

ORIGINAL ARTICLE

Characterizing the theory of energy transition in Luxembourg—Part three—In the residential sector

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Abstract

Increasing consciousness to address future concerns is a challenging subject, noticed considerably by policymakers and investors. Investigation of energy use in residential buildings in terms of quantity and sources of energy was the main focus of this study. Indeed, the paper was aimed to study the role of contextual factors on two points: the energy demand and the spreading of renewable technologies in the residential sector. It was theory-driven research to highlight some future concerns. The first theory was to reveal how the growth of single-family houses versus multi-family houses could affect the growth of energy consumption and the application of renewable technologies. The second theory was built to highlight that spreading energy measures to increase efficiency or introducing a new energy carrier should be embedded in the context of new construction activities or in a template of renovation projects. The third theory was to emphasize the priority of thinking about managing the changes in residential buildings because of the lasting impact of the decision about the type of building. Finally, the purpose of the ongoing transition was argued to highlight that the growth of renewable technologies has not been necessarily aligned with getting away from fossil fuels.

KEYWORDS

energy transition, future studies, Luxembourg, residential sector, theory of transition

1 | INTRODUCTION

Enhancing awareness about future issues has become a central concern among futurists.¹ Despite the general interest and theoretical discussions, there has been a gap between conceptual development of the future consciousness and empirical or practical applications in the future research literature. Among future researchers, future consciousness has been generally seen as a holistic concept that draws attention as an internalized and experienced phenomenon. Johan Galtung defined

future consciousness as “being conscious of what is possible, probable, and desirable in future”.² This study has investigated the future for increasing awareness in the case of consuming energy in residential buildings. The considered directions to conduct the study have been as follows:

1. Exploring the quantity of future energy consumption in residential buildings.
2. Investigation of the penetration rate of renewable energies into residential buildings.

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Studying the issues has attracted more attention owing to the high number of single-family houses in Luxembourg. As reported in the literature, single-family houses in Luxembourg have outnumbered the European average and Luxembourg was in the list of the highest ten countries in this regard.^{3,4} Indeed, the necessity of this study was emphasized by the low prices of energy carriers in Luxembourg compared with other European countries.⁵ We aimed to contribute to the growing understanding of the future energy demand in residential buildings in Luxembourg by 2030 and 2040 in two aspects:

1. In terms of quantity; the growth of energy consumption.
2. In terms of quality; shift to alternative energy sources.

With this broad aim, the paper has looked explicitly at the following questions:

1. What kind of changes have been occurred in the Luxembourgish residential energy consumption pattern?
2. What will be the energy mix to heat the future Luxembourgish residential building?
3. What is the underlying driving mechanism that has affected the future trend of energy consumption?

The reason to choose Luxembourg has been the considerable share of space heating in the residential sector compared with other European countries, detailed in Figure 1.

Indeed, the transportation sector and the public dimension have been investigated to highlight the future challenges, by the authors.^{7,8} The project has theorized concerns about three parts of the future energy system in Luxembourg. Studying the residential sector was the last part to search for the raising concerns. The share of energy consumption in the residential sector has been around 10.5% of total consumed energy in Luxembourg. Natural gas and fuel oil products have provided around 80% of the whole needed energy in the sector.⁹ Consequently, the

importance of studying the pathways to limit energy consumption in the sector was understood.

However, future energy issues have been a matter of concern in different countries. Szarka et al.¹⁰ studied the long-term development of Germany's energy sector to understand the long-term role of bioenergy in the national energy system. The purpose was to highlight the possible role of bioenergy by 2050 scenarios. Studying the household energy services in Cape Town, South Africa, by the same concern about the consumption of energy was investigated by Strydom et al.¹¹ It was aimed at identifying the intervention points toward sustainability in this sector. Existing literature also investigated the household sector based on income levels.¹² It was intended to show the tendency of different classes of society, categorized by income, to adopt different energy technologies and fuel types. The environmental impacts of metabolism of household consumption were discussed in the literature.¹³ Total energy consumption and related CO₂ emission data were calculated as a function of household income and family type. Exploring public behaviors about consuming energy in the household sector was argued in the literature.¹⁴ The study was intended to understand the interactions of the public toward different incentives to promote sustainable behaviors. Studying the theory of transition in the transportation sector in Luxembourg had a similar goal to build the theory for highlighting future concerns.⁷ It investigated how the spreading of electric vehicles in Luxembourg would be different compared with the leading countries in the field. Most notably, a common limitation of all the above studies has been the lack of socio-technical analysis investigating the drivers for energy-saving improvements in the residential section. The majority of studies in the residential sector, in this last decade, have been dominated by technical and physical research because of the lack of available disaggregated data on household energy usage. More precisely, very few studies have explored the impact of types of residential units on the growth of energy consumption or on the capacity of the units to host renewable

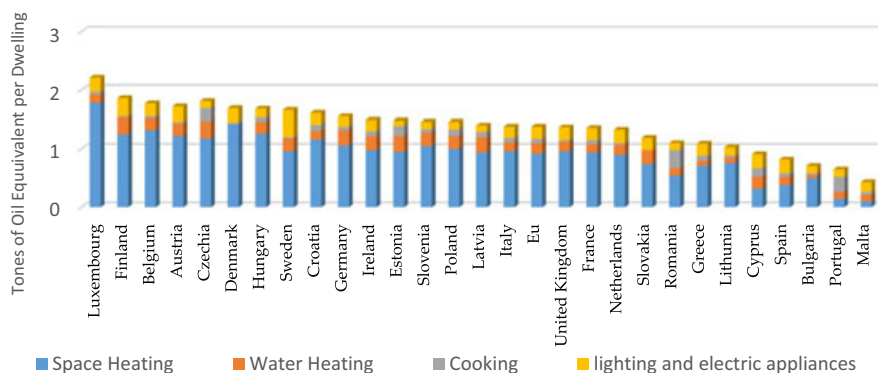


FIGURE 1 Energy consumption per end use per dwelling in some European countries, 2016⁶

technologies.^{15–17} The discovered gaps in the literature have highlighted the necessity of exploring the drivers, affecting energy consumption in space heating. To our knowledge, the present paper has been the first to use macro-level data to investigate the impact of types of future residential units on space heating energy consumption and hosting renewable technologies.

As reported in the literature, there have been three models to conduct energy transitions by socio-technical aspect.¹⁸

1. Interim energy transition—is resulted from policies without public acceptance.
2. Deliberate energy transition—is conducted by citizen-driven change without supporting regulations.
3. Transformative energy transition—they occur as a result of a combination of policy and citizen-driven change, which are more sustained.

The predicted considerable growth of population in Luxembourg⁵ and the need for new constructions have been the driving factors to investigate how the decision of people about choosing types of construction has affected the growth of energy demand. Responding to this query has been a significant aspect of the study. Therefore, the theory of transition in Luxembourgish residential buildings was characterized to understand how deliberate energy transition would affect the needed energy for heat consumption. For this purpose, the following issues were based in the context of Luxembourg to build the theories.

It was theorized that the high number of single-family houses in Luxembourg would affect the energy demand and penetration of renewable technologies in the residential sector.

Discussing the significant growth of the demand in the housing market was another noticed subject in this study. Normally, the energy issues in residential buildings have not been driving factors for changes because they have not been big concerns. Thus, it was hypothesized that in Luxembourg, the energy concerns should be addressed in the context of the new construction or renovation projects. Simply, the constructing phase of the residential units is a proper time to address the desired targets in the energy aspect.

The other issue was referred to the lasting impact of an early decision to choose the type of residential units on the construction of the future energy pathway. Therefore, it was hypothesized that the priority of intervening in the transition of the residential sector in comparison with other sectors would be higher.

