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Addressing rising energy needs of megacities – Case study of Greater Cairo

Sara Abd Alla [a], Sofia G. Simoes [b,1], Vincenzo Bianco [a,*]

[a] University of Genoa – DIME/TEC, Division of Thermal Energy and Environmental Conditioning, University of Genoa, Genova, Italy
[b] CENSE Center for Environmental and Sustainability Research, NOVA School for Science and Technology, NOVA University Lisbon, Caparica, Portugal

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ABSTRACT

Urban energy system modelling allows megacities to assess their future development and to draw sustainable pathways to meet the rapidly increasing energy needs. This paper elaborates three different scenarios for energy transition in Greater Cairo with particular emphasis on the impact of lowering the share of inhabitants living in informal settlements. A city-specific TIMES energy system model is used to investigate how energy supply and demand will evolve between 2015 and 2050. Besides, 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.

1. Introduction

Cities play a key role in the climate change mitigation as they represent the place of main economic and social activities. The challenges of decarbonization become more relevant as the urban dimension increases like in megacities, i.e. cities with more than 10 million inhabitants [1]. 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 [2].

In this context, urban energy systems modelling is fundamental in helping megacities to plan and program the steps to meet the sustainable development goals [3]. Urban energy systems are the combined processes of acquiring and using energy to meet the energy demands of cities inhabitants [4]. 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 [5], but there is still a limited set of research papers addressing the energy transition of cities and megacities [6]. In particular, the dearth of studies analyzing the African megacities was highlighted by the SAMSET project [7] 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 [7]. In fact, even if more than a hundred papers propose models of megacities urban energy systems to provide relevant guidance to policy makers, most of them addresses developed countries or Chinese cities. Very few studies focus on African countries [8] and they rarely consider the urban energy systems intra-sector interactions [7,9] despite the fact that megacities located in developing countries are expected to have higher relevance in terms of energy consumption in the near future [10]. Therefore, there is a knowledge gap related to energy planning studies related to cities and megacities in developing countries and, especially, in Africa. The present paper aims at addressing this knowledge gap.

Greater Cairo (GC) is proposed as case study for modelling the rising energy needs of a megacity 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

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[*] Corresponding author.

E-mail addresses: sara.abdalla@edu.unige.it (S. Abd Alla), Sofia.simoes@lneg.pt (S.G. Simoes), vincenzo.bianco@unige.it (V. Bianco).

[1] Currently at LNEG – The National Energy and Geology Laboratory, Alfragide, Portugal.

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clearance that are conventional solutions adopted almost universally in developing countries' informal settlements [11]. 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 [8]. The object of this study is to assess 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.

The MARKAL-EFOM System (TIMES) model is developed for 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, GHG emissions, as well as share of renewable energy resources (RES) in total final energy consumption. To do so, six scenarios are modeled: (i) a Business-as-Usual (BAU) scenario assuming that the GC urban energy system will have no important changes in the future and no policies will address the informal neighborhoods; (ii) two scenarios addressing different paces of relocation of informal settlements, namely INFA considering the pace proposed in the Cairo Vision 2050 [12] policy framework, and secondly an intermediate pace of relocation (INFB); (iii) a combination of each of the previous three scenarios (BAU, INFA, INFB) with a GHG emissions mitigation cap in 2050 of 50% below 2015 emissions.

To the best of authors' knowledge this is the first attempt to model the energy and carbon emissions impact of relocation of informal settlements in a megacity and one of the few available papers addressing the issue of energy modeling of an African mega-city.

The paper is structured as follows: section 2 proposes a detailed literature review. Section 3 introduces the case study of Greater Cairo and the modeling method adopted including basic model description and data used. Results are presented and discussed in Section 4. Section 5 concludes the paper.

2. Literature review

2.1. Urban system energy modelling in megacities

In the literature, there are numerous definitions attempting to describe the city concept. The United Nations identify three approaches [1]: 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 paper, cities are defined as urban agglomerations and, in line with this, megacities are urban agglomerations with more than ten million inhabitants [1].

