Alimentos, Ciencia e Ingeniería, 2019: 27 - 1

The need for assessing technology deployment in energy systems models to decarbonise the residential sector: a systematic literature review

La necesidad de evaluar el despliegue de tecnología en modelos de sistemas de energía para descarbonizar el sector residencial: una revisión sistemática de la literatura

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Abstract

Scientists across the world are working on understanding the potential impact of buildings' energy consumption on climate change and vice versa. Buildings comprise between 20% and 40% of overall energy consumption depending on the economic development, cultural, and geographical features of a country or region; heating and cooling can represent up to 80% of the total energy consumed in buildings. Energy systems models (ESMs) have emerged to help the research community to build logical scenarios and simulate the complexity of energy sectors of the global economy. However, current challenges must still be included in ESMs, especially challenges from the end-use energy sectors (i.e. transport, industry, and buildings). This research review assesses two of these current challenges in modelling the energy transition of the residential building sector (RBS): 1. the consideration of the residential sector in energy systems models, and 2. the available technologies to decarbonise the sector.

Resumen

Científicos de todo el mundo están trabajando para comprender el impacto potencial del consumo de energía de los edificios en el cambio climático y viceversa. Los edificios representan entre el 20% y el 40% del consumo total de energía dependiendo del desarrollo económico, cultural y geográfico de un país o región; la calefacción y la refrigeración pueden representar hasta el 80% de la energía total consumida en los edificios. Han surgido modelos de sistemas de energía (ESM) para ayudar a la comunidad de investigación a construir escenarios lógicos y simular la complejidad de los sectores energéticos de la economía global. Sin embargo, los desafíos actuales todavía deben incluirse en los ESM, especialmente los desafíos de los sectores de energía de uso final (es decir, transporte, industria y edificios). Esta revisión de la literatura evalúa dos de estos desafíos actuales al modelar la transición energética del sector de la construcción residencial (RBS): 1. La consideración del sector residencial en los modelos de sistemas de energía, y 2. Las tecnologías disponibles para descarbonizar el sector.

Keywords
Heating; cooling; residential sector; energy system models; decarbonisation.

Palabras clave
Calefacción; enfriamiento; sector residencial; modelos de sistemas energéticos; descarbonización.

Abbreviations

Energy Systems Models	ESMs
Agent-Based Modelling	ABM
Geographic Information Systems	GIS
Residential Building Sector	RBS
Buildings Energy System Models	BESM
Buildings Energy System	BES

1. Introduction

Releasing carbon dioxide into the atmosphere by burning fossil fuels for energy use is the principal cause of climate change. Climate change's impact is global, affecting all regions and economic sectors [1]. Global temperatures have reached a record over the last century, and economic activities today use approximately four times the amount of energy compared with at the beginning of the Industrial Revolution [2]. Around two-thirds of the global energy system still relies on fossil fuels despite of almost a century of climate change research, technical innovations and policy debate. This continuing reliance on fossil fuels is because it remains the most easily exploitable energy source, the cheapest energy resource and has the highest consumption subsidies worldwide. Despite some notable progress on improvements in technology for all forms of energy resources, energy-related emissions still increase global warming and climate change around the globe.

The residential building sector (RBS) concentrates a large proportion of global energy demand and resulted energy-related global greenhouse gas (GHG) emissions [3]. The main end-uses energy in buildings are space heating, space cooling, water heating, lighting, and appliances. The energy consumption in these end-uses can vary between 20% and 40% of total energy demand depending on the economic development, cultural, and geographical features of a country or region. Overall, heating and cooling can represent up to 80% of a buildings' total energy consumption [4, 5]; the RBS accounted for 32% of total global end-uses energy worldwide. Furthermore, GHG emissions from the RBS reached 9.18 $GtCO_2eq$ in 2010, accounting for 20% of all global anthropogenic GHG emissions [6]. With such high energy consumption and energy-related GHG emissions shares, the RBS represents a gigantic opportunity to decarbonise the whole energy system worldwide.

