41% 2050: 27%
Population	2.0 % Historic values 2005-2015 (World Bank) Urban population growth (annual %) (value for Egypt)		
Transport demand increase (%/year)	Proportional to the population increase per zone	2.23 between 2008-2050 JICA estimation for Cairo 2050 Vision [145]	Assumed average value between BAU & Cairo 2050
GDP Growth rate (%/year)	2.2% Historic values 2005-2015 (World Bank)	7.5% Assumed the same as national expected growth from Cairo Vision 2050 [126]	4.9% Assumed average value between BAU & Cairo 2050
Inhabited residential buildings evolution - Growth rate (%/year)	2.0% Assumed equal to population growth for all building typologies except informal settlements that are decreasing as above		
Variation of the electricity	1.0%		

Parameters / Scenario	BAU - Business as Usual	INFA - Cairo Vision 2050 [126]	INFB – "Less Ambitious Relocation"
consumption per capita of electric appliances in residential sector (kWh/capita)	Historic values 2007-2014 [130]. With relocation of informal settlements inhabitants, a share of the population is immediately assumed to have higher energy services' needs. These will grow in time at 1.0% rate for electric appliances.		
Evolution of the growth of the municipality MUN and variation in useful energy demand for COM	4.9% Equal to the national value based on IEA data and statistic yearbook 2015 per natural gas and LPG. It is assumed to be the same for all years.	7.5% Equal to GDP Considering they are building a whole new capital.	4.9% Assumed same as BAU since it already considers a very high growth from base-year.
Variation in useful energy demand for IND	Constant	Constant	constant
Variation in useful energy demand for PLG	0.1% Historic national values 2005-2015 average [130]		

A relevant assumption highlighted in Table 3.16 is represented by the hypothesis related to a consumption of 50% less in energy for people living in informal settlements. According to [89], residential energy use has the following mix: space cooling 13%, water heating 11%, lighting 31%, cooking 2%, refrigeration 13%, cloth washing 5%, dish washing 1% and other electric appliances 24%. It is supposed that informal settlements only have lighting, water heating and refrigeration which is ~50% less than a standard residential building.

It is important to mention that no statistics are available on these data, therefore to formulate assumptions is the only way to tackle this issue. The proposed assumption seems reasonable as it allows to calibrate the model on the 2015 historical data, thus it is likely that informal settlements consume an amount of energy equal or very close to a half of traditional settlements.

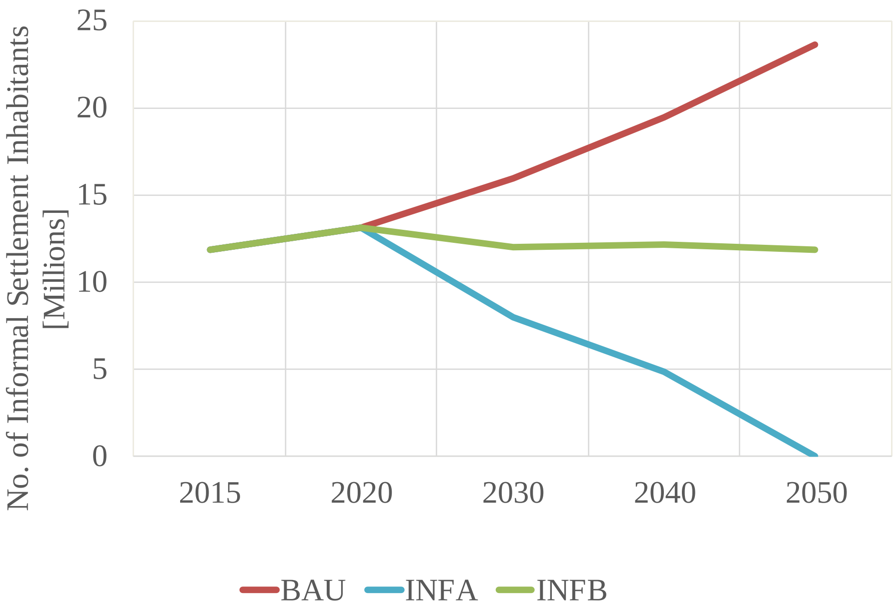


Figure 3.24 - Assumptions on relocation of inhabitants of informal settlements for BAU, INFA and INFB

Greater Cairo is composed by the three governorates of Cairo, Giza and Qalyubeya. The three governorates are modelled separately as different zones. Data are collected per each zone. The model allows to describe energy consumption per different sectors and different technologies in each zone.

In the scenarios with informal settlements relocation, the new dwellings are assumed to be in the outskirts of GC. Up to today, the relocation projects in Egypt do not consider the transit-oriented development of the new cities. This means that the new communities' members will need to move in paratransit or private transportation systems in order to the reach their jobs and, considering the 20-24 million inhabitants, this will result in a relevant transport mileage increase. In this research, the road transport mileage increases gradually in time and the values are reported in Table 3.16 and in Figure 3.25.

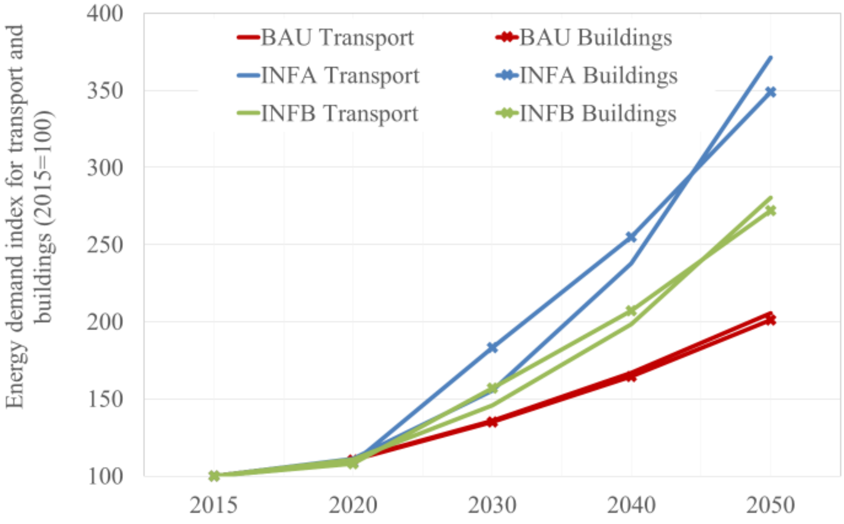


Figure 3.25 - Evolution of exogenous demand for energy in the transport and residential sector

The growth of mobility demand is assumed to be the same in all 3 zones because, historically, the geographical urban development of GC has always been circular. The new residential buildings to host the informal settlements inhabitants are supposed to be located in 6th October (Giza) and New Cairo (Cairo) [126], in areas where public transport plans do not include new metro lines, and thus no metro lines are considered in this model.

3.4.4 Results and discussion

The TIMES-GC model allowed to generate three development scenarios or pathways of energy system flows, technologies, costs and CO_2 emissions. Results assess energy changes and technological and environmental impact of different policy objectives to be adopted.

3.4.4.1 Final energy consumption

The resulting Final Energy Consumption (FEC) evolution is depicted in Figure 3.26. Following the considered energy services demand growth (as in the previous section), by 2050, FEC in Greater Cairo can grow between 31-749 PJ, respectively for BAU and INFA scenarios (i.e. 12% to 295% more than in 2015). In all the scenarios there is an increase in energy efficiency, with more efficient appliances and mobility options replacing the current ones. This explains why total FEC grows less than the considered energy services demand in Figure 3.26.

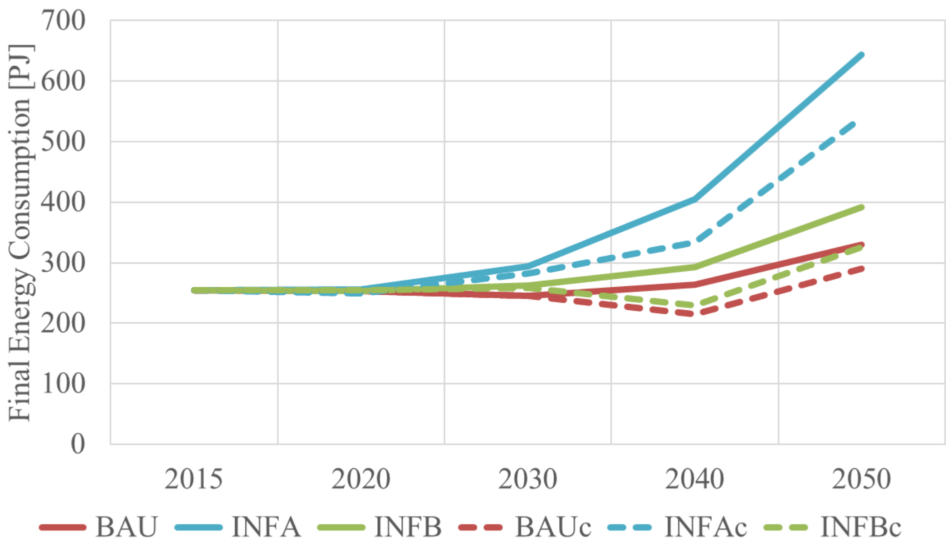


Figure 3.26 - Total final energy consumption evolution for each modelled scenario

In the scenarios with a CO_2 cap of 50% less emission than in 2015 (BAUc, INFAc and INFBc) there is a substantially lower growth in total FEC, because in order to comply with CO_2 cap, higher energy efficiency is required and more energy efficient technologies are deployed as detailed in the next section. In these scenarios with a cap, by 2050, FEC in Greater Cairo can grow between 18-318 PJ, respectively for BAU and INFA scenarios (i.e. from 7% to 125% more than in 2015).

Regarding FEC per consumption per capita, Table 3.17 shows this indicator for all modelled scenarios for 2030 and for 2050, as well as the base-year indicator. As mentioned, in all scenarios, except INFA (and to a less extent, INFB), there is a reduction in FEC per capita due to the deployment of more energy efficient technologies in buildings, transport and, to a less extent, in public lighting. The scenarios with the CO_2 cap have a lower FEC per capita than the ones without the cap. This is because fossil free energy options are limited and thus, in order to meet the emission cap, it is necessary to deploy more energy efficient technologies than in the scenarios without the cap (detailed in the following section).

Table 3.17 - Final Energy Consumption per capita

Scenarios	Energy per capita (GJ/ inhabitants)			% difference from 2015	
	2015	**2030**	**2050**	**2030**	**2050**
BAU	11.57	8.32	7.52	-28%	-35%
BAUc		8.20	6.64	-29%	-43%
INFA		9.96	14.68	-14%	27%
INFAc		9.55	12.31	-17%	6%
INFB		8.87	8.94	-23%	-22%
INFBc		8.75	7.43	-24%	-36%

In INFA, both in 2030 and 2050 there is less energy efficiency than in the base-year because the demand for energy services (cooling, lighting, cooking, electric appliances and mobility) has increased substantially following the relocation of all inhabitants in informal settlements.

Besides looking at the evolution of total FEC, it is also relevant to look into fuel switches as in Figure 3.27 that shows the evolution for the six modelled scenarios per energy carrier in absolute terms and as a share of total FEC. Whereas in 2015 most of the FEC was gasoline for the transport sector (68% of FEC), by 2030 gasoline represents only 43-53% of FEC and by 2050 only 8-20% of FEC. In all the modeled scenarios, the relative importance of natural gas increases substantially, from 4% in 2015 to 6-11% in 2050. This is because price of gas is assumed to decrease from 2030. The role of diesel also gains prominence (from 0.1% in 2015 to 0.7-2.2% in 2050), but only for the scenarios with a CO_2 cap, where blending of biodiesel with diesel becomes cost-effective. Another significant modification is the increased role of energy savings via increased buildings insulation and heat pumps from 1% of FEC in 2015 to 3.9-7.2% in 2050, with a higher relevance in the scenarios with a CO_2 emission cap. Figure 3.28 shows how energy savings decrease significantly the FEC.