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. To this purpose, Sovacool and Brown [13] 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 find a significant regionalization of energy metabolism with relevant implication for resilience, infrastructure planning, GHG emissions, and policies for infrastructure decarbonization [14]. Most studies addressing the urban energy system in the available literature recur to two main analysis approaches: (1) simulation, to simulate the operation of a given energy system, and (2) optimization, to optimise the operation costs and the investments in a given energy system [5].

This paper wants to investigate pathways for megacities to cope with rising energy needs and a deep literature review is held to find all precedent works proposing a model to analyze scenarios impact on the whole urban energy system of the biggest 20 megacities [15]. Over 2000 papers are carefully analyzed and a lack of literature is 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.

As reported in Table 1, Tokyo and the Chinese megacities have a richer database of research studies aiming mainly to improve the energy consumption in urban public [17,23], transport strategies [18,23–25], residential sector [25] and power demand [16,26–30]. The other Asian megacities have fewer papers available in literature and they address mainly transport strategy [19,20], energy related CO_2 emissions [21] and urban solid waste management.

Regarding the South American cities, less studies are found in the literature: only few papers address Sao Paulo's urban sustainable development [37–39], and transportation [35,36]. So far, there is not 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 energy demand can be satisfied in a sustainable way.

Aiming to be the first paper to model and analyze the urban energy system of an African megacity, this article seeks to fill this gap using a city energy system optimization model for the case study of Greater Cairo megacity in Egypt applied for the period from 2015 to 2050. Greater Cairo is the 7th largest city in the world with a population around 21 million urban inhabitants and the first one in Africa [15]. 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 [53].

The literature review reported in Table 1 shows that previous works do not address the nexus between informal settlements and urban energy systems. 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. The dearth of data available prevents researchers from addressing properly the energy needs of the informal settlements, therefore they are underrepresented in previous studies. In this paper, the improved energy access is addressed modeling the inhabitants relocation to proper housing as planned in Cairo Vision 2050 [12].

2.2. Energy transition in megacities – Addressing informal settlements

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.

Table 1
Main studies addressing energy systems of megacities.

Ranking [15]	Megacity, Country	Population [15]	Focus of the modelling analysis
1	Tokyo, Japan	37,393,129	- renewable energy source integration and implications on power market [16] - urban ecosystem sustainability [17] - electric vehicles impact on power demand [18]
2	Delhi,India	30,290,936	- transport strategies [19,20] - energy flow in the urban system [21] - solid waste management [22]
3	Shanghai, China	27,058,479	- transport strategies [23–25] - residential sector [25] - power demand [26–30] - fuel consumption [31,32] - environmental impact [33]
4	São Paulo, Brazil	22,043,028	- solid waste management [34] - electric mobility [35,36] - decarbonization pathways [37–39]
5	Mexico City, Mexico	21,782,378	- no studies available
6	Dhaka, Bangladesh	21,005,860	- residential energy use [40] - solid waste management [41,42]
7	Greater Cairo, Egypt	20,900,604	- no studies available
8	Beijing, China	20,462,610	- residential and transportation sectors [25] - transportation sector [43] - energy saving and emission reduction [33] - natural gas consumption [31] - energy-carbon nexus [13,44]
9	Mumbai, India	20,411,274	- transport strategies [19] - load forecasting [45]
10	Osaka, Japan	19,165,340	- commercial sector [46,47] - residential sector [48]
11	New York, USA	22,100,000	- plug-in hybrid vehicles impact on power system [49]
12	Karachi, Pakistan	16,093,786	- solid waste management [22]
13	Chongqing, China	15,872,179	- environmental impact [50]
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 [51] - water-energy nexus [52]

Researchers assessed the importance of knowledge sharing and city-to-city learning at both national [54] and regional scale [55]. In this context, Butera et al. [56] 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 [57]. 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 [58]. 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 [59]. In addition, Butera et al. [60] 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 light of these considerations, there is nonetheless a need of addressing the transition of informal settlements when studying rising energy needs of megacities [61]. In the case of Greater Cairo, nearly two thirds [62] 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 [12], 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 [11]. From an energy efficiency perspective it seems to be preferable to keep the informal dwellings, making it easier to achieve GHG emissions targets [62], 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 [8]. 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.