Since the discovery that energy-related emissions increase global warming and climate change, energy systems modelling has excited enormous scientific interest to support the decision-making process of climate and energy policy. Energy systems models (ESMs) build logical scenarios and simulate the complexity of energy supply chain; this includes energy resource extraction, conversion, transportation, consumption and demand. ESMs also simulate the energy market and the regulation of end-use energy sectors [7]; these sectors include industry, transport, agriculture, and the RBS. Recently, the energy systems modelling challenges have attracted the attention of the scientific community. Pfenninger, et al. [8] observed that ESMs across governments, industry and academia lack transparency and open availability. Similar research conducted by Li and Pye [9] showed that qualitative narratives are required in ESMs. Hughes, et al. [10] concluded that a high level of modelling uncertainty is commonly driven by non-technical and non-economic aspects. They agree that multiple actors' behaviour (e.g. investment practices, technology choices) must be considered in ESMs. Pfenninger, et al. [11] suggest that the intermittence of renewables should be also considered in ESMs, resolving details in time and space. In general, ESMs challenges could be addressed by integrating: human factors, spatial and temporal dimension, and barriers for clean technology diffusion.

The RBS represents the energy consumption in residential and commercial buildings; it has nothing to do with energy consumed when a building is being built (i.e. the construction sector). A great deal of research is currently being conducted to exploit ESMs to elaborate plausible pathways to decarbonise the RBS. Although ESMs are vast and have been developed for more than four decades, a broader scope is still required to provide better understanding of the energy transition of the RBS [12]. In order to promptly decarbonise the RBS, radical solutions must be assessed and implemented [13]. One such promising application of ESMs is the assessment of the use of renewable energy sources, energy efficiency technologies and energy conservation to decarbonise the RBS. ESMs help us to answer and better understand the RBS and the interdependencies among technology diffusion, the supply and demand of energy, and market behaviour along with the impact on global climate change.

This review aims to explore the current challenges of ESMs to simulate the decarbonisation of buildings at global scale. This review has two sections. The first section addresses ESMs that take RBS into account at the country and global level. Current and emerging technologies that can be deployed in buildings to decarbonise the sector are studied in section two. This review is the state of the art for further research to assess pathways to decarbonise the RBS.

2. Literature Review

Although ESM are vast and focus on different scales, this study focuses on models that consider the impact of the energy consumption in buildings in the whole energy system at the country and global level. This study therefore exclude models that deal with only one specific subset of problems, such as quantifying the potential for a specific technology at the building level, or the influence of physical features of buildings in models. This review assesses different ESMs that include the RBS in their approach followed by a comprehensive review of the up-to-date and emerging technologies that might lead the decarbonisation of the sector.

2.1. Energy systems models

Energy systems models are methods to build logical scenarios and simulate the complexity of the extraction of energy resources, conversion and transportation, energy services, market and regulation in scales ranging from cities to the entire globe [7, 14]. A detail classification of ESMs is made by Herbst, et al. [15]. Pfenninger, et al. [11] additionally contribute to the classification, grouping ESMs into four categories: optimization models, simulation models, power systems and electricity market models, and qualitative and mixed-methods scenarios. Hall and Buckley [16] also categorise 22 models and propose a three-classification schema: 1. Purpose and structure; 2. Technological detail; and, 3. Mathematical description. García-Gusano, et al. [17] narrowly classify ESMs in two main groups: 1. Simulation-based models that set relationships among parameters to test energy policies; and 2. Optimisation-based models that explore techno-economic approaches. Considering these classifications, ESMs are one of the most influential tools supporting energy transition policy today. These models therefore provide technical, economic, environmental, and now even social insight to offer plausible pathways of the global/regional/national energy system change.

The whole energy system consists of a network of components and factors that influence various sectors of the economy. Broadly, these components are the supply sector, the demand sector, the energy market and the emerging climate sector [18]. Figure 1, for example, illustrates the components of the energy system taking into account the whole economy. More specifically, the energy system network comprises renewable and non-renewable energy resources, conversion and transformation technologies, storage, transmission and distribution technologies, the end-use of energy, the market, and the climate [19, 20]. Researchers have contributed much to the understanding of the energy system's driving factors. Geng, et al. [20] identify six driving factors of the energy system: 1. Production structure [21-23]; 2. Energy structure [23]; 3. Consumption structure [21-23]; 4. Population size [22, 24]; 5. Per capita energy consumption [22, 25]; and 6. Energy intensity [11, 26].