The relative importance of electricity in total FEC varies depending on the scenario. In BAU in 2050 electricity represents 33% of total FEC (was 18% in 2015) and is replacing diesel in the transport sector. However, in BAUc electricity, increases up to 42% as it is also associated with PV systems with lower CO_2 emission. The share of RES in FEC varies from 4% in 2015 to 8-12% in 2030 and 15-25% in 2050. The highest RES share is obtained for BAUc in both years, since RES potentials are limited and since BAU and BAUc are the scenarios with lower total FEC.

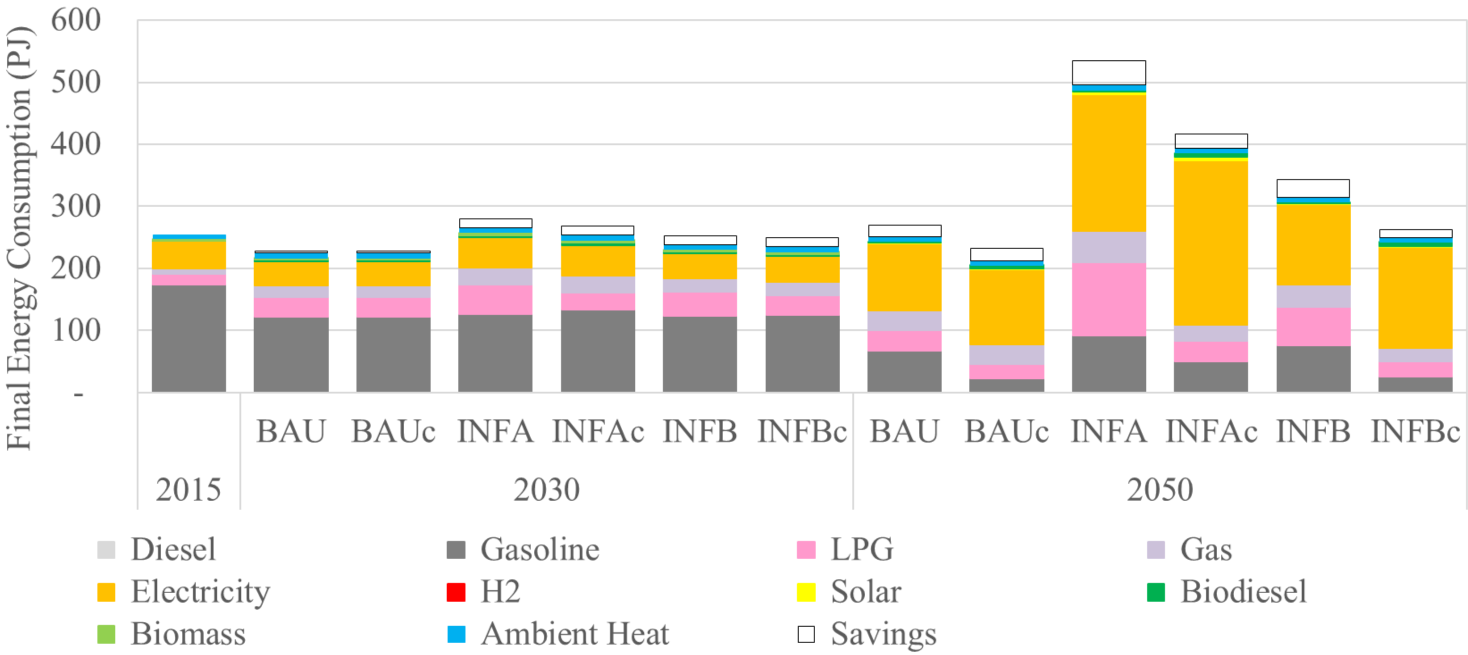


Figure 3.28 - Final energy consumption evolution per energy carrier for each modelled scenario

3.4.4.2 Final energy consumption evolution per sector

Figure 3.29 shows evolution of FEC per economic sector in GC. Transport in all years and scenarios is the sector that consumes a higher share of the megacity's FEC, although its relative importance slightly decreases from 70% of FEC in 2015 to 28-45% in 2050. The second most important sector is the residential sector (21% of FEC in 2015 and 21-32% in 2050), followed by the commercial sector, which we do not assess in detail in this study (5% of FEC in 2015 and 26-45% in 2050). Finally, municipal buildings and public lighting represent a rather small share of FEC, with respectively 0.2% and 4% of GC FEC in 2015 that in 2050 becomes 1% for municipal buildings and 1-2% for public lighting. The increase in relevance of public lighting is due to the megacity's growth, as previously explained, although this is counteracted with replacement of lighting technologies with more efficient LED options.

The results of FEC per energy carrier for transport and residential sectors are shown in Table 3.18. The table also includes ambient heat (that inputs heat pumps) and "savings" which, as mentioned, are included here as a proxy for the deployment of passive architectural measures as insulation.

In the transport sector of the BAU scenario, both for 2030 and 2050, the growing mobility demand is satisfied with higher and biofuels consumption in busses, with increased electricity consumption in buses and passenger cars, and increased natural gas consumption in trucks, replacing gasoline. This fuel switch occurs due to two causes: (i) from 2020 onwards, natural gas is assumed to become cheaper than gasoline and diesel following the start of exploitation of Zohr gas field, and (ii) electric cars and buses are much more efficient than diesel and gasoline ones. When the CO_2 cap is set in BAUc, electricity loses cost-efficiency, since it has associated emissions (as we do not consider that the electricity mix of the national grid will change). The same happens to natural gas and LPG. In BAUc, in 2050 the mobility demand is ensured with more biodiesel and diesel which are consumed in a much more efficient vehicle stock for hybrid busses, plug-in hybrid trucks and plug-in hybrid passenger cars.

The INFA, INFB, INFAc and INFBc scenarios, have much higher mobility needs, as people move out of the informal settlements to the new areas being built in the Greater Cairo outskirts and need to commute to the center. Thus, in these scenarios there is a rather similar fuel switch as in BAU and BAUc. However, in INFAc, since the mobility demand is much higher, there are limits to the amount of available biodiesel and thus a higher consumption of both diesel and electricity are needed, as well as of imported H_2. In this scenario new mobility technological options are deployed, namely electric cars and busses, electric light-duty trucks and medium-sized electric buses. The share of RES in the transport sector grows from 0% in 2015 up to 1-6% in 2050.

In the residential sector, the increasing FEC in the BAU scenario is mainly due to the increase of cooling needs following population growth. Up to 2030 the cooling demand is satisfied by an increase in electricity consumption and after that year also by the replacement of fans and air conditioning split units with more efficient cooling technologies (more efficient air conditioning). Moreover, in the BAU scenario there is an increase in deployment of insulation from the base-year. Natural gas and LPG used in cooking and for sanitary hot water production are replaced with electricity, as it is more efficient. In the BAUc scenario, both for 2030 and 2050, electricity consumption decreases (since it has associated CO_2 emissions) and is replaced by natural gas (which became cheaper in from 2020 onwards as previously described) and biomass. The latter is used for cooking, while gas is consumed by deployed gas heat pumps generating cooling especially from 2030. In this model, it is assumed that the share of RES in the electricity generation remains the same as in 2015. The INFA, INFB, INFAc and INFBc scenarios, have higher FEC (mainly for cooking and cooling) due to the informal settlements' inhabitants' relocation into residential apartments. INFA and INFB scenarios follow the same technology evolution as in BAU but in higher magnitude, since the energy services demand considered in these two scenarios is higher. The share of RES, heat pumps and insulation deployment in the residential sector grows from 1% in 2015 up to 30-45% in 2050.

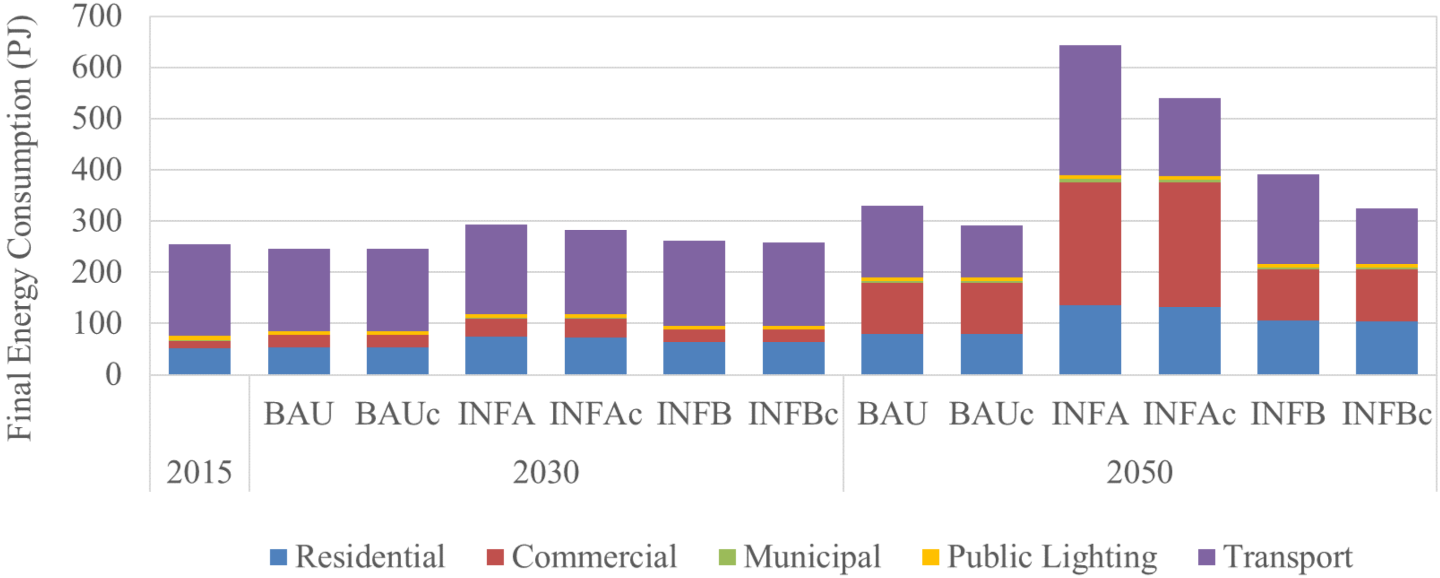


Figure 3.29 - Final energy consumption evolution per economic sector

Table 3.18 - Evolution of FEC per energy carrier for 2030 and 2050 for Transport and Residential sectors as a difference in PJ from 2015. These are the two sectors where energy services demand inputs were modified due to changes in lifestyles of inhabitants moving out of informal settlements. % of RES in each sector is also shown