Indeed, in Luxembourg, the total share of consumed energy in space heating and water heating has been around 84% of the total consumption in residential buildings, mostly provided by natural gas and oil products, reported in the literature.⁹

Framing analysis has been applied in the social sciences within political, media, sociology, and behavioral economics.^{19,20} The study was planned to use the analysis in future energy discussions. Based on the literature, the framing process was to select some aspects of a perceived reality and make them more salient in a communicating text, in such a way as to promote problem definition, causal interpretation, moral evaluation, and/or treatment recommendation for the described items.¹⁹ Defining the problems to highlight the future energy concerns in residential buildings has been the contribution of the study to the body of knowledge.

Organizing the paper was in the following order: In Section 2, the applied procedure has been described. Section 3 has been conducted to explain the employed scenarios to justify the built theories. In Section 4, in addition to arguing the limitation of the paper the results have been discussed.

2 | METHODOLOGY

The general goal of theorizing has been to elaborate an idea or what has been called in literature abduction.²¹ It has been translated as observing a fact and then professing to say what the opinion has been about and to highlight the point. The purpose has been to guess right or similar to what has been mentioned in the literature to express a type of scientific intuition.²²

The applied methodology was started with the development of the theoretical phase, and then it was proceeded to the grounding phase to confirm or to develop further the initial theory.²³ The overall structure of this type of study was composed of two phases.²² The first phase was about the early discovery of the theory, and the second phase was to provide some empirical grounds to justify the constructed theory.²⁴ Three built theories containing new ideas were explained in the introduction. The remaining sections were to explore different empirical data to support the theory.

Energy issues in the residential sector have been accompanied by various uncertainties such as the extent of the electrification growth, the penetration rate of renewable technologies, or more of the same.²⁵ To reflect the impacts of these uncertainties, generating scenarios were considered. The scenarios were to investigate a series of alternative futures to support the built theories.

The main reason for the frequent use of scenarios within the energy domain has been the requirement for long planning horizons. Energy technologies can last several decades, and it may take several decades to develop new ones.²⁶ However, the generated scenarios in this study have been written for short-term purposes until 2040.

The applied methodology to generate the scenario has been a bottom-up calculation of the techno-economic savings potential. The bottom-up approach looked at how emerging individual energy technologies could affect the provision of energy services regarding the relative cost of services.²⁷ The approach has brought more details in the energy system and insights into the technology development and its impact on final energy consumption of residential buildings and allowed evaluating a wider range of policy options.²⁸ An overview of the procedure has been shown in Figure 2.

The relative cost has been the major criterion for the substitution, driven by factors such as technology development. The typical bottom-up approach has focused on the energy system itself and not on the relationship with the economy as a whole.²⁹

This study was to investigate the final energy consumption in residential buildings. It focused on the growth of different types of buildings caused by the population growth.

The biggest concern to writing scenarios or modeling the future condition was the lack of reliable assumptions. For this purpose, different regional energy scenarios in

European countries have been explored to find a reliable range for the considered issues. However, the strength of the driving factors for each issue has been explored and compared with the Luxembourg case to deduce a lower or higher quantity for the considered assumption. The needed data, explaining the specific condition of Luxembourg, were collected based on the government statistics service of Luxembourg, STATEC.⁹

The following sections of the paper have been conducted to grounding the built theories.

3 | GROUNDING THE THEORIES—GENERATING THE SCENARIOS

This section has addressed the issues in the context of residential buildings in two complementary parts. The purpose of the section was to justify the built theories by exploring relevant data. The considered procedure for this purpose was to generate scenarios and projection of historical data to the future. The achieved results were used to defend the theories.

The first part was to explore the quantity of final energy consumption in the residential sector. For this purpose, it was planned to study the renovation rate of existing buildings and the construction rate. Indeed, investigating the changes in the consumption of energy for heating purposes in residential buildings has been the subject of this part.

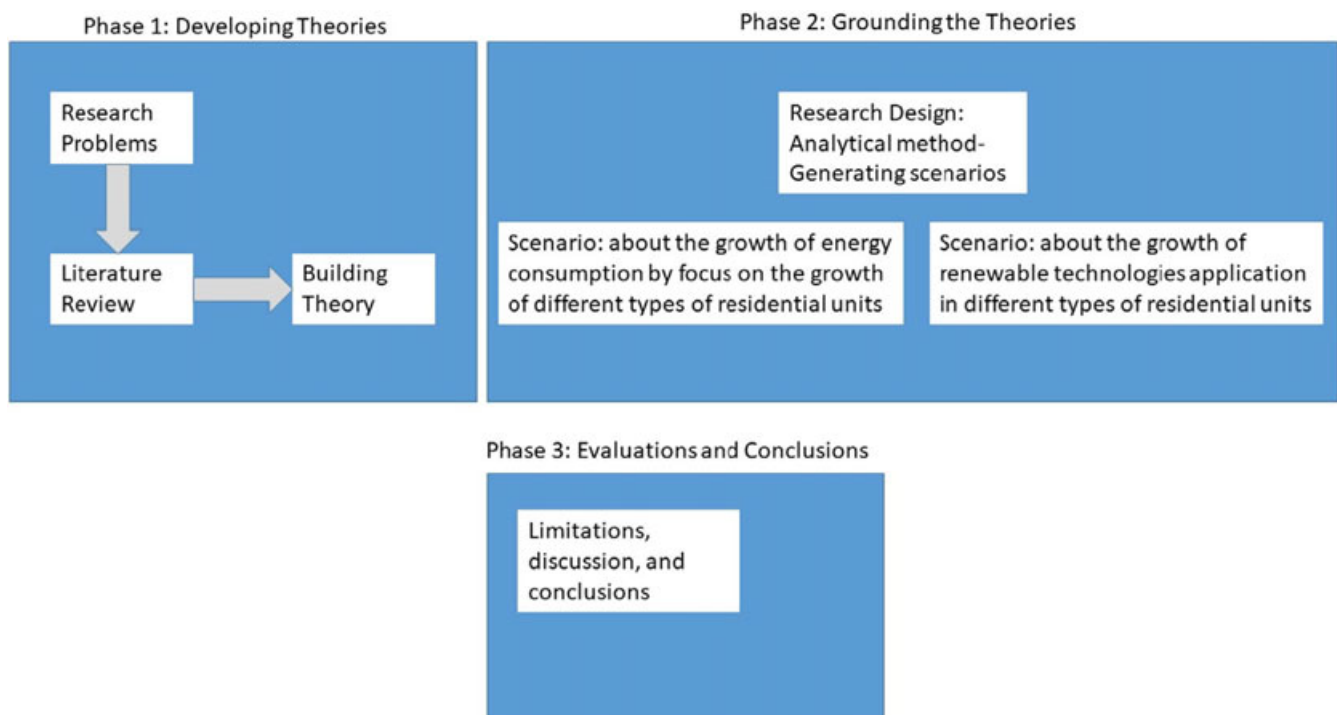


FIGURE 2 An overview of the methodology in this study

In the second part, the changes in the energy mix have been investigated. It was explored how different shares of energy sources have been affected by emerging energy technologies and local parameters such as the price of energy carriers or public affordability to endure the changes in retail prices.

The employed concept to conduct the section was the generation of scenarios. As reported in the literature, the procedure has been a known method to argue the potentials for future energy issues.^{30–33} The lack of existing capability in the available software caused the application of the classic methods for the needed calculation.