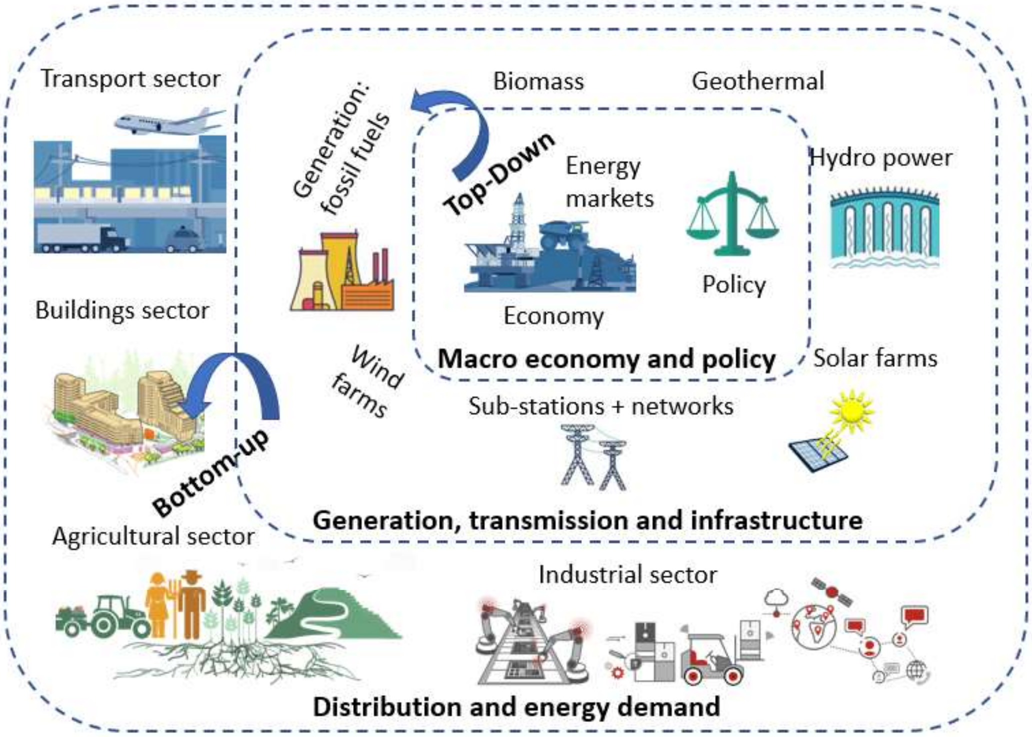

Figure 1: Energy sectors and layers of the energy system.

Other authors also consider emission intensity [22, 27], economy growth, trade structure [23, 27], technology developments [11, 23], climate influence [24, 28], climate change policy [11], and social factors [29, 30]. In other words, an energy system encompasses all the entire process chain from the extraction of primary energy to the final use of energy services and goods in a given society or economy [11] along with energy security and energy policy as seen in [18]. In general, an understanding of the interconnectedness of components and factors along the whole energy system still remains unclear. To address this challenge, ESMs have emerged to explore, analyse, ex-post evaluate, forecast, simulate, optimize, estimate, and conceptualize energy systems [15]. Emerging approaches to investigate contemporaneous challenges of ESMs have been introduced by Pfenninger, et al. [11]. Four challenges are described: 1. Resolving time and space; 2. Balancing uncertainty, transparency and reproducibility; 3. Complexity and optimization across scales; and, 4. Integrating human behaviour, social risks and opportunities. These challenges have been addressed in a number of studies. Assembayeva, et al. [31] report the inclusiveness and transparency of power systems models by adding a spatial and temporal resolution to a techno-economic model. Bosch, et al. [32] additionally consider the temporal and spatial global onshore wind energy potential. DeCarolis, et al. [33] outline best practice for energy system optimization modelling, including the mentioned challenges, named as: setting spatial and temporal boundaries, quantifying uncertainty and communicating insights. García-Gusano, et al. [17] assess the inter-sectorial behaviour in energy systems considering socio-economic drivers. Kraan, et al. [34] present an agent-based method used to model imperfect rational behaviour of investors in the electricity sector.

The RBS is a classic case that represents all of the mentioned challenges. This sector requires the adoption of clean and low carbon technologies for decarbonising space heating and cooling, water heating, lighting and appliances [11]. However, the development and understanding of energy transition pathways is not an easy task. To model the dimensions of residential sector energy transition, modelling approaches should represent the interdependencies between generation (weather conditions and renewables intermittence), operation and energy demand (electricity, heating, cooling), infrastructure investments and generation dispatch, market and user behaviour, macroeconomic interactions, and environmental impact [16]. As modelling technology deployment is vital for obtaining insights about pathways to decarbonise the residential sector, an assessment of these tools is needed. Modelling the RBS by taking the whole energy system into account can help stakeholders in academia, government, industry and users to understand and plan the use of cost-effective low carbon and renewable energy technologies [35].

