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Transition to energy sustainability in emerging cities: A study of positive-sum scenarios

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Abstract

Theoretically, all places on earth are endowed with renewable energy resources. However, the requirements for co-existence with existing energy and non-energy infrastructure limit the technical realization of these resources. Chapters 1-3 set the framework of the research study. Chapter 4 demonstrates that the city of Dakar, Senegal, has solar photovoltaic, waste-to-energy, and wind energy resources that could support transition to energy sustainability. Through the collection of readily available materials from different sources, we were able to estimate, for the first time, the potential (in Megawatt) of waste-to-energy, solar photovoltaic, and wind energy at the scale of the city, and to compare it with potential in Vienna.

Ordinarily, energy planners use modelling software to simulate the integration of this renewable energy potential into the grid. In 2018, Ringkjøb et al. identified 75 energy modelling software. Chapter 5 demonstrates that different energy modelling software return different figures of the sustainable energy transition in Dakar, with different costs and environment strains. As the differences originate from the modelling approach embedded in the software programming interface, we propose an innovative energy modelling software, known as MoCES, which is tailored to the needs of cities like Dakar. The MoCES approach integrates the multi-faceted dimensions of sustainability in simulating energy scenarios.

Policy strategies are necessary to implement the energy transition scenarios in the city. Chapter 6 proposes a combination of backcasting methods and mechanism design by identifying, among the different scenarios that feature feed-in renewable energy resources to the grid and demand side management, those that return the highest eco-efficiency, meaning the lowest environment strain at budget-balanced cost.

Together, this study's findings open new perspectives for planning and monitoring the contributions of emerging cities (according to the definition of the New Climate Economy) so they can achieve the post-2015 energy and climate objectives stated in both the Paris Agreement and the United Nations Sustainable Development Goals (SDGs).

Kurzfassung

Theoretisch sind alle Orte der Erde mit erneuerbaren Energiequellen ausgestattet. Die Anforderungen an die Koexistenz von vorhandener Energie- und Nicht-Energie-Infrastruktur schränken jedoch die technische Realisierung dieser Ressourcen ein. Kapitel 4 zeigt, dass die Stadt Dakar im Senegal über Ressourcen für solare Photovoltaik, energetische Abfallverwertung und Windenergie verfügt, die den Übergang zu einer nachhaltigen Energieversorgung unterstützen könnten. Mithilfe einer Datenerhebung von verfügbaren Materialien aus verschiedenen Quellen konnten wir erstmals das Potenzial (in MW) für Energiegewinnung aus Abfall, Solarphotovoltaik und Windenergie für die Stadt Dakar ermitteln und mit dem entsprechenden Potenzial in Wien vergleichen.

Üblicherweise verwenden Energieplaner Modellierungssoftware, um die Integration dieses Potenzials in ein Netz zu simulieren. Im Jahr 2018 haben Ringkjøb et al. 75 Beispiele solcher Energiemodellierungssoftware identifiziert. Kapitel 5 zeigt, dass verschiedene Energiemodellierungssoftware unterschiedliche Zahlen hinsichtlich der nachhaltigen Energiewende in Dakar mit unterschiedlichen Kosten und Umweltbelastungen liefern. Da die Unterschiede auf den in die Software-Programmierschnittstelle eingebetteten Modellierungsansatz zurückzuführen sind, schlagen wir eine innovative Energiemodellierungssoftware, MoCES, vor, die auf die Bedürfnisse von Städten wie Dakar zugeschnitten ist. Der MoCES-Ansatz integriert die facettenreichen Dimensionen der Nachhaltigkeit in die Simulation von Energieszenarien.

In der Praxis sind politische Strategien erforderlich, um die Energiewende-Szenarien in der Stadt umzusetzen. In Kapitel 6 wird deshalb eine Kombination aus Backcasting-Methoden und Mechanismusdesign vorgeschlagen. So lassen sich unter den verschiedenen Szenarien, in denen erneuerbare Energiequellen in das Netz eingespeist werden und bei denen ein Management auf der Nachfrageseite betrieben wird, diejenigen identifizieren, die die höchste Ökoeffizienz erzielen, mit der geringsten Umweltbelastung und hoher Kosteneffizienz.

Zusammen eröffnen die Ergebnisse der Studie neue Perspektiven für die Planung des Beitrags aufstrebender Städte (gemäß der Definition der Initiative New Climate Economy) zum Erreichen der Energie- und Klimaziele nach 2015, die im Übereinkommen von Paris und in den Zielen der Vereinten Nationen für nachhaltige Entwicklung (SDGs) festgelegt sind.

Dedication and acknowledgment

To my grand-ma Fatou Yacine Diama Fall whose generosity and dignity continue to guide my life.

To my parents, and to all friends who supported this adventure, since I started in 2016; I found the courage to start this work and you gave me the force to achieve it.

Contents

List of figures and graphs

List of abbreviations

AHP: Analytical Hierarchy Process

AIM: Asia-Pacific Integrated Model (AIM)

ASF: Atmospheric Stabilization Framework Model

CO2-eq: CO2 equivalent; sum of greenhouse gas emissions associated to an energy generation system converted to CO2 quantities using the gas radiative forcing

DSS: Decision support systems

ELECTRE: ELimination Et Choix Traduisant la REalité

ENPEP-BALANCE: Energy and Power Evaluation Program

IMAGE/TIMER: Targets IMage Energy Regional simulation model

LEAP: Long-term Energy Alternative Planning

MADM: Multi-attribute decision making

MARIA: Multiregional Approach for Resource and Industry Allocation Model

MARKAL: MArket ALlocation

MESSAGE: Model of Energy Supply Systems And their General Environmental Impact

MiniCAM: Mini-Climate Assessment Model

Mio: million as account unit

MoCES: Modelling Cities Energy Sustainability

MODM: Multi-objective decision making

PROMETHEE: Preference Ranking Organization METHod for Enrichment of Evaluation

RETScreen: Renewable Energy Project analysis software

SGM: Second Generation Model

WEM: World Energy Model

1. Introduction

1.1 Motivation

The primary motivation for this research is to bring contribution and answer to the topical issue: how to reconcile human technological progress and environment sustainability. Within this framework, the study looks into the energy sector in the context of cities, as major emitter of pollutants responsible for many environment outrages, including climate variability and loss of biodiversity. This contribution can be philosophical in many ways, as it questions human's capacity to surpass the comfort of experience forged through centuries of technology developments, and to adapt with new mechanisms to a new environment. Exploring this issue in a doctorate of philosophy (PhD) cursus opens up a wide range of perspectives in re-thinking the concept of energy sustainability, including through technological innovation, and requires a rigorous methodology to frame the study within a specific time and space.

1.1.1 Emerging cities

The city of Dakar, as a case study, offers an accurate panorama of the energy related challenges that emerging cities face: sufficient generation capacity, affordability of access, and security of supply. Our definition of an emerging city derives from the New Climate Economy report (2014), meaning "rapidly expanding middle-income, mid-sized cities (…), with populations of 1–10 million, and per capita incomes of US$2,000-20,000". Two other city categories are in the report.

- Megacities are defined as major cultural centres with populations above 10 million and per capita income over US$2,000, and include capital cities such as London.
- Mature cities are defined as mid-sized cities in high-income countries that have per capita income above US$20,000, and include capital cities such as Vienna.

Today, the global action to reducing cities' ecological footprint focuses on cities in the emerging category, who are expected to have both highest population and economic growths. According to the UN (United Nations, 2018), 515 of these cities had a population above 1 million in 2018, and the number is projected to increase to 663 cities by 2030. The same report estimates that 48 cities have populations between 5 and 10 million, and by 2030, 10 of these cities are projected to increase their population to above 10 million inhabitants. Projections indicate that 28 additional cities will cross the 5 million mark by 2030, of which 13 are located in Asia and 10 in Africa. Dakar is projected to be slightly below that mark with a population projected at 4.3 million by 2030. Figure1.1 (below) shows the projection of cities population dynamics between 2018 and 2030.

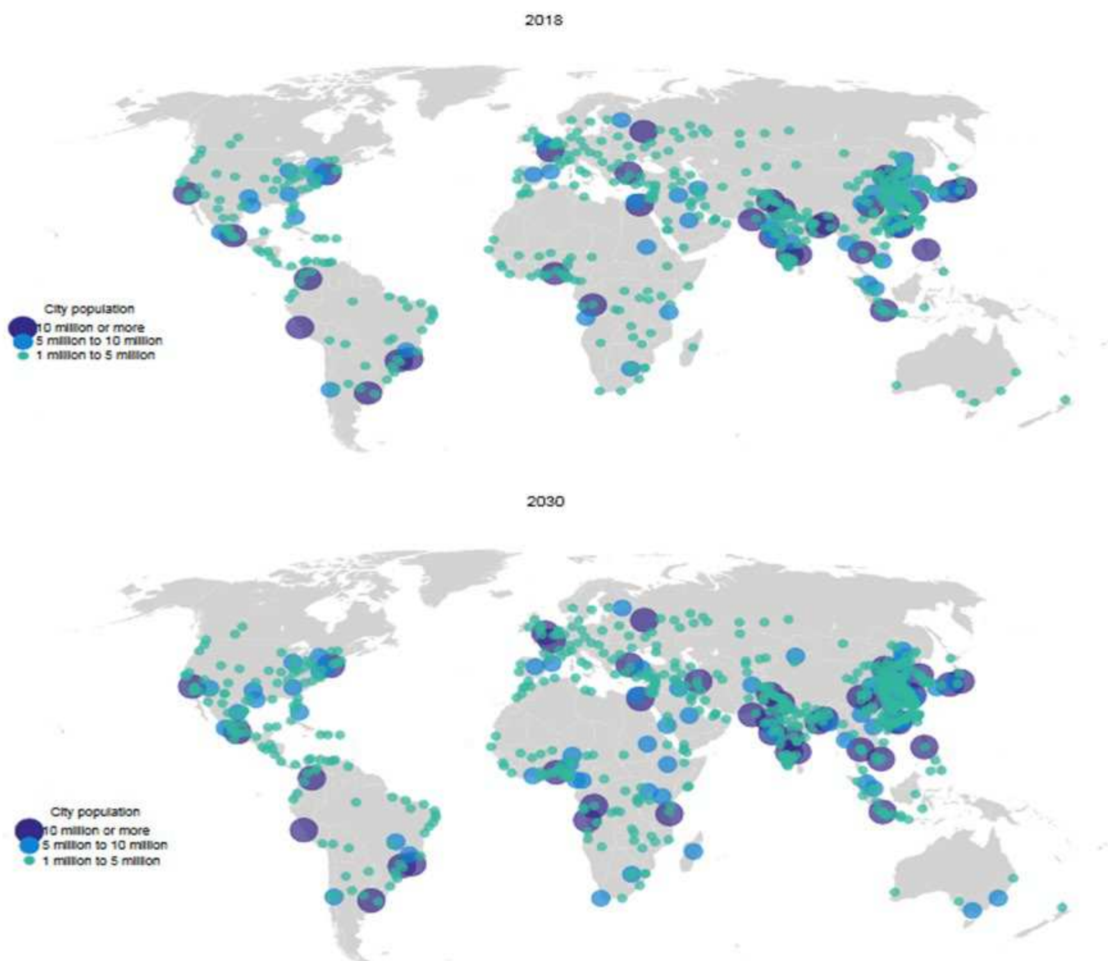


Figure 1.1: World Cities population (2018-2030)

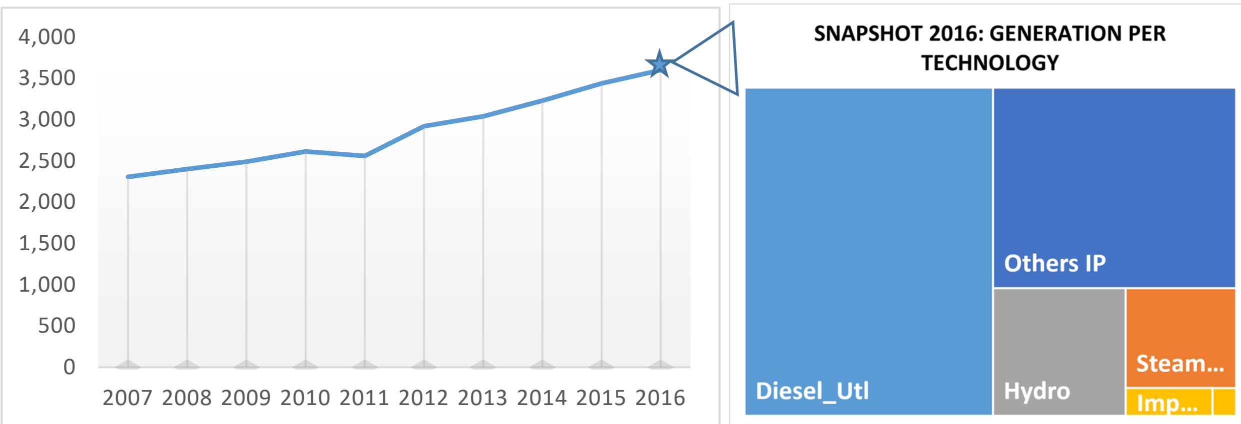
Source: United Nations (2018)

1.1.2 Energy in an emerging city

The electricity system of Dakar can be analysed through two parameters: capacity and cost. Graph 1.1 illustrates the evolution of gross electricity generation for the interconnected grid that supplies

Dakar in electricity[1] during the period 2007-2016, and a snapshot of the situation in 2016, which is considered as baseline of our study (SENELEC, 2009-2017).

Graph 1.1. Electricity supply in the interconnected grid (GWh)



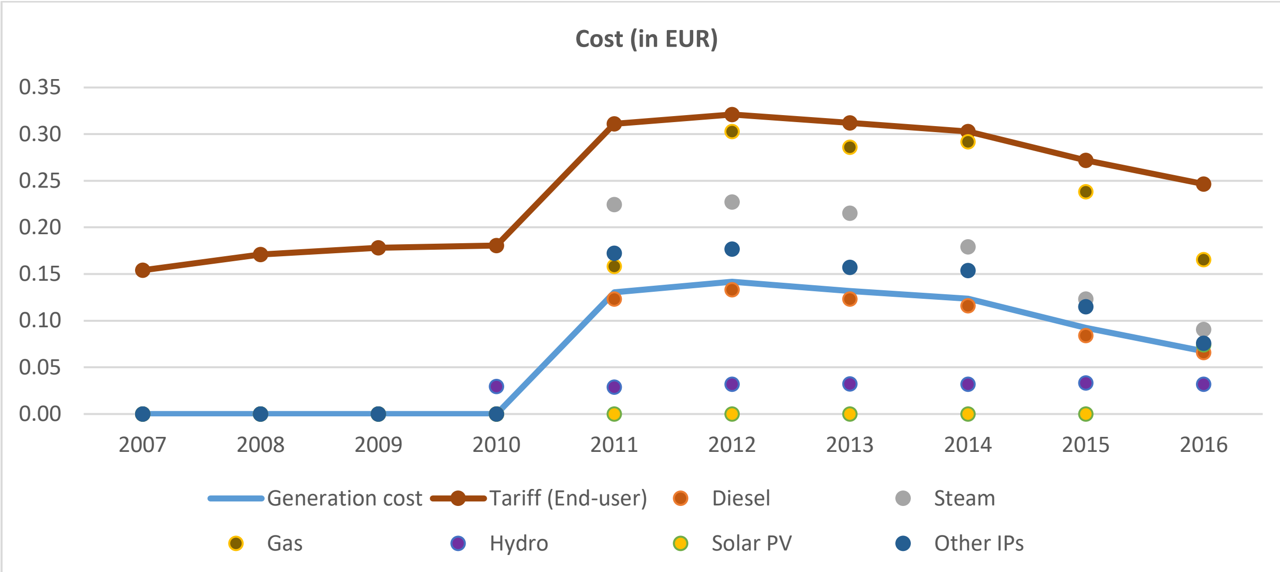
Electricity generation has steadily increased during this period, with an average rate of +5.4 percent per year, to reach 3,598.7 GWh in 2016. The annual variation was only negative between 2010 and 2011 (-1.9 percent), due to decrease of the utility generation, mainly from diesel and steam units. In 2016, these diesel and steam installations of the utility (Utl) represented, respectively, 50.6 percent and 6.8 percent of the interconnected grid supply. Independent producers (IP) represented 42.3 percent of the grid supply, among which 24.6 percent were from hydropower (Manantali and Felou dams), and 0.3 percent were from solar photovoltaic.

These energy generation quantities supplied 64% of energy access at the national level, and 90% access at the city level in 2016 (IEA, 2019). Ceteris paribus, the generation should have been 5,804 GWh to supply a universal access scenario in areas covered by the interconnected grid. The capital city of Dakar consumed 62% of the electricity distributed in 2016 to 1,782.5 GWh (ANSD, 2018).

Graph 1.2 illustrates the evolution of the electricity cost on the interconnected grid, for the utility as single operator (line blue), and for the end-user (line red) between 2007-2016, in comparison to the cost of generation technologies supplying the grid.

[1] There are isolated grids that supplies the administrative regions of Casamance (south) and Tambacounda (east).

Graph 1.2 Electricity costs and tariffs of the interconnected grid (EUR cents)



The energy generation cost during this period was on average EUR 7 cents, which is close to the utility cost of diesel units' generation. Diesel units represent on average 70% of the electricity generation park. Natural gas units have the highest generation cost of the period, but this cost has constantly decreased from 2011 to reach EUR 24 cents in 2016, which is equivalent to 33.7 percent less than the highest peak in 2012. Hydropower remains the cheapest generation option of the period (about EUR 3 cents). With the exception of hydropower units, overall the costs of the different energy technologies have constantly decreased since 2012. The large solar photovoltaic generation introduced to the grid in 2016 has a cost equivalent to the average generation cost at EUR 7 cents per kWh. In comparison, the median electricity price of all suppliers was EUR 5.4 cents per kWh for Vienna in 2016 (E-Control, 2018).

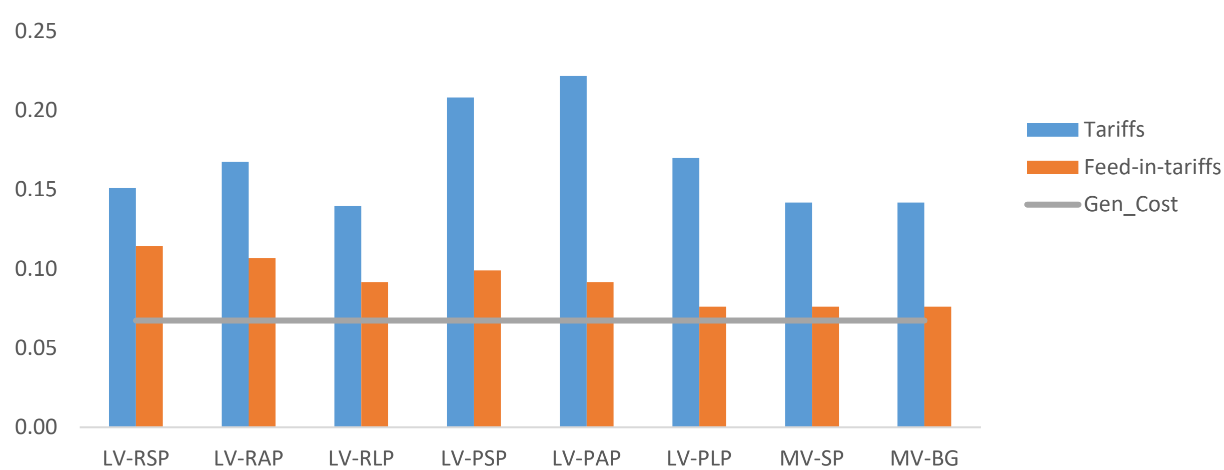
The tariffs to end-users regulated by the national regulation authority (CRSE) remained almost stable between 2010 and 2016, at around EUR 18 cents. The electricity tariffs for households varied during this period between EUR 13.8 cents (social tariff) and 18.4 per kWh. For the industry sector, the tariff varied between EUR 8 cents (connection in high voltage outside peak load) and EUR 27.9 cents (connection in medium voltage during peak load). In comparison, the average electricity tariff was EUR 20.2 cents per kWh for households[2] and EUR 9.6 cents per kWh for industries in Austria

[2] The legal framework in force in Austria does not provide a mechanism for social tariffs.

in 2016 (Statistics Austria, 2016). The price regulation mechanism in Senegal sets a framework that pre-calculates a maximum electricity sale price for a 3-year period. At the end of a calculation period, and when the utility costs verified by the regulators are higher than pre-determined tariffs, the central government pays the difference (deducted of any penalty on the utility due to non-respect of obligations in terms of grid extension, new customers connected, duration of incidents etc.).

The legal regulations in force in Dakar also provide a framework for distributed renewable energy generation and evacuation of excess through the interconnected grid. Law 2010-21 in December 2010 (Framework of energy generation with renewables) sets capacity rules on electricity auto-production and general conditions for evacuation of the excess through the interconnected grid. Decree n°2011-2014 of December 2011 organizes the conditions of electricity generation for self-consumption and the utility purchase modalities, and gives authority to the regulation agency (CRSE) on the calculation of the price guaranteed for remuneration of excess generation with renewables (feed-in-tariffs). In 2018, CRSE published the methodology for calculation of the feed-in-tariff for biomass energy, solar photovoltaic, and wind, with different subcategories related to the producer status (either residence or commerce), the subscription option, and the voltage of the system (CRSE, 2018). Graph 1.3 compares the generation cost of the utility (in 2016) to the electricity tariffs and the feed-in-tariff offered for excess generation with renewable technologies per end-user category.

Graph 1.3 Electricity generation cost vs. end-user tariff and feed-in-tariff



The feed-in-tariff is not proportional to the utility tariffs for the different categories of electricity end-users. The feed-in-tariff is highest for the low-voltage residence small power subscription (LV-RSP) and is lowest for the low-voltage professional large power (LV-PLP) and for the medium voltage (MV) categories.

1.1.3 Energy sustainability in an emerging city

Sustainability, in general, is the backbone to the post-2015 Development Agenda adopted by 193 countries, including Senegal. This agenda features seventeen development goals, including universal access to modern energy (SDG-7) and climate-resilient cities (SDG-11) to be achieved by 2030. The concept of sustainability when coupled with variants of the "development" concept usually refers to three pillars: society, economy, and environment. We undertook this research to question how the multi-faceted dimensions of these pillars affect the issues mentioned above in conjunction with accessibility and the transition to energy sustainability in an emerging city, here exemplified by Dakar. Therefore, our study is guided by the following three core questions:

1. What is the techno-economic value of energy sustainability in an emerging city?
2. Could the integration of all sustainability dimensions in modelling energy systems generate positive sum outcomes at city level?
3. Which policy mechanisms could support the realization of positive sum scenarios of energy access and transition to sustainability in emerging cities?

Among the hundreds of emerging cities worldwide, the selection of Dakar, Senegal as central city for this study is motivated by both personal and practical reasons. As someone who is Senegalese, it made sense to connect my research during this human and scientific journey called doctorate cursus to my city of birth (Dakar) and to my current city of residence (Vienna). This approach explains the frequent references to Vienna in comparing figures and legislation in the first chapters of this study. The practical reasons relate to the accessibility of city data, which was facilitated through both my previous research conducted in the framework of my master cursus that assessed the wind potential on the Senegal coastal region that includes Dakar, and my role as the coordinator of the project called Sustainable Energy Access for Sustainable Cities (SEA4cities), a joint project between Austria and Senegal.

1.2 Core objectives

The main research objective is to identify technology and policy requirements that could prepare emerging cities access and transition to sustainable energy systems, as a contribution to the global effort for a "better future" as defined by the United Nations Action Agenda for Sustainable development (United Nations, 2015). Specifically, we wanted to reach this objective through a comprehensive methodology in which we committed in these three steps:

(1) to assess the technical and economic potential of renewable energy in our sample city, Dakar, and to compare it to potential in Vienna,

(2) to consider the concept of energy sustainability in a system perspective with dynamic citizens, who have expectations that are neither necessarily long nor always rational, and

(3) To open avenues for thinking about the sustainable city of tomorrow, which integrates simultaneously a diversification of generation sources in favour of renewables and a better efficiency in management of the demand.

To assess the city technical and economic renewable energy potential is the first research objective because it frames the relevance of technology and policy options we will consider throughout the study. Results of this assessment in terms of theoretical, technical, and economic potential provide the energy value of renewables generation in the city.

To consider the many dimensions of energy sustainability in the broad perspective of a city contextualizes their value that is only relevant to agents (citizens) so they can realize their potential. Information on gains and losses related to access with a renewable energy source as alternative to grid access, sets basis for the system regulator to design policy mechanisms that orientates the citizens' preferences, while keeping the system emergent. Achieving this objective motivated us develop an innovative tool for planning energy systems in cities, the Modelling cities Energy Sustainability software (MoCES). The software addresses many of the drawbacks that appear in other current energy modelling software when integrating intermittent renewable energy technologies to planning and monitoring city energy systems.

To open avenues for thinking the best policy mechanisms achieves our primary objective to contribute to the knowledge of emerging cities access and transition to sustainability with best available technologies and policy mechanisms that could prove simultaneously technical, environmental and economic relevance.

1.3 Major literature

1.3.1 Urban Energy systems 18 Grübler et al. (2012). Cambridge University Press

Rapid population growth over the last few decades push cities to rethink their models for supplying basic services, in general, and energy services, in particular. Population growth in cities are imputable to combined phenomena of natural growth and human migrations from both national and international localities. According to the United Nations, the world's cities occupy about 3 percent of the Earth's land, and host 55.3 percent of the world population (4.2 billion) in 2018, and figures are projected to reach 60.4 percent (5.2 billon) by 2030. These cities generate about 80% of global economic output, consume 70% of global energy production, and are responsible of an equivalent share of energy related greenhouse gas (GHG) emissions (New Climate Economy, 2015). Over the last two decades, Africa recorded the highest urban growth, with cities' population projected to pass from 36% in 2010 to 50% by 2030 (Transform Africa, 2017). The capital city of Senegal, Dakar, is an illustration of this dynamic, with a population that increased from 400,000 in 1970 to 3.4 million inhabitants in 2016 (ANSD, 2018).

Grubler et al. estimate that some 80% of all commercial energy use in Sub-Saharan Africa can be classified as urban, suggesting that the current urban population (below 50%) largely dominates this region's energy use; a disproportionate phenomenon that can be amplified by population growth over the next decades. Therefore, planning for the region's future energy consumption should provide substantial leverage in anticipating solutions to most of the region's current urban challenges. In Sub-Saharan Africa cities, the sustainability challenges in the energy sector feature essentially three dimensions: access, transition to sustainable generation technologies, and efficient use of energy generated. Inspired by an old adage that says "that only what gets measured gets controlled", the publication postulates that only if the energy metrics are accounted accurately at an urban scale, then they are useful for policy guidance at this scale. Grubler et al. identify two possible energy accounting methods at the city level, which are further classified as production oriented methods (2) and consumption oriented methods (2).

a) Production oriented methods

- Final energy (physical flows) metric measures the consumption of final energy such as electricity and gasoline within the city boundaries.
- Regional energy metabolism metric measures all energy flows that cross the city boundaries. In contrast to the final energy metric, the primary energy used by the energy sector within the city is included in the regional energy metabolism.

The two production oriented methods require map to frame the city boundaries. Barles (2009) provides an illustration of how influential these boundaries could be on the metric value. She considered, for example, the fossil fuel use in Paris, its suburbs, and the larger Parisian metropolitan region. The per capita fossil-fuel use was lowest in the city of Paris, due to the lower transportation energy required by central Paris with its Metro system, compared to its suburbs. The per capita fossil-fuel use increased as the region considered expanded, which in addition to energy for transportation also includes energy-intensive industries located beyond the city center.

In addition to the slipping effect of the many geographic boundaries of a city on the energy metric, another issue is how the connection flows to external units. The final energy metric includes energy uses to manufacture goods and to provide services that are exported from the city (and consumed in other cities or in rural areas). The regional energy metabolism metric includes all the energy imported into the city, regardless of its conversion status.

b) Consumption oriented methods

- Regional economic activity metric measures the urban final energy demand aggregate (in monetary terms) that is a regional energy-to- GDP relationship, from which to derive the city-specific energy use (Dhakal, 2009).
- Energy Input-Output (I-O) metric derives from national economic I-O tables that measure, usually in monetary terms, all sales and purchases of goods and services among the production sectors. For energy analysis, these tables are extended to account physical energy flows and related emissions (Pachauri, 2007).

The two consumption oriented accounting methods require a city to set an urban economy metric; usually the gross regional product (GRP) is considered. This metric relevance is debated because it ignores the weight of energy use in excluded parameters such as the informal economy, which is relatively important in developing countries. Schneider (2012) estimates that the informal economy averaged about 40.2 percent of the total official GDP in Sub-Saharan Africa in the period 1999-2007. Comparatively, the share was 17.1 percent in OECD countries during the same period.