3. Method and model

In this section an overview of the Greater Cairo urban energy system is presented and is followed by a description of the developed TIMES-Greater Cairo (TIMES-GC) model and the six modelled scenarios.

3.1. 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 [63]. 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 [64] and to meet the sustainable development strategy goals Egypt 2030 [65]. For instance, Mondal et al. [66] 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.

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 [12]. 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% [67] 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 [12], 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 this paper, the optimization model considers 2015 as the base-year. In 2015, the total energy consumption in Greater Cairo was 254 PJ [68]. 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.

3.2. The TIMES-Greater Cairo energy system model

With the aim of investigating how to address the Greater Cairo megacity rising energy needs in a sustainable way, a MARKAL-EFOM System (TIMES) model is 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 [69]. 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) [69]. The main features of the GC TIMES model are summarized as follows:

- Methodology: identification of the optimal cost-effective solution to satisfy the energy demand in the respect of given constraints. It consists in a partial equilibrium model which uses linear programming techniques to determine the optimal solution.
- Input: energy demand projections, fuel prices, RES potential, policy constraints (e.g. emissions limit, limitation on the utilization of a specific fuel, etc.), efficiency of the considered technologies, operating life, emission factors, etc.
- Output: primary energy consumption per fuel, emissions, amount of deployed technologies, final energy prices, etc.

Pre and post processing of data can be done through graphical interface which allows to upload/download input/output data in a spreadsheet format.

Due to their flexibility, TIMES models have been implemented at global [70], national [71] and city level [72–74]. The TIMES-GC model was based on the model structure developed by [75], with several adaptations made by the authors as detailed in the following sections.

3.2.1. Overview of the TIMES-Greater Cairo model structure and main inputs

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 Fig. 1.

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 the figure. Also as depicted in Fig. 1, the most relevant TIMES-GC model outputs are the primary and final energy flows and consumption,

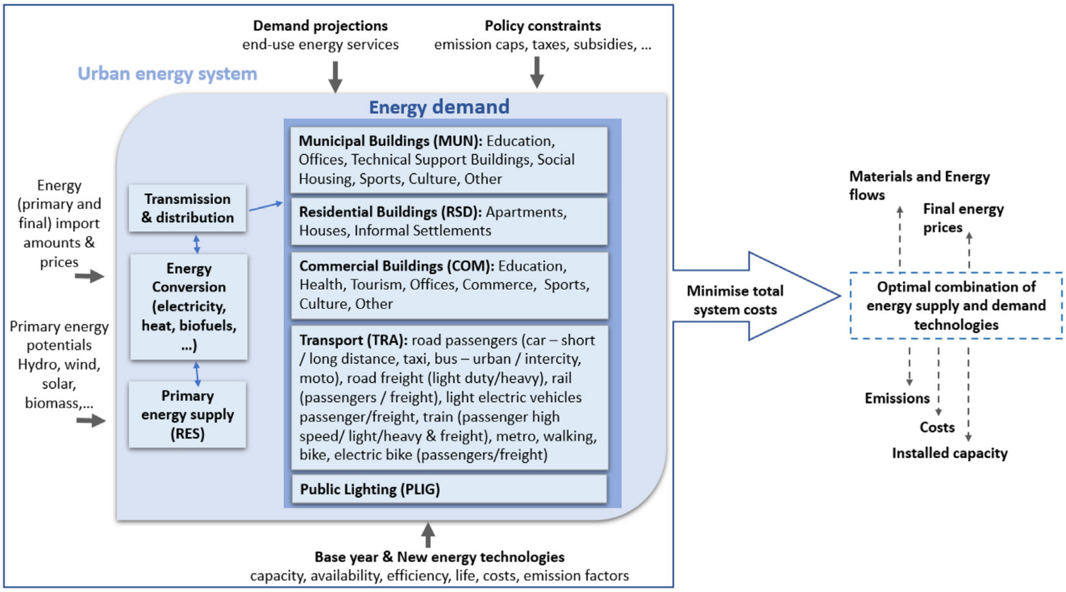

Fig. 1. Overview of the TIMES-GC model structure (). adapted from [76]