3.1 | Exploring future energy consumption in residential buildings-heating purpose

To investigate energy consumption for heating purposes, the unit area of residential buildings was focused, rather than focusing on residents of the building. Indeed, to study the impact of building types on energy consumption, it was assumed that energy was consumed in each unit area of buildings. The section has investigated how the growth of new construction or renovation projects in each dwelling type may affect energy demand in the residential sector. An overview of the whole data and the needed assumptions have been shown in Figure 3.

The collected data were referred to the STATEC website, created to respond to the need for the statistics service by the Luxembourg government.⁹

3.1.1 | New construction

The main goal in this section was to investigate different futures to explore various possibilities that might affect the growth of energy consumption in residential buildings. Two key principles were found, driving the future energy demand:

1. Growth of need happens as the result of increasing the population, which has been noticed in this study.
2. Saturation effect; how wealthy consumers gradually search for improving the quality of their food and household goods.³⁴ By increasing the income, the consumption will change, as well. Radical innovations would be another reason to expect the growth of consumption.³⁵ Studying the effect has not included in the scope of this study.

Based on STATEC projections, a considerable growth of population in Luxembourg until 2050 has been expected.⁹

It could be translated as big demand for new construction, which is resulted in the growth of the future energy consumption in residential sectors. Here, the building types were noticed to find the impact on the energy consumption in residential buildings.

The different possible future rates of new construction and renovation activities in Luxembourg were explored to obtain a suitable approximation of the future spreading of the energy-efficient envelopes into the buildings. However, before estimating the number of future buildings, it was needed to explore the historical trend of the construction. For the energy issue, two types of buildings with major shares in the residential sector were distinguished, single-family houses (SFH) and multi-family houses (MFH).

As of March 2017, the register of buildings and housing counted 142,820 residential and semi-residential buildings as well as 233,675 residential units in the Grand Duchy of Luxembourg. Half of the accommodations were classified in the single-family category, 35% in apartment buildings, and about 15% in semi-residential buildings.^{1,9}

As shown in Figure 4, the annual growth of multi-family houses in Luxembourg has been increased compared with the almost constant growth of single-family houses.

There has been an obvious relation between the growth rate of gross domestic product (GDP) and the housing market.³⁶ To study the future housing market, the assumptions in the previous investigations were followed. As reported in the literature, depending on GDP growth, the annual demand for new buildings has ranged from 7310–5881 residential units/year (GDP growth 1.5%) to 7310–6567 residential units/year (GDP growth 3%) between 2020 and 2050.⁹ However, there was a need to distinguish the changing share of single-family and multi-family houses in the available data. Therefore, the fraction of single-family houses to multi-family buildings in different decades was calculated and reported in Table 1.

The share of SFH and MFH, in two perspectives 2030 and 2040, was assumed regarding the data reported in the literature.⁹

Three scenarios in this study have been developed to represent different possible futures. In the Greening of Luxembourg, it was assumed that the growth of GDP was 3%. Incrementalism represented a world with slower growth of GDP, around 1.5%. The closed Book scenario depicted a world with the most pessimistic assumptions.

In the Greening of Luxembourg, it was assumed at least 73,100 residential units have been added every 10 years. Moreover, it was supposed that by improving the gross domestic product the growth rate of single-family houses compared with apartment buildings was increased.⁹

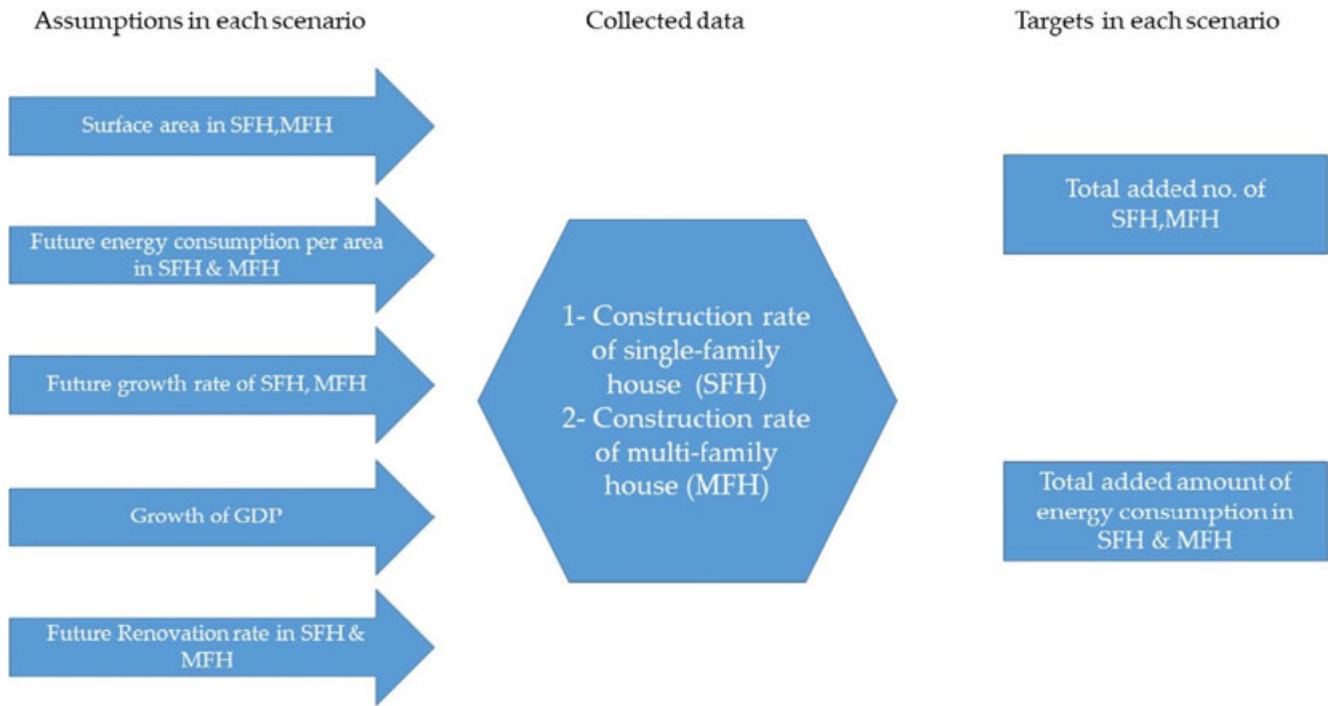


FIGURE 3 An overview of the collected data and assumptions in the scenarios

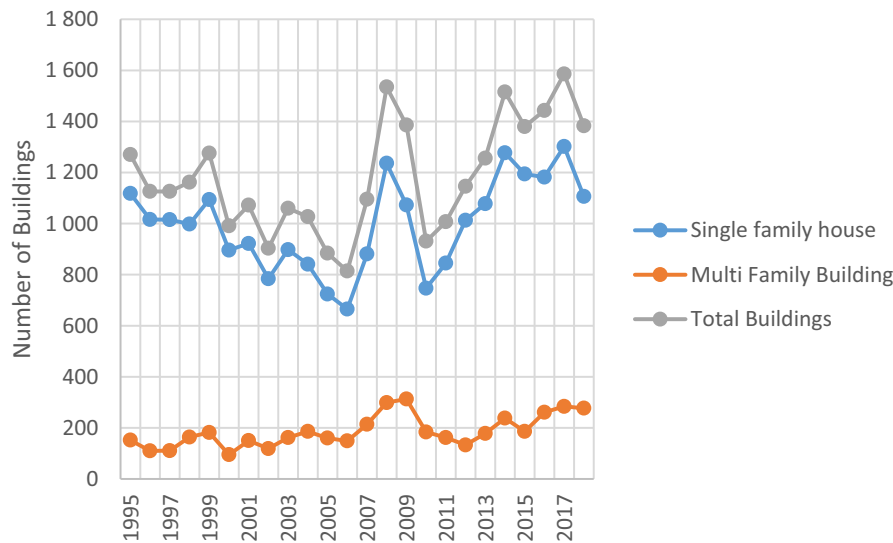


FIGURE 4 Overview of the proportion of construction rate of single-family houses to multi-family buildings in the last two decades 1995–2018 in Luxembourg⁹

Year	Total dwellings	Number of single-family buildings	Number of single-family houses to total dwellings (Percent)
1990	114,468	9091	7.94
2000	199,638	20,900	10.47
2010	220,369	29,820	13.53
2018	263,607	39,564	15

TABLE 1 Representing number of single-family house to the number of multi-family building

In Incrementalism, it was assumed that 58,810 residential units were added after 10 years.⁹ In this scenario, lower GDP growth was assumed, and consequently, higher

growth of multi-family buildings resulted. Therefore, the share of MFH in the total number of residential units was increased.