Buildings energy systems (BES) are responsible for consumption and management of energy in buildings [36] and contain electricity, heat and cold suppliers [37]. These energy systems can be represented at different levels as can be observed in [28]. At the building level, BES models focus on the physical behaviour of energy consumption in buildings and seek energy efficiency and thermal comfort [36]. At the neighbourhood, district and city levels, BES models involve detailed approaches, including information about built structures, occupants' behaviour, and urban environment effects such as meteorological loads [28, 38]. The knowledge frontier of these models has expanded to study BES at the regional and worldwide level.

Researchers are developing buildings energy system models (BESM) with a broader scope to provide better understanding of transition energy system pathways and the interdependence between energy sectors of the global economy (Fig. 2). The main concern is to understand the potential impact of climate change on energy consumption in buildings and vice versa. In this regard, Clarke, et al. [39] explore the future implications of increasing electricity usage for cooling while decreasing dependency on fossil fuels for heating at the global level. Güneralp, et al. [40] use both top-down and bottom-up approaches to conclude that in the future, urban population density will influence energy consumption as much as energy efficiency technologies worldwide. Berardi [41] also assesses historical data to report energy consumption in the RBSs of the US, EU, Brazil, Russia, India, and China. Other work has been conducted to explore the global potential for district heating and cooling [42] and people's investment behaviour in the building energy sector [43]. Although the energy model landscape is vast – as mentioned previously in [16], there is a limited number of models that evaluate the building energy systems at the regional or global level. The next section addresses the energy models that assess the RBS on a global scale.

Model type	Example	Characteristics
Dynamic-recursive simulation model	Global Change Assessment Model (GCAM)	Technology-rich; interactions energy sector, land use, water and climate mitigation
Individual simulation methodologies	National Energy Modelling System (NEMS)	Modular structure; each energy sector
Linear-programming-based optimization model	MARKAL/TIMES/TIAM family	Select optimal technology mix to meet an energy demand at minimum cost

Figure 2: Energy models that consider the RBS.

The Global Change Assessment Model (GCAM) is a dynamic-recursive simulation model; it is a technology-rich, integrated assessment tool that endeavours to represent the interactions of the energy sector, land use, water and climate mitigation in the economy [44]. GCAM has been widely used to evaluate climate change mitigation policies (i.e. carbon taxes, carbon trading, and energy technology deployment). In the RBS, GCAM has been used to evaluate the consequences of future climate change on energy expenditure worldwide [39]. Clarke, et al. [39] follow scenario-based analyses and find that, for a 2 °C global mean surface temperature increase, the global economic output increases 0.1%; this increment is measured in terms of net energy expenditure in buildings. Güneralp, et al. [40] also use GCAM to study the impact of urban density on global BES. They suggest that all global regions should adopt a compact urban development trajectory, rather than dispersed urban forms, in order to achieve likely cumulative energy savings of approximately 300 EJ worldwide through to 2050. In the literature, GCAM has been applied to assess different energy sectors of the economy; however, a global assessment of the RBS has not been conducted to the same extent as other sectors.

The National Energy Modelling System (NEMS) has a modular structure; it aims to apply individual simulation methodologies to each energy sector that facilitates model management. NEMS encompasses thirteen modules, which represent the supply, conversion, demand and market energy sectors [45]. This model is tailored to a US context, and therefore, it is not applicable to other countries. Wilkerson, et al. [46], for instance, use NEMS to examine the impact on the RBS of consumer preferences over end-use technologies. Their approach recognises four conceptual problems with NEMS end-use energy demand projections: 1. Setting of preferred return rate to guide technology choices; 2. Setting of same technology choices constraints in commercial and residential sectors; 3. Using outdated data to represent behavioural parameters; and, 4. Avoiding feedback of policy and forecasting scenarios to evaluate the preferred return price dynamics.

Cullenward, et al. [47] also present a NEMS-based method which estimates the direct policy costs of direct energy expenditure at the building level in all United States regions. Although NEMS is publicly available, its owners and developers - The US Energy Information Administration EIA - discourage its use because of the difficulty or rigidness of using it [48], which means that the model is poorly understood outside of EIA [46].

The Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA) has developed bottom-up energy systems models, the MARKAL/TIMES/TIAM family. The MARKAL (MARKet and ALlocation), the TIMES (The Integrated MARKALEFOM System, Energy Flow Optimization Model) and the TIAM (TIMES Integrated Assessment Model) are linear-programming-based optimization models aimed at selecting the optimal technology mix to meet an energy demand at minimum cost [49]. TIAM consider eleven end-use technologies for the residential sector in the energy consumption sector modules [50]. Using the TIAM approach, Labriet, et al. [51] and Gracceva and Zeniewski [52] assessed severe climate targets and the impact of using gas in end-use sector such as the RBS. They found that gas constitutes an attractive solution to address the uncertainty in the energy system. In the mid-term, gas might play a bridging role to achieve a low-carbon economy until zero-carbon mitigation options become both cost-effective and available. van den Broek, et al. [53]

and van den Broek, et al. [54] recently integrated MARKAL with temporal and spatial dimensions to assess the potential of CO_2 storage as well.

The Open Source Energy Modelling System, OSeMOSYS, is a linear optimization model developed in a modular structure. OSeMOSYS has become popular due to its open availability and flexibility to model long-term energy pathways [55]. Pinto de Moura, et al. [56] uses OSeMOSYS SAMBA - South America Model Base to evaluate the electricity export potential of Bolivia in different scenarios. However, the literature does not provide much other information regarding the OSeMOSYS usage in global studies of the RBS. Another example of optimisation models is the Model for Energy Supply Systems And their General Environmental impact (MESSAGE). MESSAGE is a linear/mixed integer optimization model that allows the representation of technical-engineering, socio-economic, and biophysical processes of energy systems [57]. Its creators and developers, the International Institute for Applied Systems Analysis (IIASA) has reported approximately a thousand scientific publications over the last four decades. Currently, MESSAGE provide a well organised open-source documentation of the entire framework [58]. Ürge-Vorsatz, et al. [59] assess the global heating and cooling energy trends in buildings based on MESSAGE projection scenarios. Overall, the literature offers limited MESSAGE applications for the decarbonisation of the RBS.

The Price-Induced Market Equilibrium System (PRIMES) model simulates the energy demand and supply; it has been used for several EU governments as well as private companies [60]. The PRIMES model is organised in modules representing the behaviour of a specific agent, an energy demander and/or a supplier. One key feature of PRIMES is its capability to support policy analysis in the demand-side such as electricity and heat demands in the RBS [61]. The Long-range Energy Alternatives Planning System (LEAP) is another simulation-based model that supports a wide range of different modelling methodologies for the whole energy sector of an economy [62]. Li [63] provides a detail assessment of previous work using LEAP model in the RBS. LEAP is a widely-used modelling tool for climate change mitigation and energy policy assessment; however, there is a lack of scientific proof of its up-to-date applications in the decarbonisation of the RBS at regional or global scales.

In general, energy systems model tools have been developed for more than four decades around the globe [11, 15, 16, 18, 36, 55, 64, 65]. Particularly, addressing the decarbonisation of the energy consumption in buildings is still a global challenge. It is well-known that the residential sector might account for 25% to 40% of the total energy consumption of a nation, depending on the demographic context and geographic location [5]. Space heating and space cooling along with water heating can represent up to 80% of all the buildings' energy consumption [12]. In order to promptly decarbonise the sector, radical solutions must be assessed to be implemented in the next decades. In that sense, ESMs play a vital role to better understand the interdependencies among technology diffusion, energy supply and demand, and market behaviour along with the impact in global climate change. Therefore, a big step forward is required to address the challenges of understanding the decarbonising pathways of the RBS. First, buildings energy system models should be able to study the technology availability and future needs, accounting for barriers at the national, regional and global scales – considering that no single technology and/or energy resource might provide a global solution. Second, buildings energy system models should include the heterogeneous behaviour of multiple actors – human factors – in order to account for their complex effects on long-term planning. Third, buildings energy system models should also consider spatial and temporal detail to examine energy supply and demand globally. The next section of this research review address one of these three challenges. Further research should address the remaining two challenges.

2.2. Current and emerging technologies to decarbonise the building stock

The ways that nations use energy have been constantly changing over the course of human development and will certainly change in the future [66]; technology development and diffusion play a key role in this energy change. Although our understanding of the relationship between the factors influencing households' energy choices, the household energy use patterns, and the cleaner energy transition drivers is very limited [67, 68]; the assessment of the current and emerging technologies to decarbonise the RBS is paramount. At the global scale, decarbonisation of the RBS can be accomplished by both energy conservation and energy efficiency [13]. Energy conservation is any behavioural change that results in less energy use while energy efficiency is the technology use that requires less energy to perform the same function [67]. This section of the literature review addresses the technologies that might play a vital role in the decarbonisation of the RBS on a global scale, classified as: heating, cooling, and electricity (e.g. lighting, appliances, cooking). Additionally, modelling approaches for technology deployment and policy recommendations are also assessed. Related behavioural change with energy conservation is addressed in the agent-based section.