Energy carrier (PJ)	**2030**						**2050**					
	BAU	**BAUc**	**INFA**	**INFAc**	**INFB**	**INFBc**	**BAU**	**BAUc**	**INFA**	**INFAc**	**INFB**	**INFBc**
						Transport						
Biodiesel	1.7	1.7	2.3	3.3	1.7	3.3	2.0	5.8	3.1	6.5	2.3	6.5
Diesel	0.5	0.5	0.6	0.6	0.6	0.6	0.4	0.3	1.0	0.5	0.6	0.3
Electricity	16.9	16.9	17.1	17.4	16.9	17.5	55.3	67.1	71.9	93.6	60.0	77.2
Gasoline	-51.8	-51.8	-47.5	-39.9	-50.0	-48.9	-106.0	-151.2	-82.6	-123.1	-97.5	-147.7
H2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0
LPG	15.8	15.8	26.4	5.7	20.2	13.4	13.5	4.8	85.6	-0.2	35.4	-0.2
Gas	58.2	41.5	116.8	34.1	81.1	38.4	50.4	-2.8	585.8	-3.5	161.3	-3.5
TOTAL	-17.2	-17.2	-1.6	-13.4	-11.0	-14.6	-36.8	-75.5	76.9	-26.1	-1.4	-67.2
% RES	*0.0%*	*0.2%*	*2.0%*	*0.1%*	*2.9%*	*0.1%*	*1.8%*	*1.7%*	*5.8%*	*0.6%*	*2.5%*	*0.8%*

Energy carrier (PJ)	**2030**						**2050**					
	BAU	**BAUc**	**INFA**	**INFAc**	**INFB**	**INFBc**	**BAU**	**BAUc**	**INFA**	**INFAc**	**INFB**	**INFBc**
						Residential						
Ambient Heat[a]	0.74	0.74	0.74	0.74	0.74	0.74	0.74	1.99	1.90	8.15	0.74	4.95
Biomass	-1.53	-0.65	-0.66	1.02	-1.12	0.33	-3.17	4.09	-3.17	-3.17	-3.17	0.30
Electricity	1.32	-5.68	11.07	-8.71	5.09	-11.47	9.18	-12.62	20.88	-8.94	20.09	-11.20

Energy carrier (PJ)	2030						2050					
	BAU	**BAUc**	**INFA**	**INFAc**	**INFB**	**INFBc**	**BAU**	**BAUc**	**INFA**	**INFAc**	**INFB**	**INFBc**
Natural Gas	-5.55	-0.37	-5.55	6.25	-5.55	3.26	-0.56	10.61	9.22	26.25	-0.25	17.52
LPG	-2.83	-3.10	2.71	3.99	-0.26	1.13	1.91	3.05	17.66	16.11	9.91	9.50
Savings[b]	7.17	7.41	10.78	20.37	9.59	19.48	19.55	25.31	46.78	48.43	33.66	38.21
TOTAL	**-0.67**	**-1.65**	**19.09**	**23.66**	**8.50**	**13.46**	**27.65**	**32.42**	**93.27**	**86.83**	**60.97**	**59.28**
% RES, Insulation and Heat Pumps	*25%*	*28%*	*25%*	*38%*	*26%*	*41%*	*30%*	*45%*	*36%*	*43%*	*33%*	*45%*

[a] Ambient heat is included here as a proxy to highlight the share of cooling being supplied by air heat pumps; [b] Savings represents energy savings due to implementation of insulation

3.4.4.3 CO_2 emissions

In 2015, Egypt adhered to the Paris Agreement and expressed the intention to decrease the GHG emissions. However, even if the willingness to increase energy efficiency and the renewable energy sources share was expressed, it was never formalized in a national plan with clear environmental goals. In this model, it is assumed a reduction of 50% of energy related CO_2 emissions in 2050 below 2015 value (22.9 kton CO_2) for the scenarios BAUc, INFAc and INFBc.

As Figure 3.30 shows, transport is the sector with the higher city CO_2 emissions contribution in 2015 (89% - 12.8 kton CO_2). Followed by the residential sector with 10%, while commercial and municipal sectors are responsible for only 1% of city CO_2 emissions in 2015. The CO_2 emissions related to industry and the electricity generation are not analyzed. In the BAU scenario, the share of emissions related to transport decreases up to 56% of total GC emissions in 2030 and up to 16% in 2050 since more efficient technologies start being deployed from 2030. In 2030 and 2050, in the BAUc scenario, the mitigation cap for the whole of the mega city leads to the transport sector to replace of gas and diesel busses with hybrid diesel engines and the deployment of hybrid diesel and gasoline cars, as previously mentioned. Thus, the share of transport emissions for overall emissions is lower in BAUc than in BAU. The same type of trend occurs in INFA and INFAc scenario, with share of transport emission going from 58% of total emission in 2030 to 32% in 2050. In the residential this share is compensated by a relative increase that changes from 6% in 2015 to 12% in 2030 and 34% in 2050 in the BAU scenario.

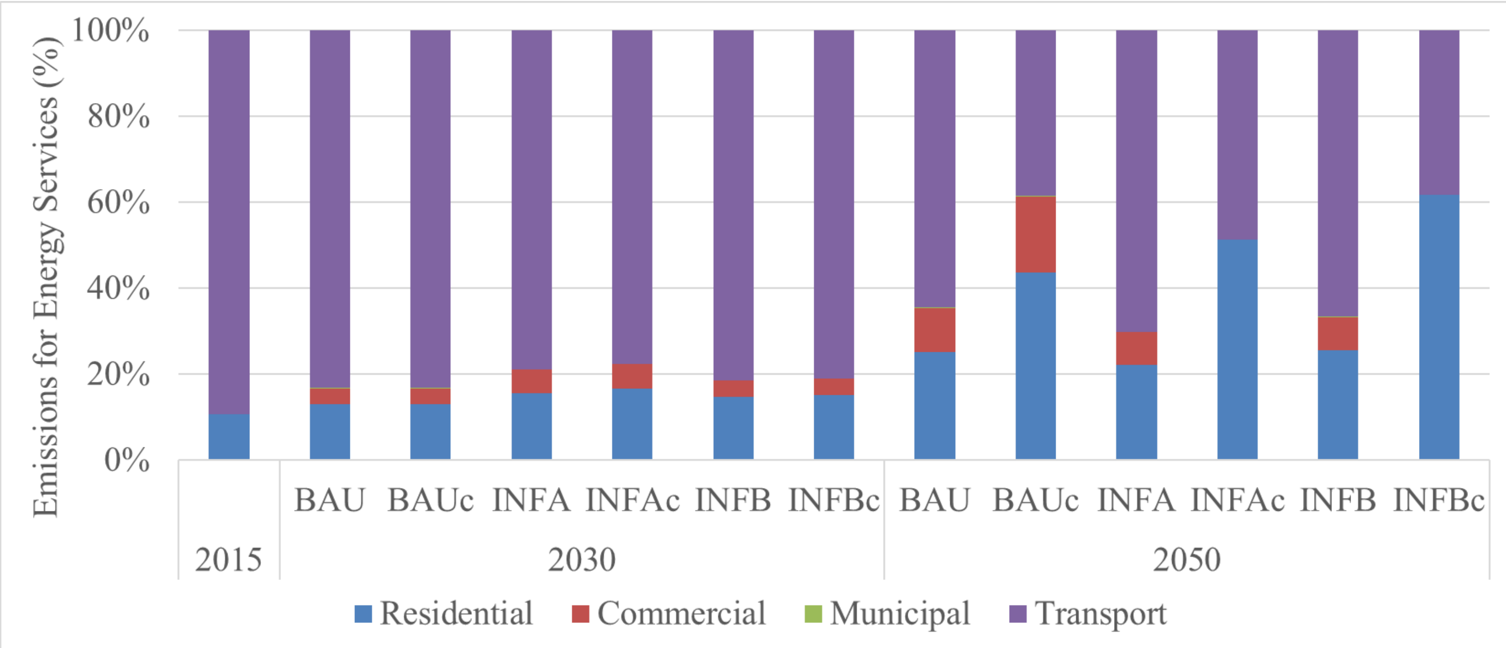


Figure 3.30 - Share of sector CO2 emissions for Greater Cairo (%)

In Table 3.19, the CO_2 emissions per capita indicator shows how the reduction of 50% allows to achieve an important decrease to 0.26 compared to the BAU (0.34) – INFA (0.66) - INFB (0.43) scenarios in 2050. In the BAU scenario, the increasing technological efficiency allows the indicator to decrease, but when the informal settlements inhabitants' relocation is considered the indicator increases again (INFA and INFB) as citizen will have higher access to energy services.

Table 3.19 - CO2 emissions per capita (kg CO2/inhabitant)

Scenario	**2015**	**2030**	**2050**
BAU	1.04	0.55	0.34
INFA		0.65	0.66
INFB		0.59	0.43
BAUc/ INFAc/ INFBc		0.38	0.26

3.4.5 Conclusions

The TIMES model for Greater Cairo is used to investigate the "connections between urban governance in its various forms and the energy sector (that) are uneven and often weakly connected in institutional and policy terms" [28]. Using a model for designing the future of a city with enough spatial and building typology disaggregation can help building these connections. The TIMES model for Greater Cairo allowed to generate three socio-economic development scenarios for the urban energy system of Greater Cairo (BAU, INFA, INFB) and to assess the impact of applying a 2050 CO_2 emissions mitigation goal of 50% compared to 2015 values (BAUc, INFAc, INFBc). The scenarios are developed with particular attention to the impact of lowering the share of informal settlements inhabitants through their relocation to the outskirts of Greater Cairo (GC) as planned by the Egyptian government. The inhabitants' relocation represents an increase of formal housing and transport demand corresponding to a higher energy demand due to the improved access to energy. In INFA all the informal settlement population is assumed to gradually move to apartments with a total of 46.1 million inhabitants relocated between 2020 and 2050. In INFB, only 50% of the informal settlement population is assumed to move to apartments by 2050. In parallel, a BAU scenario is modelled to show energy consumption development without any relocation policy.

Following the demand growth of energy services modelled, by 2050, final energy consumption in Greater Cairo can grow between 31-749 PJ (i.e. 12% to 295% more than in 2015), respectively for BAU and INFA scenarios. In all the scenarios there is an increase in energy efficiency as more efficient appliances and mobility options are replacing the current ones. In the scenarios with a CO_2 cap of 50% less emission than in 2015 (BAUc, INFAc and INFBc) there is a substantially lower growth in total final energy consumption, because in order to comply with CO_2 cap, higher energy efficiency is required and more energy efficient technologies are deployed. All the scenarios allow to draw the fuels relative importance: natural gas increases substantially, from 3% in 2015 to 6-11% in 2050 and this is because its price is assumed to decrease from 2020 when Zohr gas field will be fully operative [51]. The role of diesel and of heat pumps is relevant, but only for the scenarios with a CO_2 cap, where blending of biodiesel with diesel becomes cost-effective. PVs and hybrid technologies let electricity increase from 17% in 2015 up to 50% in 2050.

3.5 Pathways to electric mobility integration

The electrification of the road transport sector is increasingly seen as a necessary component to the urban decarbonization. A scenario analysis of electric cars deployment is developed by employing the Long-range Energy Alternative Planning (LEAP) to evaluate their contribution to the energy transition in the long term, 2030. The model is used to estimate the trend in energy consumption and polluting emissions deriving from the Italian automotive sector between 2018 and 2030.

The review of the scientific literature shows that previous studies did not consider the impact of the electrification on the Euro segmentation of the fossil fueled cars'. In this study, an innovative methodology is proposed to investigate the electrification of the private transport system. This methodology allows to analyze in detail the evolution of the car stock with regard to engine displacement, fuel supplies and relative emissions. The objectives of the proposed methodology are the following:

- the assessment of the transport-related energy consumption changes,
- the estimation of the transport-related emissions,
- the calculation of the transport-related external costs.

To the best of authors' knowledge and according to the reviewed studies, this represents the first attempt to develop a model to assess the electrification of the cars stock by taking into account both engine characteristics (e.g. fuel and engine displacement) and Euro classes. The Italian car fleet stock is proposed as case study and a scenario analysis is performed by using the Long-range Energy Alternatives Planning (LEAP) platform to estimate final energy consumption reduction, how much carbon emissions can be saved and to what extent are externality costs reduced with the electric cars' progressive introduction in Italy.
In addition to the Business As Usual scenario, four alternative scenarios compare different efficiency policies and evaluate the possible consequences related to the penetration of electric cars in the Italian automotive market until 2030.