In conclusion, Grubler et al. draws attention to the limits of policy guidance of existent publications on energy system planning for cities, which suffer from inconsistent system boundaries and irrelevant accounting methodologies.

1.3.2 Modeling Energy systems for Developing countries. Urban et al. (2007). Energy Policy, Elsevier

Since the 1970s, following the first oil crisis, regional economic organizations, national governments, and academia developed energy models in order to:

- evaluate the effect on the general economy of the energy sector,
- assess the impact on the environment of energy planning,
- find mechanisms to reduce dependence on costly energy imports.

Ringkjøb et al. (2018) identified seventy-five computer based energy-modeling tools. These models were built and used predominantly in industrialized countries. The adaptation of some of these models when planning the energy systems of developing countries assumes that the energy systems of developing countries would behave like those of industrialized countries, with variable time lags (Shukla, 1995). Therefore, the scenarios modelled derive from experience in the energy sector of industrialized countries, blurring the context of specific characteristics of energy systems that include the weight of legislation in countries (e.g tariff regulation). In Table 1.1, Urban et al. describe the treatment of different context-specific energy criteria in 12 models that record experience of use in developing countries.

Table 1-1 Experience of energy system modelling in developing countries

	Performance of power sector	Supply shortages	Electrification	Traditional bio-fuels	Urban-rural gradient/ urbanization	Informal economy	Structural economic change	Investment decisions	Subsidies
AIM			(x)	x	x				
ASF			(x)						
IMAGE/ TIMER			(x)	x	(x)				
LEAP	(x)		x	x	x				(x)

MARIA			(x)				x		
MARKAL			x	x	x				(x)
MESSAGE			x	x	(x)		x		(x)
MiniCAM			x	(x)	(x)				(x)
PowerPlan	x	x	(x)						
RETScreen			x	x	x			(x)	(x)
SGM			x	x					(x)
WEM			x	x	x			(x)	(x)

X: explicitly modelled characteristic (i.e the characteristic is an input parameter)

(x): implicitly modeled characteristic (i.e the characteristic is embedded in the equation)

Each of the 12 models were assessed in the light of 10 characteristics. The table is a matrix of 10x12, with 120 coding values. Apart from basic characteristics that all models feature, six models embedded in their equation 50% or more of the criteria the authors identified as being of particular relevance for the energy sector of developing countries.

- LEAP, MESSAGE, RETScreen and WEM integrated the largest number of criteria relevant to energy systems of developing countries (50 percent or more).
- MARKAL, MiniCAM, AIM, IMAGE/TIMER, PowerPlan and SGM incorporated a medium number of these criteria (between 30 and 50 percent).
- MARIA and ASF included the smallest number of these criteria (less than 30 percent).

In 42 percent (19/45) of the cases where a criterion is combined with a model, these criteria are implicitly embedded in the model equation. Subsidies, for instance, are only implicitly integrated in all models' algorithm where it is considered, meaning the model user can assume subsidies are in the energy system when entering data into the model, but the user cannot track the impact of these subsidies on the system outcome, for instance on the cost. Another criterion, as mentioned in the previous publication, is the informal economy that is embedded in any of the 12 models.

Urban et al. describe the informal economy as the transactions that take place in real terms, but are not reflected in official economic metrics, like the GDP or GRP for cities. Because data on the informal sector are rare, modelers have difficulties depicting them in deterministic models, where outcomes are computed with average figures, without any room for randomness. The absence of a parameter of this importance in models can lead to a bias that pushed Urban et al. to conclude that any of the current modelling approaches, whether top-down or bottom-up can represent the energy system of developing countries.

(1) Top-down approach is not realistic because market behavior (implicitly embedded as demand quantities) is a limited driver of energy consumption in developing countries, and production frontiers are not as clearly defined as in industrialized countries (e.g. the production frontier of wood fuel).
(2) Bottom-up approach could be a relevant option, mainly because the model is independent of market behavior and the deterministic factors of production frontiers, and because technologies are explicitly modelled. However, some drivers of the energy market such as demand, and technology change remain exogenous in these models, meaning the modeler cannot track their impact on the models' outcomes.
(3) Hybrid approach such as that of IMAGE/TIMER features an interesting evolution that combines a top-down approach for the energy demand and a bottom-up approach for the energy supply, which allows flexibility in the model. Still, only a limited number of context-specific criteria are embedded in these models.

1.3.3 Review on multi-criteria decision analysis aid in sustainable energy decision-making. Wang et al. (2009). Renewable and Sustainable Energy Reviews Elsevier

Energy models, whether the built approach is top-down or bottom-up, produce outcomes that are too restrictive, when only the cost and CO2 metrics are tracked to capture sustainability. Abu Taha and Daim (2013) suggest that energy planning is a more complex process with many factors and agents involved; though the interest on multi-criteria approaches as alternatives to previous deterministic approaches. Their review of current literature on the applications of multi-criteria decision-making in the field of energy sustainability identified four categories:

- Renewable energy and planning with 23 references,
- Renewable energy technology evaluation with 19 references,
- Selection of sustainable energy projects with 24 references,
- Sustainable energy issues discussion from an environmental perspective with 11 references.

Multi-criteria decision-making methods are either multi-objective decision-making (MODM) or multi-attribute decision-making (MADM).

(1) In MODM, the decision problem is characterized by the existence of multiple and competitive objectives that is optimized against a set of available constraints.

(2) In MADM, the solution to the decision problem is a set of alternatives against a set of criteria. Here the ‘‘best’’ model outcome is the first ranked alternative, which is not necessarily an optimum.

Multi-attribute decision-making analysis provides a framework that can be integrated in models with multi-faceted dimensions of energy sustainability, by giving the modeler more room to factor in account as many criteria as required by the context peculiars. The capture in algorithms of the many models' criteria is facilitated by recent developments in the field of information technology.

Multi-attribute utility theory is reported to be integral and significant in the literature of multi-attribute decision-making applications to energy according to Pohekar and Ramachadran (2004). The theory models the decision-maker's preferences in the form of a utility function that is defined over a set of attributes, where the utility of each attribute does not have to be linear. Other multi-attribute decision-making analysis tools that record application in the field of energy sustainability include the analytical hierarchy process (AHP), the Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE), ELimination Et Choix Traduisant la REalité (ELECTRE), and decision support systems (DSS). These are helpful tools that are available as software, with basic functionalities that the modeler can customize to simulate energy scenarios. Because modern cities are recognized in the urban studies' literature as complex and emergent systems (Batty, 2005), Wang et al. propose a long list of criteria related to reliability, appropriateness, and practicality that should be considered when creating context-relevant energy models.

The modularity of the multi-criteria decision making approach allows the combination of an infinite number of criteria relevant to different energy contexts. It is worth being noted that when delivered from the deterministic parameters of agents' behavior linearity and the pre-condition of market equilibrium, the only limit to system modelling is the modeler's imagination. Paradoxically, it is this infinite nature of possibilities which fixes limitations to modelling energy systems with multi-criteria decision making approach, because the model inputs, in particular the system agents 'preferences and rules, become then preponderant.

1.3.4 The Model Thinker: What you need to know to make data work for you (Page, 2018). Basic Books

In his General System Theory, Ludwig von Bertalanffy (1969) proposes two approaches for modelling a system: (1) to define the general laws that are fit to empirical observations; and (2) to arrange the empirical fields in a hierarchy of complexity of the basic individuality behavior. The energy modelling tools mentioned in the previous paragraphs, which are inspired by the neoclassic school of economics, use the first approach. This means the modelling software with a black box, features built-in-functions with algorithms that are an abstraction of the real system at different points of time. The system outcome at T+1 is determined by initial conditions (T), but the model does not capture the dynamic related to transition from T to T+1, because the modelling approach makes the implicit assumption of linearity in the system agents' behavior and generality in decisions rules. Scott Page identifies four rationales for building models.

- To use and understand data;
- To understand what's going on around us;
- To be clear and better thinkers;
- To better, design, strategize and decide.

Clearly, the general law modelling approach proposed by Von Bertalanffy can achieve the first goal of Page's rationale, but fails to achieve the three Page's other rationale in a cascade of biases. The general law approach requires deterministic factors that underlines the principles of symmetry of information and rationality of agents who can anticipate and optimize choices that should lead to the system equilibrium. We agree with Flores (2008) that such an assumption is nothing short of fantastic literature, and therefore models that assumes these principles cannot forge a clear understanding of the reality. The reason is the intrinsic limitations of mathematical theorems cannot capture the randomness that characterizes human-centered systems. Indeed, the rational of mathematical theorems is to provide same results when fitted with same data. Same parameters produce same outcomes on similar proportions (the notion of derivatives in mathematics and elasticities in economics).

However, if a model fails to make sense of the system now, then it cannot support decisions about the system's future. Back in the eighteenth century, the philosopher David Hume, who stated the basic principles of empirical science, to which economics aspire, outlines that no finite series of observations can justify the statement of a general law valid in all places, and at all times. This statement substantiates our first hypothesis that current energy models developed in the context of mature cities cannot produce outcomes relevant in the context of an emerging city.

When considering Von Bertallanfy's second approach in modelling, we can introduce the three characteristics of agent-based modeling formulated by Page: economic actors as computational objects, emergence, and complexity.

a) Economic actors as computational objects

The concept of the system agents as computational objects requires a definition of the many criteria that govern these agents' rules and the logic of their interactions in the system. There are more than just the cost and CO2 emissions to track to understand an energy system, regardless of its geographic focus. Examples of these rationales include:

(1) Anticipation of the future: the agents foresee benefits from an actual policy scenario that will incentivize them to make a decision. For instance, investment in a solar PV household at T could be more or less advantageous than making the same investment at T+1, when the regulator could revise the incentive policy (e.g feed-in-tariff).
(2) Conscious planning: other agents might show more interest in saving on their energy bill in the long-run than saving some cash in the capital investment. Therefore, they decide to invest in solar photovoltaic, foreseeing a gradual independence from the utility grid.
(3) Dedication to a cause: other agents could take more interest in protecting the immediate and/or distant environment by reducing greenhouse gas emissions than in saving money, either as an investment or on periodic bill.

The definition of rules for the system agents allows the system to capture as many rationales that would otherwise have been impossible to envision in a single theorem. Thus, Page concludes his argument by stating that agent-based models reconcile the coherence of neo-classical paradigm with the breadth of Keynesian analysis.

b) Emergence

Friederich Hayek's (1948) states that "order in a market is necessarily emergent", and Roegen-Georgescu's (1971) argues the entropy component of the second thermodynamics law implies any local change of order in a system bears cost. When the system is an electricity market, the additional cost includes greenhouse gas emissions. Reducing this cost requires that the market initially provides it with a value. A question remains on what extent the market is able to give a fair value, provided such a value exists. However, what is of interest here is the system ability to keep its emergence property while, valuing the emissions cost. For instance, the decision of an agent without energy access to either connect to the grid or to invest in a cleaner production source like solar photovoltaic, can be answered from a basic rule: the energy value of the solar photovoltaic generation should be higher than the value of the grid generation. If the value of the grid electricity happens to be higher, then the agent will choose energy access with the grid. The system order remains emergent, but the potential to have a less polluting energy generation is a probability measure that depends on the energy value. What about the energy value? It is the inverse of a kWh electricity cost, assuming the consumer's indifference on the kWh, which is worth the same service whether it is generated from solar photovoltaic or heavy fuel. The question that a sustainable energy policy primarily raises is the feasibility of the scenario, where market mechanisms can influence the agents' preferences enough to undertake the transition. Then, a relevant model outcome should depict the mechanisms' costs to influence the agents' preferences, while keeping the system emergent.

c) Complexity

Murray Gell-Mann, the 1969 Physics Nobel laureate, famously said "imagine how difficult physics would be if electrons could think" (Gell-Mann, 1994). Yet, electrons do not think, but agents planning their energy systems probably do think. Their decisions are a result of a complex architecture of rationales, learning, and adaption mechanisms. Complexity is another characteristic of the system dynamics that is particularly relevant to consider in modelling a system with externalities, like electricity. The mechanisms, which the agent-based approach uses to capture the complexity in models, pave the way to the recurrent critiques formulated on agent-based modelling in the scientific literature.

Critique 1: Agent-based models are situation-specific and are hardly falsifiable and replicable, Richiardi et al., (2006).

This implies different environments or different agent segments (in a similar environment) require different models. This critique usually comes with the general deterministic characteristic of systems.

Critique 2: Agent-based models can be deemed arbitrary and rules be somehow disconnected to previous learning of the agents in the system (Wickens, 2014).

We can substantiate this critique with the physics notion of equifinality, which states that in a closed system the final state is determined by initial conditions. For instance, the position of a planet at time T+1 is unequivocally related to its position at T. However, from a position at T, if the planet direction (the motion process) deviated for any reasons from its usual trajectory, its position at T+1 would be different.

Both critiques can be answered by agent-based modelling that assumes neither the stability of tractable data (econometric) nor the predictability of a pre-defined result (equilibrium). The freedom in modelling opens the system to all possible outcomes, inclusive of equilibrium, but does not actually exclude it, which is in accordance with the physics characterization of systems. System theory identifies four possible outcomes of system dynamics: chaos, equilibrium, pattern, and wave. Indeed, if a model featuring relevant parameters of a system results in chaos, then it is more likely the system runs into chaos rather than to a mentally constructed equilibrium.

Critique 3: The sophistication of agents' interactions, without pre-condition, can only result to either chaos or equilibrium (diverse authors).

Authors of this critique warn of a return on anarchy in economics that used to prevail before Lucas critique (1976). There, we could recall Richiardi's argument, referring to Lucas metaphor on computational equilibrium models and doctors, that assistance from models as from doctors is needed when the conditions are bad, and even in tranquil times, it is unproven these models are of practical relevance.

1.3.5 Backcasting the future (Roorda, 2001). International Journal of Sustainability in Higher Education

As stated by Page (2018), the ultimate rational of a model is to support the process of making an informed decision. Cass Sunstein and Richard Thaler (2008) argue biases of rationally predictable agents in models have real implications on policy formulation.

The policy formulation approach based on backcasting the future provides a space for capturing what Page calls the ordinal outcome of models, which differentiates from the cardinal outcomes made of numerical values. For Roorda, the definition of backcasting the future of a system is to use the information available now (T) to construct a vision of what the future (T+1) would have to look like in order to consider it (now) as a desirable system (then). For computing "then" from "now", Roorda proposes the eco-efficiency formula introduced by Barry Commoner (1971).

$$ee = \frac{E * P}{S}$$

Equation 1 Eco-efficiency formula

Where,

- ee: system eco-efficiency
- P: city population
- E: Per capita energy supply (Es) or demand (Ed)
- S: Environment strain (the change produced in response to pressure on energy resources i.e the impact per unit of E variation on parameters such as pollutant emissions or land use intensity)

The United Nations defines the concept of eco-efficiency as a key element for promoting fundamental changes in the way societies produce and consume resources, meaning a tool to achieve greater value with lower adverse environmental impacts (United Nations ESCAP, 2009).

Let us assume that the objective is to reach by "then" an improvement of a city eco-efficiency with a factor of 3, different policy options could be considered "now":

1. Improvements with existent technology (timeframe = short i.e up to 5 years)

- Subsidies to electricity generation with renewables
- Direct contribution to retrofit domestic appliances

2. Technology innovation (timeframe: medium i.e 5-10 years)

- Investment in innovation on energy conversion technologies such as off-shore wind
- Investment in new lighting appliances for improved efficiency

3. System innovation (timeframe: beyond 10 years)

- Combined investment on new generation technologies and improved domestic appliances
- Enforcement new policy mechanisms that improve households' energy behavior

In order for the policy to be efficient, it needs to fit the timeframe in terms of objective and evaluation period. For instance, measures to improve the energy performance of households should not commit the policy-maker (in terms of investment and results) more than a period of a 15 years maximum to be efficient. Here, we formulate the second hypothesis of our research that policy mechanisms, without additional cost, can drive our sample city ambitions of transition to a sustainable energy system in future.

1.4 Structure of the thesis

This research thesis is divided into three parts. Chapter 1 introduces the study and provides an overview to the foundation and rationale behind this research, and the value it can add to state-of-the-art in the fields of energy modelling and planning. The rationale of the research places the research context within a specific time and space, and consequently defines the limitations of its findings' relevance. The research's value addition to the state-of-the-art is complimented by major literature references that serve as a guiding thread throughout our reflection. Chapters 2 and 3 present the research background, and the methodology applied to the study. In the background chapter, we explore the characteristics of energy models and present rationale for our modelling approach that is agent-based. Chapter 3 presents the conditions of the study, through definition of parameters that determine significance of scenarios modelled and set conditions of the methodology replicability in a different context. The methodology is a set of comprehensive multi-criteria decision making modelling steps that answer the research questions. The flexibility of our approach combined to the consistency of the methodology motivated us to develop a new computer-based modelling software tailored to the study objectives.

From the state-of-the art, the study presents the contributions towards a new optimum in modelling transition to energy sustainability in Chapters 4 to 6. Chapter 4 frames the technical, geographic and time boundaries of the study. It describes the economic and technical parameters related to the bioenergy, solar photovoltaic and wind resources potential studied; the geographic framework is the city of Dakar and the simulation period is 15 years from the baseline starting in 2016. In chapter 4, we compute the numerical input parameters that feed our models.

Chapter 5 presents the agent-based model designed in the framework of this study (MoCES), and compares it to two alternative computer-based modelling tools featuring different approaches: ENPEP-BALANCE (computational equilibrium) and LEAP (system simulation). In Chapter 5, we also calculate the three energy scenarios (listed below), from the reference energy scenario (RES) in the baseline, and compare their outcomes in terms of system quantities and costs from the primary energy resources supply to agents' end-use. The scenarios are:

- Increase electricity generation with bioenergy, solar photovoltaic, and wind resources available in the city;
- Decrease electricity demand through change of households' behaviour in cooking, lighting, refrigeration, and cooling;
- Mitigate climate variability through reduction of greenhouse gas emissions, after integration of renewables generation and demand-side management in the residence sector.

Chapter 6 presents policy mechanisms to implement the MoCES outcomes. In this chapter, we also explore three scenario for backcasting the future of our sample city energy system.

- Improvement of the energy system with renewable energy technologies that have resource potential in the city (timeframe 15 years)
- Investment on demand side management to encourage the residence sector in improving efficiency of energy use (timeframe 15 years)
- Combination of investment on renewables integration in the supply mix and demand side management in the residence sector (timeframe 15 years).

The positive-sum policy mechanisms should improve the eco-efficiency factor of the city, and we present MoCES value addition to planning with improvement of the city the eco-efficiency.

We performed a sensitivity analysis of the models' outcomes considering resource quantities, capital cost, and technology cost (Chapter 4), modelling approach (Chapter 5), and urbanization growth rate (Chapter 6).

Chapter 7 wraps up the thesis with main findings of the study and introduces perspectives for new research avenues from this study. In conclusion, we reflect upon how the study adds value to the field of energy economics, present limitations, and summarize our key messages.

2. Research background

Further background information on models and modelling tools application to the energy sector is highlighted in this section Different models use different approaches to make sense of the energy system conceptualized. Table 2.1 categorizes the models cited by Urban et al. (2007) in terms of approach and methodology.

Table 2-1 Energy Models Methodology and approach

	Methodology				**Approach**		
	Simulation	Optimization	Computational equilibrium	Toolbox	Top-down	Bottom-up	Hybrid
AIM	x						x
ASF		x			x		
IMAGE/ TIMER	x						x
LEAP	x	x				x	
MARIA		x			x		
MARKAL		x				x	
MESSAGE		x					x
MiniCAM			x				x
PowerPlan	x					x	
RETScreen				x		x	
SGM			x		x		
WEM			x				x

The majority of energy models in the Table 2.1 have a hybrid (bottom-up and top-down) approach, and use optimization as methodology. Both approaches and methodologies are introduced in previous paragraphs (Pages 11-12). Toolboxes are rare, but the methodology has the advantage of flexibility and their computation is facilitated by existing software on programming.

Kemfert (2003) reports in Figure 2.1 the geographic and time characteristics of the models depending on their approach.

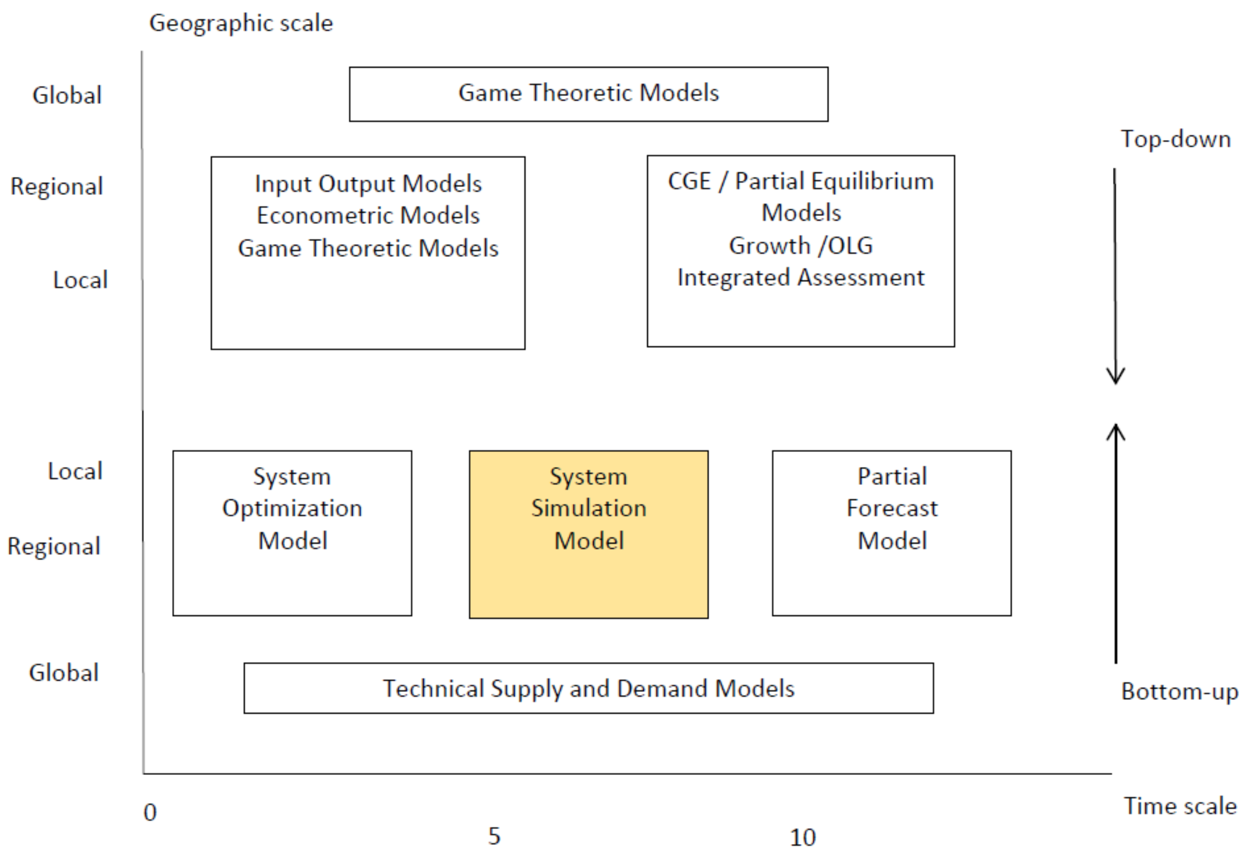


Figure 2.1 Models time and geographic characteristics

The above categories are computational equilibrium models that include the Second-Generation Model (SGM) and the World Energy Model (WEM). They are mostly used for computing large-scale system equilibrium with objectives that often go beyond energy considerations. The partial equilibrium version is more sector-specific and has records of use in the energy sector of the sample city. We will present more details about the ENPEP-BALANCE over the course of this dissertation as sample of a partial equilibrium approach in modelling an energy system.

3. Research methodology

3.1 Techno-economic assessment of renewables in cities

The assessment targets three energy resources that are renewable in compliance with the definition of the International Energy Agency, meaning energy derived from natural processes that are replenished constantly (IEA, 2002). These resources are biomass, solar photovoltaic and wind.

3.1.1 Assessment of the theoretical energy potential

Biomass energy: biomass energy, considered in this study, is organic waste generated by the city in a period of one year. Data of this energy potential in Dakar come from the city waste collection agency (UCG), and the ministry in charge of Sanitation. Comparison data on Vienna are from the Federal Waste Management Plan (2017) published by the Federal Ministry for Sustainability and Tourism.

Solar photovoltaic: assessment of each city theoretical solar energy potential relies on maps of the Global Solar Atlas. The Global Solar Atlas, jointly developed by Solargis and the World Bank, is accessible at https://globalsolaratlas.info/ and provides diverse solar energy information that includes global horizontal irradiation (GHI), direct normal irradiation (DNI), and global tilted irradiation expressed in energy potential per meter-square (kWh/m2) of the city.

Wind energy: assessment of each city theoretical wind energy potential relies on maps of the Global Wind Atlas. The Global Wind Atlas, jointly developed by the Technical University of Denmark and the World Bank, is accessible at https://globalwindatlas.info/ and provides information on wind potential in capacity per meter-square (W/m2).

Solar and wind potential information provided by the above-named sources rely on past records, which can create biases in the development of futures scenarios. Chapter 5 compares existent planning models to the model developed in the framework of this study, and addresses this concern related to intermittence of solar and wind resources.

3.1.2 Assessment of the technical potential

From the theoretical potential of each energy resource, we derive the technical potential considering a combination of geographic information system (GIS) modelling, and other technical criteria of energy landscaping. Sustainable energy landscape requires a paradigm shift from "energy for space to energy from space" according to Scheffran et al. (2015). The criteria considered to estimate a city's technical potential are:

- In areas where the resource was estimated to be theoretically available, the co-presence in spatial arrangement and interaction with local characters expressed by relief (slope)
- Distance between the energy supply location and vulnerable sites like human settlements, bat roosts or nesting sites of sensitive bird species (wind), and integration in the built environment (solar photovoltaic).
- Minimum distances between the energy supply location and the grid feed-in point to increase the energy production potential (EPP) through lowering losses. Masurowski et al. (2018) present a spatially explicit analysis of the reduction of the EPP with variable minimum distances between vulnerable sites and wind turbines.
- Geographical visualization (GeoViz) of energy systems that consists on deploying spatial science related technologies such as geographical information systems (GIS) to determine land requirements of energy technologies.

3.1.3 Assessment of the economic potential

The technical energy potential estimated for each of the resources is not all economically realizable. Brown et al. (2016) defines the economic potential of a renewable energy resource as "the subset of the available resource technical potential where the cost required to generate the electricity is below the revenue available in terms of displaced energy and displaced capacity." To estimate the generation cost of the sites identified in Dakar, we computed the long-run and short-run generation costs. The revenue available from displaced energy and displaced capacity is the sum of costs associated to installation of an equivalent energy capacity or generation of an equivalent quantity of energy in a business as usual, which is avoided by the renewable technology. The economic potential we compute at this stage does not consider customer demand, nor policy mechanisms that may incentivize renewable energy generation.

Long-run generation cost: this metric includes all costs related to installation and operation of a new generation power plant. It sums unitized fixed costs related to the installation (EUR per kWh) and variable costs related to the operation (EUR per kWh). The fixed cost labelled in EUR per kW installed are converted to unitized cost by dividing it with full-load hours of the installation.

Short-run generation cost: This metric only considers the variable part of the previous metric, meaning the fuel and environment costs related to generation of the already operational system. This metric includes a price for CO2-eq emissions associated with the energy system generation in EUR per ton CO2-eq.

Avoided generation cost: this metric considers the predominant energy generation source as a business as usual generation option. For Dakar, it is a diesel-powered system (50.6 percent of the installation park in RES).

Finally, we conclude chapter 4 on techno-economic assessment of renewable technologies in our sample city, by analysing the weight of technology and capital cost in the competitiveness of renewable energy technologies compared to conventional generation available in the city during the reference energy scenario (2016).

3.2 Modelling sustainable energy systems in cities

In chapter 5, we begin with a description of the city reference system (RES) with data from the utility and the Energy Information System (SIE in French) accessible from the Ministry in charge of Energy. Then, we recall the information related to renewable potential of the city for each technology, which constitutes inputs of our models.

With this information, we model the city reference energy scenario (scenario 1), and from it, we derive three possible future energy scenarios. Scenarios in modelling are defined by the UN Inter-governmental Panel on Climate Change as “description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving and relationships” (Data Distribution Centre, 2020).

Scenario 2: increase energy generation with available renewable energy generation resources, namely waste-to-energy, solar photovoltaic, and wind.