Heat loads in buildings are based on outdoor temperatures [69] and season requirements [70], creating a weather dependency and seasonal variation on demands of heating and cooling. Thus, heating and cooling demands vary from place to place, and even from day to day [71]. Figure 3 shows the schematic of district energy systems considering heating, cooling and power. The main component in the district cooling plant is the absorption chiller which uses heat sources (as the district heating plant) for a cooling cycle. The assessment of these technologies at the global scale must consider local weather conditions and patterns along with the availability of renewable energy sources.

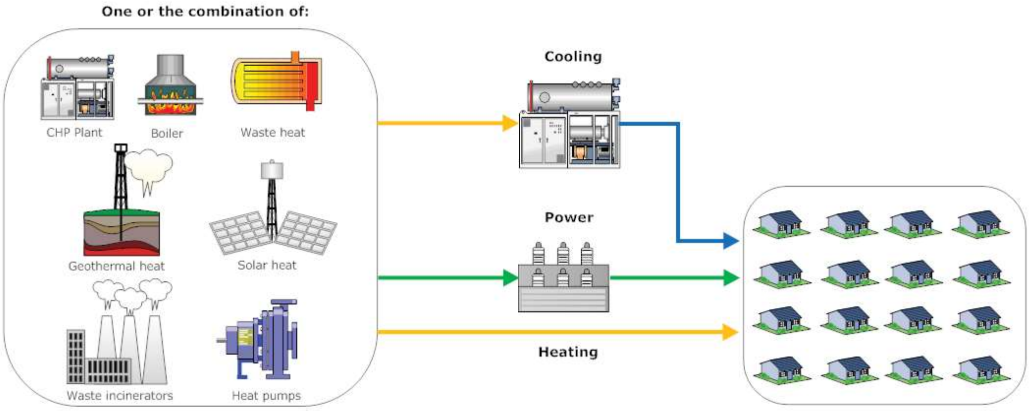

Figure 3: District energy systems.

Werner [72] finds that between 1990 and 2014, 90% of the world's heat supply is dominated by fossil fuels. Werner [72] also shows the four different heat supply methods worldwide. Results illustrate that 51% of the world heat demand is used in buildings from which 43% accounts for the use of direct use of coal, petroleum products, and natural gas as shown in [72].

Additionally, current district cooling systems only met 16% of the total demand and 7% of the residential sector demand in the European Union [72]. Findings also show that current district cold deliveries volumes worldwide are much smaller than district heat deliveries. These figures show enormous need to decarbonise the building heating and cooling sector and a potential opportunity for the introduction of renewable energy resources in the district energy systems. Therefore, future deployment scenarios of district heating and cooling technologies should consider its favourable characteristics such as higher supply security, lower costs, and lower carbon dioxide emissions due to the high possibility of introducing renewables [73].

Lake, et al. [74] analyse six energy sources for district heating and cooling systems. They study the pros and cons of geothermal or ground heat, biomass, waste incineration, waste heat, fossil fuels, and solar thermal. Werner [69] presents the Swedish example in the evolution of use heat supply methods for district heating as can be seen in [69]. In this example, renewable boilers use biomass as fuel and there is no use of other renewable energy resource such as solar or geothermal. In another study, Werner [72] also describe the describe the use of natural cold resources available in deep sea and its use in during warm summers in different parts of the world. Overall, the use of renewable resources would vary depending on the season and geographic location, identifying the need of a worldwide assessment of the different technologies priorities for different regions and countries.

Despite the low awareness of district heating and cooling system benefits, these are a promising heat and cold supply technologies for further mitigation of climate change worldwide [72]. Four further efforts are identified to expand the potential of district heating and cooling system worldwide: 1. Study future conditions associated to renewables and buildings with low heat demands [75]; 2. Study the impact of introducing the fourth generation of district heating technology [76]; 3. Assess the global potential to mitigate climate change within a common and aggregated vision [72]; and 4. Assess the global potential for future district cooling systems.