TABLE 2 Representing the number of two types of buildings in various scenarios

Year	Number of new buildings		Increased number of dwellings per each decade		Total number of added dwellings until 2040
	Single-family houses	Multi-family buildings	Total dwellings	Total dwellings	
Historical data					
1990	9091	722	13,055		
2000	20,900	2188	32,462		
2010	29,820	4035	43,666		
2018	39,564	5938	58,657		
Scenario incrementalism (1.5% GDP growth)					
2030	39,204	6534	58,810		121,072
2040	38,049	6918	62,262		
Scenario Greening of Luxembourg (3% GDP growth)					
2030	58,979	8307	75,593		155,188
2040	63,351	8122	79,595		
Closed Book scenario					
2030	3607	11,080	59,007		128,192
2040	2705	13,296	69,185		

In the closed Book scenario, it was assumed that the number of residential units followed the Incrementalism pattern while the difference was referred to the significant growth of the MFH.

The existing scenarios in the literature were selected to estimate the number of residential units.⁹ The assumed number of residential units in the multi-family buildings was, respectively, from the scenario with the highest GDP growth, two, three, and five. Based on these assumptions, the results have been presented in Table 2.

The main feature of Table 2 was to represent different combinations of dwelling types to provide the needs of residential units. This section has discussed how the combinations of dwelling types would affect heat demand.

For this purpose, it was needed to find reliable assumptions for energy consumption in future residential buildings. By supposing that the improvement in energy consumption was related to insulation, shading, and advanced windows, then the corresponding figures for the energy consumptions, based on the literature, for a multi-family and single-family dwelling type were 133 and 155 kJ/m²/year, respectively.^{37,38} The supposed figures for the consumption were pessimistically higher than what was reported, representing the ideal condition. It has worth mentioning that the figures were proportionally aligned with the empirical data reported in the literature.^{39,40}

Estimating the floor area for each type of building was necessary to calculate the final energy demand with the method. As reported in the literature, on average, there have been two rooms per person and there have been 2.3 persons per household, in Luxembourg.⁵ The average size for each multi-family house was assumed around 75 sq. meters equals 4.6 rooms per household. However, the average living size for a single-family house was around 125 sq. meters.⁹ The total added area in the last column in Table 3 was to show the difference between dwelling types.

The number of dwellings in the Greening of Luxembourg scenario was around 20 percent higher than the closed book scenario, but the consumption was around twice as presented in the last column of Table 4.

As shown in Table 4, the key parameter in the growth of energy demand was the type of buildings, that is, being single-family houses, or multi-family buildings.

3.1.2 | Scenarios for potentials of renovation and impacts on energy use

The first step was to make assumptions for the number of renovated buildings in two perspectives, 2030 and 2040. Based on the first assumption, the renovated buildings were suffered the needed changes for energy as well. The

TABLE 3 Representing the comparison of area in different building types in the scenarios

	Year	Number of buildings SFH	Surface area SFH (m ²)	Number of buildings MFH	Surface area MFH (m ²)	Total added area (m ²) until 2040
Scenario incrementalism (1.5% GDP growth)	2030	39,204	4,900,500	6534	1,470,150	12,683,325
	2040	38,049	4,756,125	6918	1,556,550	
Scenario Greening of Luxembourg (3% GDP growth)	2030	58,979	7,372,375	8307	1,246,050	17,755,600
	2040	63,351	7,918,875	8122	1,218,300	
Closed Book scenario (The high growth of multi-family house trend)	2030	3607	450,875	11,080	4,155,000	7,719,400
	2040	2705	338,125	13,296	4,986,000	

TABLE 4 Comparison of total consumed energy in different building types based on unit of area in the scenarios

	Year	Surface area SFH(m ²)	Consumed energy SFH (kJ)	Surface area MFH(m ²)	Consumed energy MFH (kJ)	Total added energy (kJ)
Scenario Incrementalism (1.5% GDP growth)	2030	4,900,500	759,577,500	1,470,150	195,529,950	1,900,657,975
	2040	4,756,125	737,199,375	1,556,550	208,351,150	
Scenario Greening of Luxembourg (3% GDP growth)	2030	7,372,375	1,142,718,125	1,246,050	165,724,650	2,697,902,300
	2040	7,918,875	1,227,425,625	1,218,300	162,033,900	
Closed Book Scenario	2030	450,875	69,885,625	4,155,000	552,615,000	1,338,048,000
	2040	338,125	52,409,375	4,986,000	663,138,000	

construction date was referred to estimate the total number of buildings for renovation. Therefore, the buildings with the construction date before 1990 were considered to renovate, around 9813 units.⁹

In 2017, Luxembourg's building renovation rate was <1%.⁴¹ The assumed figures for the Closed Book scenario, Incrementalism, and Greening of Luxembourg were 0.7%, 1.1%, and 1.4%, respectively.

Retrofitting in the existing houses in the Organization for Economic Co-operation and Development (OECD) countries was considered the potential for improving efficiency.⁴² Important retrofit options have been efficient windows and insulation. According to the literature, the former option can save 39% of the space heating energy demand in current buildings, while the latter can save up to 32% of the needed energy.^{38,42}

However, to show the impact of renovation, it was assumed optimistically that the renovated cases have experienced energy renovation. With a conservative viewpoint, each renovated case was considered like a single-family house, saving 100 kJ/m²/year per case. The calculated number of buildings with the renovation and the impact on energy consumption have been shown in Table 5.

This section presented the impact of new construction and renovated activities on added energy consumption

in possible futures with different shares of single-family houses and multi-family buildings.

As observed in Table 5, the optimistic impact of renovation projects on energy consumption was not comparable with the effect of new construction.

3.2 | Exploring future mix of energy in residential buildings

The other important issue in future of residential buildings has been the contribution of different energy carriers to provide required energy services. Exploring the literature revealed that the contextual factors have affected the penetration of renewable energy technologies into residential buildings.⁴³ In this section, the strength of these factors has been argued by generating three scenarios. In the first part, future scenarios in the electrification of residential buildings have been explored. Next, the penetration of solar thermal technologies in residential buildings has been investigated. Finally, the future growth of rooftop solar panel systems in the residential sector has been studied. Local assumptions for the growth rate of the considered technologies were made regarding its global feature and the strength of the driving factors for each technology in Luxembourg.