Scenario 3: decrease energy demand through citizens’ behaviour change in cooking, lighting, refrigeration, and cooling. Data on citizens’ behaviour in consumption of the four listed energy services are:

(1) The first source of data collected in three districts of Dakar: Diamniadio (low standard district), Sicap-Amitie and Fann-Point E (High standard districts). The survey sample is

computed considering the number of households per stratum provided by the National Agency for Statistics and Demographics (ANSD). The strata sampling, with a significance factor of 95%, returned the following sample size per stratum.

Table 3-1 Households in surveyed areas

	Low standard district	High standard district
Population	2,274	1,146
Sample	329	453

(2) The second source of data are publications from third-party organizations.

Scenario 4: develop a sustainable energy scenario that combines a renewable generation and an efficient demand to mitigate greenhouse gas emissions (in CO2-eq).

The scenarios 2 to 4 are modelled using three computer-based modelling tools that are LEAP (system simulation), ENPEP-BALANCE (partial equilibrium), and MoCES (agent-based modelling).

3.3.1 Long-range Energy Alternatives Planning System - LEAP

The software is an integrated energy-modelling tool that is distributed and maintained by the Stockholm Environment Institute (SEI). LEAP provides a flexible framework for building scenarios of energy demand, resources, and transformation processes. The platform flexibility enables simulation of energy scenarios at different scales, including the urban scale. LEAP enables both simulation and optimization of the energy scenarios. SEI claims a community of 36,000 member users worldwide, which we joined when requesting the software license for this study. LEAP is downloadable at https://www.energycommunity.org with a license that is granted to researchers free of charge for a period of six months. Figure 3.1 (below) shows LEAP interface.

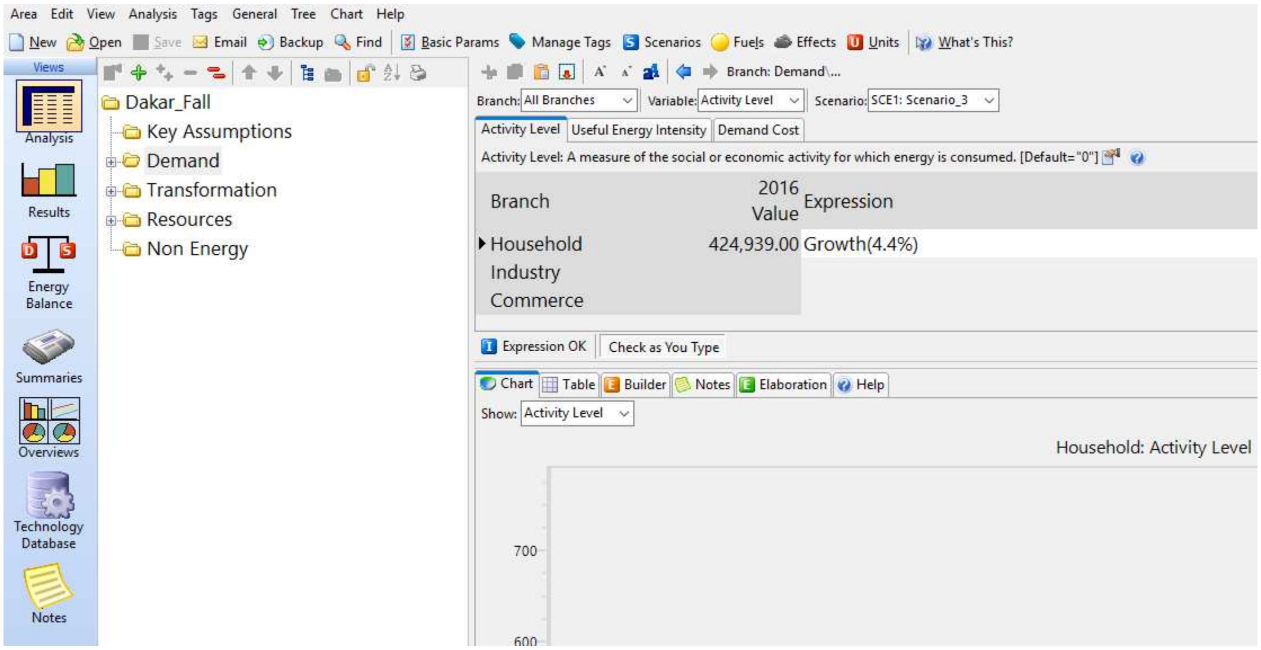


Figure 3.1 LEAP Interface

3.3.2 Energy and Power Evaluation Program - ENPEP-BALANCE

Typically, equilibrium energy models such as those listed in Table 2, namely MiniCam, Second Generation Model (SGM), and World Energy Model (WEM) have large geographic focus and long simulation periods. The ENPEP-BALANCE is an exception. The nonlinear, equilibrium model matches the demand for energy with available resources and technologies at any scale, including the city scale. It was developed by Argonne National Laboratory (USA) in 1999. The ENPEP-BALANCE approach determines the responses of the energy system to changes in energy prices and demand levels. The underlying principles of the equilibrium are:

- All decision-makers optimize their energy choices based on their own needs and desires;
- No single person or organization controls all energy prices and decisions on energy use;
- A lag factor accounts for delays in capital stock turnover;
- There is an “ideal market” subject to government policies, fuel availability, and market constraints.

The result is a nonlinear, market-based equilibrium solution within policy and technology constraints. ENPEP-BALANCE software is accessible by mail request to the Argonne National

Laboratory (operated by University of Chicago for the US Department of Energy), which sends by mail an executable file after request approval. Figure 3.2 shows the ENPEP-BALANCE interface.

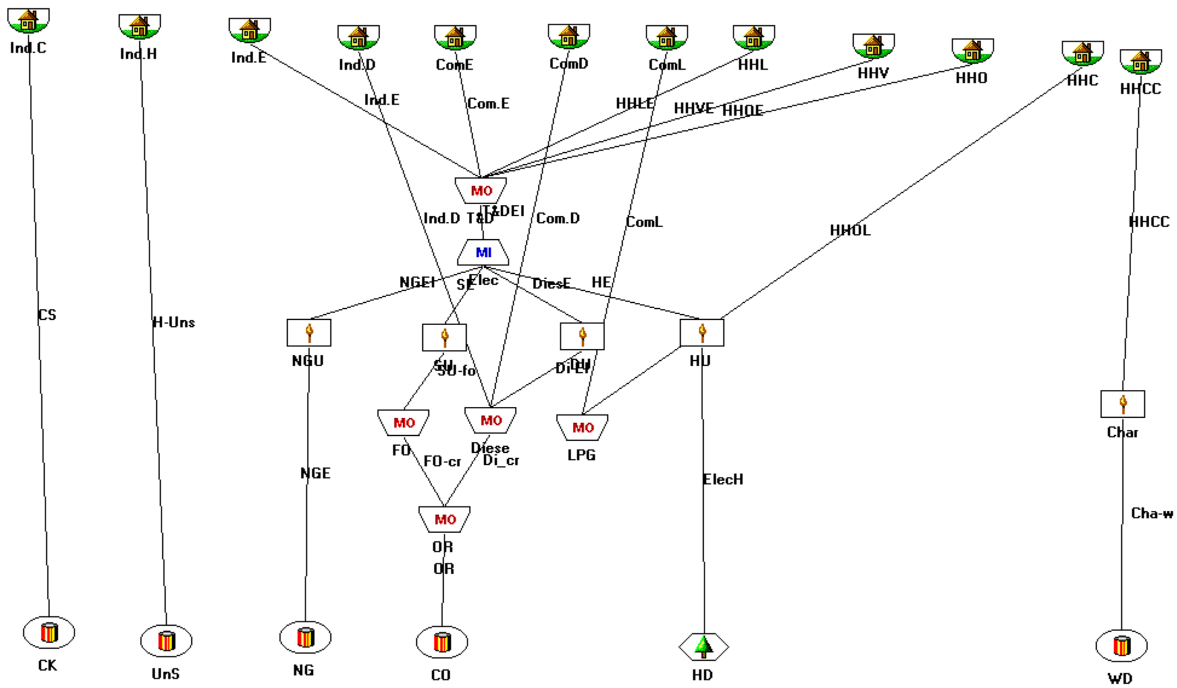


Figure 3.2 ENPEP-BALANCE Interface

3.3.3 Modelling Cities Energy Systems - MoCES

The software concept and sketch was developed in the framework of this research. MoCES provides a comprehensive answer to different categories of drawbacks that appeared when applying previous models to the sample city energy system. Those drawbacks include:

a) Limits on the modelling approach

For Van Beeck (1999), the implicit assumption of constancy from historical trends of models with a top-down approach is not realistic, because rapid population and economic growth affect energy use. The bottom–up approach features constancy weaknesses assumed here in exogenous parameters such as demand, technology change, and resources that are main drivers of the system dynamics.

b) Limits of the model methodology

An adaptation to a city level of energy planning software that was originally developed for national and regional levels requires convergence criteria and linking metrics, i.e energy metrics that link the national and the city scales. As reminded by Grubler et al. (2012) these methodologies suffer from inconsistent system boundaries and irrelevant accounting methodologies.

c) Limits of the models' outcome validity

The absence in energy models with experience of use in developing countries of the relevant parameters identified by Urban et al. affect these models' empirical validity. The linear adaptation of models developed in the mature cities context to emerging cities causes biases, which explain the absence of parameters related to access, structural economic changes (e.g urbanization), presence of charcoal in the cooking service etc. In addition, the intermittence dimension of renewable energy technologies are not integrated in any of the models, which assumes a fixed average over the modelling period.

MoCES provides a framework for developing an energy system that combines sustainability of generation and efficiency of the demand at three scales of analysis: the city, the district, and the building.

Four energy generation technologies are embedded in the software's current version: (1) solar photovoltaic, (2) waste recycling to energy, (3) wind, and (4) grid connection as a default alternative and benchmarking option. MoCES provides real-time update (less than 12 hours) of meteorological factors that influence these technologies generation capacity such as irradiation, wind speed, and temperature in order to anticipate excess generation to evacuate through the grid or store, and deficit of generation to import from the grid.

The demand section features four categories: (1) cooking, (2) heating, (3) lighting, and (4) cooling. A single block named *Other demand* features demands that are not recorded among the four previous categories, including refrigeration. The creation of an efficient demand scenario is through variation of appliances and devices parameters such as appliance type (e.g LED instead of CFL lamp), balance temperature point (e.g in cooling), and hours of operation.

The user can combine both sustainable generation and efficient demand in a scenario, and further create subsequent scenarios considering variations of the original scenario parameters. In addition, to its design at the city scale, the software provides two major innovation in the field of modelling energy systems:

- Ninety-three (93) result outcomes computed from input data that provides information on the energy system value vis-à-vis the multifaceted dimensions of sustainability that includes economic affordability, social acceptance, and environment friendliness;
- Virtual installation of the energy system in the built-environment of the city:

MoCES provides a unique platform to answer in a consistent manner our three research questions on the city's energy potential, the sustainability of its realization, and the supportive policy mechanisms this realization requires.

We end Chapter 5 with a discussion on how MoCES is a system beyond the current state-of-the art on modelling energy systems. MoCES software is accessible online https://esmp-sea4cities.ept.sn. External users can access it after validation of the request to access by the system administrator.

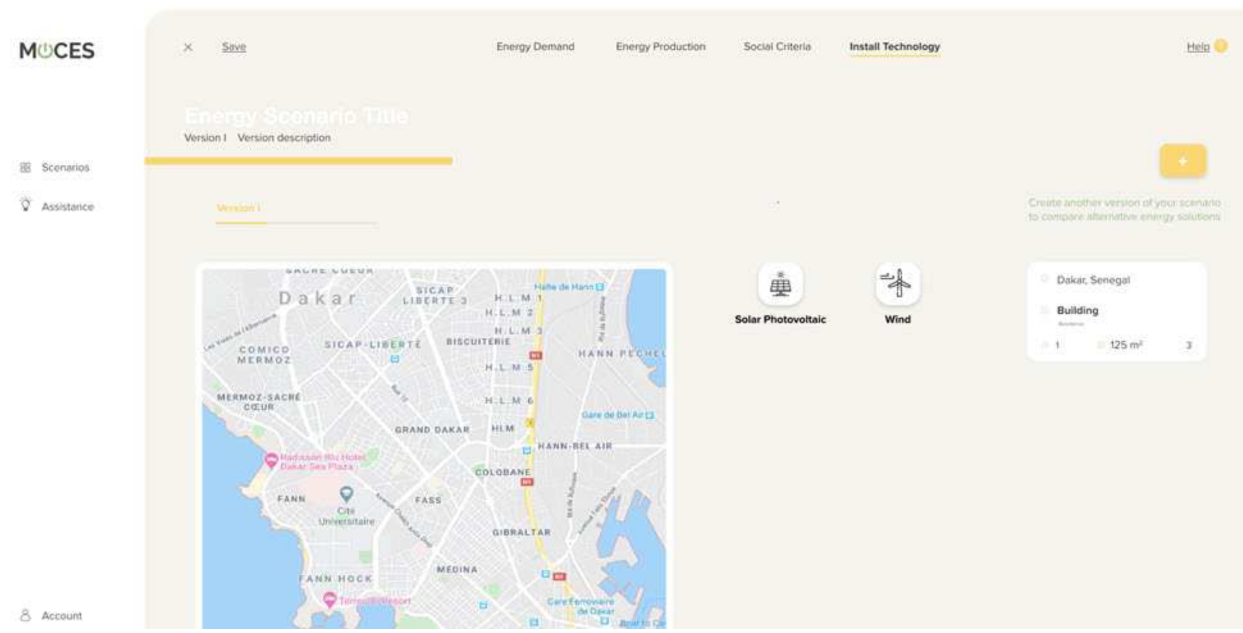


Figure 3.3 MoCES Interface

3.3 Sustainable energy policies for sustainable cities

Chapter 6 discusses the policy mechanisms for the realization of the energy scenarios previously modelled. We use the backcasting approach to describe the policy mechanisms and their tractable implications in the parameters of the city eco-efficiency formulae, from the reference energy scenario (scenario 1).

The policy mechanisms related to scenario 2 (increased generation with renewables) are:

- Carbon tax on pollutant energy supply in the system
- Private wire network that promotes solar photovoltaic generation in the residence and commercial sectors of the city

The policy mechanisms related to scenario 3 (reduced demand with efficiency) are:

- Direct contribution to retrofit domestic appliances in the residence sector (e.g direct contribution to lamps retrofit)

The policy mechanism related to scenario 4 (reduced environment strain)

- Combination of increased generation with renewables and reduced demand with improved efficiency in the residence sector.

In Chapter 6, we introduce new policy formulations that combine eco-efficiency and mechanism design, and present results of this combination in assessment of our policy options.

In Chapter 7, we connect the research findings and research initial motivation, outlined in the introduction, in a section titled: synthesis of the research findings and way forward. This section discusses how improving the city eco-efficiency can address other topical issues that include:

- Collective action problems such as reduction of the city environment strain,
- Climate justice (the historical responsibility of mature cities and the defiance of emerging cities) on bearing the energy transition cost.

4. Techno-economic assessment of renewables' energy potential of the city

4.1 Introduction

Theoretically, all cities throughout the world have renewable resources that include solar, waste to energy, and wind resources. Scientific publications on the renewable energy potential of cities mainly rely on geographic information system (GIS) data such as solar and wind maps. However, planning systems that realize the potential of renewable energy resources needs additional tools beyond GIS. In this study, we consider two additional dimensions to GIS maps in the assessment of cities' renewable energy potential: competing space and competing resources.

For Wolsink (2018), the energy available from renewable sources is abundant, but the real scarcity derives from the space needed for the infrastructure. Natural landscape and principles of co-existence with existent energy and non-energy infrastructure limit these resources technical realization. The concept of competing space includes three layers of technical constraints.

The first layer of constraints is the landscape formatted by natural processes over time. The presence of mountains (valleys), irregular fields (slope), and natural screens such as canopies are all parameters that impose limits to the renewable resources potential. At this point, it is worth mentioning that there is confusion between the terms "sustainable" and "renewable" energy resources, which we can consider the criteria of landscape co-presence to justify differences. For instance, it is indisputable to call solar photovoltaic a renewable resource, but if capture of solar photovoltaic irradiation requires people to clear the canopy, we consider co-presence to be outraged, thus, this energy cannot be named sustainable. The same goes for scenarios where valleys are levelled to install hydropower technology.

The second layer of constraints is co-presence in a finite area of the energy technology with human and other animals' settlements and with concurrent infrastructure.

(1) Co-presence with existent settlements considers the possibility to integrate the energy technology in the built environment.

(2) Possible concurrent infrastructure to energy technologies include infrastructure that supply services such as water and communication, which could be impacted by wind turbines.

The third layer of constraint to energy potential realization is the requirement to minimize distance between the energy transformation system and feed-in-point to the grid to increase the energy production potential (EPP) through lowering losses.

The competing resources are in majority conventional generation that features the value of having technology infrastructure readily available in the supply mix, which can be numerically accounted as economies of scale. For a technically realizable site to be economically viable, the costs associated to its realization should be lower than that of existing alternatives, which were, in majority, diesel power generation in the reference energy scenario.

The core objective of the chapter is to identify the technical and economic constraints that place boundaries on the theoretical infinite potential of bioenergy, solar photovoltaic, and wind energy in our sample city. The subsequent objective is to derive, from this identification, an assessment of the energy potential technically exploitable for the city's transition to energy sustainability at a competitive cost.

4.2 Materials and methods

The sample city of Dakar overlaps boundaries of the administrative region, meaning it has a territory of 547 km2 with four administrative subdivisions: Dakar Peninsula (District 1), Guediawaye (District 2), Pikine (District 3), and Rufisque (District 4).

Due to our distinction between a renewable and a sustainable energy resource, we assess the bioenergy potential that excludes from the technical potential of bioenergy, forests and biomass from all other areas in the city classified as green or wet. Therefore, our definition of bioenergy potential for the city is limited to the recycling of waste from the city activities. The assessment of the potential on waste-to-energy relies on second hand data from the city waste collection agency (UCG, 2016), and from the results of a study completed on Dakar's waste characterization completed in 2017 as part of a PhD thesis (Fall, 2017). From the theoretical potential, we derive the technical potential based on the assumption of 100% waste collection rate, which is not constrained by layers we defined.

The co-presence layer constraints integration of solar photovoltaic systems in the city. Therefore, despite solar maps showing uniform energy potential in the overall city, we chose to exclude from the technical potential, solar photovoltaic potential of areas such as animal parks, bird reserves, lakes etc. This approach assumes human responsibility in mitigating impact of its action on other animals, in particular when identifying sustainable energy solutions. The assessment of the city solar photovoltaic energy potential relies on second hand data downloaded from the Global Atlas Map that is provided by the World Bank and Solargis. From this theoretical potential, we add layers of excluding parameters (e.g green and water areas), in order to isolate sites where the theoretical potential can be realized with technology, marking it as a technical potential.

The co-presence with competing infrastructure layer constraints the installation of wind technology in the city. Therefore, despite wind maps showing different levels of potential, we chose to exclude from the technical potential, the potential of sites located in residential areas. The assessment of the city wind energy potential relies on second hand data downloaded from the Global Wind Atlas that is provided by the World Bank and the Technical University of Denmark. From this theoretical potential, we add layers of excluding parameters (e.g residences), in order to isolate sites where the theoretical potential can realize with technology, making it the technical potential. Due to our third layer of technical constraint that minimizes the distance between generation site and grid feed-in-point, we did not explore wind offshore for Dakar, despite a significant theoretical potential. This distance is inversely proportional to the energy production potential.

The assessment of each of the three technologies economic potential relies on excel based computation of the long run generation cost of the technology, which formula is:

$$\mathbf{LRGC} = \frac{(CRF \qquad CAPEX)}{H} + SRGC$$

Equation 2. Long-run generation cost

Where,

$$\mathbf{SRGC} = \frac{F_{cost}}{EF} + \text{Other O\&M} + \frac{(CO2_{price} * CO2_{fuel})}{EF}$$

SRGC: Short-run generation cost

LRGC: Long-run generation cost

- Capital recovery factor (CRF) is computed with a weighted average capital cost of 9 percent equivalent to Senegal discount rate (Ministry of Finance, 2015), and a service life of 15 years. CRF is 12.4 percent.
- CAPEX is the technology capital cost expressed in EUR per kW installed.
- H is full load hours, which are defined as equivalent hours of production at full (rated) capacity. It is the capacity factor expressed in hours.
- F_{cost} is the fuel cost.
- EF is the efficiency factor of the conversion process.
- Other O&M stands for other operation and maintenance costs.
- $CO2_{price}$ is the price of 1 metric tonne of CO2 generated by the conversion process. Carbon prices available in the literature varies widely per country, and inside the country per companies/ projects, and per partner buyers. Theretofore, we consider mean value of the recommendations formulated by the High-Level Commission on Carbon Pricing (World Bank, 2019) cited by the United Nations Framework Convention on Climate Change, which are $40-$80 per metric ton by 2020 and $50-$100 per metric ton by 2030. Therefore, carbon price in the LRGC is EUR 54 (60 USD).
- $CO2_{fsef}$ is the conversion process specific emission factor.
- Conversion rate USD to EUR is 0.9, which is the average rate in 2016 (www.statista.com consulted 7 January 2020).

In the event the renewable's LRGC is higher than diesel generation cost, or even in a scenario of costs neutrality, the comparison outcome favours the diesel alternative, because it features the value addition of experience termed as economies of scale. The cost and quantities computed for each technology are compared to equivalent figures in Vienna for conducting the sensitivity analysis.

4.3 Theory and calculation

4.3.1 Estimation of the bioenergy potential

Figure 4.1 displays the theoretical potential of the city biomass waste.

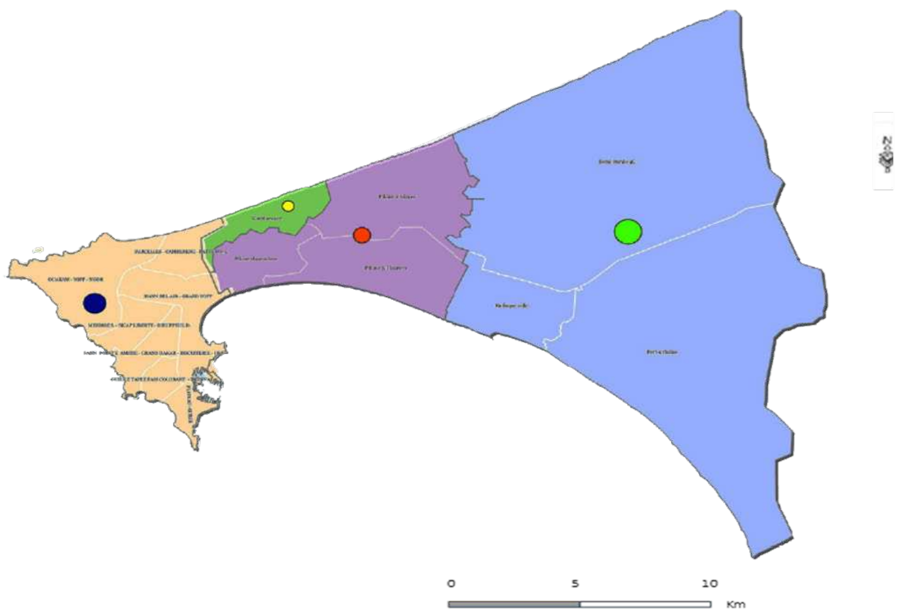


Figure 4.1 Waste collection per district

Source: UCG (2016)

Legend: Waste collected (in metric tonnes in 2016)

0 – 5,000   5,000 – 10,000   10,000 – 30,000   30,000 – 50,000

a) Estimation of the theoretical potential

Table 4.1 displays the amount of waste collected per department per district.

Table 4-1 Waste collected (in metric tonnes)

	District 1	District 2	District 3	District 4	Total
Collected	29,558	3,101	9,162	43,179	85,000
Collection rate (a)	85.8	87.5	80.4	64.5	
Total waste	**34,449.8**	**3,544**	**11,395.5**	**66,944.2**	**116,333.6**

(a) The collection rate is the estimate of the percent of waste collected by UCG as a fraction of the overall waste collected during the period.

Private operators collected the remaining fraction of waste collected during the period. The non-collected waste was dumped in irregular landfills, where neither quantities nor waste composition are measured.

The calorific part of the biomass waste collected in the city during the period constitutes the theoretical waste-to-energy potential.

b) Estimation of the technical potential

The technical potential of waste to energy is the thermal fraction of waste composition calculated from total quantities of waste available in the city, meaning the quantities collected by the public collection agency and by private collectors. Table 4.2 displays waste components in quantities (tons) and proportion (%) of the total collected.

Table 4-2 Composition of waste collected in Dakar

Quantities (in tonnes) [(a)]		**District 1**	**District 2**	**District 3**	**District 4**	**Total**
Waste collected		29,558	3,101	9,162	43,179	55,442
Collection rate		85.8	87.5	80.40	64.5	
Waste available		34,449.9	3,544	11,395.5	66,944.2	116,333.6
Composition [(b)]	(%)	(tons)	(tons)	(tons)	(tons)	(tons)
Fine elements (Ø less than 20 mm)	36.64	12,622.44	1,298.52	3,356.96	15,820.79	42,624.63
Organic	22.40	7,716.77	793.86	2,052.29	9,672.10	26,058.72
Plastics	9.04	3,114.27	320.38	828.24	3,903.38	10,516.56
Complex	6.62	2,280.58	234.61	606.52	2,858.45	7,701.28
Textiles (incl. sanitary products)	6.67	2,297.81	236.38	611.11	2,880.04	7,759.45
Paper (incl. cardboard)	5	1,722.49	177.20	458.10	2,158.95	5,816.68
Metal	2	689.00	70.88	183.24	863.58	2,326.67
Glass	3	1,033.50	106.32	274.86	1,295.37	3,490.01
Wood	4	1,378.00	141.76	366.48	1,727.16	4,653.34

Others (DMS, flammable, non-flammable elements)	5	1,595.03	164.09	424.20	1,999.19	5,386.25

(a) Report of Unite de Coordination et de Gestion des Déchets (UCG, 2016); (b)Dissertation thesis (Fall, 2017)

We calculated the technical potential of the waste to energy considering the calorific value of the city waste fractions recoverable as energy. The organic, plastics, paper, textiles, and wood are waste components recoverable as energy. The net calorific value is the approximate net calorific value of common municipal solid waste fractions provided by the World Energy Council (2016) quoting the International Solid Waste Association (ISWA). However, the previous document does not provide calorific value information on wood component of municipal waste. Therefore, we assume the most common wood species in Dakar, beefwood tree (*Casuarina esquisetifolia*), as source of the wood waste. Information on the calorific value of the beefwood tree (20.9 MJ/kg) is from the World Agroforestry Centre database. Table 4.3 displays the technical potential of the city waste fractions recoverable as energy.

Table 4-3 Dakar technical waste-to-energy potential (2016)

	Fractions (in metric tonnes)[a]	Net calorific value (MJ/kg)[b]	Energy (GJ)	Energy (MWh)[c]	Full load hours (H)[d]	Efficiency factor (e)	Power potential (kW)
Organic	26,058.72	4	104,234.9	29,185.8	7,358	0.66	6,009.6
Plastics	10,516.56	35	368,079.5	103,062.3	7,358	0.8	17,507.6
Paper	5,816.68	16	93,066.9	26,058.7	7,358	0.8	4,426.7
Textiles	7,759.45	19	147,429.6	41,280.3	7,358	0.8	7,012.4
Wood	4,653.34	20.9	97,254.9	27,231.4	7,358	0.8	4,625.9
Glass	3,490.01	0					
Metal	2,326.67	0					
Other materials	55,712.16	Undefined					
Total			**810,065.7**	**266,818.4**			**39,584.3**

[(a)] The column compiles values in Table 4.2.

(b) The net calorific value are from the International Solid Waste Association quoted by the World Energy Council and other publications we accessed.

(c) The column Energy displays calculation results with previous columns parameters.

(d) The column Full load hours assumes 84 percent capacity factor provided by IRENA (2019) for operating bioenergy power plants in 2016 equivalent to 7,358 hours. This figure is within the range (6,000- 8,700 hours) of baseload plants load hours mentioned by IEA Bioenergy (2019).

(e) The column displays efficiency of the waste to electricity conversion technology: anaerobic digestion for organic waste and dendro liquid energy for other wastes.

The technical waste-to-energy potential of Dakar in the baseline year is 39.6 MW that can be converted with anaerobic digestion (6 MW) and Dendro Liquid Energy (33.6 MW) technologies.

In comparison, the Vienna technical potential of waste recoverable in energy is displayed in Table 4.4. Net calorific values of the waste components are the values provided by the World Energy Council quoting ISWA. For wood waste, we consider the white poplar (*populus alba*) net calorific value (19.13 MJ/kg). The white poplar is a stereotypical species of Vienna vegetation.