This research work is published in:

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Abd Alla, S., Bianco, V., Scarpa, F., & Tagliafico, L. A. (2020). The impact of e-mobility on the Italian electricity system, *Transportation Research Procedia*, 48. https://doi.org/10.1016/j.trpro.2020.08.263

3.5.1 The Italian car fleet stock

Private cars are the favorite and most used mean of transportation in Italy and, in 2018, represented the 59.1% of the modal share [146]. In 2018, 39,018,170 cars were registered representing about 75.5% of the total Italian vehicles fleet [147]. During the period 2000-2018, the number of cars in circulation increased by around 18% [147]. In particular, the car fleet in 2018 increased by almost 500,000 units compared to 2017. Furthermore, the entire fleet grew by about 6.4 million units compared to 2000 and by about 3.3 million compared to the year 2007, as highlighted in Figure 3.31(a). Indeed, the historical data analysis show that the total number of cars, in the last 18 years, always increased, with the exception of only three years: 2004, 2012 and 2013. These declines might be related to the economic crisis that led to a higher number of scrapping than first enrollments.

The eco-incentives allowed to renew the fleet in 2007 with 2,193,085 units and in 2009 with 1,950,664. The cars retirement normally takes place by scrapping, exporting or other (for example vehicles abandoned and removed by the authorities). In 2018, the total number cars radiated amounted to about 1,505,325 units [147].

As highlighted in Figure 3.31(b), the predominance of oil products for refueling is still evident in Italy and the development of electric mobility is slowly finding its path. In 2018, the vehicles stock comprised around 120.000 hybrid and electric cars representing only 0.4%. Diesel and petrol cover the higher share of fuel consumption with respectively 44% and 47%.

Regarding the different Euro classification directives, it is interesting to analyze the change that the car fleet has undergone in the last 10 years, having to adapt to the new regulations in force. In fact, the engines that belong to the Euro 5 (dated September 2009) and Euro 6 (dated August 2014) increased consistently, as reported in Figure 3.31(c), to the detriment of the other classes, since the latter can no longer be purchased due to the new standards. In 2018, Euro 5 and Euro 6 represented the highest share with approximately 38% of the total car fleet and were followed by Euro 4 (approximately 30%). It should to be noted that the percentage of cars belonging to the Euro 0 class, therefore prior to December 31st 1992, is still 9.8% despite the fact that 25 years have passed; this relevance is probably due to the fact that many fashionable vintage vehicles belong to this category.

Another interesting insight concerns the subdivision of the car fleet by engine displacement, as in Figure 3.31(d). The Automobile Club d'Italia (ACI) [147] published the statistics distinguishing in 6 different segments: 0-800 c.c.; 801-1200 c.c.; 1201-1600 c.c.; 1601-2000 c.c.; 2001-2005 c.c.; more than 2500 c.c.. About half of the Italian cars belong to the category of displacement 1201-1600 c.c.; and if this is added to the 801-1200 cc category, about 70% of the total is reached, revealing the importance of these segments where the electric mobility will have the higher incidence. The segment of displacement 1601-2000 includes about 21% of the total car fleet, while the remaining ones have a lower influence, covering less than 5% each. It should be also mentioned that in the last years many car manufacturers have started a gradual decrease in engine displacement.

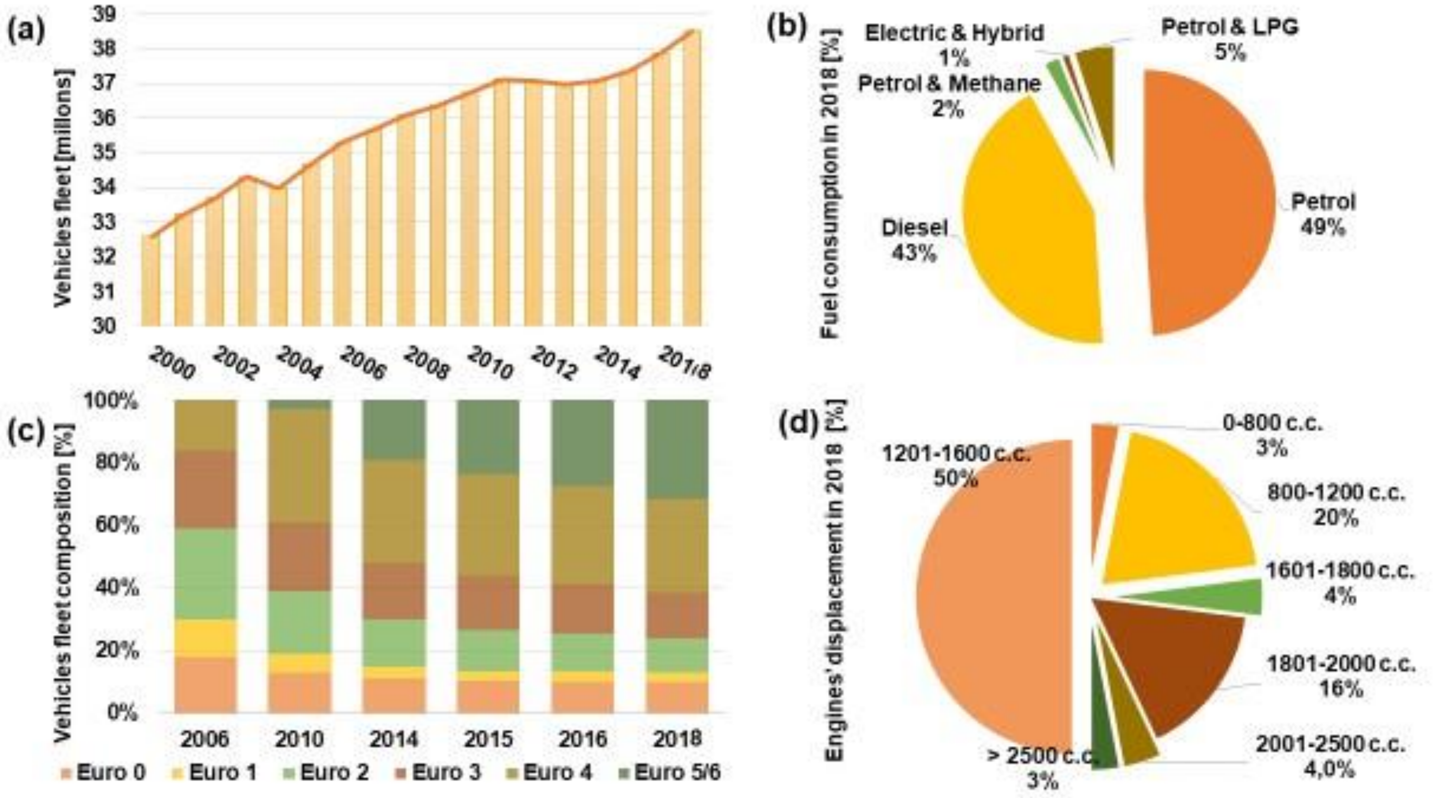

Figure 3.31 - The Italian car fleet: (a) evolution of the fleet in the period 2000-2018; (b) breakdown for typology of fuel; (c) evolution and breakdown for compliance to EU regulations; (d) breakdown for engine displacement.

3.5.2 Methodology

Transport electrification is at the center of decarbonization policies. The Italian private car fleet stock is used to elaborate an innovative methodology to investigate in detail which categories of vehicles should be addressed first by the replacement with electric cars. The proposed innovative methodology allows to investigate the electrification of the private transport system. As depicted in Figure 3.32, this methodology consents to analyze the evolution of each segment of the car stock.

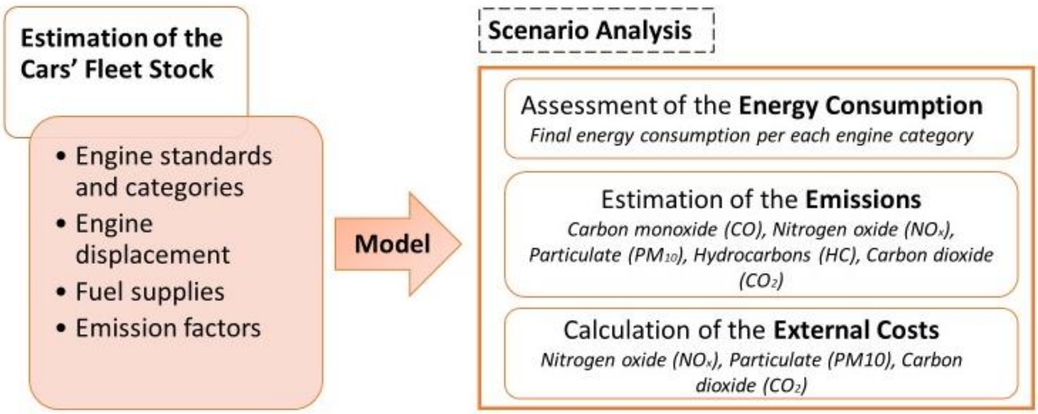

Figure 3.32 - Structure of Methodology

The review of the scientific literature, summarized in Table 3.20, shows that previous studies did not consider the impact of the electrification on the Euro segmentation of the fossil fueled cars'. In the European market, vehicles' engines are classified by 'Euro' standards for cars that describe limits on the pollutants' emissions.

The novelty of the proposed approach compared to previous studies available in the literature is the use of a detailed bottom-up forecasting model to assess the feasibility of the transition to electric cars by considering the impact on all the Euro emission classes and engines' characteristics. To the best of authors' knowledge and according to the reviewed studies, this represents the first attempt to develop a European country-based model to assess the electrification of the cars stock by taking into account both engine characteristics (e.g. fuel and engine displacement) and Euro class. The results allow to estimate the electrification impact in terms of energy consumption, emissions, and external costs.

Table 3.20 - Main findings of previous studies on the electric mobility impact.

Target	Region	Highlights
Test and enhance policy effectiveness	World [79], Italy [80], Spain [82], Indonesia [97]	Regulatory barriers exist in the implementation of alternative fuels and vehicle limitation schemes. A novel scheme for the sustainable mobility, based on electric vehicles and electric energy storage systems is needed. Significant reductions in energy demand are achievable by applying measures to decarbonize the transport and residential sectors.
Investigate the electric mobility impact on the power system	Canada [81], India [84], Italy [87] Germany [87], Croatia [89], World [10],	High penetrations of electric vehicles have a positive effect on energy systems but can cause significant instabilities in power grid. Electrifying the entire road vehicle fleet will require generation capacity to increase. This may result in a rise in emissions from thermal power plants, thus offsetting the reductions in tailpipe emissions. Indeed, the generation mix is confirmed to highly affect electric vehicles sustainability.
Assess the environmental impact of electric mobility and elaborate decarbonization pathways	USA [83], Denmark [88], Norway [88], Sweden [88], EU [91], UK [92] [94], India [93], Portugal [98] [99], Brazil [56]	There is a need for a higher level of policy ambition towards the deployment of less polluting vehicles in Europe. The authorities might have to start discussing a hybrid car ban in the near future. An ambitious multi-policy approach is needed to achieve cuts in absolute emissions.
Assess the social impact of electric mobility	Norway [95], Denmark [96]	Electric vehicle price and incentives are major barriers. All the policy instruments considered here might enhance a transition from fossil fueled to hybrid and electric cars.