On top of DHC systems, District Energy Systems would be able to provide electricity, low-temperature domestic hot water, heating, and cooling [74, 77]. District Energy Systems are the combination of combined heat and power plants with district heating and cooling systems suitable to meet electricity, heat and cooling demands [78]. These systems are also called distributed multi-generation technologies or trigeneration district energy systems [79]. District energy systems offer a potential climate change mitigation solution due to the opportunity to implement large polygeneration energy conversion technologies connected to buildings over a network [80]. Figure 4 illustrates the evolution of district energy systems. The combination of technologies plus the use of renewable energy sources in the 5th district energy generation present a promising solution to decarbonise the RBS. Apart of district heating and cooling technologies within District Energy Systems, a more sustainable energy future of the RBS requires the understanding of the potential implementation of storage technologies, fuel cell technologies, high efficient lighting technologies, and smart grids at global scale.

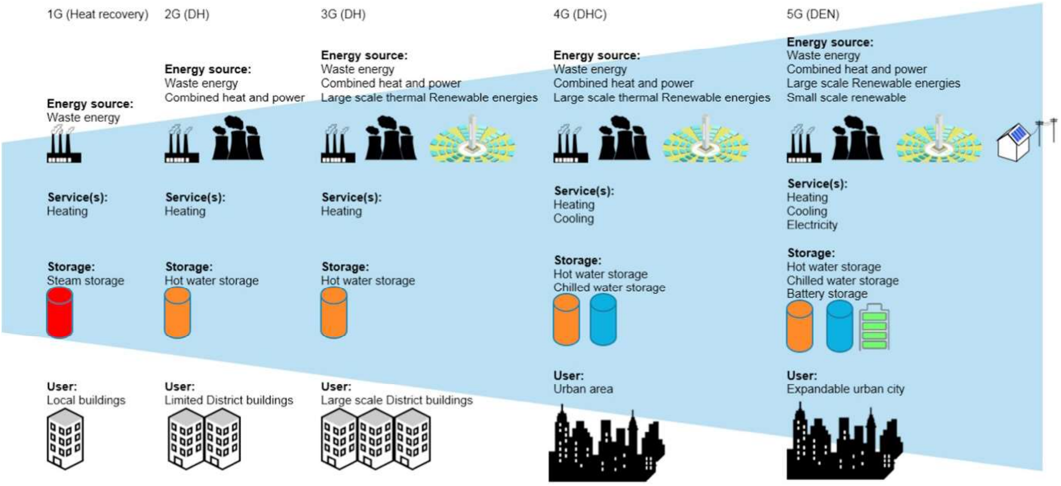

Figure 4: Future generation of district energy systems – concept of the 5th generation [70].

Del Pero, et al. [81] assess the key role of several energy storage technologies to manage intermittency of energy supply and demand, and efficient use of renewable energy sources. von Geibler, et al. [82] also identify the opportunities to implement micro-fuel cell technologies in the RBS in combined heat and power production. High efficient lighting in residential buildings can reduce between 60% and 80% of lighting related greenhouse gas emissions [83, 84]. Installation of efficient lighting at large scales, as in regions where incandescent bulbs are still in place, could help to prevent energy crisis. This is the case of Nigeria where 70% of power generated for lighting can be saved by efficient lighting use, as reported in [85]. Another example of massive replacement of incandescent bulbs for fluorescent compact lamps is Ecuador. Sixteen million bulbs were replaced countrywide, saving 10 million USD and 360 GWh of energy consumption each year [86]. Kolokotsa [87] explore the role of smart grids towards increasing energy consumer awareness and rational energy use. Smart grids offer the opportunity of connecting devices and renewables at low voltage level. Smart grids can be viewed as aggregators of consumers, buildings, and low-carbon technologies that allow better supply and demand matching. The impact assessment of these technologies implementation at the global scale and its benefits in terms of climate change mitigation and energy security is still missing.

The deployment strategy valuation of the mentioned technologies as well as the overall system cost estimation can be assessed by energy system models. Depending on the modelling approach, ESMs can also analyse the impact on climate change along with the decarbonisation pathways of the RBS – as this research focus is. Previously, this study described a number of ESMs. Overall, depending on the different level of detail and chosen model structure, building energy system models can be simulation- or optimisation-based, differ in time frame and region considerations, and follow top-down or bottom-up approaches [88].