Table 4-4 Vienna technical waste to energy potential

	Fractions (in metric tonnes) (a)	Net calorific value (MJ/kg)	Energy (MWh)	Full load hours (H)	Efficiency factor	Power potential (kW)
Paper, printed material and packaging	123,046	16	551,248.1	7,358	0.8	74917.92
Textiles	4,023	19	21,402.4	7,358	0.8	2908.72
Plastic packaging	6,810	35	66,738	7,358	0.8	9070.13
Bulky wood and wood packaging (b)	42,232	19.13	226,211.5	7,358	0.8	30.743.61
Glass packaging	28,726	0	0		0.8	
Bulky metals and metal packaging	14,884	0	0		0.8	
Other materials (c)	665,743	Undefined			0.8	

Total	**885,464**		**865,597.9**			**147,050.48**

[(a)] Data are from Vienna Federal Waste Management Plan (2017)

[(b)] Data are from Griu and Lunguleasa (2015) in their publication” The use of the white poplar (Populus alba L.) biomass as fuel”.

[(c)] Other waste fractions includes in majority mixed municipal solid waste (79 percent) followed by bulky waste, waste of electrical and electronic devices and other recoverables.

From the Vienna Federal Waste Management Plan document, we could not segregate the waste fraction made of organic materials; therefore, we only considered paper, plastics, textiles, and wood waste in the contrasting figure. Therefore, the waste to energy potential of Vienna in the baseline year (2016) is 147.5 MW, excluding the potential of organic waste.

c) Estimation of the economic potential

For the potential of a city’s waste conversion to energy to be economically viable, the long-run generation cost of conversion should be lower than the cost of a kWh energy generated with diesel power plants, which is equivalent to the grid kWh average cost in the baseline year (2016).

For the organic fraction, the conversion technology proposed is anaerobic digestion (AD). Anaerobic digestion is the conversion of organic materials by microorganisms in the absence of oxygen, to produce biogas and a digestate used as fertiliser. The waste material requires pre-treatment, such as removal of all packaging, plastics, and grit, before entering the AD technology. AD is a mature technology with proven experience in conversion of organic waste to energy both in practice (e.g Thecogas power plant in Dakar) and in literature (Adannou, et al., 2019).

For paper, plastics, textiles, and wood fractions that typically have lower moisture content than organic waste, the conversion technology proposed is dendro liquid energy (DLE). DLE is a recent German technology that converts a mix of different waste fractions such as plastic waste and wood logs into energy. Ghougassian (2012) quoted by the World Energy Council claims DLE technology is up to four times more efficient than AD in terms of electricity generation. The same source mentions DLE technology can reach over 80 percent efficiency depending on the waste mix, and a typical 30.000 tonnes/year installation needs an investment of EUR 14.5 mio and annual operating costs of about EUR 1,750,000. The excel-based computation of the waste-to-energy technologies cost includes the following parameters:

Fuel cost (**F_{cost}**) we assume equal to 0

Efficiency factor of the conversion process (**EF**) estimate is based on data provided by Ng et al. (2013):

- Biogas production: 303.6 m3 per ton of municipal solid waste;
- Conversion factor Biogas to electricity (in MWh per m3) is 0.0024;

Therefore, 1 metric tonne municipal solid waste yields 0.728 MWh electricity, which is equivalent to 0.728 kWh per kg of municipal solid waste. Considering the initial energy content of the organic fraction that is 1.11 kWh per kg of waste (4 MJ per kg), the efficiency of the anaerobic digestion energy recovery is 65.6 percent. This rate meets the R1 formula as established by the European Commission Waste Directive (2011), which provides that only thermal waste to energy plants with energy efficiency equal to or higher than 0.65 are regarded as an energy recovery operation. For Dendro Liquid Energy, we consider the efficiency figure provided by Ghougassian (2012), namely 80 percent.

Other O&M are from IRENA Renewable Power Generation Cost (IRENA, 2019), which estimates O&M costs associated to anaerobic digestion as:

- Fixed O&M: 2.1-3.2 percent of CAPEX; The average being 2.55 percent of CAPEX
- Variable O&M: EUR 4.2 (4.7 USD) per MWh equivalent to EUR 0.004 per kWh.

For DLE technology, we consider O&M figures provided by Ghougassian (2012), which is equivalent to EUR 0.01 per kWh.

$CO2_{price}$ is EUR 54 (60 USD)

The IPCC (2006) estimates that 1 GJ energy conversion of municipal solid waste produces on average:

- 100 kg CO2emissions, which is equivalent to 0.36 kg per kWh.
- 30 kg CH4 emissions, which is equivalent to 0.107 kg per kWh. Considering a global warming potential (GWP) of 25, the CO2 equivalent emissions are 2.7 kg per kWh.

- 4 kg N2O emissions, which is equivalent to 0.014 kg per kWh. Considering a global warming potential of 298, the CO2 equivalent emissions are 4.29 kg per kWh

Therefore, carbon emissions per kWh generation is estimate to 7.35 kg CO2-eq.

For Anaerobic digestion, we consider IRENA (2019) average **CAPEX** of bioenergy technology in 2016, which is EUR 1,890 (USD 2,100) per kW installed. For Dendro Liquid Energy technology, we consider the CAPEX per tonne waste provided by Ghougassian (2012), which is equivalent to EUR 517.3 per kW installed. DLE is considered an improvement of traditional bioenergy technologies in terms of conversion cost, and efficiency.

IRENA (2019) estimates **full load hours (H)** of operating bioenergy power plants in 2016 to 7,358 hours (84 percent capacity factor). This figure is within the range (6,000- 8,700 hours) of baseload plants full load hours proposed by IEA Bioenergy (2019).

Capital recovery factor **(CRF)** computed with the discount rate is 12.4 percent.

4.3.2 Estimation of the solar photovoltaic potential

Figure 4.2 downloaded from Global Solar Atlas Website provided by World Bank and Solargis displays the theoretical potential of solar photovoltaic of Dakar.

Figure 4.2 Dakar Theoretical solar photovoltaic potential

Legend: Report generated on 9th January 2020 from https://globalsolaratlas.info/

a) Estimation of the theoretical potential

The energy potential, considering the direct normal irradiation (DNI), is 1,523 kWh/m2 per year. In comparison, the energy potential in Vienna is 1,107 kWh/m2 per year.

The surface area of the city is 547 km2. Therefore, the theoretical potential of Dakar on solar photovoltaic is 833,081 GWh per year.

b) Estimation of the technical energy potential

The most recent map of the city land use was downloaded from the website of the National Directorate in charge of Land Planning (DPU). These maps were used for planning the city masterplan towards 2035 (DPU, 2016). Table 4.5 displays the percent of land occupied by different uses.

Table 4-5 City Land Use

	Land use	
	(in percent)	(in km^2)
Dakar		547
Industry and logistics	2.7	14.8
Natural parks	0.1	0.6
Cemeteries	0.1	0.6
Beach and other sand areas	3.4	18.6
Green areas (forest and savannah)	29.6	161.9
Agricultural lands	35	191.4
Wet areas (lakes and rivers)	3.1	16.9
Roads and roadways	0.1	0.55
Other uses (incl. residential, administrative, etc.) [a]	25.9	141.7

[a] Other uses group areas that can host solar photovoltaic systems, including shops, administrative buildings, education buildings, and nude areas that did not have any geographical or natural affectation.

From Table 5, we derive the surface that can host solar photovoltaic systems equivalent to 141.7 km^2. Figure 4.3 shows the city grid network, we considered when identifying the minimum distance to feed energy systems to the grid (DPU, 2016).

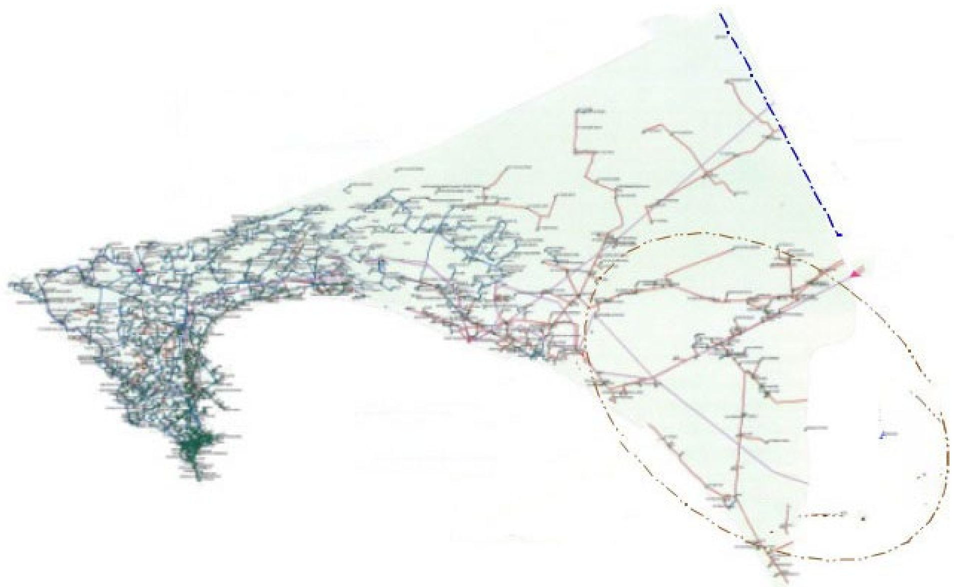


Figure 4.3 Transmission and Distribution Network

The grid network has different levels of densities. The decentralized systems installed in District 1 have a shorter distance to feed-in points compared to District 4, which is equivalent to a higher energy production potential (EPP). However, the overall city can host solar photovoltaic systems and evacuate excess generation through the grid, at variable distances. These distances affect energy losses of individual systems that we do not consider in this study.

Therefore, the technical potential of solar photovoltaic of the city is 215,768 GWh. Considering a capacity factor of 17 percent equivalent to 1,489.2 full load hours and an average module efficiency of 21 percent, this technical potential is 689.95 GW.

In contrast, Vienna's city Energy Report (data of 2016) estimates 6.5 m^2 are necessary to generate 1,000kWh in the city, which is equivalent to a technical potential of 153.8 kWh per m^2 (MA20, 2018).

c) Estimation of the economic potential

The excel-based computation of the solar photovoltaic cost includes the following parameters:

Fuel cost (**F_{cost}**) is 0

Solar module efficiency factor is assumed to be 21 percent, which is a standard for mono-crystalline technology. Recent test labs in Germany returns in-lab cell efficiencies of 26.7 percent (Fraunhofer Institute, 2019).

Other operation and maintenance costs (**O&M**) have been for a long time considered insignificant in solar PV systems, but as modules' cost decrease, their share in the overall system cost increases. Still, few studies are accessible with estimates of this cost share in PV systems cost. A German study (deea, 2016) quoted by IRENA (2019) estimates that the cost ranges between 20 and 25 percent of the solar PV levelized cost of energy (LCOE). We considered the mean value of 22.5 percent in this study and the LCOE computed by IRENA to derive a cost of EUR 2.7 cents value per kWh.

$CO2_{price}$ is EUR 54 (USD 60) per metric tonne, based on recommendations of the High-Level Commission on Carbon Pricing (World Bank, 2019) cited by the United Nations Framework Convention on Climate Change.

We assume specific emission factor of a solar photovoltaic system **($CO2_{fsef}$)** at 0.

IRENA (2019) estimates capital cost (**CAPEX**) of solar technology was on average EUR 1,448 (USD 1,609) per kW installed in 2016. The cost can be as low as USD 714 in India and as high as USD 2,187 in Canada.

Full load hours (**H**) is 1,489.2, which is equivalent to a capacity factor of 17 percent.

Capital recovery factor (**CRF**) is 12.4 percent.

4.3.3 Estimation of the wind energy potential

Figure 4.4 downloaded from the Global Wind Atlas website provided by the Word Bank and Technical University of Denmark displays the theoretical potential of wind energy of Dakar.

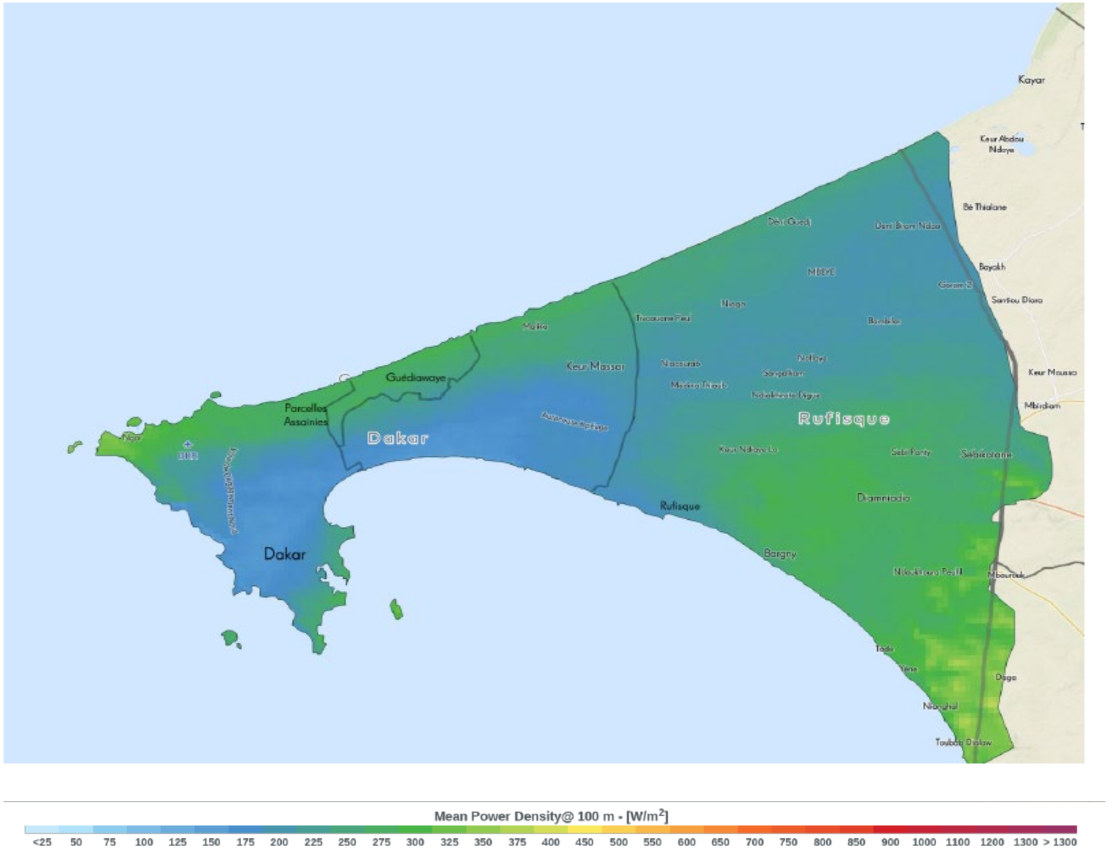


Figure 4.4 Dakar Theoretical wind energy potential

Legend: The average wind speed is 6.95 meter per second (m/s). The mean power density is estimated at a height of 100 meters.

This Report was generated on 10 January from https://globalwindatlas.info/

a) Estimation of the theoretical wind potential

The energy potential computed with the Mean Power Density for the 10 percent windiest areas of the city is 320 W per m^2. In comparison, it is 405 W per m^2 for Vienna.

The surface area of the city is 547 km^2. Therefore, the city's theoretical potential on wind energy is 175.04 GW.

b) Estimation of the technical potential

As opposed to solar photovoltaic, wind technologies cannot be integrated in the built environment of the city. Wind technologies are ideally installed in peripheral areas of a city, to minimize interactions with competing infrastructure such as communication infrastructure. The map on soil occupation, from the National Directorate in charge of Land Planning (DPU, 2016) indicates that about 3.4 percent of the city' land is made of these nude areas that do not have any geographical or natural affectation. From this, we can derive a surface area equivalent to 18.6 km^2 that can host wind systems with a technical potential for wind energy equivalent to 5,951.4 MW.

Höltinger et al (2016), while considering physical restrictions related to the natural landscape and to competing infrastructure, estimates to zero the Vienna technical wind potential as shown in Figure 4.5.

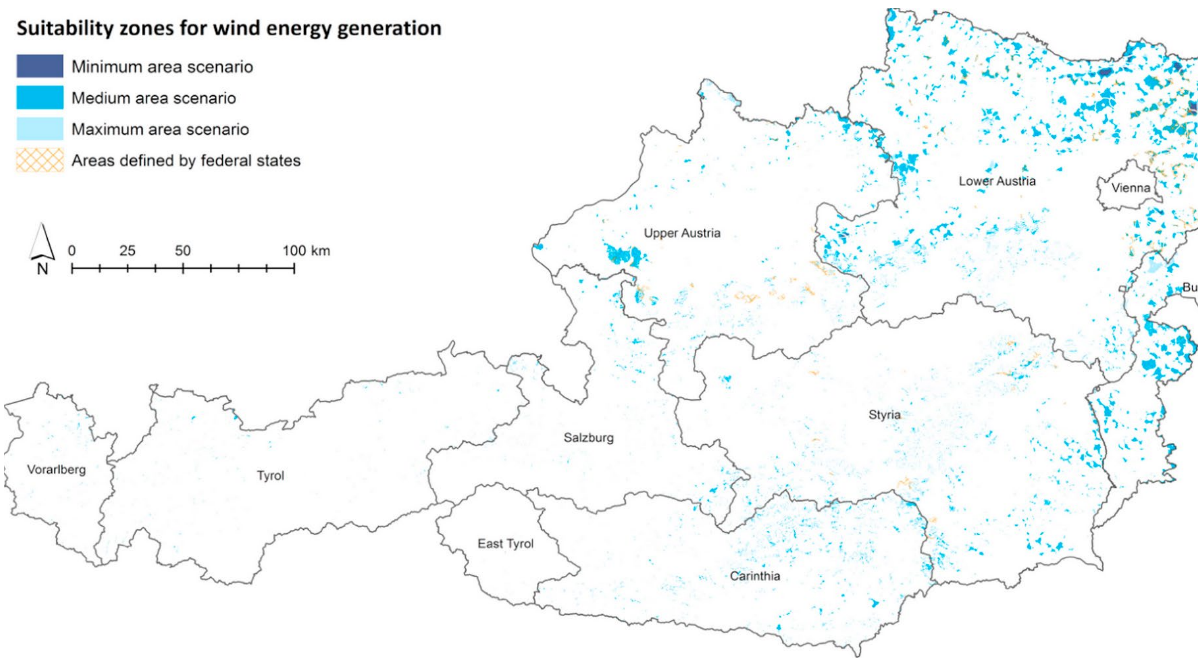


Figure 4.5 Wind technical potential of Austrian regions

c) Estimation of the economic potential

The excel-based computation of the wind energy cost includes the following parameters:

Fuel cost ($\mathbf{F_{cost}}$) is 0

Fraunhofer IEE (2020) proposes an efficiency factor (**EF**) of 40 percent for wind technology.

IRENA (2019) estimates the other cost associated to operation and maintenance (**O&M**) of wind technology ranges between EUR 0.7 (China) and 1.3 cents (Central and South America). We consider a mean value of EUR 1 cents for Dakar.

$CO2_{price}$ is EUR 54 per metric tonne, based on recommendations of the High-Level Commission on Carbon Pricing (World Bank, 2019) cited by the United Nations Framework Convention on Climate Change.

We assume specific emission factor **(CO2fsef)** of wind at 0.

IRENA (2019) estimates capital cost (CAPEX) of wind was on average EUR 1,448 (USD 1,609) per kW installed in 2016.

Full load hours (H) is 2,715.6, which is equivalent to a capacity factor of 31 percent (IRENA, 2019).

Capital recovery factor (**CRF**) is 12.4 percent.

4.3.4 Excel-based simulation of the renewable energy unit costs

Table 4-6 Excel based simulation of waste-to-energy cost

Reference Energy Scenario - 2016		
	Anaerobic digestion	Dendro Liquid Energy
Fuel cost (EUR)	-	-
Efficiency factor	0.656	0.80
Other variable O&M costs (EUR)	0.00	
Fixed O&M cost (EUR)	0.0000017	
Total O&M costs (EUR)	0.0042	0.01
CO2 price (EUR per tonne)	-	-
CO2 fuel specific emissions (tonne per kWh)	0.00735	0.00735
SRGC (EUR)	0.0042	0.01
Discount rate	0.09	0.09
Service life	15	15
Capital recovery factor	0.124	0.124
Investment cost (USD per kW)	2,100	
Investment cost (EUR per kW)	1,890	517.3
Load hours	7,358.4	7,358.4
LRGC (EUR)	0.036	0.019

Table 4-7 Excel-based simulation of solar photovoltaic and wind costs

RES - 2016	Solar PV
CAPEX (USD per Kw)	1609
CAPEX (EUR per Kw)	1448.1
Fuel cost	0
Other O&M cost (EUR per kWh)	0.027
CO2 price (EUR per ton)	54
CO2 specific emission factor	0
Efficiency factor	0.21
Discount rate	0.09
Lifetime (years)	15
CRF	0.124058883
Capacity factor	0.17
Load hours (H)	1489.2
SRGC (EUR per kWh)	0.027
LRGC (EUR per kWh)	0.161038908

RES - 2016	Wind
CAPEX (USD per Kw)	1609
CAPEX (EUR per Kw)	1448.1
Fuel cost	0
Other O&M cost (EUR per kWh)	0.01
CO2 price (EUR per ton)	54
CO2 specific emission factor	0
Efficiency factor	0.4
Discount rate	0.09
Lifetime (years)	15
CRF	0.124058883
Capacity factor	0.31
Load hours (H)	2715.6
SRGC (EUR per kWh)	0.01
LRGC (EUR per kWh)	0.083505208

In comparison, the city conventional generation cost parameters in the reference energy scenario (RES) are (in EUR per kWh):

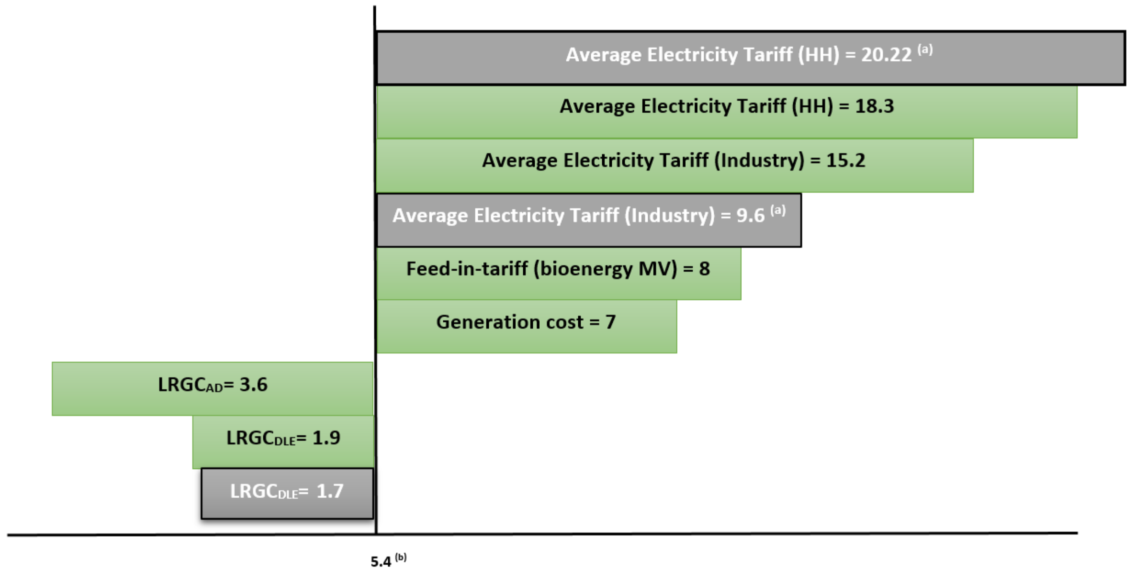
- Electricity generation cost: 7 cents
- Average tariff for end-users:17.9 cents
- Feed-in-tariff proposed by the energy regulation Authority (CRSE):
    - Bioenergy medium voltage: 8 cents
    - Solar Photovoltaic medium voltage: 8 cents

4.4 Results discussions

4.4.1 Bioenergy

From Excel Table 4.6, the cost of organic waste conversion to electricity with anaerobic digestion technology (EUR 3.6 cents per kWh) is lower than Dakar's average generation cost in the baseline year. The cost of other calorific waste materials (plastics, paper, textiles, and wood clogs) conversion to electricity with Dendro Liquid Energy technology (EUR 1.9 cents per kWh) is lower than Dakar's average generation cost in the baseline year. Therefore, the installation of a 39.6 MW waste to electricity conversion system is economically viable in Dakar. Graph 4.1 shows the bioenergy generation costs, in comparison to different costs information in the baseline year (2016).

Graph 4.1 Bioenergy costs comparison (EUR cents per kWh)



The green boxes include Dakar costs information. Grey boxes include Vienna costs information.

[a] Average electricity tariff of households (HH) and industry for Vienna in 2016 are from Statistics Austria accessible at www.statistik.at.

[b] Median electricity price of all suppliers per kWh for Vienna in 2016 (E-Control, 2018).

In the Vienna scenario of DLE cost, the discount rate has been lowered to 7.5 percent (IRENA, 2018). All other cost parameters remained unchanged. In addition to the discount rate, the quantities of waste collected is another parameter significantly different than Dakar's figures.

In 2016, Dakar was home to 3.4 million habitants (ANSD, 2018). Fall (2017) estimates the waste generated in Dakar at 171.82 kg per capita per year, which is equivalent to 589,234 tonnes per year. Graph 4.2a displays a comparison of the energy demand of Dakar and the potential of energy produced by waste at three waste collection quantities, which are:

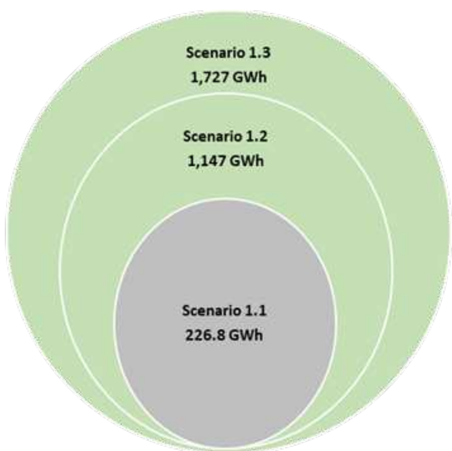
- Scenario 1: quantities equivalent to the waste collected in 2016 (baseline)
- Scenario 2: quantities equivalent to the total of waste generated (based on Fall estimates), with equivalent proportions of organic and other waste materials.

- Scenario 3: waste quantities equivalent to that of a mature city (Vienna), keeping the same materials composition and calorific values.

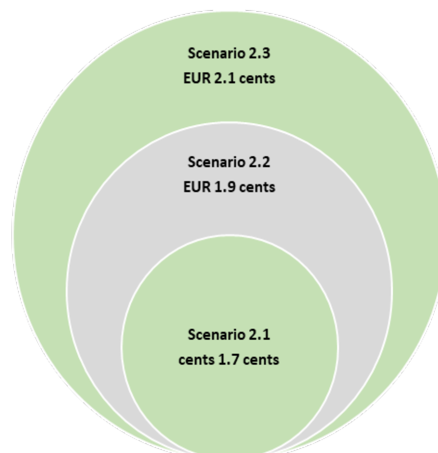
The second parameter of comparison is the cost of capital. The unit cost of DLE technology is less in Vienna due to lower discount rate. Graph 4.2b displays a comparison of the energy cost in the baseline year (discount rate = 9 percent) and the DLE cost at two levels of discount rate, which are:

- Scenario 2.1: discount rate equivalent to 7.5 percent (as in Vienna)
- Scenario 2.3: Discount rate equivalent to 14 percent (fictive)

Graph 4.2 Sensitivity of energy potential (GWh) to costs and quantities



Graph 4.2a (Simulation of Quantities)



Graph 4.2b (Simulation of costs)

Scenario 1.1 and 1.2 (quantities) provides Dakar with the potential to partially cover its energy demand in the baseline year, through recycling its waste, with proportions equivalent to 7 percent and 35 percent, respectively. Scenario 1.3 provides Dakar with the potential to cover up to 53 percent of the city electricity demand in 2016. The city's total electricity demand was 3,257.4 GWh, which details of demand per sector are available in Chapter 5.