The Italian Electric Cars Fleet Model (IECaF) describes the Italian vehicles stock development in the long term providing possible scenarios of cars electrification and investigates the impact in terms of final energy consumption, emissions and externalities. The different scenarios allow to obtain a complete picture of how the automotive sector can evolve over time. IECaF is a simulation model elaborated in LEAP framework. LEAP is a software developed by the Stockholm Environment Institute (SEI) to simulate energy policies and climate change mitigation [148]. The platform is widely used in the literature with application to different sectors, such as hotel sector [149], thermal power plants [150], oil sands production [151] and renewable energy [57]. The proposed methodology can be easily applied to other countries and developed on other simulation or optimization modelling platforms.

3.5.2.1 Structure of the Italian Electric Cars Fleet Model

IECaF has a disaggregate hierarchical structure based on four levels: vehicle typology, engine displacement, fuel type and environmental impact. The base year of the simulations is 2018 due to the latest data availability [147]. As depicted in Figure 3.33, the vehicle typology describes the Euro emissions class or electric technology adopted. Seven categories corresponding to the different Euro classes are included. Euro 5 and Euro 6 cars are considered combined since the ACI database [147] considers them aggregated (Euro 5_6). In addition, the Euro 6d class is added to simulate a more efficient technology that policies plan to introduce in 2021. Two more typologies are created: the hybrid and the electric vehicles.

Afterwards, all the typologies are differentiated per engine displacement: *Small cars*, engine capacity up to 1200 cc, and *Medium cars*, from 1201 c.c. to 1600 c.c .. As mentioned before, the 800-1600 cc capacity represents 70% of the vehicles fleet and those are more likely to be interested by an electrification process. Vehicles with larger engine displacement are not considered as they will hardly be replaced by electric cars, which have a reduced mileage and are considered as city cars.

Then, a further subdivision is made based on the fuel type by distinguishing by petrol and diesel. The hybrid cars are modeled considering two possible combinations: electricity/petrol or electricity/diesel. The electric cars consume only electricity.

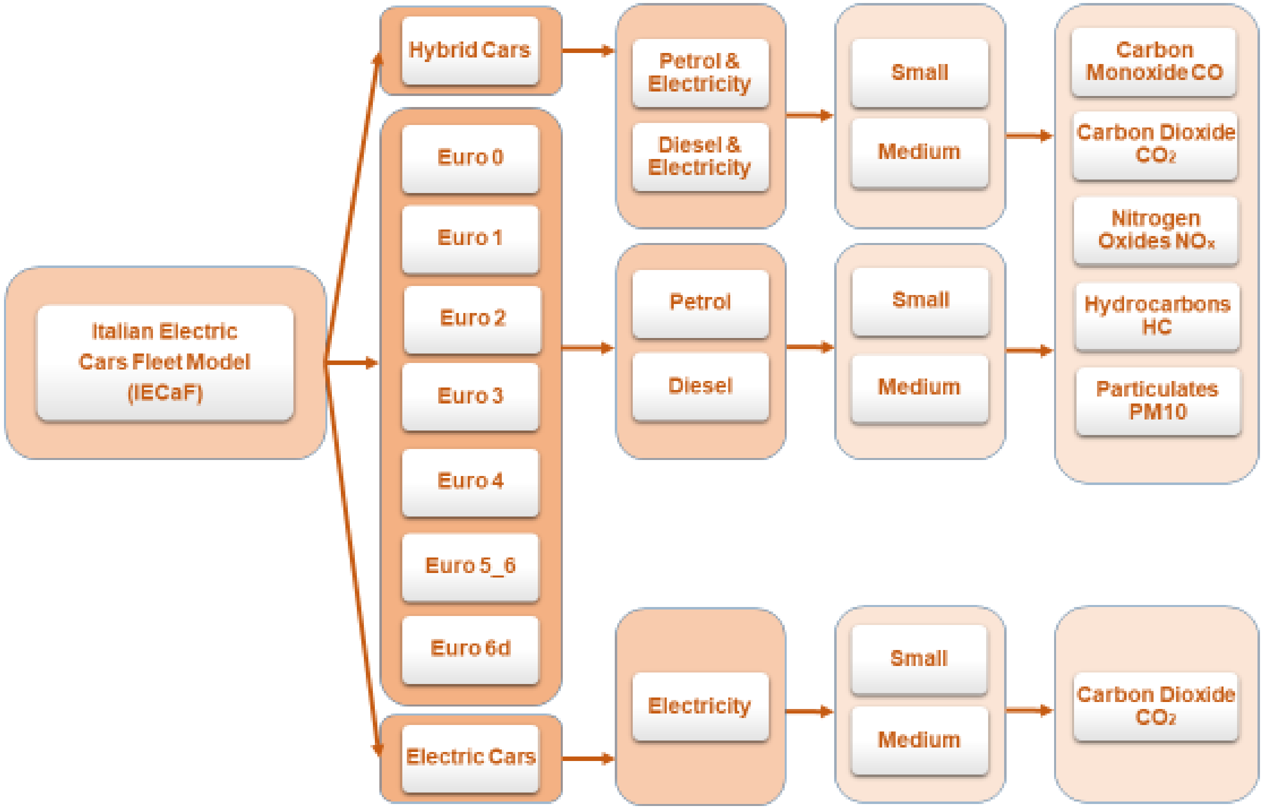

Figure 3.33 - Scheme of the Italian Electric Cars Fleet Model (IECaF)

Finally, the following emissions are considered: Carbon dioxide (CO_2); Carbon monoxide (CO); Nitrogen oxide (NO_x); Hydrocarbons (HC) and Particulates (PM10), the latter only for diesel cars.

3.5.2.2 Input data, main assumptions and limitations

All the subdivisions shown in Figure 3.33, concerning standards, displacements and fuel supplies, are quantified as shares of the stock. The stock amount is defined by specifying the total number of cars, small and medium, present in the base year 2018, namely 28,578,164 vehicles. Indeed, the analysis period is established as follows: 2018 as the base year, 2019 as the first year of the scenario and 2030 as the last year of the forecast. Due to the dearth of data, the share of small and medium car is not differentiated per each Euro class. The stock shares are estimated according to the ACI database [147]:

- Petrol cars: 45.23% small cars, 54.77% medium cars, for each Euro class,
- Diesel cars: 2.25% small cars, 97.75% medium cars, for each Euro class,
- Electric and Hybrid cars: 1.1% small cars, 98.9% medium cars.

The annual car *Stock* considers the number of new cars, *Sales*, and the vehicles still circulating, *Survival*, as described by equations (1) and (2):

$$\text{Stock}_{t,y,v} = (\text{Sales}_{t,v} + \text{Survival}_{t,y\text{-}v}) \quad (1)$$

$$\text{Stock}_{t,y} = \sum_{v=0}^{V} \text{Stock}_{t,y,v} \quad (2)$$

where:

- *t* is the type of vehicle,
- *v* is the vintage year,
- *y* is the considered future year,
- *Stock* is the number of vehicles in circulation in the year,
- *Sales* is the number of new vehicles,
- *Survival* is the number of cars that are still circulating,
- *V* is the maximum number of vintage years.

Table 3.21 - Fuel consumption input data [km/l]

	Fuel Consumption [km/l]			
	Petrol		*Diesel*	
	Small	*Medium*	*Small*	*Medium*
Euro 0	14.3	12.5	16.5	16.5
Euro 1	14.3	12.5	16.5	16.5
Euro 2	16.6	12.5	18	18
Euro 3	16.6	13.5	20	20
Euro 4	16.6	15.5	20	20
Euro 5_6	20	16.6	25	22.5
Euro 6d	22	18.2	27.5	25

The *Sales* of new cars are set as 1,614,951 vehicles/year, as it is the total number of first registrations of small and medium cars in the year 2018 [147].

A *lifecycle profile* describes how the total stock is composed of cars of different typologies considering the vehicles retirement over the years. Therefore, a vehicle survival analysis was performed using the Weibull distribution, a continuous probability distribution defined on positive real numbers and described by two scale parameters *T* and *k* [152]. To best describe the trend of the stock, it is assumed T = 20 and k = 2. This is due to the fact that *T* represents the average life span of cars. Accordingly, the *survival ratio* and the *scrappage rate* are defined respectively by equations (3) and (4):

$$SR_i\,(t) = \frac{SP_i\,(t)}{RP_i} = \exp\left(-\left(\frac{t}{T_i}\right)\right)^{k_i} \qquad (3)$$

$$v_i\,(t) = \frac{k_i\,(t)^{k_{i-1}}}{T^{k_i}{}_i} \times SR_i\,(t) \qquad (4)$$

where:

- $SR_i(t)$ is the *survival ratio* of cars registered with age *t* and registered in year *i*,
- $SP_i(t)$ is the number of vehicles not scrapped with age *t* and registered in year *i*,
- RP_i is the number of vehicles registered in year *i*,
- T_i is the scale parameter or characteristic life,
- k_i is the parameter of form,
- $v_i(t)$ is the *scrappage rate* with age *t*.

The fuel consumption per Euro class is estimated considering the average values of different vehicles available in the market [153]. As reported in Table 3.21, for the future Euro 6d class, it is assumed an efficiency increase of 10% compared to Euro 5_6.

Table 3.22 - Emissions input data [g/km]

Fuel	**Size**	**Euro Class**	**CO**	**HC**	**NO_x**	**CO_2**	**PM_{10}**
Petrol	Small	Euro 0	12.3	0.5	1.90	200	
		Euro 1	3.16	0.3	0.47	190	
		Euro 2	2.30	0.2	0.30	180	
		Euro 3	2.20	0.2	0.15	170	
		Euro 4	1.00	0.1	0.08	140	
		Euro 5_6	1.00	0.1	0.06	120	
		Euro 6d	1.00	0.1	0.06	95	
Petrol	Medium	Euro 0	12.30	0.5	2.40	210	
		Euro 1	3.16	0.3	0.47	200	
		Euro 2	2.30	0.2	0.30	190	
		Euro 3	2.20	0.2	0.15	190	
		Euro 4	1.00	0.1	0.08	150	
		Euro 5_6	1.00	0.1	0.06	140	
		Euro 6d	1.00	0.1	0.06	95	
Diesel	Small	Euro 0	3.16	0.20	1.00	190	0.2000
		Euro 1	2.72	0.16	0.97	190	0.1400
		Euro 2	1.00	0.15	0.55	180	0.0800
		Euro 3	0.64	0.06	0.50	170	0.0500
		Euro 4	0.50	0.05	0.25	120	0.0250
		Euro 5_6	0.50	0.05	0.08	95	0.0050
		Euro 6d	0.50	0.05	0.08	95	0.0045
Diesel	Medium	Euro 0	3.16	0.20	1.00	200	0.2000
		Euro 1	2.72	0.16	0.97	190	0.1400
		Euro 2	1.00	0.15	0.55	180	0.0800
		Euro 3	0.64	0.06	0.50	170	0.0500
		Euro 4	0.50	0.05	0.25	130	0.0250
		Euro 5_6	0.50	0.05	0.18	105	0.0050
		Euro 6d	0.50	0.05	0.08	95	0.0045

The hybrid and electric vehicles energy consumption is set according to the scientific literature [154]:

- hybrid diesel: 152 MJ/100km for small cars and 134 MJ/100km for medium ones,
- hybrid petrol: 181 MJ/100km for small cars and 149 MJ/100km for medium ones,
- electric: 51 MJ/100km for small cars and 64 MJ/100km for medium ones.

Besides, a mileage of 13,140 km/year (36 km/day) [155] is assumed to be constant throughout the period considered.

The emissions data are estimated considering national policies [156] and public institutions databases [157] as reported in Table 3.22. In particular, for the future Euro 6d policy, which is supposed to start in 2021 and oblige new cars limit CO_2 emissions to a maximum of 95 g/km, the values of CO, HC and NO_x are kept equal to Euro 5_6.