TABLE 5 Representing the number of renovated buildings and saved energy in each case

	Greening of Luxembourg		Incrementalism		Closed Book	
	Number of renovated buildings	Saved energy (kJ)	Number of Renovated buildings	Saved energy (kJ)	Number of Renovated buildings	Saved energy (kJ)
2030	1374	17,175,000	981	12,262,500	686	8,575,000
2040	1181	14,762,500	883	11,037,500	638	7,975,000

3.2.1 | Electrification in residential buildings by heat pump

Electrification for heating purposes has been expected to be delivered via heat pumps in the residential sector. Heat pumps could take low-temperature heat from the environment and turn it into higher-temperature heat by using electrical energy.⁴⁴

The attention to this technology has been steadily increased because it could also provide cooling. The task of cooling in the Grand Duchy of Luxembourg climate has not been significant. However, the demand for technology in housing has increased due to comfort reasons as well as nearly zero-energy buildings.⁴⁵ Since heating and cooling have been provided through the same investment, the profitability of investments has been highlighted.

Except for the capital cost, there have been other effective contextual factors on the spreading of the technology, discussed in the study. The pursued goal in this section was to investigate the effective players in the growth of heat pumps to find the share of the technology in future.

Present condition of heat pump technology in Luxembourg

Regional scenarios or action plans in other countries have been studied to find the scale of future growth of heat pumps. The UK's renewable energy target was to deliver 12% of its heat from renewables by 2020.⁴⁶ However, the EU has not set separate targets for the delivery of renewable heat.

The targeted figure for the share of heat pumps is 422 GWh (1519 TJ) in the energy system of Luxembourg by 2030.⁴⁷ Based on the literature, the whole oil-product consumptions in the residential sectors were contributed to 33% of total energy final consumption.⁴⁸ It could be calculated that the whole heating demand in the residential sector in 2018 was 18,618 TJ. Consequently, the approximate share of generated heat by the heat pump in Luxembourg has been around 0.5%.⁹

As shown in Figures 5 and 6, the annual growth rate of the total number of heat pumps in Luxembourg was exceeded the average number in EU-28. The remarkable point was the considerable growth of ground source heat pumps despite the slow growth of this technology in the whole region of Europe. As shown in Figure 5, the availability of the ground source heat pump in Luxembourg has reached around 30%.⁴⁹

However, the replacement issue of conventional heating systems with heat pump technologies has been challenging regarding different retail costs of electricity and fossil fuel carriers in different regions, which has not been in the scope of the study.

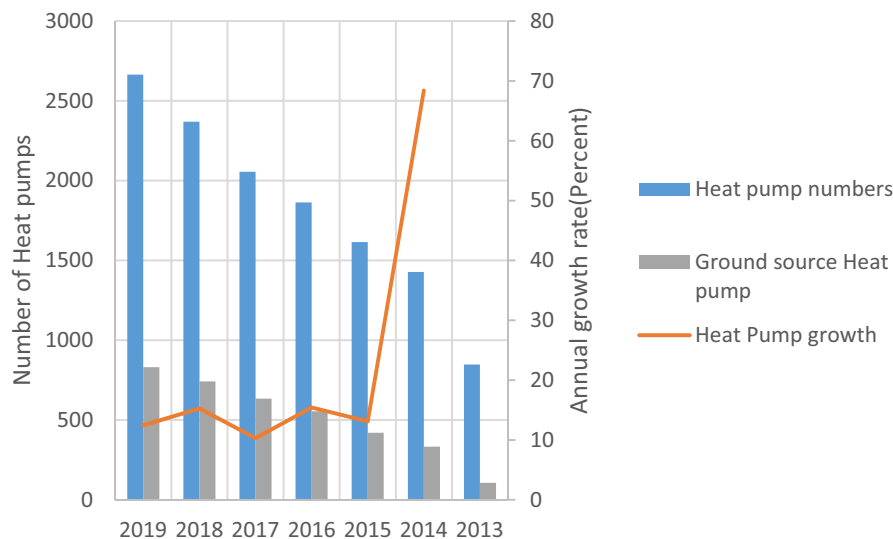


FIGURE 5 The growth of Heat Pump technology in Luxembourg 2013–2019^{5,9}

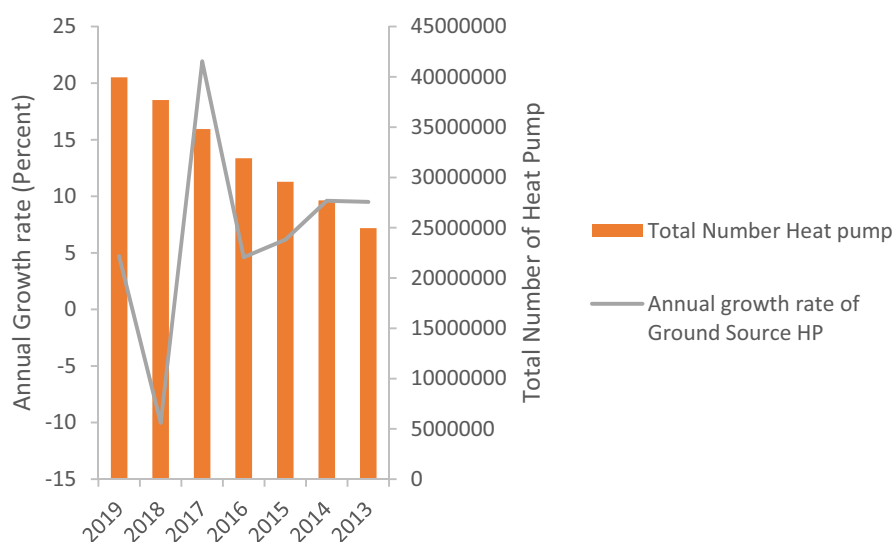


FIGURE 6 The growth of Heat Pump technology in Europe 2013–2019⁵

Contribution of heat pumps in future buildings

The general development path for most countries has followed an early adoption of the technology in the new single-family housing segment, followed by the renovation segment for the same housing type.⁵⁰ The supporting reason for this development has come from the fact that it has been easier to convince individual investors of the benefits of heat pumps than to convince project developers or groups of individuals.⁵¹ As mentioned, the development of heat pump has been in the initial phase; therefore, it was assumed that the first targeted type of dwelling was the single-family house. This assumption fitted well with the historical development of heat pumps in the United States and Europe. As reported, by 2005, 8% of the US homes used heat pumps as their primary heating system, while 38% of new single-family houses in 2011 had heat pumps as their primary system.^{52,53} It was confirmed in the literature that the single-family houses in Europe have had the greatest potential to host the technology.⁵⁴

Two main barriers to the growth of heat pumps in multi-family buildings were heat capacity and heating supply temperature.⁵⁵

Three scenarios were generated to characterize the development of the heat pumps in Luxembourg. Therefore, the development of heat pump technology was assumed in single-family houses. It was supposed that 35% of new single-family houses has been equipped with heat pumps in the ‘Greening of Luxembourg’ as the optimistic scenario by 2030. The results have been shown in Table 6.

It was assumed that heat pumps were penetrated in single-family houses in renovation projects. Moreover, it was supposed that the growth of heat pump in “Greening of Luxembourg” has been limited to 10%. The results have been presented in Table 7.