In scenarios 2.1 to 2.3 (capital discount rate), the generation cost remains below the tariff in the baseline. The generation cost (EUR 7 cents per kWh) is relatively high, compared to the costs at different discount rates. The discount rate should be 85 percent for DLE to reach grid parity, which is unlikely.

c) Another parameter that is of interest in the waste-to-energy scenarios is CO2 price. CO2 pricing assumes a voluntary commitment of Dakar to reduce its carbon emissions as a component of its nationally determined contributions; Senegal being a non-Annex 1 party to the United Nations Framework Convention on Climate Change (UNFCCC, 2020). Therefore, we assume a fourth scenario with voluntary carbon pricing that returns, a long run-generation cost of:

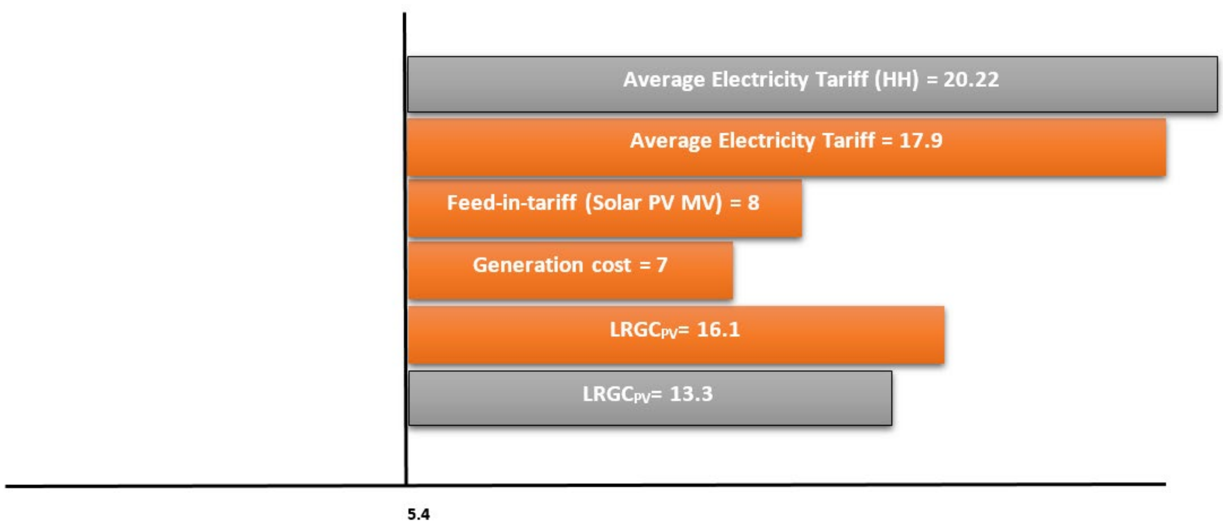
- EUR 64.1 cents for anaerobic digestion technology,
- EUR 51.5 cents per kWh for Dendro liquid energy technology.

Therefore, prices for carbon emissions make the waste to energy technology cost 7 to 9 times higher than the average cost of electricity generation, which makes waste to energy technology too expensive and no longer a competitive option for Dakar.

4.4.2 Solar photovoltaic

From Table 4.7, the long run generation cost of solar photovoltaic is EUR 16.1 cents per kWh for Dakar. In comparison, the long run generation cost of solar photovoltaic for Vienna considering previous parameters and a capital cost of 7.5 percent is EUR 13.3 per kWh.

Graph 4.3 Solar photovoltaic costs comparison (EUR cents per kWh)



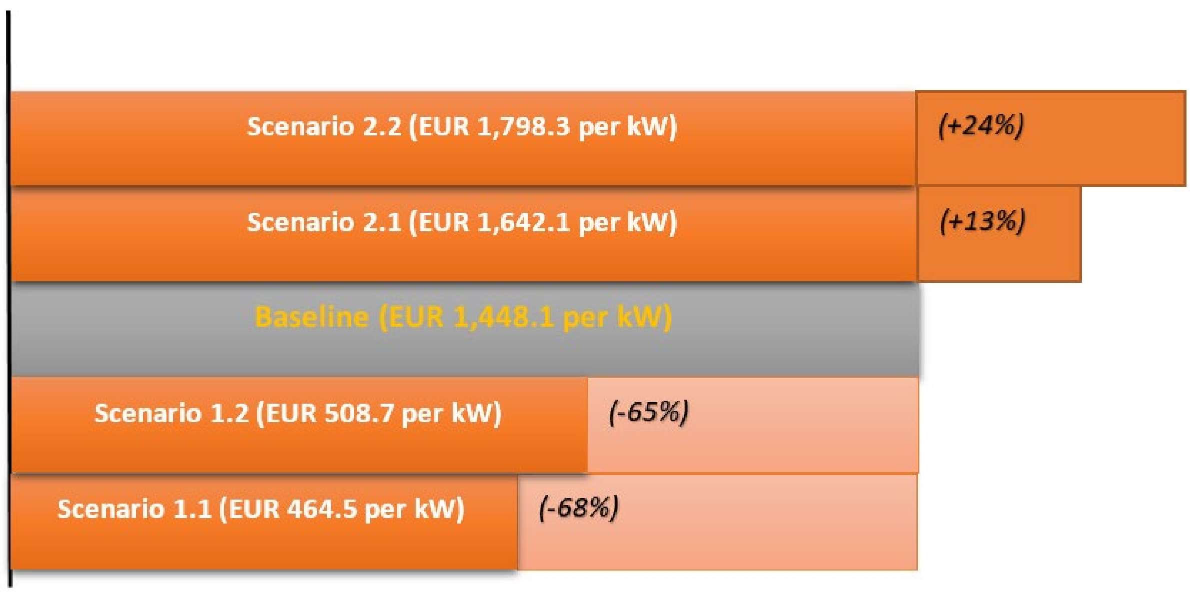
Solar photovoltaic cost is lower than the electricity tariff but is higher than average generation cost. Therefore, we can assume an economic potential for decentralized systems installed by citizens who would pay less for their solar electricity than from grid connection. However, at utility scale solar PV is economically not viable in the baseline conditions.

The sensitivity analysis considers the impact on the long run generation cost of the capital cost (CAPEX) and the discount rate. Unit capital cost of solar photovoltaic depends on capacity installed due to economies of scale. Large-scale (e.g utility scale) power plants have lower costs than distributed systems.

- Scenario 1.1: Capital cost is at the level to reach grid parity, all other parameters remaining unchanged.
- Scenario 1.2: Capital cost is at the level to reach grid parity. Discount rate is set at 7.5 percent (Vienna figure), and all other parameters remain unchanged.
- Scenario 2.1: Capital cost is at a level intended to reach consumer neutrality (i.e cost = end-user tariff), all other parameters remaining unchanged.
- Scenario 2.2: Capital cost is at the level to reach consumer neutrality. Discount rate is set at 7.5 percent (Vienna figure), and all other parameters remain unchanged.

Graph 4.4 shows solar photovoltaic capital cost related to scenarios 1 and 2, in comparison to the baseline scenario.

Graph 4.4 CAPEX Scenarios Comparison



In scenario 1.1, the unit cost should decrease by 68 percent to reach grid parity, which is equivalent to a capital cost of EUR 464.5 per kW installed.

In scenario 1.2, the unit cost should decrease by 65 percent to reach grid parity with a discount rate at 7.5 percent, which is equivalent to a capital cost of EUR 508.7 per kW installed.

In scenario 2.1, the unit cost should increase by 13 percent to reach consumer neutrality over decentralized solar photovoltaic and grid generation, which is equivalent to EUR 1,642.1 per kW installed.

In scenario 2.2, the unit cost should increase by 24 percent to reach consumer neutrality over decentralized solar photovoltaic and grid generation, which is equivalent to EUR 1,798.3 per kW installed.

4.4.3 Wind energy

From Table 4.7, the long run generation cost of wind energy is EUR 8.3 cents per kWh. This cost is slightly higher than that of Dakar's generation cost for the baseline year. In addition, we assumed that wind could not be integrated in the built environment, which excludes comparison with end-user tariffs for decentralized generation. Therefore, in the baseline conditions, the wind technology is not economically viable. As stated earlier in this chapter, when we consider the cost as exclusion criteria to compare renewable energy technology with competing energy technologies, the result favours existent generation options (mainly diesel units), as they feature economies of scale accounted in terms of experience on technology use.

We computed one sensitivity scenario in the wind energy, which sets the discount rate at 7.5 percent, equivalent to Vienna's figure. The analysis returns at this rate, the wind cost is EUR 7.7 cents per kWh, which is still higher than grid generation cost at the baseline. The discount rate should be 5.7 percent to reach grid parity.

4.5 Conclusion

Chapter 4 assessed the technical and economic potential of three renewable energy resources available in Dakar, going beyond geographic information system (GIS) tools. The main lesson derived from this assessment is that context specific parameters like space, technology costs, and capital costs matter in making a renewable energy resource economically viable or not. When considering Dakar's space restrictions and presence of competing (conventional) energy resources, we found that that waste-to-energy is the most economical alternative to grid generation within the reference energy scenario. The technology is readily available, and the city already has experience with recycling its waste to energy with anaerobic digestion. One example is the Thecogas waste-to-energy plant operational in the main slaughterhouse of Dakar. Dendro Liquid energy is another option for recycling the other calorific waste materials that the city generates in significant quantities (paper, plastics, textiles, and wood). An improvement of the waste collection in Dakar to the equivalent levels in Vienna could even produce and supply more than half of the city's electricity demand in the baseline year. Solar photovoltaic and wind energy technologies are other supply options for the city, as the resources are available and technically usable. However, technology cost and cost of capital (discount rate) should significantly decrease in order to be competitive with grid supply. Still, solar PV can be an alternative to grid at baseline costs, but only at the level of the end-user where tariffs are higher. Wind on-shore face the double limitations due to space restriction and lack of economic competitiveness, compared to competing resources.

5. Modelling sustainable energy transition for cities: case studies of LEAP, ENPEP-BALANCE, and MoCES

5.1 Introduction

Energy planning, as a computational approach, features a subjective dimension that affects its metric value, whether it is termed as renewable generation or per capita demand of the city. Beyond the quantities and costs parameters outlined in Chapter 4, the computation approach used to simulate the future of the city energy system influences technology competitiveness in the city.

Chapter 4 shows that Dakar has the technical potential for transition to energy sustainability with bioenergy, solar photovoltaic, and wind energy resources. Usually, we use modelling software to simulate the integration of these potential energy sources to the city's system. Since 1970s, energy software have been used to understand, plan, and monitor energy systems. The first energy modelling software appeared between the Oil Crisis of 1973 and the Energy Crisis of 1979, with the Market Allocation model known as MARKAL (1978) and the Wien Automatic System Planning Package known as WASP III (1979). Since then, energy software technology has constantly evolved and expanded in number. In 2018, Ringkjøb et al (2018). identified a total of 75 energy modelling software. We anticipate this dynamic to increase further in the next decades, due to increased connectivity of energy devices and the sophistication of modelling technologies. However, the weight of the model's approach on future systems computed is still unclear.

Publications on energy modelling software in our literature review answers the question of the approach by pointing to the modeller's responsibility As the World Back famously said in modelling literature: "the selection of a model only depends on the user preferences". These preferences do not necessarily translate to an informed decision that considers all alternatives, but more than often relates to accessibility of the modelling software (free download or paid license), knowledge of the model operations (inputs and outputs), previous use in the system (available documents) etc. In this chapter, we hypothesize that the modelling approach impact the city energy metrics and different software can result in different portraits of the future energy system, which together affect policy recommendations for transition to sustainability.

The core objective of the chapter is to explore how different approaches of energy modelling software affect energy metrics computed by various software. A subsequent objective is to introduce a new modelling approach known as agent-based modelling that is not frequently used in energy planning despite its popularity in other areas of economic planning, especially since the 2008 economic crisis. In this chapter, we introduce MoCES, the energy planning software we developed based on individual agents' rules in planning the city energy system. A third objective of the chapter is to consider the concept of energy sustainability from perspective of citizens, who act as individual agents who are neither rational as in computational equilibrium nor long-term strategists as in scenario simulation. The rationale of agent-based approach is relevant because energy modelling is at a crossroad of two important developments that we expect to be amplified in the next decades: cities requirement to make bigger contributions to climate change mitigation through transition to energy sustainability, and the rapid spread of information technologies among citizens.

5.2 Materials and methods

In Chapter 5, we compare three energy modelling software in order to answer the question: can a city's energy transition can simultaneously integrate all sustainability dimensions of environment friendliness, social acceptance and economic viability from a single reference energy scenario (2016)? In this comparison, we continue with our sample city, Dakar, which we assessed bioenergy (waste-to-energy), solar photovoltaic, and wind energy potential in the previous chapter. From the reference energy scenario, we compute the future energy system in three sample energy software that use different approaches in modelling energy systems. The sample software are LEAP (system simulation), ENPEP-BALANCE (system optimization), and MoCES (software with agent-based approach designed in the framework of this study).

5.2.1 Long-range Energy Alternatives Planning System - LEAP

a) Approach

The LEAP's approach is a simulation of energy scenarios from a baseline (Current Accounts) to end of the scenario period (End-Year). The user enters the baseline data in the Current Accounts, and enters changes in scenarios in the form of numerical values. In the Analysis window (View) of LEAP, the user can model the system energy demand, transformation (conversion from primary energy resources to secondary energy production), and evolution of resources reserves. The software features a Technology and Environmental Database (TED) that enables the user to connect appliances, devices, fuels, and technologies entered in the model to a database that include metadata on these appliances, devices, fuels, and technologies such as pollutant emissions. LEAP also provides an option to optimize the energy system modelled.

b) Formulae

Energy planning software, including LEAP, typically feature many built-in-functions coded as thousands of line codes that are not accessible to the front user. For instance, MoCES developed in this study features on its current version about 7,000 lines of code. LEAP built-in functions use numerical values entered by the user to compute expressions using mathematical formulae. In Current Accounts, the expression defines the baseline values of the variable, while in scenarios, the expression defines how that variable changes over time.

c) Inputs

Data are numerical values related to the energy system variables, which are entered by the modeller as units (e.g Gigawatt-hour) or as percent of technology/fuel share or saturation. The variables are structured as a set of branches hierarchically connected with categories (e.g lighting) and technologies (e.g lamps).

d) Outputs

The results of simulation process are displayed in two other windows, which are the Energy Balance View and the Results View. The Energy Balance window displays the energy situation per year (baseline and scenarios) per fuel and per sector. The Results View can display results per year, per branch, and per fuel.

5.2.2 Energy and Power Evaluation Program - ENPEP-BALANCE

a) Approach

The ENPEP-BALANCE's approach is an optimization of an energy network made of energy production, conversion, transport, distribution, and uses nodes, as well as the flows of energy and fuels among those nodes. Opposite to LEAP and MoCES, the ENPEP-BALANCE software interface is an empty workspace that the modeller fills in configuring an energy network with embedded nodes and links. ENPEP-BALANCE simultaneously finds the intersection of supply and demand curves for all energy supply forms and all energy uses included in the energy network. Equilibrium is reached when the model finds a set of market clearing prices and quantities that satisfy all relevant equations and inequalities.

b) Formulae

ENPEP-BALANCE uses a Logit Function to estimate market shares of competing commodities at the decision node. The market share of a specific fuel is sensitive to the fuel's price relative to the price of alternative fuels. User-defined constraints (e.g. capacity limits), government policies (taxes, subsidies, priority for domestic resource over imported resource, etc.), consumer preferences, and the market's ability to respond to price signals over time (i.e., due to lag times in capital stock turnover) affect the market share of a fuel.

c) Inputs

The software features two levels of data requirements:

- Case level data include the study period, convergence (e.g number of iterations), parameters' units of electric and non-electric processes, and the type of generation report.
- Process level data include the technical and economic properties of energy resources, conversion technologies, and the decision on energy resources allocations (energy mix).

d) Outputs

The result of the optimization process is an equilibrium solution across the energy system that balances the conflicting demands, objectives, and market forces.

5.2.3 Modelling Cities Energy Systems - MoCES

a) Approach

MoCES is an agent-based modelling software that can estimate a city's energy system based on individual citizens energy behaviour. At city and district levels, MoCES computes the total energy end-use considering the average energy per capita and the population, which is similar to calculations without models. The model trades-off its basic features in these levels of analysis with a more detailed interface for individual agents, whether it is a residence, commerce or industry building.

(1) In the demand side, MoCES simulates the building energy services, including lighting, cooling, heating, and cooking while considering these variables: number of service devices in the building, wattage (W), and usage time per day.
(2) In the supply side, MoCES simulates generation technologies in the catalogue, including solar photovoltaic, solar thermal, wind, waste recycling, and grid-connection, while considering these variables: power (kW), efficiency, capacity factor and operational hours per period.

In MoCES, we tried to solve some abstractions of the comparing software, which we think are as much relevant for planning energy systems as parameters like energy quantities, costs, and pollutant emissions. Among these abstractions are:

- Land requirement of energy scenarios to account for a city's competing land surface, and urbanization dynamic, which we integrated with visualization tools (Google map). When considered the exclusion criteria in our sample city, solar photovoltaic becomes a better option than wind energy, because it can be integrated in the built-environment, and therefore have a better co-presence factor.
- Intermittence of renewable resources, which is treated differently in the competing software. In LEAP, the energy resource potential (Yield) is entered as an aggregate value, with assumptions of annual growths. In ENPEP, the energy generation of renewable resources are entered as base year value and optional increments over years, both entered manually by the user. In MoCES, the energy potential is derived from an algorithm integrated with Google map that is updated according to the weather parameters, including the solar irradiance and wind speed every 15 minutes. These updates give real time generation of the system installed, which is particularly relevant to individual agents in a demand side management that integrates internet of things (IoT).

Another issue, we address in MoCES is the combination of energy system's quantitative and non-quantitative parameters such as:

- social parameters that include willingness to adopt another technology, appliance or device (e.g the comfort of use, and the performance perception).
- other environment parameters that include odour pollution created by charcoal or noise pollution of wind turbines.

In the current version of MoCES, these parameters are listed as string labels, where the user can select each input in the scenario. In the results window, they appear as selected in words, near energy quantitative results such as generation quantities, costs, and pollutant emissions figures. We consider solving the problem with an algorithm to compute social and environment indexes (between 0 and 1) for each of the non-quantitative parameters associated to a string label, which are then combined as a unique index, through an analytical hierarchy process (AHP). The only restriction when using AHP is that AHP is a registered software accessible online from a commercial website (not open-source), and therefore, we need to write the AHP lines of code to integrate in the existent MoCES code based on available literature.

During MoCES development, we primarily faced the aggregation problem, which is the difficulty to compile the high number of individual data at individual agents' level, in order to display a consistent portrait at the upper levels (district and city). An integration of the software interface to the interface of the city's grid operator can solve the problem. Buildings could be abstracted as individual dots and monitored with colour codes to visually represent data in the following:

- Green when the energy consumption over the period did not change above a threshold.
- Yellow, when the energy consumption of the dot changes between a given interval.
- Red, when the energy consumption changes above the yellow upper limit.

These innovations in energy planning software should align planning tools with promotion policies in renewables that specifically target the end-user, including third party access to the grid and feed-in-tariff. This approach also solves the impact of unclear city boundaries on city energy metrics (Grubler, et al., 2012); because, the buildings in the network constitute the city boundaries.

Still, the aggregation problem is not only problem with the MoCES program. The aggregation solution at LEAP level assumes:

- similar balance point temperature (BPT) for all citizens that enables the model to compute cooling in terms of energy use per household.
- similar level of brightness in lighting that allows the model compute the required lumen per square meter and therefore energy lighting per household.

b) Formulae

MoCES algorithms are traditional energy formulae coded in computing results parameters. For instance, the technology generation quantity is a result of the technology capacity (kW), hours of operations (capacity factor), and efficiency. Costs are calculated as unit cost multiplied by number of technologies or appliances. Pollutant emissions quantities are calculated based on the emission factor per kWh, and the technology generation quantity (kWh). Ninety other results such as net present value, cost of lighting saving, or CO_2 sink potential are computed based on input parameters with formulae available in the scientific literature.

c) Inputs

At the city and district levels, the input data is energy per capita demand times population, which is similar to what is possible with other computational tools without software models. At buildings level, the input data are power (wattage for appliances and devices), capacity factor (use time per day for appliances and devices), and efficiency.

d) Outputs

The MoCES results window feature three components:

- Virtual installation of the scenario technology in the area located with Google maps.
- Demand and supply columns where the results computed are categorized as technical, economic, environmental, and social. Currently, MoCES computes ninety-three (93) results, which is more than any comparable software.

As an agent-based model, the equilibrium of demand and supply is not a pre-requisite, therefore, a fourth column of the software displays the load curve per period, which shows excess or deficit generation of the period. Figure 5.1 depict a sample of MoCES' results window.

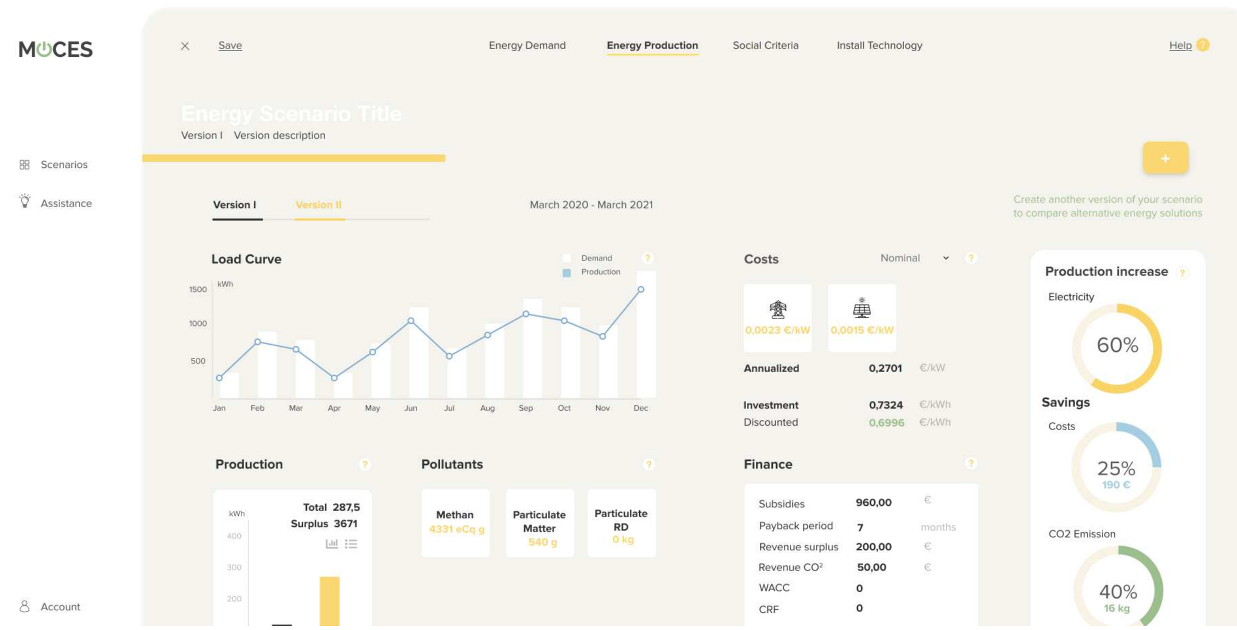


Figure 5.1 MoCES Results window

5.3 Theory and calculation

The data used in this chapter to build the reference energy scenario of the city (2016) mainly come from three documents:

(1) The 2016 report of the Senegal Information Energy System (SIE, 2018) that is accessible from the ministry in charge of Energy since 2018.

(2) The utility report of 2016 on the electricity situation (SENELEC, 2017)

(3) The matrix of data collected during the survey on citizens' energy behaviour performed in different districts of Dakar between July and November 2019, which was conducted in the framework of the project Sustainable Energy Access for Sustainable Cities (SEA4cities 2019). We have provided as supplementary material of Chapter 5 in Annex 1, the survey sampling techniques and collection methods.

Whenever we assume data in the RES considering sources different from those mentioned above, we name the source and relevance for our study.

5.3.1 Reference Energy Scenario

In chapter 5, we modelled a simplified version of the city energy network. Figure 5.2 displays the simplified city energy network.

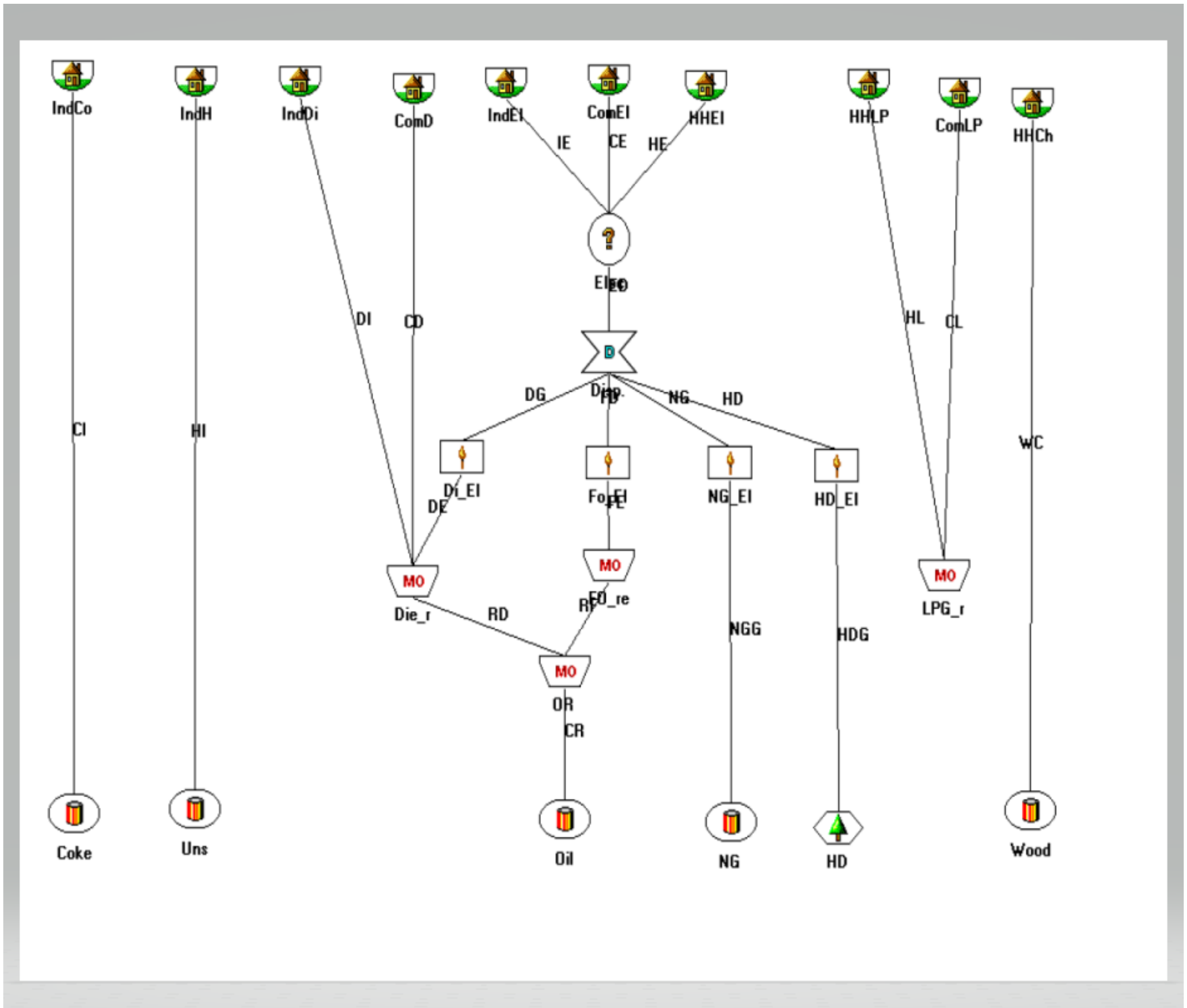


Figure 5.2 RES City energy network (created with ENPEP)

We provide the details of input parameters in below paragraphs.

a) Primary energy resources

Energy in our network flows from the primary energy resources to end-use in residence, commerce and industry sectors. Table 5.1 displays the quantities, conversion factors, and costs in EUR per tonne oil equivalent (toe) of primary energy resources in the network.

Table 5-1 RES Primary Energy Resources

Resources	Consumption (toe) [a]	Price (USD) [b]	Conversion factor (in toe)	Price (USD per toe)	Price (EUR per toe) [c]
Coke	416,566	120.59 per metric ton	1 metric ton = 0.64 toe	187.50	168.75
Crude oil	1,102,202	43.74 per barrel	1 barrel = 0.14 toe	312.43	281.19
Natural gas	416,604	2.87 per million BTU	1 million btu = 0.026 toe	108.80	97.92
Wood	1,691.86	23.8 per metric ton	1 metric ton = 4.8 8 (10-3) toe	49,790.79	44,811.72

[a] Consumption values are figures from SIE (2018).

[b] Fuel prices are the average of 2016 prices in the international market of commodities downloaded from Statista on February 2020. For wood, we considered the reforestation cost of EUR 991 per ha (SIE 2016).