Table 3.23 - Electricity generation forecast – generation share [%][39]

Year	**CCGT**	**Coal**	**Petroleum products**	**Turbogas**	**RES**
2018	43.0	13.3	4.0	4.0	35.7
2019	43.0	12.9	4.0	4.0	36.1
2020	43.0	12.6	4.0	4.0	36.4
2021	43.0	12.2	4.0	4.0	36.8
2022	43.0	11.9	4.0	4.0	37.1
2023	43.0	11.5	4.0	4.0	37.5
2024	43.0	11.1	4.0	4.0	37.9
2025	43.0	10.8	4.0	4.0	38.2
2026	43.0	10.4	4.0	4.0	38.6
2027	43.0	10.1	4.0	4.0	38.9
2028	43.0	9.7	4.0	4.0	39.3
2029	43.0	9.4	4.0	4.0	39.6
2030	43.0	9.0	4.0	4.0	40.0

Electricity carbon emissions are assumed equal to 0.348 t/MWh due to the Italian electricity generation system [158]. However, a decrease of 0.003 t/MWh per year is assumed to take into account the increasing use of renewable sources [158].
The considered electricity generation profile is the results of an hourly simulation with a power market model representing the Italian system [158]. The results of this model are used as input for IECaF with a soft linking approach as suggested in [159]. In particular, a progressive reduction of coal-based generation from 14% to 9% is assumed, corresponding to an increase in renewable energy sources (RES) from 35.7% to 40% from 2018 to 2030 [158] as reported in Table 3.23.

The main limitation of this methodology is data availability at a granular and detailed level. The Italian case study could rely on European and national databases. In case a non-European country is modeled, data collection and definition of the main vehicles' categories are the main challenges.

3.5.3 The scenario analysis

The Italian Electric Cars Fleet Model (IECaF) is used to propose a scenario analysis with alternative assumptions about future electrification of the car fleet. First, the business-as-usual (BAU) scenario is referred to as the base case where the current situation [147] and the estimated future changes are based on expected or likely plans. Then, four different policy scenarios are modelled and compared to the BAU as summarized in Table 3.24. In all scenarios, it is assumed that the total number of cars circulating remains equal to the BAU scenario.

Table 3.24 - Main assumptions of the modelled scenarios

Scenario	Main assumptions
Business As Usual (BAU)	The status quo is maintained with regard to consumption and emissions. The Euro 6d technology is introduced as planned. The sales of hybrid and electric vehicles increase slightly.
Best Available Technologies (BAT)	A strong introduction of the new Euro 6d technologies is assumed since 2021. The sales of hybrid and electric vehicles is maintained equal to BAU. In 2030, the Euro 6d cars will represent 35% of the sales, namely almost 3 million vehicles.
Equal Technologies Share (ETS)	An equal share of sales is considered for all new technologies (Euro 6d, hybrid and electric cars). In 2030, all technologies will have the sales share equal to 25%.
European Policy 1 (EUPO1)	A possible implementation of the Transport 2050 [160,161] policy is proposed. The scenario considers a linear growth of hybrid and electric car sales reaching 90% in 2030. Electric cars are predominant.
European Policy 2 (EUPO2)	A possible implementation of the Transport 2050 [160,161] policy is proposed. The scenario considers a linear growth of hybrid and electric car sales ending in 2030 up to 90%. Hybrid cars have the highest sales share.

In the Business as Usual (BAU) scenario, simulations are carried out assuming the maintenance of the status quo with regard to consumption and emissions: the Euro 6d technology is introduced but no new initiative is undertaken to increase the stock energy efficiency. The sales of hybrid and electric vehicles increase slightly, as reported in Table 6. The car fleet in 2018 was 28,578,164 cars, while in 2030, based on the simulation carried out, it will include 29,744,705 units, showing an increase of 4.1% (1,166,541 units). This increase is in accordance with the trend of recent years, in fact the number of cars has always grown with the exclusion of 2012 and 2013, in which there was a decline due to the severe economic crisis that involved the country. With regard to the cars retirement, there is a decrease that becomes increasingly attenuated over the years; this is due to the high seniority of the car fleet during the first years of simulation which includes several cars over 20 years old. With time, the older vehicles are decreasing, consequently the scrappages also decrease, while those of Euro 5_6 cars, that meanwhile are increasing in age, intensify.

Table 3.25 - Sales rates of modelled scenarios

Year	Cars typology	Business As Usual (BAU)	Best Available Technologies (BAT)	Equal Technologies Share (ETS)	European Policy 1 (EUPO1)	European Policy 2 (EUPO2)
2018	Euro 5_6			99.6%		
	Euro 6d			-		
	Hybrid			0.4%		
	Electric			-		
2021	Euro 5_6	95%	90%	76%	67%	67%
	Euro 6d	3%	8%	8%	3%	3%
	Hybrid	1.5%	1.5%	8%	10%	20%
	Electric	0.5%	0.5%	8%	20%	10%
2025	Euro 5_6	90%	80%	52%	24%	24%
	Euro 6d	6%	16%	16%	6%	6%
	Hybrid	2.5%	2.5%	16%	20%	50%
	Electric	1.5%	1.5%	16%	50%	20%
2030	Euro 5_6	70%	50%	25%	5%	5%
	Euro 6d	15%	35%	25%	5%	5%
	Hybrid	10%	10%	25%	30%	60%
	Electric	5%	5%	25%	60%	30%

The Best Available Technologies (BAT) is the scenario that assumes a strong introduction of the new Euro 6d technologies since 2021. Indeed, the 2021 will be a year of fundamental importance because all the new registered cars will have to respect the Euro 6d regulation that will allow to reduce the release of emissions; in particular, the new cars will have to produce less than 95 g of CO_2 per kilometer traveled. In BAT, it is assumed that starting from 2021 there will be a strong decrease of first registrations of internal combustion cars Euro 5_6 (90%) compensated by the Euro 6d (8%). The sales of hybrid and electric vehicles is maintained equal to BAU, as reported in Table 3.25. Then, in 2025 a further increase in registrations of Euro 6d is assumed and sales reach 16% of the total. Finally, in 2030, the Euro 6d cars will represent 35% of the sales, namely almost 3 million vehicles.

The Equal Technologies Share (ETS) scenario considers an equal share of sales for Euro 6d, hybrid and electric cars. Since 2021, the three technologies increase the sales share. Finally, in 2030, the four technologies have the same 25% sales share. This will lead to a very fragmented stock in 2030: Euro 5_6 are 13,467,181; Euro 6d are 2,675,826; hybrids are 2,675,826; and electric cars are 2,883,636.

The European Policy Scenarios show two possible implementations of the Transport 2050 [161], the European strategy that wants half of the urban car stock not to rely on fossil fuels by 2030. The European objectives in terms of sustainable mobility development have been summarized in the document Transport 2050 [161] in which member states engage for reducing carbon dioxide emissions in the transport sector of 60% compared to values of 1990. In line with this, countries will also have to halve fossil fueled urban transport by 2030 in order to reach the 2050 goal of cities without fossil fueled cars [160]. The scenario considers a linear growth of hybrid and electric car sales ending in 2030 up to 90%. In this case, the urban stock in 2030 will accommodate 11,040,937 million hybrid and electric cars on a total of 29,744,705 million. In particular, in the European Policy 1 (EUPO1) electric cars are assumed predominant while in the European Policy 2 (EUPO2) hybrid cars have a higher sales share.

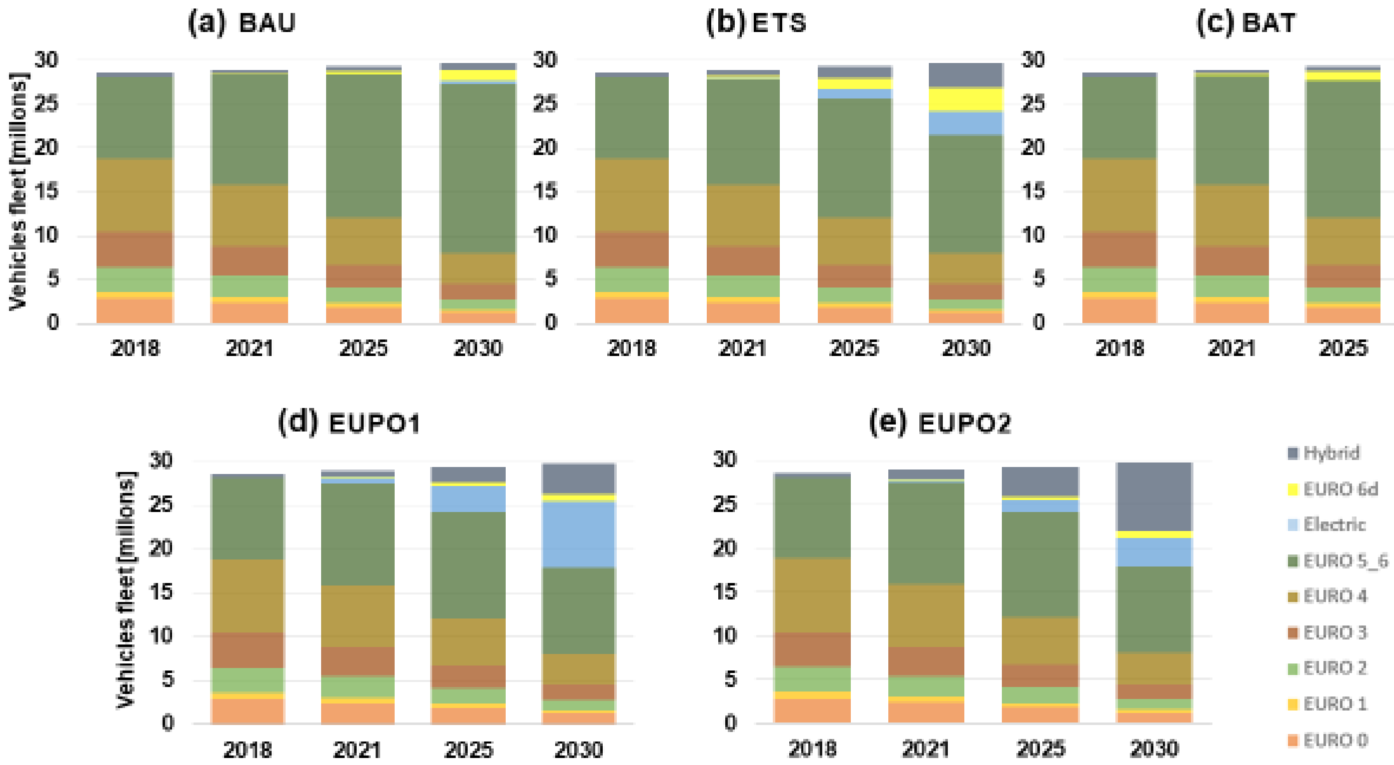

Figure 3.34 - Evolution of the vehicles fleet stock per scenario: (a) BAU, (b)ETS, (c)BAT, (d) EUPO1, (e) EUPO2

3.5.4 Results and discussion

The proposed methodology applied to the Italian case study allows to analyze in detail the evolution of the car stock with regard to engine displacement, fuel supplies and relative emissions. The results are described below in terms of assessment of the energy consumption changes, estimation of the emissions, and calculation of the transport-related external costs.