Table 2
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$)	[77]
Residential	*Stock*	Statistical Yearbook 2015	[68]
	Energy consumption	OntarioTech University Database on Megacities	[78]
	Shares of energy carrier	IEA	[79]
	Growth rate of inhabitated buildings	Statistical Yearbook 2015	[68]
	Growth rate	Statistical Yearbook 2015	[68]
Transportation	*Stock*	Statistical Yearbook 2015	[68]
	Energy consumption	OntarioTech University Database on Megacities	[78]
	Shares of energy carrier	IEA	[79]
	Modal Share split	World Bank Cairo Traffic Congestion study	[80]
	Shares of vehicles type per zone	Statistical Yearbook 2015	[68]
	Trips per day (25 million)	National Authority for Tunnels	[81]
Commercial	*Stock*	Statistical Yearbook 2015	[68]
	Energy consumption	OntarioTech University Database on Megacities	[78]
	Shares of energy carrier	IEA & Statistical Yearbook 2015	[68]
Municipal	*Stock*	Statistical Yearbook 2015	[68]
	Energy consumption	OntarioTech University Database on Megacities	[78]
	Shares of energy carrier	IEA & Statistical Yearbook 2015	[68]
Public Lighting	*Energy consumption*	Statistical Yearbook 2015	[68]
	Growth rate	Statistical Yearbook 2015	[68]
Electricity	*Electricity demand and generation plants*	Annual Report, Ministry of Electricity, 2016/2017	[63]

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.

3.2.2. Main data inputs, assumptions and limitations

Data collection is 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 are used to complete the urban energy system background. More details about the data used in the model can be found below in Table 2.

The Statistical Yearbook 2015 [68] published by the national statistics authority CAMPAS provides most of the stock data for all sectors. The OntarioTech University Database on Megacities [78] contains the energy consumption data and the shares of energy carrier are calculated based on the IEA Statistics per sector [79]. 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 [78]. To this regard, for commercial and municipal sectors, IEA provides only the share of electricity consumption so the data are integrated with the natural gas and LPG values in the Statistical Yearbook 2015 [68]. This is necessary as the commercial and municipal sectors include restaurants and canteens that require natural gas and LPG.

In this model, several assumptions are necessary to provide a closer similarity with the real energy system. The public lighting energy consumption are set according to the national values of the Statistical Yearbook 2015 [68]: a GC value is calculated as a weighted average of the national value on the population. An optimal number of

Table 3
Overview of the modelled scenarios.

Parameters/scenario	BAU – Business as Usual	INFA - Cairo Vision 2050 [12]	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 [12], 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	2.2% between 2008 and 2050 JICA estimation for Cairo 2050 Vision [84]	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 [12]	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 consumption per capita of electric appliances in residential sector (kWh/capita)	1.0% Historic values 2007–2014 [68]. 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 [68]		

lamps is 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 is 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 [82]. 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 [83]. In the residential sector, it is assumed that there is no space heating or space cooling for the informal settlements buildings.

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 paper, 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.

Besides, a sensitivity analysis on carbon intensity of electricity generation should be developed. Similarly, a sensitivity analysis on share of relocated people from informal settlements that are commuting back to the center would be appropriate to confirm the historic increase trends applied in this paper. Finally, innovative informal energy services provision (as prepaid electricity or off-grid fuel sources and technologies) is not considered although it would be relevant for countries without an already structured electricity infrastructure as Egypt.