[c] This column uses information in precedent columns to compute unit cost of each primary energy resource in the system per tonne of oil equivalent.

Crude oil and coke are imported. Natural gas and wood are domestic resources.

The reforestation cost is EUR 991 per ha, charcoal land intensity is 8,333.3 kg per ha. The wood to charcoal conversion efficiency is 20 percent (SIE 2016), and the energy content of the wood that we assumed at 20.9 MJ per kg, then the wood price is 23.8 per metric tonne.

Oil refining

From crude oil imported (1.1 million tonnes), the local refineries produce diesel, fuel oil, and LPG with an efficiency of 88%. The remaining diesel, fuel oil, and LPG consumed in the network is imported

Charcoal production

In our simplified energy network, we consider charcoal, because it can easily be replaced by other fuels in the system, since electricity and LPG provide the same cooking service. Charcoal comes from the local production of wood that uses kiln with an average efficiency of 20%. Table 5.2 displays wood to charcoal production information.

Table 5-2 Charcoal production parameters

	Km2	ha
Green areas in the city	161.9	16,190
Green areas with beefwood (5%) [(a)]		810
Charcoal intensity (ha/kg) [(b)]		0.12
Charcoal potential (kg)		6,745,833.33
Charcoal potential (MJ/kg)		20.9
Charcoal potential (MJ)		140,987,916.67
Equivalent wood potential (MJ)		70,493,958.33
Equivalent wood production (toe)		1,691.86

[(a)] We assume beefwood as wood species for charcoal production. We were not able to find in the literature a specific figure on beefwood share in the woodland of the city. Therefore, we assume a 5 percent share. The share could also be understood as a sustainable wood harvesting process that requires 20 years for a woody land to regenerate; therefore, 5 percent of the woodland should be harvested every year.

[(b)] The charcoal intensity in kg per ha is form SIE 2016.

b) Energy conversion

Electricity Transmission and Distribution

According to the utility (SENELEC, 2017), the losses in the electricity transmission and distribution network in 2016 was:

- Transport: 1.2%
- Distribution: 16%

Energy generation

Table 5.3 provides parameters related to secondary energy sources (conversion from primary resources) in thousand tonnes oil equivalent (ktoe).

Table 5-3 RES Secondary Energy Production in ktoe

Conversion per technology	Production	Availability rate	Efficiency rate	Cost (EUR per kWh) [a]	Cost (EUR/toe) [d]
Diesel (for electricity generation)	144.3	0.88	0.39	0.07	766.86
Fuel oil (steam)	14.2	0.60	0.39	0.09	1,053.85
Natural gas	0.33	0.92	0.39	0.17	1,922.81
Imported hydropower	19.2	0.80	0.80	0.032	371.02
Charcoal	46.7		0.2		123.25
LPG [b]	423.3				65.34
Diesel (for end-use) [c]	119.8				494.4

[a] The columns production, availability rate, efficiency rate, and costs of conversion power plants are from the utility report.

[b] The figures for charcoal and LPG are from SIE (2018). LPG is used in 86% of households at a cost of EUR 0.76 per kg (EUR 4.6 for the 6 kg bottle). The energy intensity of LPG is 0.07 toe per household. Charcoal is used in 14% of households. The energy intensity of charcoal is 0.11 toe per household. Charcoal expense is on average EUR 9.3 per household.

[c] Diesel end-use is a computed figure that reconciles figures of energy end-use in the commerce and industry sectors from SIE 2016 and our assumptions on the city's share of energy consumption from these sectors in the RES. For instance, the diesel end-use of

commerce is the city's commerce end-use estimated as 39.5 percent of national figures minus other fuels end-use in the sector provided in SIE 2016.

[(d)] This column converts unit cost provided in the above-named documents, considering the conversion rate 1 toe = 11,630 kWh.

The hydropower resource is outside the city. The geographic situation of the city (coastal region at about 20 meters above sea level) does not provide a suitable environment for hydropower generation.

On capacities, we assume the overall installed capacity in the interconnected grid available to supply the city. Then, we input in the model availability rates provided by the utility for these installations in 2016 and peak load data per month (Annex 2). The efficiency of thermal units was on average 39 percent in 2016. We assume 80 percent efficiency for hydropower units.

The dispatching of power plants considers running cost rule, meaning plants with lowest generation costs (diesel, fuel oil, and steam) are baseload plants, and plants with highest generation cost (natural gas) are peak load plants.

c) Energy Demand

Residence

Figure 5.2 shows the energy end-use of households are electricity, charcoal, and LPG. Electricity is used for cooling, lighting, refrigeration, and for operating other domestic appliances. Table 5.4 displays the households' electricity demand per service.

Table 5-4 Intensity of households' electricity services

Service	Lighting	Cooling	Refrigeration	TVs	Phones &others
	506.1	1,153.5	1,297.5	73.2	36.0
Total					3.066.3

For each service, we computed an average of the energy intensity data from the surveys on Dakar's energy behavior completed in May 2019 (low standard district) and November 2019 (high standard districts). For lighting, the average energy intensity per household per year was 409.5 kWh (low standard district) and 602.7 kWh (high standard districts). The city average was 506.1 kWh per household per year. We use the same method to estimate the energy intensity of other services.

For additional information on the survey, see Annex 1.

The total electricity' services amount to 3,066.3 kWh per household per year in the city. These figures are consistent with consumption statistics provided by the utility. According to the utility, the average electricity consumption per household at the national level was 2,914.4 kWh. Higher figures for the city of Dakar (0.03%) can be justified by the relatively higher living standard compared to other cities in Senegal. Residential grid users in the city were 424,939 in 2016.

Industry

Total industry energy consumption was 723 ktoe in 2016 (SIE 2016). Ninety-one (91) percent of these industries were located in Dakar according to the 2016 General Survey of Enterprises (ANSD, 2017). Therefore, the energy intensity of industries in our sample city was 657.9 ktoe of which 1,716.7 GWh of electricity. Other industrial energy uses are coke (cement industry), diesel for backup generation, and unavoidable steam that results from some industries (e.g phosphates) in their business-as usual activities.

Commerce

Among non-industrial enterprises identified in the 2016 General Survey of Enterprises (ANSD, 2017), 39.5 percent were located in Dakar. The commerce energy consumption was 1,122 ktoe at national level, therefore, the energy intensity of enterprises in the city is estimated at 443.2 ktoe. Other energy uses of the commerce sector are diesel as back-up energy and LPG for some commerce enterprises (e.g restaurants).

5.3.2 Renewables in electricity generation (Scenario 2)

In scenario 2, we assume:

i. City population grows by 3.7 percent per year; figure provided for Dakar by World Bank (2019) for the period 1990-2018;
ii. Number of households connected to the grid increases by 4.4%, which is an average of the period 2009-2016 computed from the utility annual reports of the period;

iii. The city's renewable energy potential computed in Chapter 4 is integrated in its generation mix.

The technologies unit cost are figures computed in Chapter 4, and here summarized in Table 5.5.

Table 5-5 Renewables' potential capacity and costs

Technology	Bioenergy		Solar photovoltaic	Wind
	DLE	AD		
Capacity (MW)	33.6	6	689,945.3	5,951.4
Efficiency factor (%)	80	66	21	40
Capacity factor (%)	84	84	17	31
Installation cost (EUR per kW)	517	1890	1609	1609
O&M cost (EUR per kWh)	0.01	0	0.027	0.01
CO2 cost (EUR per kWh)	0	0.01		

5.3.3 Demand-side-management in the residence sector (Scenario 3)

In scenario 3, we take the assumptions from the Scenario 2 as baseline, and predict improvements in individual household's energy behaviour compared to observations during the survey, as following

a) Lighting energy intensity decreases by two-thirds equivalent to a retrofit of bulbs from halogen (18 Watt) to compact fluorescent light (CFL) (6W) standard or from CFL to LED (2 W) at constant brightness of 200 lumen per m2.
b) Cooling energy intensity decreases by 20 percent equivalent to an increase of the balance temperature point (comfort temperature) by 1 degree Celsius. For example, a building with constant environment factors such as air exchange factor, specific heat capacity, and air density will require 164 Wh energy at 22 degree Celsius balance temperature point, when the outside temperature is 25 degree Celsius. When we increase the balance temperature

point to 23 degree Celsius, the cooling energy requirement becomes 131Wh, meaning a decrease by 20 percent.

c) Refrigeration energy intensity decreases by 32 percent equivalent to retrofit from low standard fridges of 220 Watt to medium standard fridges of 150 Watt.

d) TVs, phones, and other appliances energy intensity decreases by 10% due to manufacture improvement in the autonomy of batteries or sleep mode consumption, without additional action from the user.

a) All households use LPG for cooking.

5.3.4 Mitigation of environment strain (scenario 4)

Scenario 4 assumes a reduction in greenhouse gas emissions from the city's energy system, after demand management and integration of renewable energy systems. The scenario targets reduction of energy pollutants that affect the environment, including carbon dioxide (CO2), methane (CH4) and nitrous oxides (N2O).

5.4 Results discussions

5.4.1 Reference Energy Scenario (RES)

The figure 5.3 displays Dakar's simplified Reference Energy Scenario (2016) generated with LEAP.

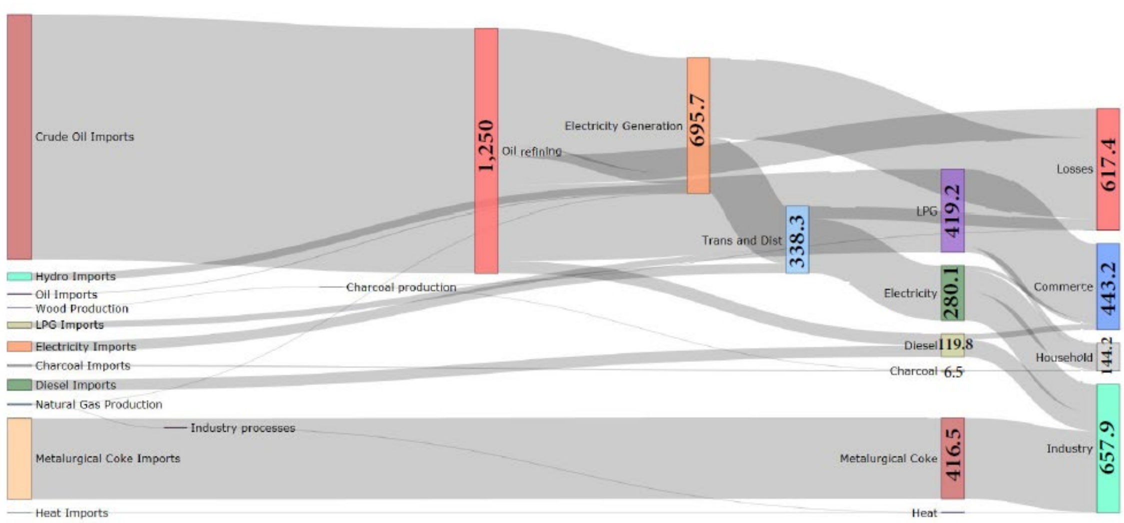


Figure 5.3 RES-LEAP (in thousand tonnes of oil equivalent-ktoe)

The energy balance is presented in tonnes of oil equivalent, with all input parameters converted with the embedded LEAP energy units' conversion. It is possible to convert the figures to other energy units such as GWh for electricity, using the international Energy Agency online unit converter accessible at https://www.iea.org/reports/unit-converter-and-glossary.

The overall electricity generation of the system was 697.5 ktoe in 2016. This generation mainly relies on diesel (85.8 percent), and fuel oil (8.5 percent) produced from crude oil imported by refineries. Hydropower (5.5 percent) and natural gas (0.2 percent) complete the electricity generation resources of the system. Energy losses (617.4 ktoe) include refineries, power plants, and grid losses. It represents more than electricity distributed to end-users due to the relatively low efficiency of thermal units (diesel, fuel oil and natural gas). As electricity demand of end-use sectors (280.1 ktoe) is more than the system supply (229 ktoe) after transmission and distribution losses, the system imports 51.1 ktoe electricity to meet the demands of the end-use sectors. Other energy imports in the system include:

- Fuel oil (4.7 ktoe) for electricity generation,
- Diesel (56.8 ktoe) for end-uses in the commerce and industry sectors,
- LPG (33.2 ktoe) for end-uses in the commerce and residence sectors,
- Coke (416.5 ktoe) used by the industry sector,
- Charcoal (6.4 ktoe) for cooking due to the limitations on wood production (5% of available woodland per year)

Wood and natural gas resources in the system are domestic productions. The heat use of industry is totally from domestic activities (natural gas) and there is no import of heat in the RES, despite the fact LEAP displays it with 0 as value.

5.4.2 Renewables in electricity generation (Scenario 2)

a) LEAP

The Figure 5.4 displays the future energy system under Scenario 2 that assumes an integration of the renewable energy potential on bioenergy (waste-to-energy), solar photovoltaic, and wind in the electricity generation system in LEAP.

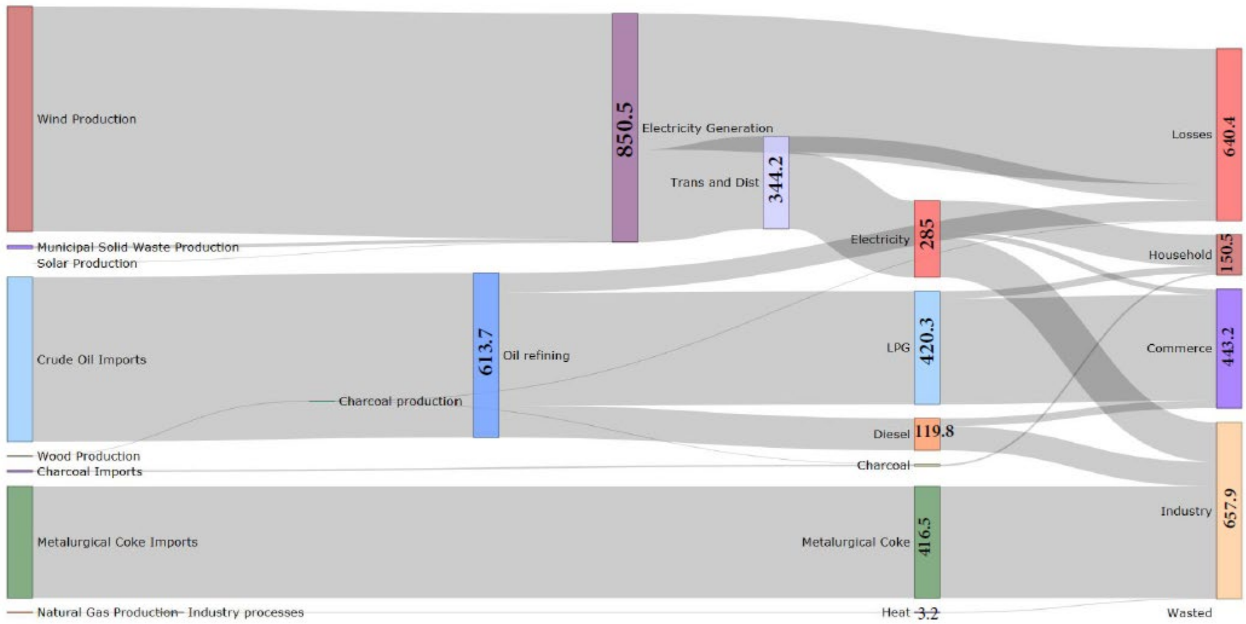
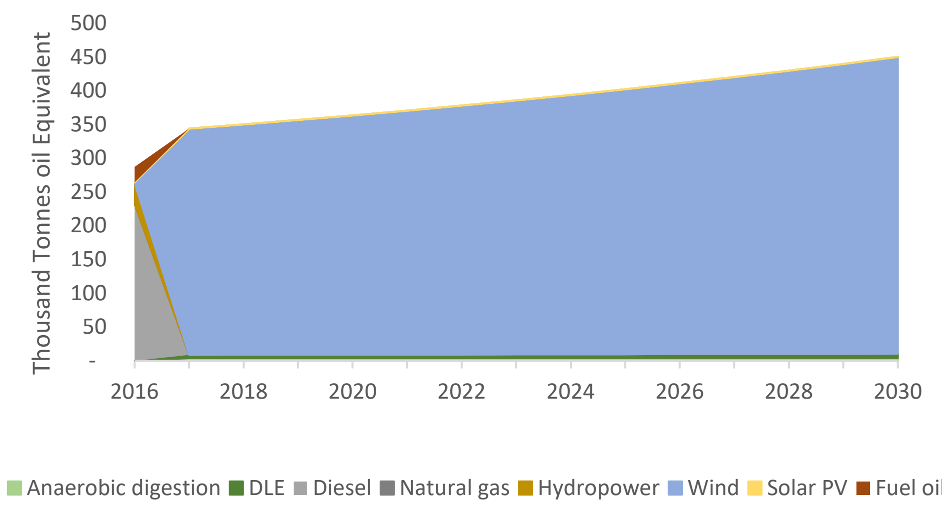


Figure 5.4 LEAP-2017 City Energy System (in ktoe)

In this scenario, the electricity generation increased by 179 percent, and supplies the overall city electricity demand (imports=0). Wind energy resources converted to electricity at the average cost of EUR 8.3 cents per kWh supplies 98.8 percent of the city electricity demand. This generation cost is higher than diesel units cost (EUR 7 cents per kWh) and hydropower unit cost (EUR 3 cents per kWh). However, both technologies run with imported fuel, and LEAP computes results to prioritize domestic resources, per default. In this scenario, crude oil imports decrease by 52.1 percent, and its refining only produces LPG and diesel for the commerce and industry sectors end-uses.

The remaining electricity generation (1.2 percent) is from waste-to-energy (anaerobic digestion and Dendro liquid energy) that is the cheapest domestic resource. The system cost is EUR 5,864.6 mio. Graph 5.1 displays the annual electricity generation during the period 2016-2030 according to LEAP Model.

Graph 5.1 Renewables in electricity generation (LEAP)



Caption: The gap between 2016 and 2017 includes a deficit generation met through imports of electricity in 2016.

b) ENPEP-BALANCE

Figure 5.5 displays the future energy system under scenario 2 in ENPEP-BALANCE.

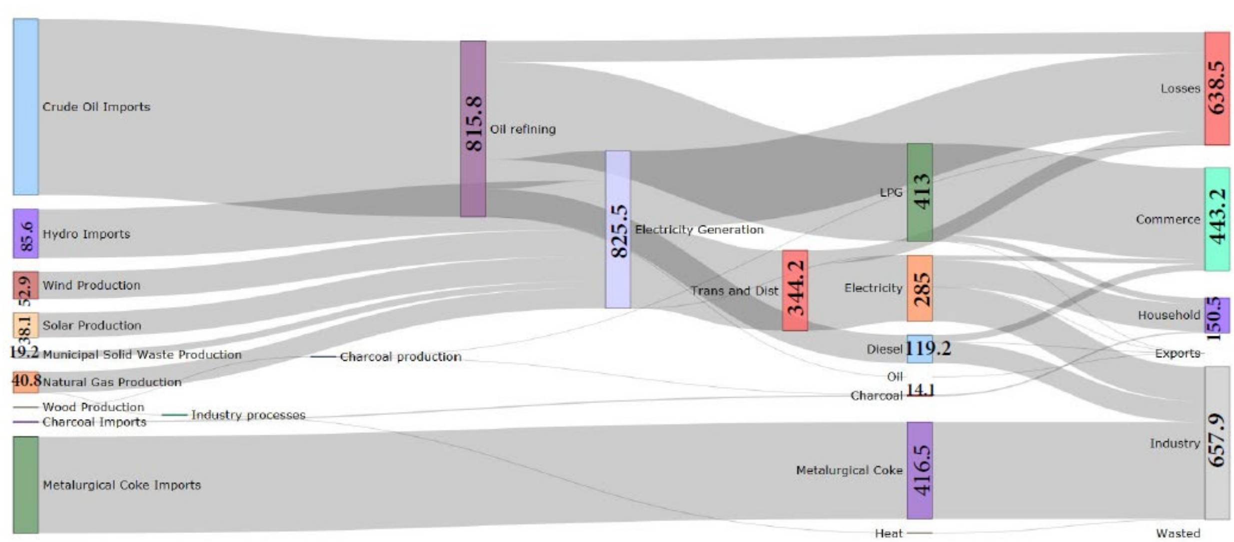


Figure 5.5 ENPEP-2017 City Energy System (in ktoe)

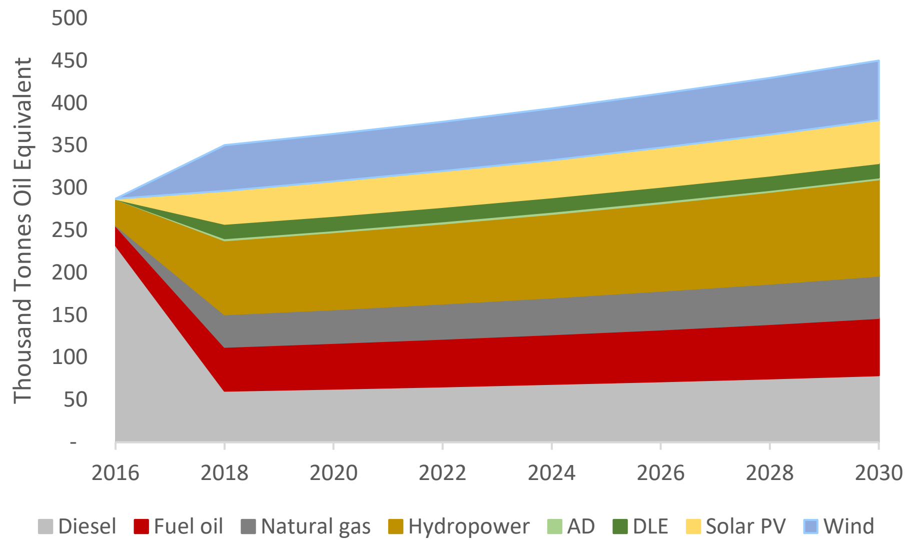
The model constant parameters are:

- Premium multiplier that we assumed at 1 to indicate neutrality over fuels available as option. Premium multipliers reflect the preference for a fuel over others. Multiplier greater than 1 raises the price of competing energy products in the market share equation. Multiplier less than 1 lowers the price of competing energy products in the market share equation
- Cost sensitivity factor we assumed at 0.5. Value of 0 is an extreme case and indicates the least degree of share sensitivity to prices. Value above 1, indicates a high degree of share sensitivity to relative prices
- Lag factor that we assumed at 1. The lag value ranges between 0 and 1. Value of 1 indicates there is no lag, and shares respond to current prices. Value of 0 indicates no response to prices; base-year shares are maintained throughout the study period.

In ENPEP, the share of fuel in the city supply mix is inversely proportional to its cost. The market share of the fuel is its relative price over the sum of all fuels relative prices. Therefore, ENPEP modelling result in a situation where all available fuels are in the supply mix; with the cheapest option, having the higher share. In 2017, DLE was the cheapest option (EUR 1.9 cents per kWh), but it has a capacity constraint (33.6 MW) that limits the generation to 17.1 thousand tonnes oil equivalent per year. The other waste to energy technology (AD) is also used at full capacity (6MW) as the third cheapest generation technology. In between, hydropower import with a unit generation cost of EUR 3.2 per kWh is the main supplier to the grid, followed by wind energy. Diesel generation decreases by 74 percent compared to the RES. Natural gas with the highest generation cost (EUR 17 cents per kWh) has the lowest contribution to grid supply. The overall system cost is EUR 943.2 mio.

Graph 5.2 displays the city electricity generation per fuel predictions during the period 2016-2030, according to ENPEP-BALANCE.

Graph 5.2 Renewables in electricity generation (ENPEP)



We assume, constant fuel prices over the simulation period, therefore fuel shares remain unchanged. Increase on generation quantities are driven by increasing electricity demand in the residence sector.

c) MoCES

In MoCES, the user is required to enter both changes on the average end-use demand and on supply options compared to RES figures. This provides the user with plenty of flexibility in selection of different supply options, compared to LEAP, and without the pre-requisite of a system equilibrium as in ENPEP.

If the city's objective is to dispatch power plants as per running cost rule, meaning generation technologies enters first the supply. Figure 5.6 displays the future energy system under Scenario 2 in MoCES.

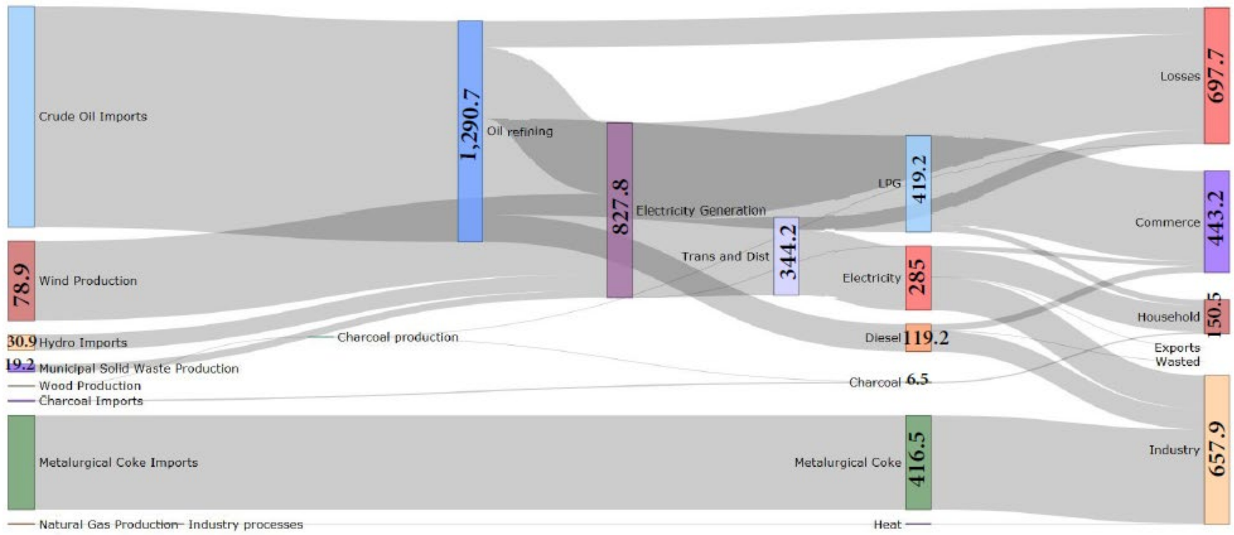


Figure 5.6 MoCES-2017 City Energy System (in ktoe)

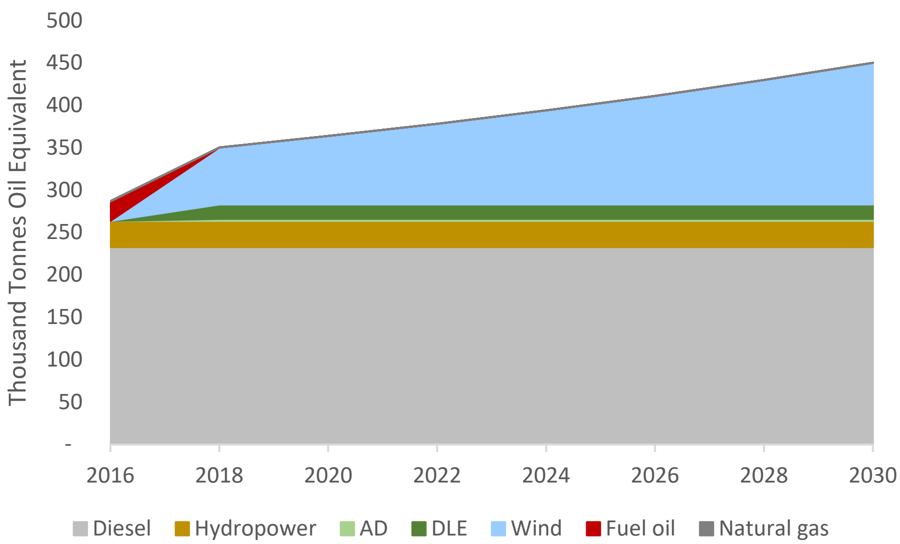
As for ENPEP, the full potential of municipal solid waste to energy is integrated, as being the first and third cheapest generation options in the supply mix followed by hydropower, diesel, and wind. Hydropower also enters the generation mix at its baseline import capacity due to the possibility to limit power in the production window. About 11 percent of the city's wind energy potential is used to complete the mix. The system cost is EUR 1,088.8 mio, which is higher than the ENPEP predicted system cost.

If the city's objective is to secure autonomy of supply, meaning to rely only on domestic available resources, then the full potential of municipal waste to energy is integrated. Wind energy generation is multiplied by a factor of 4.2, equivalent to 58 percent of the city wind potential.