Based on the literature, the consumed electricity to provide heat has been presented in Figure 7, depicting the energy-saving impact of applying heat pumps.⁵⁶ It was

TABLE 6 Representing the share of heat pump in different scenarios

Scenarios	Assumed penetration rate by 2030 (%)	Assumed penetration rate by 2040 (%)	Contribution of heat pump in heat provision by 2030 GWh	Contribution of heat pump in heat provision 2030–2040 GWh
Greening of Luxembourg	35	70	400	859
Incrementalism	25	50	190	368
Closed Book scenario	30	60	21	31

TABLE 7 Contribution growth of heat pump in renovated buildings

Scenarios	Penetration rate by 2030 (%)	Penetration rate by 2040 (%)	Contribution of heat pump in heat provision by 2030 GWh	Contribution of heat pump in heat provision 2030–2040 GWh
Greening of Luxembourg	10	17	3.88	2.66
Incrementalism	8	14	2.39	1.52
Closed Book scenario	6	16	1.98	0.8

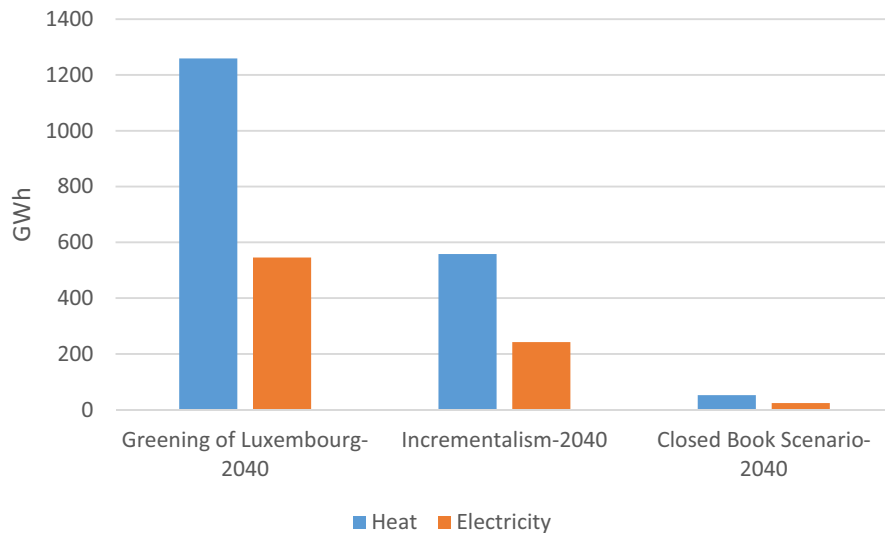


FIGURE 7 Comparison of electricity consumption for heat pump demand vs. reduction in heat demand by 2040 in scenarios

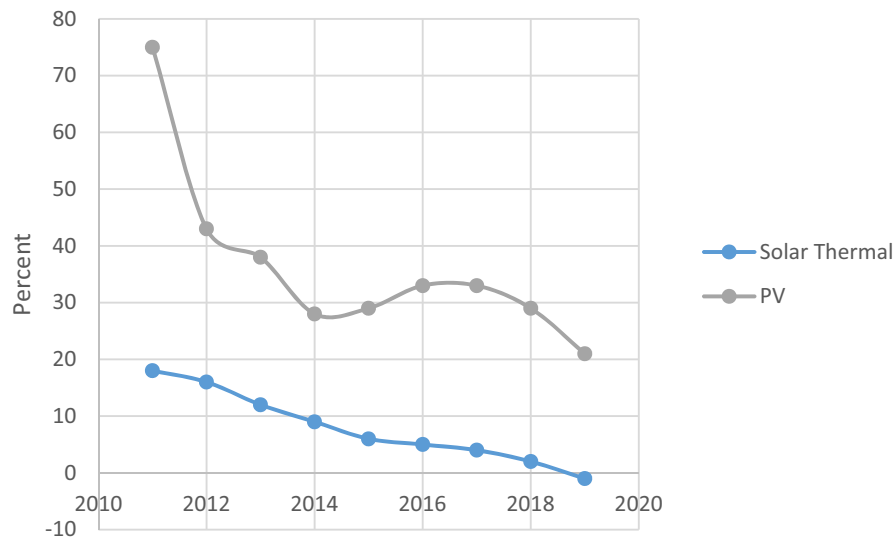


FIGURE 8 Representing the annual growth rate of solar technologies globally⁵⁹

assumed around 30% of installed heat pumps was ground source type and the rest of aerothermal heat pumps.

The highlighted feature of the scenarios was the high dependency of the heat pump market on types of buildings, which has been argued in Section 4.

3.3 | Penetration of renewable technologies in residential buildings

The section presented the future role of solar thermal and rooftop solar photovoltaic panels in residential buildings in Luxembourg.

3.3.1 | Solar thermal

Solar thermal system for residential applications has known as a matured technology, successfully deployed in

several countries for more than thirty years. However, on the global scale, only 1.2% of space and water heating in the buildings sector has been covered by the solar thermal system.⁵⁷

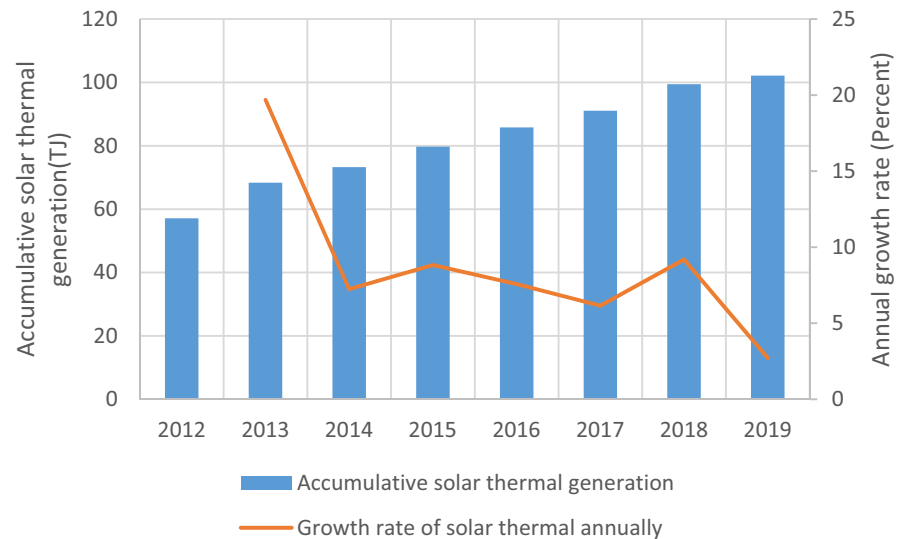
Present and future condition of solar thermal

As reported, in large parts of Europe, but also China, these applications have been come under increasing pressure from photovoltaic systems and heat pumps and have lost market share in recent years.⁵⁸ The impact of overlapping various renewable technologies has been shown in Figure 8.

The growth rate of solar thermal in Luxembourg has been shown in Figure 9, following the trend in Figure 8. Based on the literature, the current share of solar thermal has been around 0.3% in the energy system of Luxembourg.⁹

The growth rate of installing the collectors for solar thermal after 2009 has had a decreasing trend. The

FIGURE 9 Representing the accumulative and annual growth rate of solar thermal generation in Luxembourg⁹



issue has been observed in Austria, Germany, and the Netherlands.⁵⁸ In Denmark, the market for the individual system has been at a low capacity level, in the range of 2–10 MW/year, with a downward trend.⁵⁸

The reasons for the downward trend of solar thermal compared with PV solar panels and heat pumps are as follows:

1. In many scenarios, the share of electrification in residential buildings has been considerably higher than its current status. Electricity's share has been planned to reach about 35% by 2050, compared to <20% today in total final energy consumption.^{60–63} Therefore, attention and incentives have been drawn to develop electricity in building as the future energy carrier.
2. The type and the size of the system have been the other important factors, as they could affect the investment costs, or the proportion of useful solar energy provided by the system. The levelized cost of heat has been a decisive parameter and has been affected by the value of local variables.^{64–66}

In summary, it could be concluded that the role of solar thermal in future residential buildings in the Grand Duchy of Luxembourg would be negligible and ignored. Therefore, the future growth of solar thermal would be negligible in the residential sector.