MARKAL/TIMES/TIAM family, bottom-up, technology-rich cost optimization models, consider district heating and combined power and heat technologies maximising profit in the long-term technology investment [89, 90]. Wang, et al. [91] apply the Global TIMES model to study the RBS transition at the global scale, finding that between 28 Gt and 32 Gt of CO_2 emission reductions can be achieved in this sector under 1.5- and 2- degree targets respectively. In addition, GCAM, a recursive dynamic bottom-up market equilibrium model, thanks to its logit specifications represents the heterogeneity of technologies market shares [92]. Clarke, et al. [39] use GCAM to study the effects of long-term climate change conditions on building energy expenditures on a global scale, explaining the drivers that link building energy expenditures to regional climate. Although NEMS is a technology-rich model, it does not consider district heating and cooling technologies for the RBS. Wilkerson, et al. [46] analyse the RBS, concluding that NEMS's economic analysis is simplistic and does not consider market failures and behavioural complexities. In general, the assessment of decarbonisation pathways for the RBS on a global scale including human, temporal, and spatial dimensions are still missing in the literature.

The aforementioned models have been used to enhance national and international energy security and low-carbon economy development. In terms of climate change mitigation pathways assessment, the applications of building energy system models can be summarised as: 1. Scenarios-based policy recommendations; and 2. Technology research and development prioritisation. These two main applications involve decision-making in the academia-research, government and industry sectors. ESMs of the RBS play important roles in seeking pathways to decarbonise the sector. In order to provide accurate results, these modelling approaches still require to consider human investment decision and technology choices, market behaviour, temporal and spatial distribution of energy demand and energy sources at the global scale. As the demand for heating, cooling and electricity in buildings depends on climatic and geographic conditions (population density, life style and culture), technologies assessment and market interaction should be considered at a global perspective.

Concluding remarks

The energy use in nations have been constantly changing over the course of history and will certainly change in the future. While long-term energy transitions occur, global energy-related challenges need to be addressed as well. One of the challenges in energy systems is climate change because of both high share of fossil fuels and related greenhouse gas emission. Particularly, the end-use sectors (transport, industry and buildings) are the focus of developing pathways to decarbonise the energy system. In the RBS, the energy consumption can vary up to 40% of the total energy consumed in nations, depending on economic development, technological innovation and diffusion, energy policy implementation, and cultural and geographical features. These features are likely to be increasingly prominent in shaping the 21st century energy transition.

The RBS represents an enormous opportunity to decarbonise the whole energy system at the global scale. In this regard, ESMs have been developed for decades; and have played a key role in past and present national energy transitions to study the pathways to decarbonise the sector. However, contemporary challenges of energy systems (e.g. human behaviour, renewables intermittence) are more complex to address today and still need to be included in ESMs to provide pathways for future energy transitions. These challenges can be addressed by integrating the techno-economic perspective, the socio-technical perspective, the spatio-temporal dimension and the political perspective. The techno-economic perspective explains the energy systems of the RBS defining the energy uses and services coordinated through energy markets. However, the techno-economic perspective is based on supply-demand balance often aligned with neoclassical economic idea of market equilibrium. The socio-technical perspective explains emerging technologies innovations, diffusion and deployment by considering the energy system as a socio-technical system – a social system intertwined with technology. Socio-technical energy transition models of the RBS would be able to capture the techno-economic detail with explicit actors' heterogeneity (agents) and transition pathway dynamics of market imperfection. The spatio-temporal dimension contributes to the understanding of the influence of geographical restrictions in the diffusion of technology at national and even global scales. The intermittence of renewables and its different dispatchable reserve capacity in grid services are the main considerations that current and emerging low-carbon energy systems modellers are considering in models. Finally, the political perspective focuses on the change of energy policy that directly affect the energy system. In the RBS, regulations around electricity pricing systems, carbon taxes, and heating/cooling usage are the main concern of policy makers at the country, region and global levels. However, political perspective is different from the techno-economic, socio-technical and spatio-temporal perspectives as most energy policies are driven by economic actors and normative recommendations. Further research should include the assessment of technology deployment to decarbonise the RBS considering agents heterogeneity and the spatio-temporal dimension of energy demand.

Acknowledgement

The PhD research of Mr Diego Moya has been funded by the Secretaría de Educación Superior, Ciencia, Tecnología e Innovación - SENESCYT, Award No. CZ03-35-2017, and by the Universidad Técnica de Ambato - UTA, Award No. 1895-CU-P-2017 (Resolución HCU), and supported by The Science and Solutions for a Changing Planet Doctoral Training Partnership, Grantham Institute, UK Natural Environment Research Council (NERC) at Imperial College London, and the Goodenough College. The Institute for Applied Sustainability Research (iSUR) supports international research on global sustainability applied to the Global South.

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