3.5.4.1 Energy consumption

By comparing the scenarios considered, it is clear that electric mobility plays a fundamental role in achieving energy saving goals. As reported in Table 3.26, the total final energy consumption in 2018 was 209 TWh. In the BAU scenario it decreases of 10.5 TWh in 2030. The technological improvement is the main reason laying behind the energy saving. In fact, the older Euro 1, Euro 2, and Euro 3 are being retired and substituted by more efficient technologies as Euro 5_6, Euro 6d, and electric or hybrid vehicles. The modern technologies allow to cover more kilometers for every liter of fuel consumed. The BAT scenario, that maintains the same amount of electric and hybrid vehicles as the BAU, shows a relatively higher energy saving (11.8 TWh) due to the increase of the Euro 6d cars to compensate a lower Euro 5_6 sales share. In the ETS scenario, the energy consumption decrease is more significant and allows to save 25.4 TWh thanks to the higher rate of new electric and hybrid vehicles penetration in the stock. The EUPO scenarios show how important are electric cars to achieve a higher energy saving. In fact, if the sales of electric cars are increased, as in the scenario EUPO1, the total energy consumption decreases of 48.2 TWh in 2030. Whereas, in case the policy focus is moved to the hybrid vehicles, the only 34 TWh can be saved in 2030. This is mainly due to the share of petrol and diesel consumption still being deployed by the hybrid vehicles. Indeed, the simulation results show that even if the hybrid vehicles might be important for a transition phase, the electric cars still play a more important role in the decarbonization.

Table 3.26 - Final energy consumption for all the considered scenarios [TWh]

Year	Euro0	Euro1	Euro2	Euro3	Euro4	Euro5_6	Electric	Euro6d	Hybrid	Total
					Business As Usual (BAU)					
2018	25.2	7	23.4	30.3	60.8	59.7	0	0	2.6	209
2021	21.3	5.9	19.8	25.5	51.4	80.3	0	0.6	2.4	207.2
2025	16.2	4.5	15.1	19.4	39.1	104.2	0.1	2.4	2.6	203.6
2030	10.8	3	10	12.9	26	123.8	0.6	7	4.4	198.5
					Equal Technologies Share (ETS)					
2018	25.2	7	23.4	30.3	60.8	59.7	0	0	2.6	209
2021	21.3	5.9	19.8	25.5	51.4	76.4	0.4	1.5	3.5	205.7
2025	16.2	4.5	15.1	19.4	39.1	87.5	1.8	6.3	7.2	197.1
2030	10.8	3	10	12.9	26	86.4	4.5	15.4	14.6	183.6
					Best Available Technologies (BAT)					
2018	25.2	7	23.4	30.3	60.8	59.7	0	0	2.6	209
2021	21.3	5.9	19.8	25.5	51.4	79.3	0	1.5	2.4	207.1
2025	16.2	4.5	15.1	19.4	39.1	99.8	0.1	6.3	2.6	203.1
2030	10.8	3	10	12.9	26	112	0.6	17.5	4.4	197.2
					European Policy 1 (EUPO1)					
2018	25.2	7	23.4	30.3	60.8	59.7	0	0	2.6	209
2021	21.3	5.9	19.8	25.5	51.4	74.5	1.1	0.6	3.8	207.1
2025	16.2	4.5	15.1	19.4	39.1	77.4	5.1	2.4	8.5	187.7
2030	10.8	3	10	12.9	26	63	12.6	4.8	17.7	160.8

Year	Euro0	Euro1	Euro2	Euro3	Euro4	Euro5_6	Electric	Euro6d	Hybrid	Total
					European Policy 2 (EUPO2)					
2018	25.2	7	23.4	30.3	60.8	59.7	0	0	2.6	209
2021	21.3	5.9	19.8	25.5	51.4	74.5	0.5	0.6	5.4	204.9
2025	16.2	4.5	15.1	19.4	39.1	77.4	2.3	2.4	17.1	193.5
2030	10.8	3	10	12.9	26	63	5.5	4.8	39	175

The old internal combustion cars are replaced with the modern Euro 6d cars and the hybrid and electric cars with higher efficiency. It should be remarked that, as a transversal consequence of incrementing the hybrid and electric cars stock, the national electricity demand will be higher and it will be necessary to increase the electricity import or generation by trying to exploit a higher percentage of renewable sources [100]. Hence, the assessment of the amount of electricity required to satisfy the electric cars penetration is necessary to understand if the Italian energy system will be able to cover the increasing electricity need. In all the alternative scenarios modelled the introduction of electric cars corresponds to an increase of electricity consumption. In particular, the scenarios show that in 2030 the electricity required is around 2.8 TWh for BAU and BAT and reaches 25 TWh for the EUPO2. Table 3.27 reports the increase in electricity required to meet the demand due to the introduction of electric cars, which will therefore depend on the percentage of hybrid and electric vehicles. It should be noticed that the EUPO2 scenario, that has a higher share of hybrids and a lower share of electric than EUPO1, allows lower energy saving compared to latter (-16.3% for EUPO2 and -23.1% for EUPO1).

Table 3.27 - Electricity impact in 2030 for all the considered scenarios

	Business As Usual (BAU)	**Best Available Technologies (BAT)**	**Equal Technologies Share (ETS)**	**European Policy 1 (EUPO1)**	**European Policy 2 (EUPO2)**
Hybrids share of the stock	2.9 %	2.9 %	9.7 %	11.8 %	26.0 %
Electrics share of the stock	1.1 %	1.1 %	9.0 %	25.3 %	11.1 %
Electricity required	2.8 TWh	2.8 TWh	11.8 TWh	21.5 TWh	25.0 TWh
Total energy consumption	199 TWh	197 TWh	184 TWh	161 TWh	175 TWh
Consumption decrease compared to 2018 (211 TWh)	5.0 %	5.6 %	12.2 %	23.1 %	16.3 %

Disaggregating by fuel, the BAU and BAT scenarios show an interesting increase of diesel consumption and decrease of petrol in 2030. This is related to the retirement of old Euro 0 and Euro 1 that used to have more petrol cars than diesel ones. The Euro 5_6 and Euro 6d have a higher share of diesel cars and are responsible of an increase of consumption of around 10% in 2030 compared to 2018. Whereas, if the electric and hybrid sales are preferred, as in the ETS, EUPO1 and EUPO2 scenarios, both the diesel consumption and the petrol one decrease as highlighted in Figure 3.35.

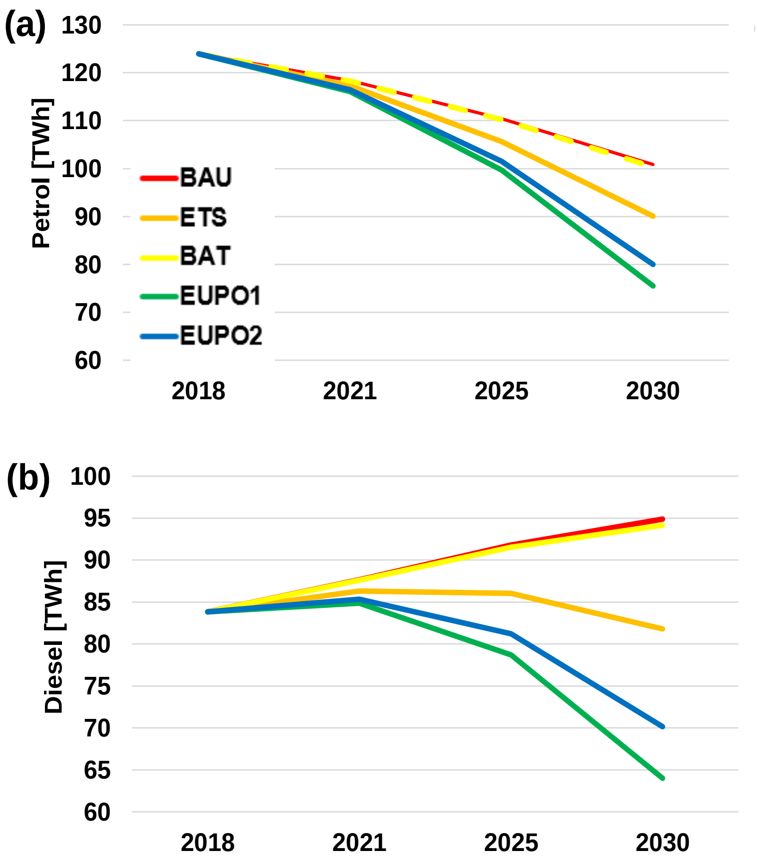

Figure 3.35 - Scenarios' comparison: (a) Petrol consumption; (b) Diesel consumption

3.5.4.2 Emissions

The implementation of electric mobility in Italy facilitates the reduction of all the polluting emissions thanks to the large share of renewable sources in the electricity generation system. In Figure 3.36, the environmental impact is reported in terms of emissions of Carbon dioxide (CO_2); Carbon monoxide (CO); Nitrogen oxide (NO_x); Hydrocarbons (HC); and Particulate (PM_{10}), the latter only for diesel cars. All scenarios show a decrease of emissions and this is due to the fact that the old internal combustion cars, in particular the Euro 0, characterized by very high levels of emissions, are being retired and replaced by more efficient technologies.

Nevertheless, even the most modern fossil fueled vehicles, as Euro 5_6 and Euro 6d, still produce more emissions than hybrid and electric cars. Hence, the sharpest decrease is reached in the EUPO1 scenario that has the higher electric vehicles share in the stock. The emissions of CO, NOx, HC and PM10 produced during the generation of electricity are not considered as this study focuses on electric cars, which are urban cars. However, even if it is true that electric vehicles do not eliminate emissions but "move" them to places of electricity generation, they facilitate the reduction of pollution in urban areas. It should be mentioned that batteries performance improved a lot [162] and recent research shows possible reusages of the lithium-ion batteries that are the most desirable ones for the automotive applications because of high power, energy capacity and long lifetime [163].

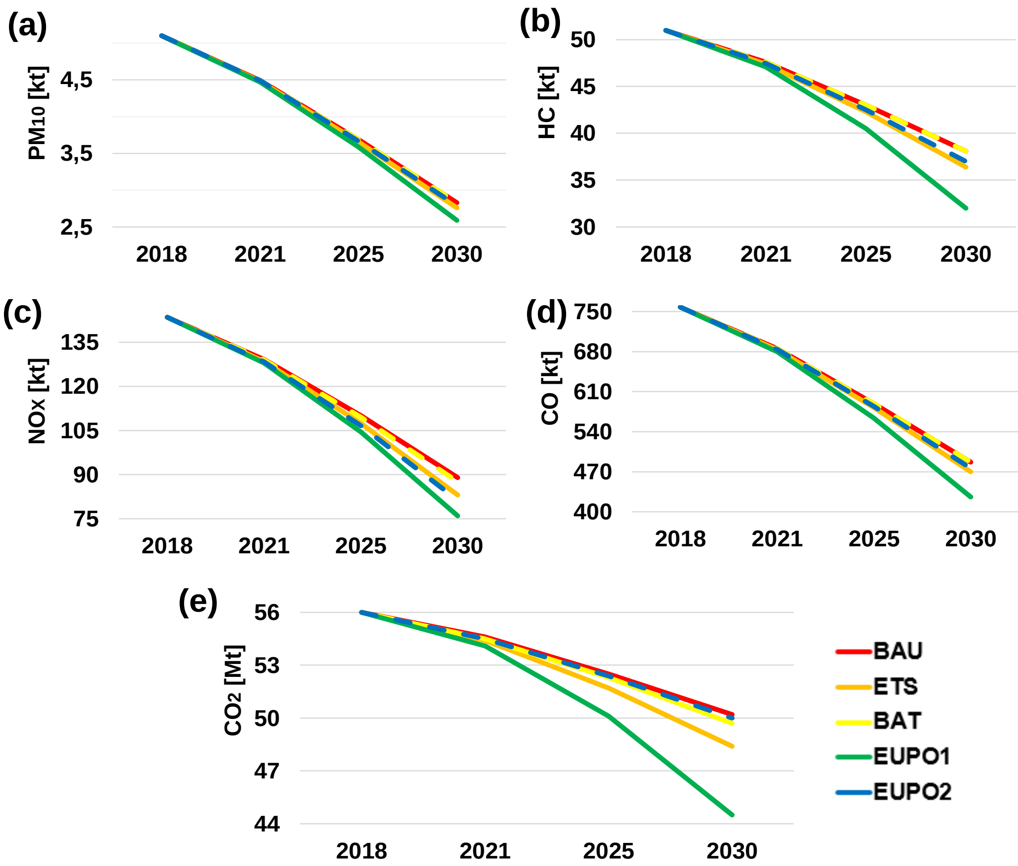

Figure 3.36 - Emissions estimations for the considered scenarios: (a) Carbon monoxide (CO); (b) Nitrogen oxide (NOx); (c) Particulate (PM10); (d) Hydrocarbons (HC); (e) Carbon dioxide (CO2)