3.3. 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 [12] 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 2 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

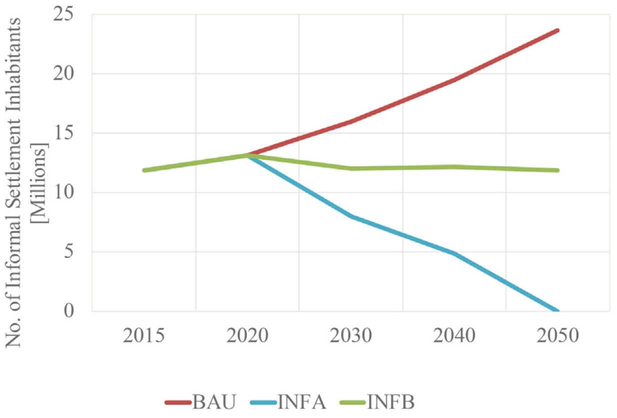

Fig. 2. Assumptions on relocation of inhabitants of informal settlements for BAU, INFA and INFB.

relocated between 2030 and 2050 in this scenario. The visualization of the differences between inhabitants of informal settlements is depicted in Fig. 2 and further detailed in Table 3.

A relevant assumption highlighted in Table 3 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.

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 paper, the road transport mileage increases gradually in time and the values are reported in Table 2 and in Fig. 3.

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) [12], in areas where public transport plans do not include new metro lines, and thus no metro lines are considered in this paper.

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.

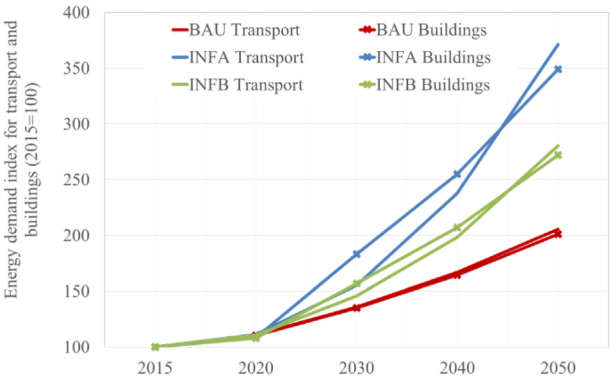

Fig. 3. Evolution of exogenous demand for energy in the transport and residential sector.

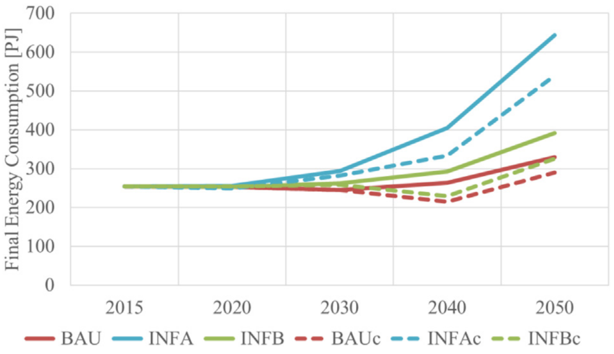

Fig. 4. Total final energy consumption evolution for each modelled scenario.

4.1. Final energy consumption

The resulting Final Energy Consumption (FEC) evolution is depicted in Fig. 4.. Following the considered energy services demand growth (as in the previous section), by 2050, FEC in Greater Cairo can grow between 31 and 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 Fig. 3.

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 and 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 4 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 neces-

Table 4
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%

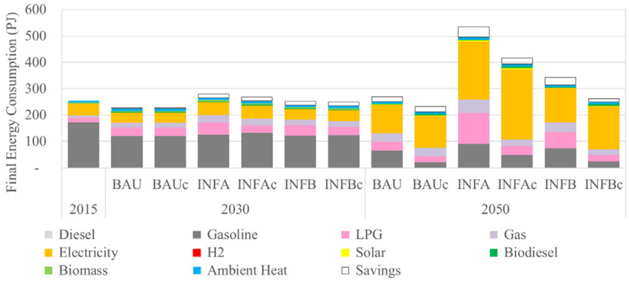

Fig. 5. Final energy consumption evolution per energy carrier for each modelled scenario.