MoCES does not make any assumption on the user's expectations. The user inputs their representation of the system and the model displays what it looks like. This approach provides more flexibility for different agents to simulate the same energy system based on different rationales. It also requires a considerable number of input parameters compared to LEAP, which are still less than ENPEP input requirements. In MoCES, we tried to minimize the burden of specific input data for users, by adding an option for default data that are city-specific, which the user can change. For instance, 250 W polycrystalline for solar panels (can be 365 W or monocrystalline).

Graph 5.3 displays the electricity generation during the period 2016-2030 according to MoCES, with the running cost rule in power plants dispatch.

Graph 5.3 Renewables in electricity generation (MoCES)

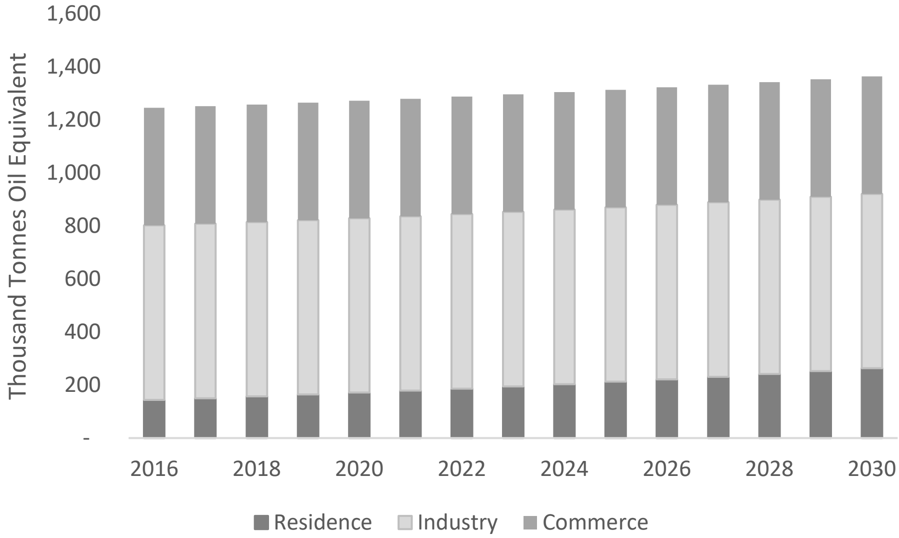


The model results in a future energy system with one conventional resource generation (diesel) and three renewable resources generation (hydropower, waste to energy, and wind) from 2017. Two among these electricity generation resources are imported into the city network, namely diesel fuel and hydropower.

5.4.3 Demand-side-management in the residence sector (Scenario 3)

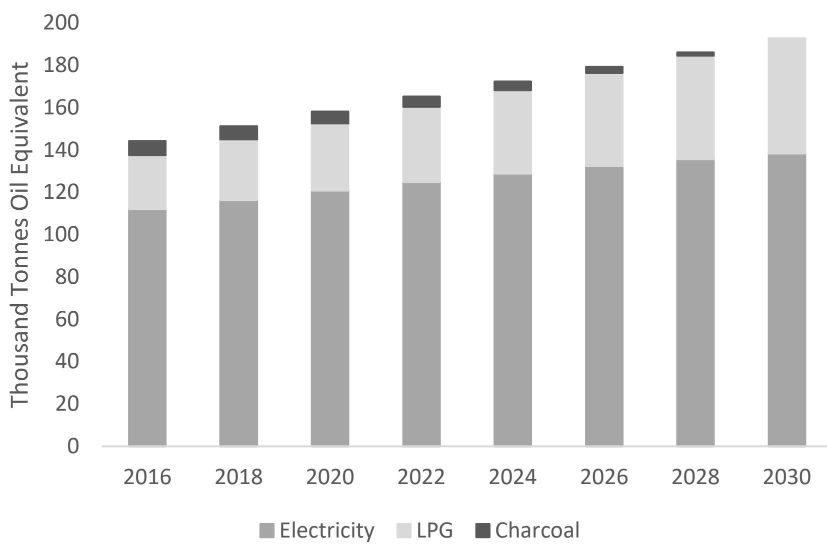
Graph 5.4 displays results in LEAP of scenario 3 that assumes, from scenario 2, an improvement of citizens' energy behaviour in terms of energy demand for lighting, refrigeration, cooling, cooking, and other domestic appliances.

Graph 5.4 Demand-side management (LEAP)



The households, energy demand increases on average by 2.1 percent per year, despite an increase in the number of city households of 4.4 percent per year. Graph 5.5 displays the household energy demand per fuel.

Graph 5.5 Energy demand per fuel in the residence sector (LEAP)



a) LEAP:

Electricity demand represents the main part of a household's energy demand, but it only increased by an average 1.52 percent during the period, due to improvements in the energy performance of electric appliances. In comparison, LPG use increased by an average 5.5 percent during this period to account for progressive (interpolate function) replacement of charcoal and increase of the number of the city's households. Charcoal demand decreases by an average 19.8 percent per year to reach zero by 2030.

b) ENPEP:

- Electricity demand increases by an average 2 percent over the 15-year period.
- LPG demand increases by an average 1.25 percent, while the charcoal demand increases, because the presence in the energy mix of a fuel depends on its price. The growth of charcoal demand is driven by the increasing number of households, as for other fuels.
- Gross electricity generation, before losses, decreases by an average 1.4 percent due to decreasing demand compared to scenario 2.
- As the model always runs to an equilibrium, all electricity generation technologies decrease generation quantities in proportion of their market shares.

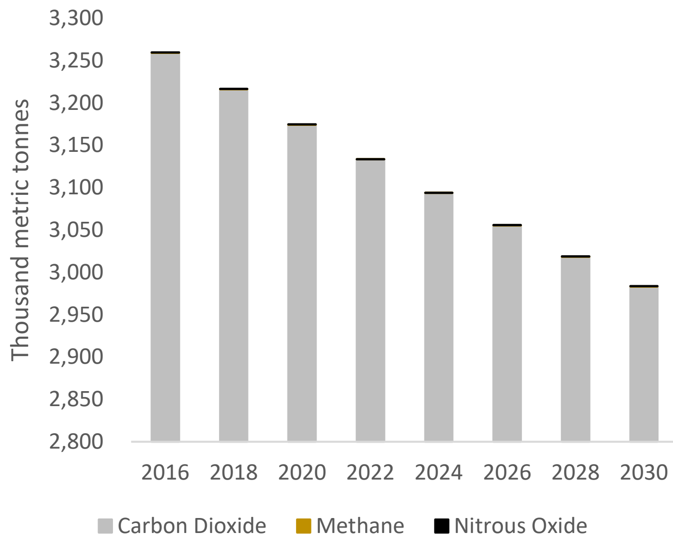
c) MoCES

- Electricity demand decreases by an average 0.17 percent over the 15-year period.
- LPG demand increases by an average 3.3 percent, while the charcoal demand decreases by an average 23.3 percent to reach zero by 2030.
- Gross electricity generation, before losses, decreases by 1.5 percent due to a decreasing demand compared to scenario 2.
- Compared to scenario 2, the demand side management decreases the wind energy generation by 48 percent equivalent to a 572 MW wind power plant or the decommissioning of 310 MW diesel capacity in 2032.

5.4.4 Mitigation of environment strain (scenario 4)

Graph 5.6 displays the environment effects of scenario 3, which include scenario 2, compared to the reference energy scenario (2016).

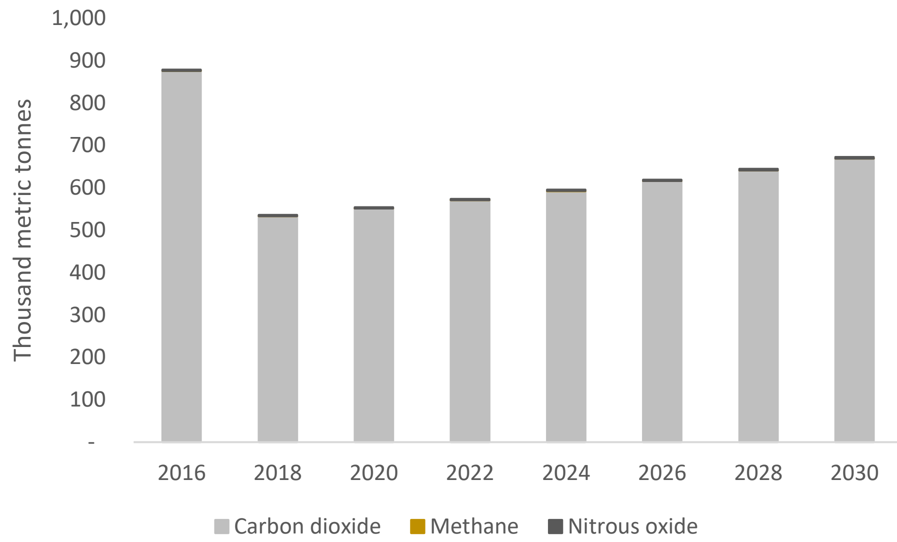
Graph 5.6 LEAP-Environment impact



The majority of pollutant emissions associated with the energy system is carbon dioxide as it relates to the energy demand. To avoid a double accounting of these emissions, LEAP does not provide options to calculate emissions in the conversion process. For appliances and devices entered, we used IPCC Tier 1 emission figures, and when these figures are not available (for fridges and lamps), we used the South Africa emission figures in the Technology and Environment Database. The CO2 emissions decrease over time due to the reduction of the energy intensity of the demand appliances and devices. In 2030, carbon dioxide emissions are estimated at 2,772 thousand metric tonnes, while it was 3,157.2 thousand metric tonnes in 2016.

Graph 5.7 displays the environment related impact of scenario 3 in ENPEP.

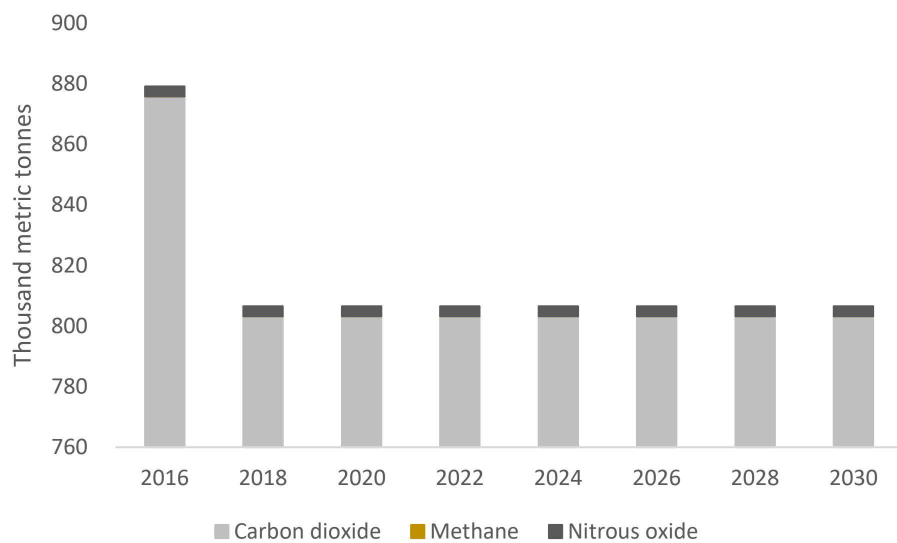
Graph 5.7 ENPEP-Environment impact



As found in LEAP, most of the pollutant emissions computed by ENPEP is carbon dioxide. The quantity decreases between 2016 and 2017, corresponding to the entry in the electricity generation of renewable technologies that causes decrease of other technologies market shares. After 2017, an increase of emissions is attributed to an increase of electricity generation, while shares remain unchanged. Two ENPEP results are notable compared to the LEAP results. Carbon emissions are overall less in the ENPEP scenario than in the LEAP scenario in terms of absolute values. This may be related to different emissions factors embedded in LEAP. However, as we could not access the values in the LEAP database, we were not able to compute the impact of this factor difference, or even consider the influence of other factors in the calculation of emissions in LEAP.

The second surprising remark is on the consistent rate of carbon emissions over years studied in the LEAP scenario, where wind energy generates overall electricity consumed from 2017. This may be related to the fact that emissions are considered from the demand side (appliances and devices) in LEAP while emissions are measured from the conversion side in ENPEP (electricity generation). Still, these findings suggest a weakness in the environment effect algorithm, because the emissions should have decreased in this scenario with wind as main electricity generation source. Graph 5.8 displays the environment related impact of scenario 3 in MoCES.

Graph 5.8 MoCES-Environment impact



The decrease between 2016 and 2017 is due to the withdrawal of fuel oil and gas units in the energy network. From 2017, diesel and waste to energy power plants are sources of pollutant emissions in the supply mix. Therefore, emissions of carbon dioxide (CO2), methane (CH4), and nitrous oxides (N2O) remains stable between 2017 and 2030.

In the following paragraphs, we discuss the four main findings from Chapter 5.

The selection of the model influences the future energy system. From a single reference energy scenario, we derived different results regarding supply mix, system cost, and related environmental impact. Therefore, the claim that the selection of an energy-planning model only depends on subjective considerations (the modeller preference) does not hold, as objective factors like the approach and the algorithm formulae also play out in the result.

One-Hundred (100) percent renewables supply mix such as in Scenario-2 LEAP does not guarantee the lowest environment impact, at least considering the model results, nor the lowest system cost. Energy transition in the conditions of Scenario 2-LEAP is the most expensive for the city.

Dispatch of the city's generation technologies are considered to be the running cost rule, meaning technologies with lowest generation cost (long run generation cost) enter first the supply mix but it does not guarantee the lowest cost of this mix. The Scenario 2-ENPEP features a share of all available technologies, including the most expensive natural gas, and has the lowest cost compared to Scenario 2-LEAP (waste to energy and wind) and Scenario 2- MoCES (diesel, hydropower, waste to energy, and wind).

Accessible demand side management in the residence sector has a significant impact in the system's generation quantities. Measures such as retrofitted lamps, higher balance temperature point (BTP) in cooling can save up to the equivalent of 572 MW wind energy. The adoption of 100 percent LPG cooking saves 17 thousand tonnes of oil equivalent that corresponds to a woodland area of 41 km^2. Also the majority of charcoal is imported from outside the city in the RES. Overall, changes in agents' energy behaviour, like cooking, save 0.13 tonne oil equivalent energy per household per year. This result confirms the valuable action of individual agents in a city scenario of transition to energy sustainability, and the relevance of providing these agents with tools such as MoCES to better inform individual decisions and their contributions at city level.

Discussions about which modelling approaches, and consequently on which software to use in modelling energy systems is actually of philosophical substance, because it questions our perception of real life situations that can be coded as algorithms. The model embedded parameters – those the user cannot change- translate into a representation of our perception of what is or what should look like the system.

LEAP has been utilized in the context of emerging cities. The community page of the website provides information on these cities. Compared to other software, the LEAP approach is a step forward in better capturing the reality of energy systems (see Urban et al., 2007). However, this approach implies a restricted understanding of the energy system that only input average values for agents and limit results to economic and environment dimensions of the energy system. It is commonly found in all energy modelling tools we reviewed within this study that the social dimension of energy is overlooked. Still, social value is the third dimension of sustainability. Decisions involving an energy system affect social well-being, and easily tractable parameters such as comfort termed as balance point temperature of cooling appliances, and brightness termed as lumen per m2 (lux) of lighting bulbs can be monitored in through models. They also affect less tractable parameters such as willingness to adopt new technologies (e.g wind) or appliance (e.g LED lamp) in replacement of existent technologies and appliances. This adoption involves subjective parameters such as experience, opinion, openness to new idea, and many other factors. Today, these parameters can be integrated in energy modelling software in the format of an index derived from an analytical hierarchy process. In addition to tracking these social dimensions of energy in future energy system, we propose in MoCES to capture the following:

- options to reduce renewable energy land intensity, taking into account urban competing space;
- alternatives to reduce the energy demand intensity of individual buildings, without changing comfort in the baseline.

Social parameters in optimum calculation is challenging. Should all systems necessarily run on an optimized equilibrium? If the answer is yes, then ENPEP-BALANCE is the appropriate model. The model implies rationality of the system agents to select among a variety of energy technologies (they do not necessarily know) the least cost option based on the price allocation formula we displayed above. The equilibrium models assume static agents disconnectedly making optimization decisions permanently set. Neither the interactions of these agents nor their learning over time is captured. Murray Gell-Mann, 1969 Physics Nobel Prize laureate, once said "Imagine how difficult physics would be if electrons could think" (Gell-Mann, 1994). Yet, electrons do not think, but economic agents in a system such as that of energy do. They interact, they learn, and adapt their planning strategies. Any regulator –can be a municipality- who wants the adhesion to efficiency measures, needs to know and be able to measure what matters to these agents. The equilibrium approach in modelling was very popular in the 1970s, and not only in energy. In recent years, two main factors have limited its propagation in development of scientific tools.

(1) In economics, the dynamic stochastic general equilibrium model (DSGE) has been named among other factors that caused the non-anticipation of the 2008 financial crisis. Since, then, economists have constantly called for development of new economic models (Farmer & Foley, 2009).
(2) The second parameter that makes equilibrium models less attractive is the development of computer engineering, specifically with tools that allow to include more parameters in models (e.g non-quantitative parameters with Fuzzy logic) and in different shades. This reduces the number of assumptions in the model, with averages, and provides flexibility to the user in entering context-specific energy parameters.

Still, equilibrium models are widely used in the energy sector, and international organizations such as World Bank and IMF continue to publish forecasts of energy systems based on these tools.

5.5 Conclusion

Chapter 5 demonstrates that energy modelling software can integrate different dimensions of transition to energy sustainability at city level, including the selection of an electricity generation technology, security of supply, reduction of greenhouse gas emissions, and improved efficiency in energy use. Moreover, it particularly shows that different pathways exist to reach the same objective of energy transition, and each produces different externalities. LEAP produces the most secure future energy scenario for a city by only using domestically available resources, but it is also the most expensive option. ENPEP displays the cheapest future energy scenario for the city, but it is also a less secure option as it continues to rely on imported sources that are cheaper than domestically available resources. MoCES displays results somewhere between security (more wind in supply), and affordability (presence of diesel). In addition, when considering the environment dimension of the future energy system, MoCES results generate emissions between ENPEP scenario (lowest) and LEAP scenario (highest).

We also observed that energy software are tools that can provide relevant information to various users. The experience of solving ENPEP equations in Excel showed how much time and debug efforts energy software saves a user. In this case, the Excel workbook contains height different sheets to compute intermediate values that fills a ninth sheet, which is a matrix of 59 rows x 37 columns. This required a significant amount of time to check errors and trace the formulae entered.

However, existent software also features limitations. These limitations include the abstraction of relevant energy parameters that affect the future system modelled by the software, and the absence of flexibility in integrating different (agents) rationales on energy demand and supply options. Energy is a social good, as individual agents produce and consume its services; therefore, a relevant modelling approach should integrate the complexity of these agents' rationales to produce and/or to consume it.

6. Policy mechanisms for sustainability of energy systems: Backcasting the cities of tomorrow

6.1 Introduction

In the first chapter, we mentioned a rationale, explained by Page (2018), for building models that is to better, design, strategize and decide. Energy systems are primary contributors to greenhouse gas emissions and cities in Africa consume about 80 percent of the energy produced (Grubler, et al., 2012). Different modelling software return different future sustainable energy systems of the sample city in terms of supply mix, costs, environment impact, and agents' contributions. The different scenarios simulated in the previous chapters show that our sample city has the resource potential to undertake a transition to sustainable energy production and consumption. Each model portrayed unique representations of the future energy system based on modelling approach and scenarios' objectives. However, energy planning features different dimensions that are simultaneously environmental, economical, and social. The core objective of this chapter is to explore different policy mechanisms that will set the framework for mobilization of the city renewable energy resources in simultaneously reducing its ecological footprint, lowering the cost of transition to sustainability, and bearing the social dimension of individual agents' behaviour.

6.2 Materials and methods

The backcasting method consists of computing the city's eco-efficiency of different policy mechanisms that frame different energy scenarios. The formula of the eco-efficiency factor is an adaptation of the formula introduced by Barry Commoner cited by Roorda (2001). In this study, we replace the average prosperity per person used by Roorda in its analysis of economic inequalities by the energy per capita supply and demand. In practice, the backcasting method consists on using the information available now (T) to construct a vision of what the future (T+1), would have to look like in order to consider it (now) as a desirable scenario (then) (Roorda, 2001).

For instance, if we consider a city where we hypothesize that the energy per capita supply will double, and the city population (P) will increase by 50 percent in a 15-year period, then the city eco-efficiency factor should improve by a factor of 6 in order to reduce its environment strain by 50 percent during the same period. Similarly, to keep the city eco-efficiency unchanged, while population increases by 50 percent and environment strain reduces by 50 percent, the per capita energy supply should decrease by 33 percent. A third option consist on maintaining the per capita energy demand, while reducing the environment strain through less pollutant emissions on the supply side. The United Nations defines the concept of eco-efficiency as a key element for promoting fundamental changes in the way societies produce and consume resources; a tool to achieve greater value with lower adverse environmental impacts (United Nations ESCAP, 2009).

Still, in public policy action, it is not enough to know what needs to be done, but it is also necessary to know how it should be done. For formulation of the city relevant energy policy, three basic questions require answers:

- Is there a mechanism to enforce the policy, for instance one that improves the eco-efficiency factor by 6?
- How much does it cost?
- What externalities does it produce?

In order to answer these questions, we designed mechanisms to identify among the many policy alternatives the one that can lead to achieving the city energy objectives, here simultaneously (1) reducing the environment strain, (2) lowering transition cost, and (3) ensuring an effective contribution of citizens, through energy behavior change. In order to achieve these objectives, the city has two available levers of action: to feed-in the electricity grid renewable energy technologies and to incentivize demand side-management in the residence sector.

In addition to backcasting methods, we used mechanism design in assessment of this public action. The simplest definition of mechanism design in the context of our study is, for the city energy planner, to create incentive structures that produce a desired outcome. Hurwicz and Reiter (2006) define a mechanism as a formal entity intended to represent a system for organizing and coordinating economic activities, which are constrained by resource availabilities, and knowledge of technological possibilities distributed among the many agents of the system. The mechanism tested will produce a negative or positive externality, here the change on environment strain, which is fed in the eco-efficiency formula to compute the improvement factor. The higher is the eco-efficiency factor, better is the policy mechanism.

6.3 Theory and calculation

The eco-efficiency equation is:

$$ee = \frac{E * P}{S}$$

Where,

- ee: city eco-efficiency
- P: city population
- E: Per capita energy supply (Es) or demand (Ed)
- S: Environment strain (the change produced in response to pressure on energy resources, meaning the impact per unit of E variation on pollutants emissions)

The population dynamic (P) remains an exogenous parameter, which is not on the energy planner capacity to influence. The population change considers the 3.7 percent annual population growth (World Bank, 2019) assumed in the RES, which is equivalent to population increase by a factor of 0.67 by 2030, compared to the 2016 level.

We assume the end-use energy demand of households (charcoal, electricity, and LPG), and commerce (electricity, LPG, and diesel) supply services that can use grid electricity. In the industry sector, only demand for electricity and diesel can be substituted with grid electricity. Coking coke demand and unavoidable heat that proceeds from industrial activities remain in the city's energy mix.

The environment strain associated to the RES scenario per fuel is in Table 6.1.

Table 6-1 RES Environment Strain

	Diesel	Electricity	LPG	Charcoal	Coke	Heat	Total
Emissions (kg per toe)	3,621	7,560	3,084	6,544	4,765		
Energy (ktoe) (a)	119.8	280.1 (b)	419.2	6.5	416.5	3.2	1,245.3

Emissions (metric tonnes)	433,747	2,149,874	1,292,557	35,817	1,984,784	5,896,778

[(a)] Emission factors of diesel, LPG and coke are form IPCC (2006).

[(b)] Emission factor of electricity corresponds to 0.65 kg per kWh and is from Senegal NDC (UNFCCC, 2015).

The policy mechanisms for improving the city eco-efficiency should produce the desired outcomes formulated below.

6.3.1 Outcome 1: Reduction of environment strain through feed-in renewables in the grid supply mix (timeframe = 15 years)

The policy for achieving this outcome should promote the use of domestically available renewable energy resources (Scenario 2 of Chapter 5) to reduce the city environment strain by 2030, with a mechanism that balances the policy revenues and costs. Two policy options are considered:

- Carbon tax on pollutant emissions as per recommendations of the High-Level Commission on Carbon Pricing (World Bank, 2019) cited by UNFCCC, meaning EUR 54 per metric tonne of carbon by 2020 and USD 90 by 2030;
- Establishment of a private wire network that promotes decentralized solar photovoltaic generation and transfers between the three sectors in the city energy system: residence, commerce, and industry.

6.3.2 Outcome 2: Reduction of the city environment strain through demand side management in the residence sector (timeframe = 15 years)

The policy for achieving this outcome should promote demand side management, including change of agents' behaviour, in the residence sector (scenario 3 in Chapter 5) to reduce environment strain by 2030, with a mechanism that balances the policy revenues and costs. Two policy options are considered:

- Direct contributions to finance retrofit of domestic appliances;

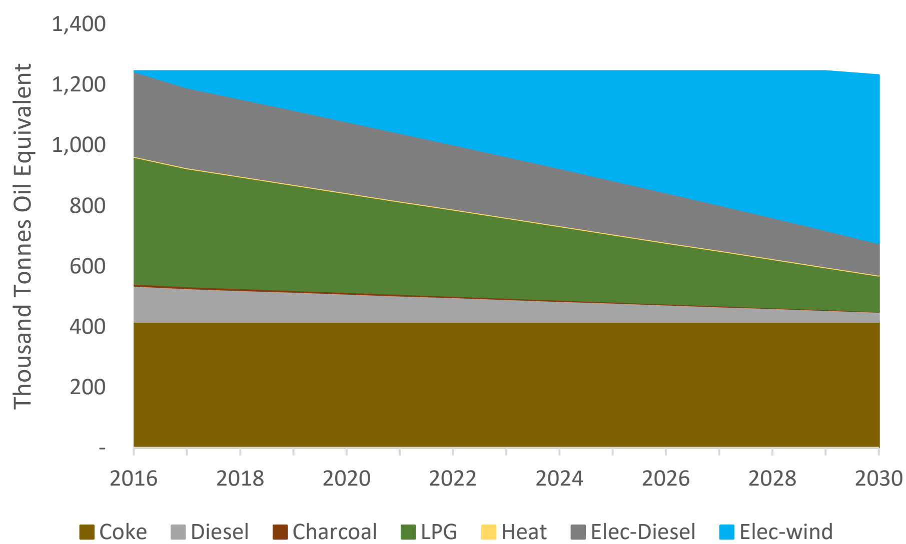
- Direct contribution to finance retrofit of domestic appliances combined to the policy with highest eco-efficiency factor in achieving outcome 1.

6.4 Results discussions

6.4.1 Reduction of environment strain through feed-in renewables in the supply mix

The city can achieve a reduction of carbon emissions from the energy sector of 44 percent by 2030 (-2.4 mio metric tonnes) compared to 2016 level with a budget-balanced mechanism, meaning revenues form tax carbon equals investment required for renewables generation. The tax on CO2 emissions reduces the emissions from pollutant energy technologies in the system through reduction of fuel consumption. Graph 6.1 displays the evolution of the fuels consumption in the energy supply mix of the city.

Graph 6.1 Fuels consumption with Carbon Tax (Outcome 1 Policy1)



Reduction of fuel quantities consecutive to the carbon tax assumes a price-quantity elasticity of negative value.

Pollutant fuels consumption is replaced by wind electricity generation supplying the grid.

CO2 emissions per fuel are from IPCC (2006). The CO2 price annually increases from EUR 42 in 2017 to EUR 90 by 2030, with intermediate value of EUR 54 in 2020.

On average CO2 emissions decrease by 5.3 percent per year during the period 2017-2030.

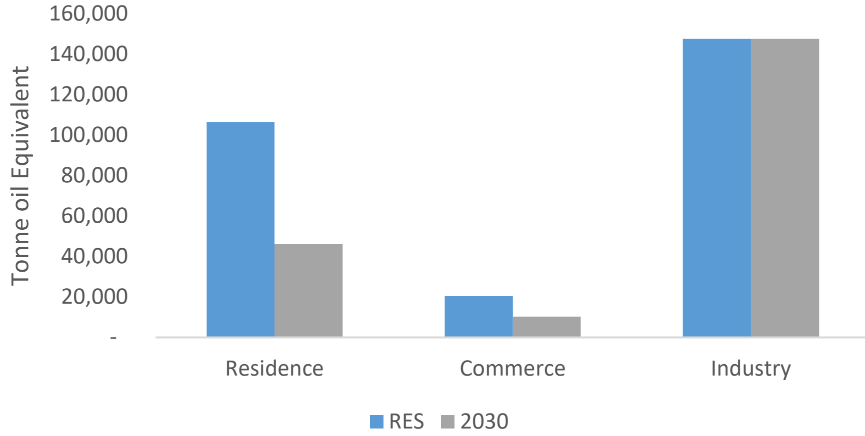
The reduction of charcoal, diesel, and LPG fuels over years implies that services provided by these fuels are supplemented by electricity from the grid. By 2030, charcoal, LPG, and diesel end-uses decrease by 72 percent compared to 2016 levels. Diesel fuel for electricity generation decreases by 63 percent.