3.3.2 | Rooftop solar panel in residential sector

There has been a big difference between this specific technology and others like solar thermal or heat pump technology. The difference has referred to the purpose of applying the technology, used to generate electricity. Solar thermal and heat pump technologies have been called alternatives for the existing options. However, the case for generating electricity via solar panels has been new in the residential sector, and regarding the availability of grids, it has not been recognized as a true need to generate electricity.

The growth of rooftop solar panels has been completely affected by government policy. Indeed, the future growth rate of solar electricity has been independent of the historical rate. The government and the made policies have been responsible to describe the reasons for moving toward/outward solar panels in different periods.^{67,68} As reported in the literature, four scenarios were defined in the context of Luxembourg.^{69,70} The predicted figure in scenarios and the realized figure of the growth rate of solar PV in Luxembourg have been presented in Table 8.

As observed, the occurred growth rate in the reality was lower than what was predicted in the most pessimistic scenario about the growth rate of solar PV in Luxembourg. The presented data in Table 8 have emphasized the independent growth of solar rooftop PV panels of historical trends.

TABLE 8 Comparison of scenarios for the growth rate of Solar PV and the realized figure

Ploss ⁶⁹			Schön et al ⁷⁰	Realized figure ⁹
Scenario 1	Scenario 2	Scenario 3	Scenario 1	Based on statistics
5.6 MWp/annually	8.8 MWp/annually	12 MWp/annually	20 MWp/annually	3.6 MWp/annually

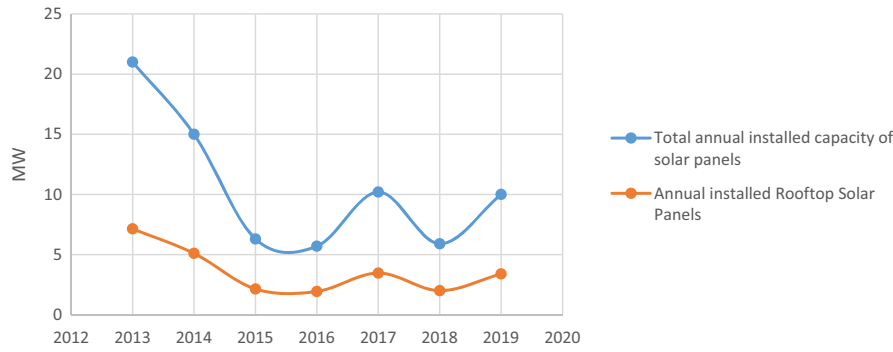


FIGURE 10 Annual installed capacity solar-Luxembourg⁵

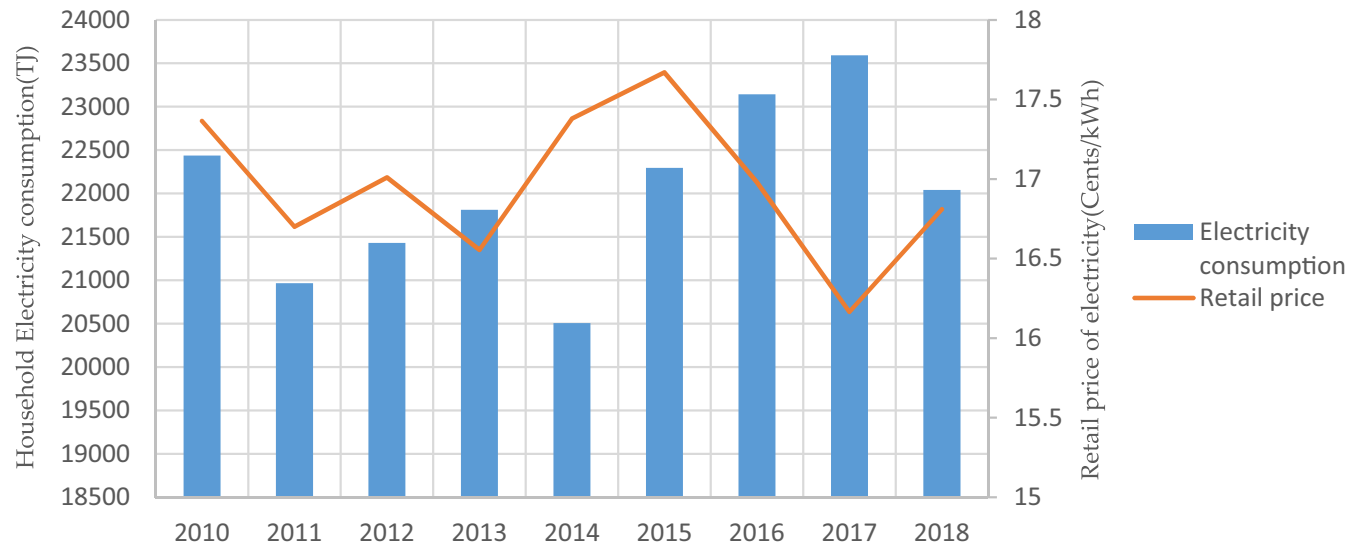


FIGURE 11 Representing historical trend of household electricity consumption and retail price of electricity in Luxembourg⁹

Present condition of rooftop solar panel in Luxembourg
The recorded electricity generation by the solar systems in 2019 was 130.3 GWh (469 TJ), in Luxembourg, which was responsible for 8.81% of total renewable electricity in Luxembourg.¹³ It was equivalent to 1.71% of total electricity consumption in Luxembourg by 2019. Based on the literature, the planned figure for the share of PV, including rooftop panel generation, in 2030 is 616 GWh (2217 TJ) and this figure in 2040 is 729 GWh (2624.4 TJ).⁴⁷

As reported in the literature, the available rooftop area in Luxembourg is 9 km².⁵ The technical potential of the rooftop solar panels is 696 GWh/year. However, the economic potential of the technology is 395 GWh/year in Luxembourg.⁷¹ The technical potentials have been referred to as the available suitable surface area, system technical performance, and sustainability criteria, while the economic potential has been mostly defined with technology costs and avoided supply costs.⁷¹

To the best of the authors' knowledge, there have been no further data about the contribution of each sector (residential, commercial, and industry) to generate electricity via rooftop solar panels in Luxembourg. The provided

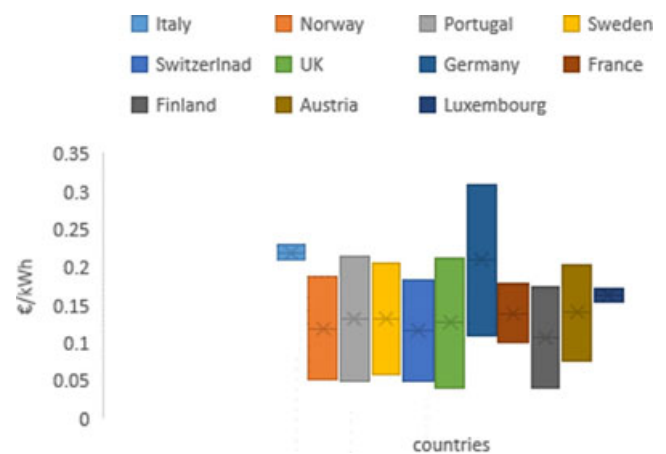


FIGURE 12 Comparison of retail electricity price and export price to the grids in Luxembourg and countries with a high rate of solar PV by 2019⁵

data in the literature were accumulative.⁹ Therefore, the global pattern has been referred to address the issue. The global average contribution of the residential sector in

the solar rooftop panels was around 34.5% between 2015 and 2020.⁷² The results have been presented in Figure 10 by assuming the same rate of rooftop solar panels in Luxembourg.