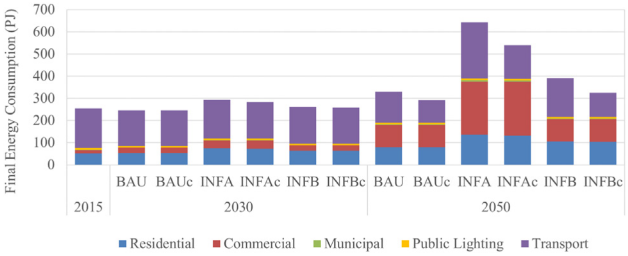

Fig. 6. Final energy consumption evolution per economic sector.

sary to deploy more energy efficient technologies than in the scenarios without the cap (detailed in the following section).

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 Fig. 5 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 as previously explained in section 2.2.2. 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. Fig. 5 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.

4.2. Final energy consumption evolution per sector

Fig. 6 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 5. 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,

Table 5
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%
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
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

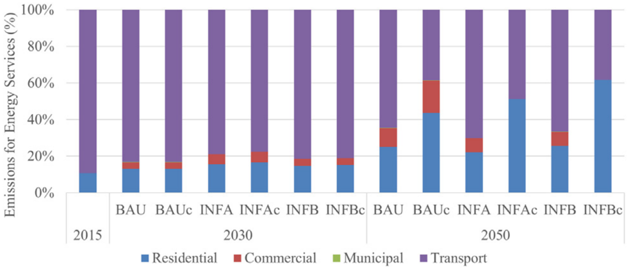

Fig. 7. Share of sector CO2 emissions for Greater Cairo (%).

Table 6
CO_2 emissions per capita (kg CO_2/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

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. As stated in section 2.2.2, 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.

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 Fig. 7 shows, transport is the sector with the highest city CO2 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. In this paper, 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.

In Table 6, 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.

5. Conclusion

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" [6]. 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.

In this research, a technology-oriented approach is adopted to investigate the urban energy transition of Greater Cairo. 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 need to be considered, without forgetting the active role of people living in informal settlements which contribute with their own innovative technological and behavioral innovations.

Following the demand growth of energy services modelled, by 2050, final energy consumption in Greater Cairo can grow between 31 and 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.

The role of (national and local) governance is undoubtedly important for any successful technological transition [6] and the research and policy tools, such as TIMES model for Greater Cairo can support the future energy policy making and planning. The results assess energy changes and technological and environmental impact of the different scenarios and outlines policy objectives to be adopted. The main policy recommendations are listed here below:

- Renewable energy sources (RES) and clean electricity generation are necessary for the sustainable urban energy transition of megacities and can improve energy security of the country. Improving quality of life leads to a necessary increase in energy consumption that if satisfied with non-renewable energy sources will almost double the CO_2 emissions per capita (INFA). Renewable energy systems can provide energy for the summer shortages, reduce the imports, solve the on-going energy crisis, and thus improve the Egyptian energy security;
- Greater Cairo Region should establish a unit solely responsible for the energy planning and management of the three governorates and the follow of the energy impact of the urban expansion programmes;
- Energy efficiency should be encouraged and improvement programmes should be launched to substitute all the outdated devices in residential, transportation, municipal and commercial sectors. TIMES model for Greater Cairo showed that energy efficiency is a viable strategy to achieve a carbon emission reduction also without mitigation policies (BAUc).
- Energy data on demand and supply should be made available for energy modeling and forecasting analysis.

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. This research concludes that modelling the energy-environment-economic nexus is highly important for elaborating cost-effective and environment-friendly policies. Finally, the authors recommend that future research focuses on the integration of urban expansion and energy consumption in order to address the sustainable development of megacities. Similarly, issues related to the assessment of current and future level of energy poverty as well as the financial impact of energy efficiency policies are to be considered in future works.

CRediT authorship contribution statement

Sara Abd Alla: Conceptualization, Methodology, Writing - original draft. **Sofia G. Simoes:** Conceptualization, Methodology, Writing - review & editing. **Vincenzo Bianco:** Conceptualization, Methodology, Writing - review & editing.

Declaration of Competing Interest

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

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