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Luxembourg's energetic self-sufficiency in the wake of the energy transition. A potential analysis.

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Affidavit

I, **MATTHIEU HANSEN B.A.**, hereby declare

1. that I am the sole author of the present Master's Thesis, "LUXEMBOURG'S ENERGETIC SELF-SUFFICIENCY IN THE WAKE OF THE ENERGY TRANSITION. A POTENTIAL ANALYSIS.", 79 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

There is academic consensus that shifting away from fossil fuels to renewable energy sources is crucial in order to mitigate human-induced climate change. However, there is no unanimity on how to structure the energy transition. To this day, the Grand-Duchy of Luxembourg has always been strongly dependent on energy imports due to the absence of any major domestic fossil fuel deposits. Renewable energies on the other hand, are not dependent on fuels and can also be generated at the domestic level. However, in Luxembourg this potential has only been exploited to a marginal level. Most electricity is being imported and the import capacities are currently being expanded in order to ease the sectoral electrification.

This paper wants to offer an alternative to the current energy strategy by assessing Luxembourg´s potential energy self-sufficiency. Firstly, the benefits and throwbacks of domestic energy production are presented. Secondly, the government´s current efforts and projections for 2030 are outlined before analysing the current energy mix and consumption patterns. Thirdly, the potential of efficiency measures is studied before evaluating the maximal energy demand reduction possible until 2030. Finally, the domestic potential of solar, wind and biomass are estimated and subsequently, various models of self-sufficiency thoroughly studied.

The research concludes that domestic electricity production offers a range of benefits, such as improved cost-efficiency, reduced environmental impact and social benefits like employment offers. However, climatic unpredictability, grid capacities and limitations in storage discourage full energy autarky. International exchange remains important in order to mitigate surplus energy production and import during periods of low production. This being said, in order to reach a maximum in energetic self-sufficiency, the energy demand has to be reduced through efficiency measures such as the electrification of transport and heating appliances. In addition, Luxembourg offers a large potential of yet unexploited renewable energy sources despite the spatial limitations. By harvesting these and implementing the necessary efficiency measures, Luxembourg may reach an optimum of 30 % to 50 % of energetic self-sufficiency. Any level above this has been proven unfeasible as it is either detrimental for the environment, uneconomic due to necessary infrastructure expansion or would lack public support.

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1. Introduction

1.1. Contextualisation

Over the past decade, Luxembourg has shifted from an economy dominated by heavy industries such as steel production to a major financial hub. An attractive fiscal environment and a well-established know-how attract companies, banks and capital from all over the world to the Western European country. In terms of energy use, Luxembourg aims at drastically changing its energy sources and improve its ecological footprint. As one of the initiators of the European community, Luxembourg has always advocated a common market among European member states and the free flow of goods and human capital. Luxembourg has therefore with approximately 51 % one of the highest proportions of foreigners and one of the highest shares of cross-border commuters. In addition, due to its limited size and its specialisation on the financial sector, very few goods are manufactured inside the country. A similar trend can be observed for basic commodities such as food and energy. This is not only due to the relatively small territory but also due to the comparably high labour wages. Hence, in a free market, unless specialised, basic Luxembourgish products are not competitive against French or German mass production. However, as energy production requires little manual labour, variable costs are close to zero. Hence, the current electricity dependency remains questionable.

Confronting him with these thoughts, Claude Turmes, Minister of Energy points out that Luxembourg has always been energy dependent. The bare absence of nearly any fossil fuels resources, besides a negligible fraction of domestic coal, and the opposition towards fracking and nuclear have contributed to the current energy dependency of the Grand-Duchy. However, this could change with the current energy transition in sight which raises the ambition to increase renewable energy production.

In light of recent events such as a global pandemic and an armed conflict between the two largest territories in Europe which at the same time are crucial energy providers for the European Union (EU), stresses the importance of Europe's strategic energy autonomy. The Covid-19 pandemic has demonstrated how fragile global supply chains are, on which fossil fuels depend. The Russian invasion of Ukraine stressed a number of polemics. Firstly, energy dependence hampers foreign policy. Due to Germany's strong energy dependence on Russian gas, decisive, active condemnations were limited. Secondly, economies dominated by fossil fuel extraction enable dictatorships to flourish. This is not only the case for Russia but also Saudi Arabia, Venezuela or Saddam's Iraq. As a single resource, requiring little technical expertise generates the vast majority of a country's wealth, power is quickly amassed among a small oligarchy, dominating the economy and political landscape.

In order to secure our vital needs and contribute to avoid feeding authoritarian regimes, it is therefore of crucial importance to develop a certain strategic autonomy. The development of domestic renewable energy production could be a key to mitigate climate change while addressing global political challenges.