Recognizing self-generation of electricity as a luxury issue in Luxembourg

The generation of electricity in residential buildings has been a new concept. Moreover, developing solar panels in the sector has been challenging.^{67,73,74} It has been already stated that the growth of rooftop solar panels has been affected by policy means.^{67,75} The section analyzed the price of energy carriers as an effective contextual factor for the growth of solar PV technology.

It was assumed that the scale of the benefit of installing rooftop solar panels in residential buildings has not been beyond the cost reduction in electricity. Therefore, it was a matter to what extent individuals in Luxembourg have thought about electricity bills compared with other living costs. In Figure 11, changing the retail price of electricity since 2010 was compared with changing electricity consumption in this period.

The noticeable issue was the response of modification of consumption to the change of the price, explained by the concept of price elasticity. Standard economic theory states that customers react to changes in prices by adjusting their demand for the goods in question.⁷⁶ As it has been shown in Figure 11, there has been a weak signal between the growth of price and reduction of electricity consumption. The high gross domestic product per capita in Luxembourg has supported the results in Figure 11. Moreover, households have had a fixed rate for energy consumption with a base rate tariff.⁷⁷ Consequently, there has been no concern for people about the volatile wholesale market or show any reaction even to drastic price changes.⁷⁸ However, easy access to electricity grids for new construction has been another reason that reduces the motivation for the self-generation of electricity in the residential sector.⁷⁹ Therefore, the judgment that the electricity bills have not been a problem for Luxembourgish residents is logical. *Simply, concluding non-attractive features of rooftop solar panels to tempt the public to take the challenges in the residential sector is straightforward.*

As shown in Figure 12, the retail price of electricity and the export price of electricity to grids have been compared in different countries with different ranges of applying rooftop solar panels. Therefore, it is concluded that the strength of the export price of power to the grids in comparison with the retail price of electricity has not been enough to increase the share of rooftop solar panels in Luxembourg.⁸⁰

3.3.3 | Discussing the generated scenarios

The generated scenarios in Section 3 were contributed to supporting the built theories by presenting different futures.

1. The generated scenarios revealed that the building type has been an important factor affecting energy consumption. The other accomplishment was to show the impact of building types on the growth of energy demand and hosting renewable technologies.
2. Exploring the penetration of renewable technologies under different assumptions showed that solar thermal technology would be an ignorable player in future of the residential sector in Luxembourg. The reason supporting this consideration was the growth of electrification trend in the residential buildings in all future energy scenarios. It should be noted that the lower competitive advantages of the solar thermal technology compared to other similar technologies have been effective as well. However, it was deduced that the short-term growth rate of rooftop solar panels in the residential sector has not been changed considerably. The major obstacles in Luxembourg have been the price of energy carriers, easy access to the grids for the new construction, and the price elasticity issue. Concluding the ignorable share of the solar thermal and solar PV panels in the residential sector in the generated scenarios was another raised issue.
3. The generated scenarios highlighted that the type of dwellings would be strongly effective in the growth of the heat pump technology in Luxembourg. Simply, the growth of new single-family houses would accelerate the number of heat pumps. Nevertheless, the limited number of renovated projects would reduce the impact of the technology.
4. The other derived result was referred to the types of heat pumps reflecting the saving energy opportunity. The amount of energy saving was affected by applying different types of heat pumps, mentioned just for future studies.

4 | DISCUSSION

4.1 | Limitations

It is important to acknowledge that there have been considerable uncertainties in all these figures with the accuracy of input data and thus projections significantly varying across regions and variables. Data on population, GDP, and households have been more reliable, whereas

there have been much more uncertainties about the data on floor space, building energy use, and specific energy consumption. While such data have been neither collected nor reported in developing countries like Luxembourg. However, a lack of certainty has not affected the justification process of the first theory. Nevertheless, the presented data have been supported by historical data.

The economic feature and social and environmental aspects were not investigated in the considered viewpoint to generate scenarios. Simply, the scenarios concentrated on future market concerns.

Indeed, the increase in energy consumption was projected on the growth of living areas. Then, it was aimed to tie the future energy need to future building types. The highlighted issue was about the assumptions for future construction, which might be different from the growth of populations.

The other issue, which was assumed constant, was about the proportion of ground source heat pumps to the total number of heat pumps in future. Regarding this assumption, the needed electricity would be affected.

It should be noted that the generated scenarios were directed to support the built theories and not planned to cover the whole domain.

4.2 | Discussing the results and conclusions

The study was to address transition management. It was organized to highlight some concerning issues of the future in the residential section in Luxembourg. The contextual factors were investigated to find how the specific features of the residential sector would be shaped in Luxembourg.

Linking the dwelling types with the consumed energy for heating purposes has been the topic of the first theory. Section 3.1 was to present how the growth of single-family houses versus multi-family houses could cause an increase in energy consumption. Moreover, exploring the spreading of renewable energy technologies in various building types revealed that going toward energy demand reduction has not had the same path as increasing penetration of renewable technologies. The paradox has been highlighted when it has been noticed that lower energy demand in multi-family buildings has been accompanied by a lower capacity of this type to host renewable energy technologies. The first key achievement was to show the low applicability of the strategy of increasing the share of renewable sources to decrease the dependency on conventional fuel sources with the carbon footprint.

The second theory was about the dependent character of future energy issues. In other words, changes in

the existing energy system happen on a changing basis. Spreading energy measures to increase efficiency or to introduce a new energy carrier should be embedded in a template of renovation or new construction activities. Indeed, deciding about energy issues should happen at the constructing phase of a project when there is no technology or at the renovation phase when changes are started. Therefore, in Luxembourg, it was hypothesized that the construction is ahead. The second key accomplishment was to show the high dependency of energy efficiency schemes on construction activities. Simply, on the macro-scale, the energy concerns should be addressed as a function of construction in the sector, not independently.

The third theory was to argue the higher priority of energy concerns in the residential sector compared with other sectors. It is about the different types of residential units. The clients have been responsible for a decision, which has had deep and lasting impacts on the future energy system in residential buildings. However, to prevent any surprising results due to the growth of constructing the residential units, it is needed to conduct the trend consciously. It is a matter of clarifying the purpose of managing the transition. Moreover, the theory has confirmed that we already have entered into the transition path in the residential sector. The third key point was about the high priority of the sector to intervene to avoid a surprising future.

The important feature of the findings was to reveal the consequence of the growth of each type of residential unit on energy issues. Regarding the achievements, policymakers could decide to go toward renewable energy by sustaining single-family houses or get away from fossil fuels by limiting energy demand by supporting multi-family buildings.

The significance of the paper has been referred to introducing the types of buildings as a driver, which causes two different results in the residential section:

1. Move toward the renewable energy
2. Get away from fossil fuels.

Adding new sources of energy will support bigger demand. However, it is unprecedented for these additions to cause a sustained reduction in the use of established energy sources. The results have fit well with findings in the literature.^{81,82} Founded on the literature, adding a new energy source will not cause the transition from the established energy sources. Moreover, the addition of newer energy sources has simply allowed for a further increase in overall energy consumption, rather than serving as a replacement for older sources.⁸³ In line with the literature, the findings in the study have confirmed the distinction of two pathways characterized by adding a new energy

carrier or explained with limited energy consumption. Nevertheless, deciding to go toward each pathway is a matter of how to manage the transition.

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ENDNOTE

¹ It refers to buildings that are used partly for residential purposes and partly for non-residential purposes.

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How to cite this article: Arababadi A, Leyer S, Hansen J, Arababadi R. Characterizing the theory of energy transition in Luxembourg—Part three—In the residential sector. *Energy Sci Eng*. 2022;10:1296–1313. doi:[10.1002/ese3.1098](https://doi.org/10.1002/ese3.1098)