Grid generation includes wind that simultaneously increases generation quantities in absolute terms and replaces the diesel component of the electricity supply mix (Diesel Elec). Wind is the least expensive of non-pollutant renewable energy resources available in the city. Waste-to-energy produces carbon emissions (100 kg per GJ) that are higher than emissions from diesel generation. The wind to electricity generation in the scenario should reach 555.2 ktoe by 2030, which is still below the full wind potential of sample city.

This policy scenario requires a mechanism that collects annual carbon revenues and directs this funding to new wind to electricity generation. The carbon revenues that fund the wind investment is recovered annually from the remaining part of the carbon emissions in the supply mix. The city eco-efficiency improves by a factor of 2.9.

In the alternative policy option to achieve outcome 1, the city promotes the adoption of solar photovoltaic technologies in decentralized electricity generation to reduce electricity demand from the grid. Compared to baseline (RES 2016), solar photovoltaic generation cost is lower than electricity tariffs of residence and commerce sectors. However, cost is EUR 0.9 per kWh higher than the industry tariff. In a network with these sectors as agents, a budget-balanced mechanism requires that money transfers (subsidies) to the industry sector be equivalent to amounts saved from residence and commerce sectors in transition from the grid to solar photovoltaic. Graph 6.2 displays the changes in electricity demand per sector to finance the transition scheme.

Graph 6.2 Electricity demand per sector (Outcome 1 Policy 2)



Negative transfers to balance transfers required in the industry sector is at the pro-rata of electricity demand (quantities) in the RES.

Electricity tariffs are EUR 18.3 cents in the residence sector, EUR 18.6 cents in the commerce sector, and EUR 15.2 cents in the industry sector.

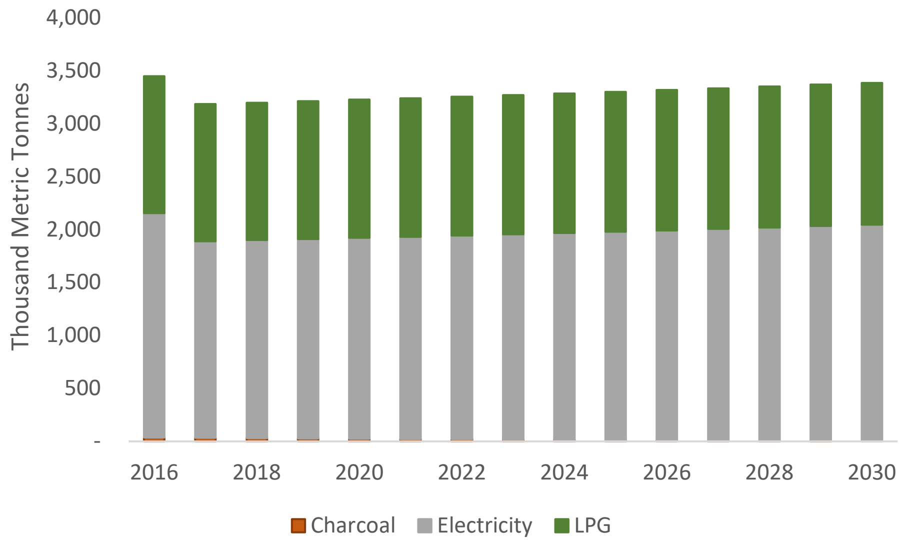
The mechanism consists on harmonizing tariffs in the private wire network, where the residence and commerce sectors would have saved money (EUR -2.1 and – 2.5 per kWh, respectively) and the industry would have paid more (0.9 per kWh) to transition from the grid to solar photovoltaic generation. The balancing mechanism should equal amounts saved by the residence and commerce sectors and additional payments of the industry sector. In real terms, the mechanism collects the industry's additional payments (positive transfers to support the residence and commerce sector investment (e.g with concessional loans) on solar photovoltaic (negative transfers). This reduces grid electricity demand, which is then replaced by decentralized solar photovoltaic generation, with factors of 41.2 percent in the residence sector and 50.3 percent in the commerce sector by 2030, compared to levels in 2016. Overall, the mechanism reduces carbon emissions from grid generation. The equivalent carbon emissions saved by 2030 are 0.4 mio metric tonnes, equivalent to 7 percent of 2016 emissions level. Therefore, the mechanism improves the city eco-efficiency by a factor of 1.8.

Both policies can achieve the outcome of reducing the city environment strain through action on the energy supply side with a budget-balanced mechanism. However, policy 1 that features a tax on carbon emissions returns a higher eco-efficiency improvement factor.

6.4.2 Reduction of the environment strain through demand-side-management

The city can achieve a reduction of carbon emissions from the energy sector of 1 percent by 2030 (-61.1 thousand metric tonnes) compared to 2016 level, by changing the energy behaviour in the residence sector. Graph 6.3 displays the evolution of emissions from the three households 'fuels.

Graph 6.3 Emissions from HH fuels (Outcome 2 Policy 1)



Electricity emissions factor is 0.65 metric tonne per kWh, which is the grid emission factor.

Charcoal emission factor is 112 kg per GJ and LPG emission factor is 63.1 kg per GJ, from IPCC (2016).

Electricity use in the RES is 0.26 toe. Electricity use decreases to 0.18 toe per household as per assumptions formulated in scenario 3 (chapter 5): lighting (-2/3 percent), cooling (-20 percent), refrigeration (-32 percent), other electric appliances (-10 percent).

Charcoal use decreases annually by 7 percent to reach 0 by 2030.

LPG use increase annually to replace charcoal at 0.07 toe per household in the residence sector and remains unchanged in the commerce sector.

Households increase by 4.4 percent annually.

The demand side management contributes to decrease the energy demand, and consequently carbon emissions per unit of residence sector, but the increasing number of households mitigates this effect, contributing to raise the grid electricity and LPG demands over years.

The mechanism's challenge is how the city can find appropriate contribution amount to incentivize households to change energy intensive appliances. The amount depends on local prices of old and efficient appliances. These prices may vary on time (over years) and space (per seller), therefore the city regulator should complete a thorough survey of market prices in order to determine the amount of the contribution. If the city considers a budget-balanced mechanism in enforcing this policy, negative transfers related to change on energy behaviour (cost of energy saves from cooling and cooking) should compensate positive transfers required to retrofit lamps and fridges. Efficient cooling did only require increasing the balance point temperature by 1 degree Celsius, which reduces electricity demand and related emissions cost. On cooking, the efficiency gain is rooted in switching from charcoal to LPG, and LPG cost in the RES (EUR 65.34 per toe) is lower than charcoal cost (EUR 125.23 per toe). Table 6.2 displays transfer amounts related to the mechanism in 2017.

Table 6-2 Mechanism transfers in 2017 (Outcome 2 Policy 1)

	Cooking	Cooling	Lighting	Refrigeration
Households	443,636.3			
Energy saves (toe per household)	0.04	0.02	0.03	0.04
Total energy saves (toe) [(a)]	17,371.5	8,614.8	12,597.9	15,503.9
Cost saves (EUR per toe)	(-57.91) [(b)]	(2,127.20) [(c)]	2,127.20	2,127.20
Transfers (EUR)	-1,006,034.2	-18,325,381.0		
Total transfers (EUR)	-19.331,415.3			
Transfer (EUR per household)			44.51	

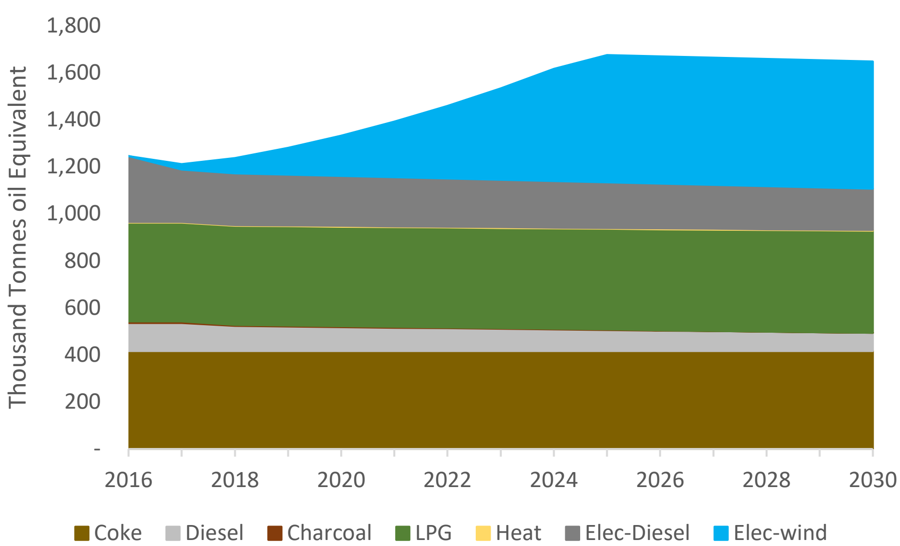
[(a)] Energy saves per end-use appliance are as per assumptions in scenario 3 (chapter 5) [(b)] Cooking energy saving cost is the difference between charcoal cost (123.25) and LPG cost (EUR 65.34) per toe.

[(c)] Saving cost of electricity appliances is the cost for households of 1 toe electricity (EUR 0.18 cents per kWh).

The mechanism requires a transfer of EUR 44.51 per household to retrofit lighting and refrigeration appliances in 2017. This policy mechanism reduces the environment strain in the city by 1 percent and improves the city eco-efficiency by a factor of 0.6. Compared to the eco-efficiency factors in outcome 1, the results also suggest that more than behaviour change are needed, and the city could be better off investing in mechanisms to relieve city congestion. We verify this hypothesis in the second policy mechanism of this outcome' when both supply and demand are dynamic.

In the alternative policy option to achieve outcome 2, the city makes a concerted action on both supply and demand; a mechanism with carbon tax on pollutant fuels (supply) and direct contribution to retrofit domestic appliances. The residence demand-side-management decreases annual electricity demand, and consequently wind generation requirement. Graph 6.4 displays the evolution of the fuels consumption in the energy supply mix of the city.

Graph 6.4 Fuels consumption with carbon tax and DSM (Outcome 2 Policy2)



Electricity savings are deducted from annual electricity quantities before wind electricity substitute.

Charcoal energy decreases annually to reach by 2030, replaced with LPG.

LPG increase is included in annual LPG demand before grid electricity substitute.

Pollutant fuels (diesel and grid electricity) consumption is replaced by wind electricity generation supplying the grid.

Reduction of fuel quantities consecutive to the carbon tax assumes a price-quantity elasticity of negative value.

CO2 emissions per fuel are from the IPCC. The CO2 price annually increases from EUR 42 in 2017 to EUR 90 by 2030, with intermediate value of EUR 54 in 2020.

On average, energy demand decreases by 22 percent per year during the period 2017-2030. By 2030, charcoal disappears. Diesel end-uses and electricity demand decrease by 29 percent and 35 percent, respectively, compared to 2016 levels. LPG end-use increases by 4 percent driven by the increasing number of households and the charcoal to LPG substitute.

Grid generation includes wind that simultaneously increase generation quantities in absolute terms and replaces diesel component of the electricity supply mix (Diesel Elec). Wind is the cheapest non-pollutant renewable energy resources available in the city. From 2026, the overall wind potential of the city is used to generate electricity in replacement of a portion of pollutant energy fuels in the system. The mechanism reduces the environmental strain by 13 percent and improves the city eco-efficiency by a factor of 1.9. Halving the units of households' growth rate, will reduce the environment strain by 16 percent and would improve the city eco-efficiency by a factor of 2.

6.5 Conclusion

From the previous results, we derive three key messages. First, the commitment to reduce greenhouse gases should carefully consider the accounting scope. Since 2014, the Global Protocol for Community-Scale Greenhouse Gas (GHG) Emission Inventories provides cities with a unified methodology to account their GHG emissions in three scopes. Scope 1 accounts greenhouse gases from the source (outcome 1). Scope 2 accounts GHG emissions occurring because of the use of grid-supplied electricity within the city boundary (outcome 2). A third scope compiles all other GHG emissions that occur outside the city boundary because of activities taking place within the city boundary. The results showed that accounting emissions from sources provides with a better eco-efficiency, and better figures of contribution to the global effort in reducing greenhouse gas emissions.

Second, action on the demand-side of the system features both uncertainties of costs and limited efficiency on improving the city eco-efficiency. This mechanism returns a relatively low eco-efficiency factor. The appropriate mechanism to achieve it should encourage citizens pay for its cost. The city should avoid direct contributions that generate only expenses.

Third, the solution to energy sustainability does not need to be an energy object. When considering simultaneously, a decrease of demand driven by efficiency, an increase of demand driven by households growth in units, and a technology substitution (from diesel to wind) in supplying this demand, it can be useful for the city to take a step back and consider alternative solutions. One of the solutions to addressing the three parameters of the previous equation is to relieve the city congestion by creating a new city enough accessible to absorb the households growth or at least reduce it significantly in the old city. Outcome 2 shows that when the households' growth rate is divided by a factor of 2, then reduction of the environment strain is more.

These findings open new perspectives for designing energy transition policies, with a clear assessment of the cost and identification of those in the city who bear it. A design of budget-balanced mechanisms is possible, but they do not all produce the same externality on environment.

For many years, energy regulators have considered equilibrium policies, where concepts of preferences and elasticities are not accessible to all citizens. The design of mechanisms that provide each citizen with information for cost-benefit comparison can improve public adhesion and reduce the cost of free riding. Many citizens know that both energy consumption and production produce environmental externalities, however the debate remains open on whom should bear these externalities cost and for what role the city has in improving the common environment. Our approach of mechanism design to identify the policy options with higher eco-efficiency is a contribution to answering this question that is common to management of all public goods.

Page in Model Thinking[3] defines public goods as goods that all agents in the system want, but agents do not want to individually pay for it. However, public goods also generate benefits. In the city context, we can suppose reducing the environment strain can save health expenses due to

[3] The MOCC Model Thinking delivered by Scott Page in Coursera

pollution related problems or improve productivity by a percent of gross regional production (GRP). Knowing the city population, every agent can compare its net contribution to the policy, for instance (carbon) taxes paid on fuel use, and expenses saves per citizen.

7. Synthesis of the research findings and way forward

To the question why do we model, Scott Page answers: in order to be clear and better thinkers. Throughout this study, we designed and tested possible futures of a city energy system. In this first quarter of the twentieth first century, cities are at the confluence of major development that make their energy system particularly relevant to understand. Among these developments are climate change, population growth (urbanization), and rapid economic growth, particularly for emerging cities.

Literature on the city's energy system usually answers ad-hoc questions such as the quantity of electricity saved or generated with a technology or a policy mechanism. More than often, the studies use models, which justify their choice by use in previous similar studies. The model's relevance in terms of approach and influence of its deterministic methodology on the future of the city modelled is not explained.

In this study, we take Dakar as example of an emerging city. Emerging cities are the homes of the majority of the world population and rapidly grow, in terms of economic production, energy demand, and related greenhouse gases emissions (United Nations, 2018). The majority of these cities are located in countries listed as non-annex 1 Parties to the United Nations Framework Convention on Climate Change, which make their contributions to mitigate climate change in a voluntary basis, as per the Article 4 of the Convention. They are historically not responsible of emissions that contribute to climate change, but they can certainly take responsibility on emissions that push the climate tipping point, which is the point where it will not be possible to reverse human action on the climate.

Emerging cities can contribute, in the framework of the current agreements to mitigate climate change; they have energy resources for it, whether it is the recycling of municipal waste, solar photovoltaic, or wind energy. Still, this transition bears cost, and it is unclear whether the revenues of transition can balance this cost. Economic growth in emerging cities is as necessary, if not more, as energy transition in these cities. It contributes to solve other sustainability related issues that include creation of decent jobs, for instance in the industry, and improved living standards to reach that of mature cities. The energy contribution to these economic objectives at local level, can be reached with diesel, wind electricity or a combination of both in the mix.

At the beginning was energy, and everything derives from it. The reconciliation of ecological and economic motivations in the energy sector at local level commands innovative policies to conceptualize the future energy system of a city from information available today. In this study, we demonstrated that various city specific parameters are important to consider in the reconciliation process.

In Chapter 1, the study sets three objectives in relation with three research questions, we committed to answer throughout the study.

Objective 1: to assess the technical and economic potential of renewable energy in our sample city, and to compare with potential in Vienna

In Chapter 4, we found that the competitiveness of the renewable energy resources available in the city are more or less sensitive to:

- cost of the technology (solar photovoltaic),
- cost of the investment capital meaning the discount rate (wind energy),
- and carbon price (waste to energy).

The co-presence of renewable energy technologies with other infrastructure is also important. Cities have competitive lands, and in Chapter 4, we demonstrated that even with a higher generation cost, solar photovoltaic has the highest potential to transition to energy sustainability in our sample city, because of surface area it can occupies, including the built environment.

Objective 2: To consider the objective of energy sustainability in a system perspective with dynamic citizens who have expectations that are neither necessarily long nor rational

In Chapter 5, we found that depending on how the city planner apprehends the future of the city, different system configurations are possible. If the planner has as priority to balance supply and demand with domestically available resources, as pre-coded in LEAP, then the software provides recommendation to invest on recycling of municipal solid waste and on wind energy at a cost that is relatively high. The cost is even higher in real terms, as the environmental impact and cost of recycling waste to energy, which is higher than diesel to electricity generation, is not displayed in the software result. LEAP accounts emissions from demand side.

If the city planner has as priority to balance supply and demand at the lowest system cost, as pre-coded in ENPEP-BALANCE, then this software provides recommendation to invest on a proportion of all energy supply options available in the city, including diesel, fuel oil and imports of hydropower. These resources are relatively cheaper than domestically available renewable energy resources.

If the city planner has as priority to balance supply and demand, with a mechanism that makes individual agents of the system (citizens) be involved in the design of the future city energy system, then MoCES provides the unique platform that exist today to implement it. MoCES provides two major innovations compared to existent energy planning software.

(1) It is accessible to all citizens, including non-energy professionals, through user design and experience design techniques.
(2) It provides an individualized experience of energy planning, as it does not pre-code the user rationale for modelling, rather let the agents organize the system considering their relevant criteria.

The challenge is up to the city planner side to integrate the software with the grid operator interface in order to manage individual agents, who are individual citizens, contributions to the future energy system. MoCES also demonstrated in this study that considering lower cost generation options in the dispatch does not provide the cheapest generation system. ENPEP delivered a system mix at a cheaper cost.

Two issues are usually challenging for the city energy planner when using one of these models.

- The planner cannot see and compare the result of the model being used with the other resulting systems delivered by other energy planning software,
- Unless the planner reads a user's guidelines of hundreds of pages, the rationale of the resulting system is not provided with the software result.

Objective 3: To open avenues for thinking the sustainable city of tomorrow, which integrates simultaneously a diversification of generation sources in favour of renewables, and a better efficiency in management of the demand

In Chapter 6, we found that addressing collective action problems such as the reduction of a city environment strain requires innovative methods that go beyond individual policy mechanisms. Because local city conditions matter in magnitude or visual of the energy problem, policy mechanisms that address specific problems such as a pollutant grid generation or inefficient electricity use in the residence sector can be aggregated in an innovative way to address them simultaneously. City energy planners should be creative in addressing their specific city problems, rather than replicating experiences; sometimes solutions to energy sustainability are beyond the energy sector as we have seen on the impact of the units of households in percent of environment strain reduction.

Transition to energy sustainability does not need to be costly for emerging cities, which usually are heavily indebted, to fund other important sectors such as health systems and to cope with high urbanization rates. Budget-balanced mechanisms are an incentive for these cities to envision serenely the transition. The question of whom should pay for the transition either is the historical polluters or current contributors is still too much polemic to only rely on external funding.

While, clearly outline how an emerging city can become energy sustainable, the study opens opportunities for further research.

Chapter 4 points researchers to new perspectives for integration of the social criteria of acceptance and other social dimensions that affect the transition to sustainable energy technologies, which resources are readily available for use. It could be informative in a future study to discuss the impact of revenues, education, and other relevant criteria that may influence an agent on its energy behaviour. Such a study could provide regulators with other lever mechanisms, outside information, and finance incentives.

Chapter 5 introduces new perspectives on management of intermittent renewable energy technologies in the grid. With MoCES, we provide part of the solution with visualization of the technology sites and real-time weather updates. However, practical research on integration of MoCES interface with management tools of private suppliers and grid operators can be streamlined in a single platform, where the overall city energy system would be accessible to the planner. Individual citizens could automatically, through an application, report their daily energy behaviour and get recommendations based on weather conditions such as lowering non-essential consumption when it is cloudy, and solar rooftop supplies entirely or partly the demand. Such a platform can also provide the grid operator with flexibility to address peak loads with renewables in the dispatching order provided by software such as LEAP.

Chapter 6 assesses new legislation mechanisms and validates different combinations of policy mechanisms that have more or less success in different city contexts. A future study can constitute a portfolio of all policy mechanisms that promote sustainable energy systems and/or reduce environment strain, and simulate combination of two or more mechanisms in the study sample city or in another city. To further the research highlighted in chapter 6, a next study could explore the impact of rebound effect on the reduction of the environment strain. Rebound effect is defined as a state where improving the efficiency of resource-use per unit is outstripped by the absolute increase in demand for the goods, and the deterioration of resource efficiency in consumption (United Nations ESCAP, 2009).

The main limitation of this study is on the localized aspect of parameters used in the models. We tried throughout this study to fashion new optima on our understanding of a city energy system, including on the assessment of its renewable energy potential, on the planning of the entire energy system, and on the design of action policies. However, replication in another city does not only require changes to the figure of parameters in any energy planning-software, but also needs a clear understanding of the city energy planner approach for sustainability, whether it is an autonomy in supply or a lower cost generation.

Another limitation is our reliance on second hand data in our models. The data sets are from reliable sources. Whenever possible, we requested and received the official statistics on parameters of the reference energy scenario. Our second source of data was international organizations publications, and whenever there has been conflictual information on a parameter value, we made assumptions based on related data from proven sources. However, those are data we did not collect directly, and therefore cannot endorse the absence of errors. These data include solar and wind maps in Chapter 4, and data on the reference energy scenario from the national information system (SIE, 2018) in Chapter 5. Our results are as good as these input data. A correction of input figures will affect outcome results.

Conclusion

When we started this study, we called it a journey. It has been in fact a long journey for building a new breadth of knowledge from existing literature on city energy systems. Throughout this journey, we felt the necessity to:

- Develop a new tool for planning energy systems in cities (MoCES,;
- Integrate the land dimension of energy in planning.
- Integrate the social dimension of energy in planning.

We also explored situations where parameters were different from the system cost and environment strain can influence decision, namely in the first policy mechanism to achieve outcome 2 in chapter 6 and the reduction of balance temperature point in scenario 3 of chapter 5. We developed new methods that combines eco-efficiency and mechanism design in assessment of energy policy alternatives. These all methods and tools can be replicated and tested in different city environments.

We experienced some challenges along the way, like when we needed to access the comparable software and to build our own software. The same goes in reconciliation of data from different sources. An example is, we considered the figure of 2,092 Gg carbon emissions from the grid in 2014 in the Nationally, determined contributions (NDC, 2015), which made a factor of 0.65 kg CO2-eq per kWh generated that year. Before, we fed the model with Ecometrica (2011) that provides a factor of 0.59 kg per kWh, then we saw the IEA (2013) grid emission factor of 0.64 kg per kWh for 2011. The emission factor that was computed from NDC (UNFCCC, 2015) emissions' data for this 2011 was also 0.65 kg per kWh.

However, it has been an enriching journey. The fundamental message that we derived from this study is that action to reconcile emerging cities economic growth and reduction of greenhouse gas emissions is possible; and it even does not require external funding to make meaningful impact as suggested in outcomes1 and 2 in reducing the environment strain. The action only requires 4 steps: to identify a reference year, to compile parameters related to its energy scenario, to define clear objectives for these parameters in subsequent years, and to select an energy planning software to conceptualize it. The latter is probably the most challenging of this four-step action. The selection of a software is usually based in different criteria, including in its simplest form, that it its accessible. However, this selection has a considerable impact on the future portrait of the city energy system.

City energy planners need innovative planning tools and policy mechanisms in contemporary times of complex environmental, economic, and social, where action in the energy system can affect living standards, availability of decent jobs and all other sustainable development goals in the urban space.

The unconditional commitment to climate change mitigation of countries hosting these emerging cities, in application of the 2015 Paris Agreement on Climate Change, is between 5 to 10 percent, without external funding resources. Senegal committed 6 percent emissions reduction in the energy sector by 2030 compared to Business As Usual (BAU) in its NDC (UNFCCC, 2015). This study demonstrated that the primary contributing sector to emissions, which is energy, can achieve a minimum of 13 percent emissions reduction with the appropriate policy mechanisms. Emerging cities should host 55 percent of the world population by 2030 and account for 65 percent of greenhouse gas emissions between 2012 and 2030 (NCE, 2015). An unconditional commitment of each to achieve 13 percent emissions reduction at non-additional cost in the energy sector will make a significant contribution by 2030, at the time to evaluate the Paris Agreement.

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Appendices

Annex 1- Supplementary materials related to the SEA4cities survey on energy behavior of Dakar citizens

Table: Survey strata

District	Number of residences [a]	Sample size [b]	Number of residences surveyed [c]
Diamniadio	2,165	327	368
Fann-Point E Amitie	2,128	326	360
Total	4,293		728

[a] The number of residence in a district is from the municipality.

[b] The sample size is computed for a confidence interval of 95 percent and p =0.5.

[c] The number of residences that completed the survey questionnaire

Dates of survey

The survey in Diamnniadio was completed between April and May 2019 (Dry season with average temperature of 30 degree Celsius).

The survey in Fann-Point E Amitie was completed during November 2019 (End of the rainy season with average temperature of 25 degree Celsius).

Table: Average energy consumption

	Diamniadio	Fann - Point E	City (Average)
Lighting (Wh) per day [a]	369,087.5	403,478.5	
Number of days (2016)	366	366	
Number of households	330	245	
Lighting (kWh per household)	409.4	602.7	506.1
Cooling (kWh per household) [b]	995.8	1,311.2	1,153.5
Refrigeration (kWh per household) [c]	1,041.7	1,553.3	1,297.5
TV (kWh per household) [d]	35.8	110.7	73.2
Other appliances (kWh per household) [e]	29.7	42.4	36
Total (kWh per household)	2,512.3	3,620.3	3,066.3
Total (toe per household)			0.26

[(a)] The row summarizes the total lighting energy of surveyed households per day. Lighting per household per day is computed with the following parameters from the questionnaire: type of lamp, lamp wattage, number of lamps in the building, and hours of operation per day.

[(b)] The row is an average of energy consumed by cooling appliances present in the residences surveyed. The cooling appliances from the completed questionnaires are air conditioners, celling and standing fans. Cooling energy per appliance per day is computed with the following parameters: appliance type, power, and average hours of operation per day in dry and rainy seasons.

[(c)] The row is an average of energy consumed by fridges present in the residences surveyed. Refrigeration energy is computed with following parameters: Type of fridge, power, and hours of operation per day assumed to 24 hours for all fridges.

[(d)] The row is an average of energy consumed by TVs present in the residences surveyed. TV energy is computed with following parameters: Type of TV, power, and hours of operation per day.

Other appliances tracked in the survey are phones and laptops. The energy per device is computed with following parameters: power and hours recharge per day (average value provided by surveyed residences).

Questionnaire for residence buildings can be provided as supplementary material (6 pages)

Annex 2- Peak load data of the interconnected grid in 2016 [4]

Table: Grid Peak load

	Senegal [(a)]	Dakar [(b)]	in % of Dakar Peak
January	474	293.88	84.6%
February	476	295.12	85.0%
March	477	295.74	85.2%
April	489	303.18	87.3%
May	495	306.9	88.4%
June	528	327.36	94.3%
July	532	329.84	95.0%
August	544	337.28	97.1%
September	547	339.14	97.7%
October	560	347.2	100.0%
November	531	329.22	94.8%
December	512	317.44	91.4%

[(a)] Peak load data at the country level in 2016 is from the utility [4].

[b] Peak load data for the city assumes that it represents 62 percent of the country peak load. This figure was the share of electricity from the interconnected grid consumed in the city in 2016 [5].