1.2. Motivation

I chose this topic for my master thesis as I am convinced that restructuring our energy supplies proves to be one of the most important challenges for humankind. I therefore wanted to explore in depth, the efficiency measures, and potentials possible in Luxembourg. Luxembourg's relatively small size serves as a well conductible case study which could be scaled to other regions or larger urban conglomerations. The Luxembourgish government is currently investing a lot of efforts in an appropriate energy transition; however, I personally, sometimes question the fruitfulness of some of their undertakings, hence I would like to propose an alternative model to the common rhetoric. In addition, I am strongly interested in the potential of decentralised photovoltaics in isolated underdeveloped regions. Although I did not choose neither an isolated, nor an underdeveloped region, this research enabled me to get a first glimpse of the potential of photovoltaics.

1.3. Aim of the research

Since the industrial revolution, human activity has severely affected the environment leading to accelerated climate change, an unforeseen decline in biodiversity and environmental pollution, such as air or water pollution posing direct threats to humans and animals. In order to mitigate the effects of human-induced climate change, national governments met in Paris for the United Nations Framework Conference on Climate Change, also known as COP21 in order to collectively establish a number of commitments. The most prominent among these is to limit the rise in average global temperatures to 1.5 °C in comparison to preindustrial times (France Diplomacy 2020).

However, avoiding trespassing this threshold requires large modifications of the current socio-economic system. Firstly, the emissions of greenhouse gases and other pollutants have to be limited. In order to realise this, fossil fuels have to be abandoned as the main sources of energy. Hence, most European member states are currently shifting away from fossil fuels to renewable sources of energy. However, to this day, renewables only represent a relatively small fraction of national energy production in Luxembourg. Among the main reasons cited, the most recurrent one is the relatively small territory of the Grand-Duchy. Other frequent reasons hampering the expansion of renewables such as public opposition or lack of financial means are being regarded as less of a barrier. (Turmes 2022)

In addition, to the imminent threat stemming from the repercussions of climate change, recent geopolitical events have marked an additional incentive to shift away from fossil fuels and restructure current energy supply chains. The reliance on often authoritarian regimes as main suppliers of polluting energies has repeatedly proven detrimental. European countries often faced the dilemma of conducting a coherent foreign policy and risking their supply security or ignoring human rights abuses and continuing business as usual. Hence, shifting away from import-dependent fossil fuels to self-sufficient renewable production constitutes a major policy goal. Besides environmental benefits, regional self-sufficiency might have a wide array of further impacts such as job creation and long-term energy costs reduction. As visualised on Fig. 1.1, this research assesses the potential of Luxembourg´s energy self-sufficiency in the frame of the energy transition.

This research will therefore analyse the following research questions:

Research Question *(1): To what extend can the current Luxembourgish energy demand be reduced through efficiency measures until 2030?*
Research Question *(2): What degree of energy self-sufficiency is most beneficial for Luxembourg?*

In order to answer these two questions, the research will firstly briefly review the current literature on energy self-sufficiency and review various options. Secondly, the Luxembourgish climate and energy plan will be thoroughly analysed before reviewing the EU's directives for 2030. Thirdly, the current Luxembourgish energy mix will be inspected and the limitations of the various sources of renewable energy in the Luxembourgish context evaluated. Subsequently, a profound potential analysis of urban photovoltaics, wind and biomass in Luxembourg will be considered before evaluating various scenarios of energetic self-sufficiency. The research will be rounded up with an analytical discussion and conclude by answering the above-mentioned research questions.

The year 2030 was chosen due to the imminent climate emergency and the required need to change patterns of production and consumption. Since the EU also established an energy and climate framework for the year 2030 such as the Luxembourgish government, the year 2030 seems to make most sense for any energy potential research. (European Commission 2020; Gouvernement 2018)