3.5.4.3 External costs

The costs of externalities are calculated to assess the air pollution and the climate change impact. The unit value of externalities for Nitrogen oxides (NO_x), Particulate (PM_{10}) and Carbon dioxide (CO_2) are assumed equal to 21.3 €/kg; 22.3 €/kg, and € 100/tCO_2-eq respectively as suggested by the European Commission [164]. In particular, the Nitrogen and Particulate emissions effect is assessed via a damage cost approach, covering the following impacts: health effects, crop losses, material and building damage, biodiversity loss. Whereas, the Carbon dioxide (CO_2) externalities estimation focuses on the targets of the Paris Agreement, i.e. preventing temperature rises above 1.5-2 degrees Celsius (i.e. CO_2-concentration in the atmosphere below 450 ppm). The externalities costs highlight the importance of combining electric mobility with a process of modernization of internal combustion vehicles, necessary to achieve the objectives of energy saving, economic and environmental sustainability as highlighted in Figure 3.37. With a slight introduction of hybrid and electric vehicles in the stock, the BAU and BAT scenarios allow a saving of 1.8 billion€ and 1.9 billion€ respectively comparing 2030 to 2018. This is mainly due to the higher efficiency of the newer technologies as Euro 5_6 and Euro 6d with lower polluting emissions. As the electric and hybrid vehicles share of the stock increases, the positive payback is higher and reaches a total saving of around 2.1 billion€, 2.6 billion€ and 2.0 billion€ for the ETS, EUPO1 and EUPO2 scenarios respectively.

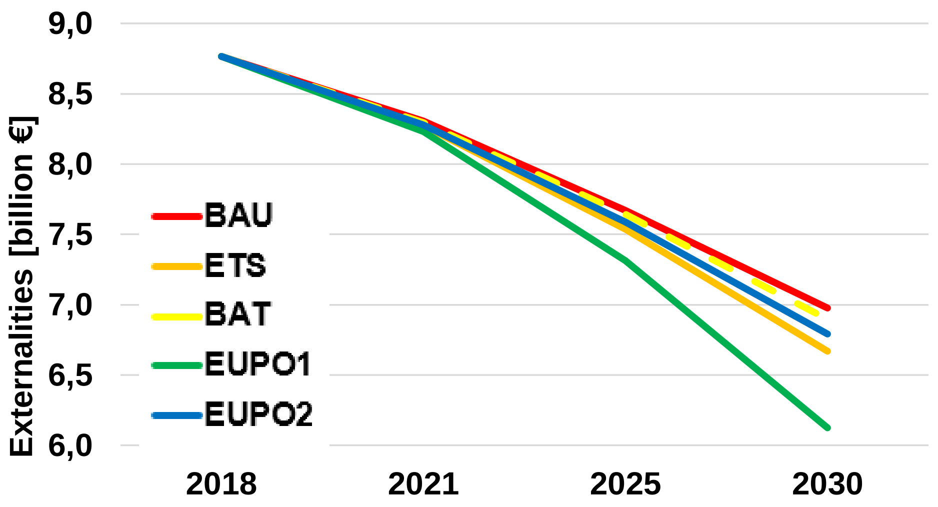

Figure 3.37 - Evolution of externalities savings

3.5.5 Conclusions

The Italian Electric Cars Fleet Model (IECaF) is used to elaborate the methodology and analyze the Italian car fleet stock according to engines typology, fuel type and compliance to specific EU regulations (Euro classes). Last decades technological developments for the decrease of fossil fuel consumption in cars are reflected in a decrease of the energy used in the coming years. The model allows to estimate the reduction of primary energy consumption and emissions deriving from the introduction of electric cars and the improvement of the efficiency of traditional cars. The scenario analysis shows the impact of the replacement with electric vehicles in terms of energy consumption, emissions, and external costs. In addition, the detailed investigation of the future sales helps policy makers to define the Euro classes and cars' typologies to be addressed first by the incentives.

Following a modest spread of electric vehicles in the BAU scenario, positive effects are found, and they can be summarized as a decrease in energy consumption (~ 5%), emissions (~ 10%) and externalities (~ 20%). In case the improvements on internal combustion engines are implemented (BAT), a reduction in the energy consumption of 11.8 TWh is obtained compared to 2018, accompanied by a decrease in polluting emissions (~ 11%). Thanks to the fragmented and detailed analysis, this scenario reveals how the research and development of more efficient and modern engines, geared to reducing consumption, has the effect of reducing energy demand. This is due to the generational replacement of cars and to the increase of modern engines with limited consumption.

The BAU scenario highlights how the regulations implemented in recent years, starting from Euro 1 in 1992, have affected the decrease in atmospheric pollution, improving the quality of the air and consequently the health of citizens. The scenario analysis shows that the implementation of electric mobility increases energy savings. If electric mobility is encouraged and there is a strong penetration of electric cars in the circulating vehicle fleet, the positive effects discussed above would be even more intense, leading to a saving of around 48 TWh (~ 23%) of energy. Hybrid vehicles can be considered as a transition technology as the positive results increase with the higher number of electric vehicles in circulation. Indeed, a continuous evolution of internal combustion engines with the aim of improving fuel consumption and efficiency is required.

The methodology can be easily applied to other countries guaranteeing data availability at a granular and detailed level. In particular, this methodology allows to investigate in detail the evolution of the car stock in terms of engine displacement, fuel supplies and relative emissions. Firstly, the energy consumption changes are assessed, then the pollutant emissions are estimated and finally the external costs are calculated for each modelled scenario.

4 Discussion and conclusion

In the previous sections, the author presented a collection of her research contributions aiming to investigate energy transition pathways towards the decarbonization of the urban context. After a deep analysis of the scientific literature, specific recommendations are outlined to improve the energy policy making process. All the elaborated methodologies are presented through case studies and can be applied to other cities or countries.

More precisely, the urban level is investigated in both developed (Italy) and developing countries (Egypt). Furthermore, the two more consuming energy sectors, the building and the transport sectors, are investigated in detail and the importance of the efficiency measure and the clean energy technologies is assessed for the medium and long term. Indeed, the role of (national and local) governance is undoubtedly important for any successful technological transition [28] and the research and policy tools, such as the energy GIS maps for Riva Trigoso and the TIMES model for Greater Cairo, can support the future energy policy making and planning.

Energy efficiency should be encouraged and improvement programmes should be launched to substitute all the outdated devices in residential, transportation, municipal and commercial sectors. In light of the conducted research on the residential sector, the author invites designers and policymakers to consider also the environmental impact during the production process or the import of the materials for the retrofitting. Indeed, this research draws attention to the added value of the embodied energy evaluation and the local climatic conditions, since they may lead to a completely different decision on the choice of efficiency measure interventions.

Regarding the transportation sector, it is clear that electric vehicles can help reduce the negative impacts of transport on the urban and global environment, to maintain international commitments to reduce greenhouse gas emissions and limit dependence on oil. In order to realize these scenarios, it is necessary that, from both a technological and governance point of view, co-operation is set in the development of electric mobility. Furthermore, it is important to emphasize that together with the spread of electric cars it is essential to strengthen the weight of renewable sources in the production of electricity. Only if the electricity is produced by renewable energy sources, the environmental balance of electric cars is unequivocally positive.

In this perspective, renewable energy sources and clean electricity generation are necessary for the sustainable urban energy transition of cities and megacities and can improve energy security of the country. Even if development is a necessary condition, improving the quality of life leads to a necessary increase in energy consumption that if satisfied with non-renewable energy sources will increase the CO_2 emissions per capita. Renewable energy systems can provide energy for the summer shortages, reduce the imports, solve the on-going energy crisis, and thus improve the national energy security. Therefore, this research concludes that accurate energy modeling is necessary for defining the optimal energy transition pathways, achieving the decarbonization goals and guaranteeing a better future for the upcoming generations.

List of publications

Journal papers:

Abd Alla, S., Bianco, V., Tagliafico, L. A., & Scarpa, F. (2020). Life-cycle approach to the estimation of energy efficiency measures in the buildings sector, *Applied Energy*, 264. https://doi.org/10.1016/j.apenergy.2020.114745

Abd Alla, S., Bianco, V., Tagliafico, L. A., & Scarpa, F. (2020). An innovative approach to local solar energy planning in Riva Trigoso, Italy. *Journal of Building Engineering*, *27*. https://doi.org/10.1016/j.jobe.2019.100968

Abd Alla, S., Bianco, V., Scarpa, F., & Tagliafico, L.A. (2020). Retrofitting for Improving Energy Efficiency: The Embodied Energy Relevance for Buildings' Thermal Insulation. *ASME Journal of Engineering for Sustainable Buildings and Cities*. (Under review)

Abd Alla, S., Bianco, V., Tagliafico, L. A. & Scarpa, F. (2021). Pathways to electric mobility integration in the Italian automotive sector, *Energy* , 221, 119882 https://doi.org/10.1016/j.energy.2021.119882

Abd Alla, S., Simoes, S. G., & Bianco, V. (2021) Addressing rising energy needs of megacities – case study of Greater Cairo. *Energy & Buildings*, 236, 110789 https://doi.org/10.1016/j.enbuild.2021.110789

Conference papers:

Abd Alla, S., Bianco, V., Scarpa, F., & Tagliafico, L.A. (2020). Retrofitting for Improving Energy Efficiency: The Embodied Energy Relevance for Buildings' Thermal Insulation. *Proceedings of the ASME 2020 14th International Conference on Energy Sustainability*. *ASME 2020 14th International Conference on Energy Sustainability*. V001T16A001. https://doi.org/10.1115/ES2020-1628

Abd Alla, S., Bianco, V., & Simoes, S. G. (2020) The Importance of Renewable Energy Systems in Meeting Rising Energy Needs of Megacities in a Sustainable Way: Case Study of Greater Cairo. *Proceedings of the ASME 2020 14th International Conference on Energy Sustainability*. *ASME 2020 14th International Conference on Energy Sustainability*. V001T10A003. ASME. https://doi.org/10.1115/ES2020-1629

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Abd Alla, S., Bianco, V., Scarpa, F., & Tagliafico, L. A. (2018). Energy demand, efficiency measures and embodied energy in the Italian residential sector. *ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE), 6*A-*144113*. https://doi.org/10.1115/IMECE2018-86400

Abd Alla, S., Bianco, V., Tagliafico, L. A., & Scarpa, F. (2018). Effect on the energy market of the potential switching to heat pumps for space heating. *Modelling, Measurement and Control C*, *79*(3). https://doi.org/10.18280/mmc-c.790312

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