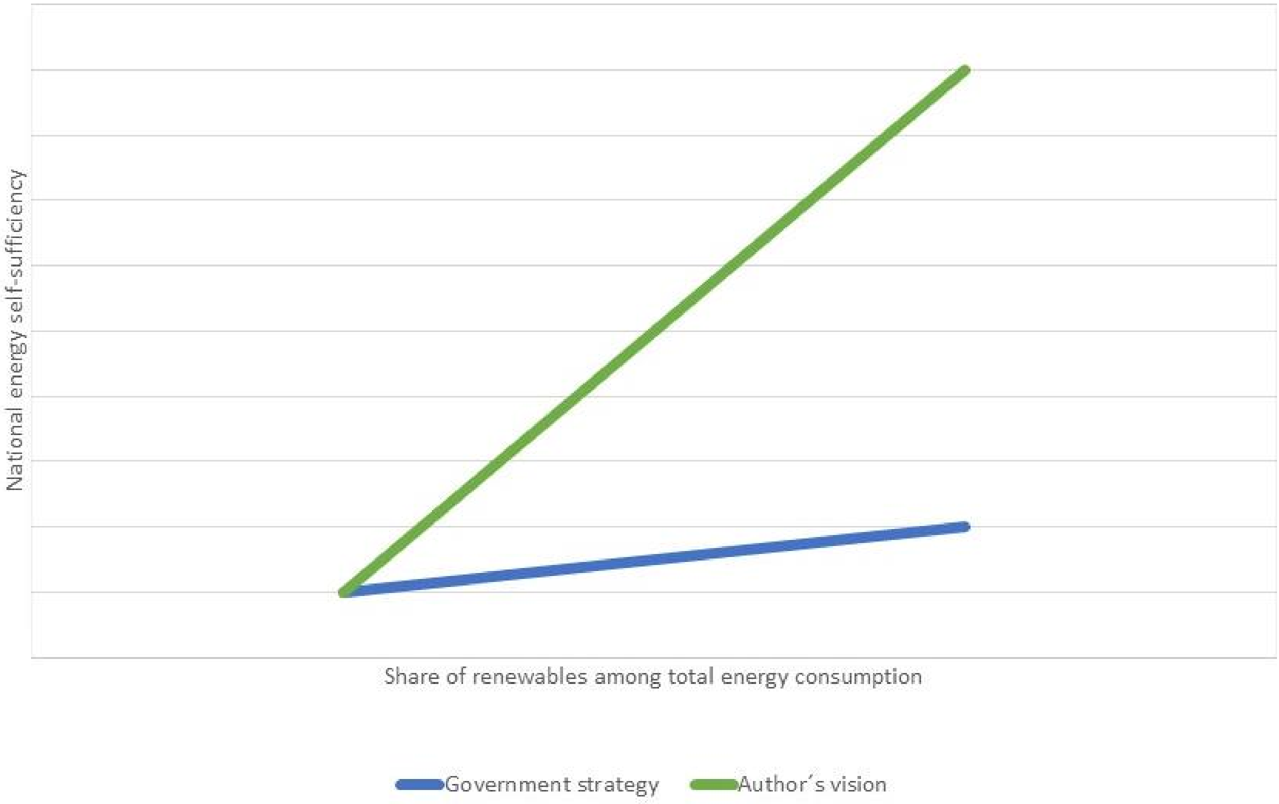

Fig. 1.1: Aim of the research

1.4. Method

In the frame of this research, a mixed method approach will be used. It will mainly consist of a mathematical potential analysis which is completed based on information from the literature and two interviews conducted. The first interview was with the Luxembourgish Minister of Energy and Minister of Spatial Planning. The second interview was conducted with Paul Zens, president of Eurosolar Luxembourg and Albert Calmes, a representative of the energy cooperation TM Ennercoop. Both interviews were conducted in person in Luxembourg. In addition, I spoke to Professor Dr. Susanne Siebentritt, researcher at UniLuxembourg, specialised on semiconductors and photovoltaics. Furthermore, I met Sebastian Dietz, doctoral researcher at the University of Luxembourg, who shared a few interesting insights, as he is also member of an energy community in Luxembourg.

2. Literature review: Regional energy self-sufficiency

Previous studies such as the one conducted by Schmidt et al. 2012 have analysed regional autarky in the context of a rural Austrian region. Others have taken a more general approach an analysed the challenges and limits to European energy self-sufficiency (Tröndle et al. 2020). In another study, Tröndle et al. (2019) studies the feasibility of European municipalities to become independent from energy imports.

Regarding renewables, Defaix et al. (2012) studies the technical potential of photovoltaics integrated into buildings on an EU wide scale. In addition, Buffat et al. (2018) establish a model to predict solar insolation on urban constructions. Huld et al (2018), specifically research the potential of rooftop photovoltaics in light of the Paris agreement. Hoogwijk et al. (2004) estimated the global and regional, technical and economic potential of onshore wind energy. McKenna et al. (2015) continue further by analysing the cost-efficiency of onshore wind turbines in the EU and Europe in general. A number of studies also assess the potential of a particular renewable on national scales. Wind potential studies for Spain, Sweden, Germany and Austria have been conducted. (Fueyo et al. 2010 ; Siyal et al. 2015 ; McKenna et al. 2014 ; Höltlinger et al. 2016)

When analysing the literature published on Luxembourg's energy potential, a limited number of publications have surfaced so far. Wolter analysed the national potential of forestry biomass in 2020 but neglected agricultural potentials. Fraunhofer (2015) conducted a potential study of various renewables for 2015. However, whereas biomass calculations are relatively detailed, estimations regarding photovoltaics seem simplistic. The estimations are based on previous research from 2005 and the potential of national self-sufficiency is not analysed. (Schön et al. 2015)

So far, no detailed analysis regarding Luxembourg´s maximal efficiency potential has been conducted. In addition, no projections of the national energetic self-sufficiency capacities have been developed. By analysing the efficiency potential and subsequently modelling various degrees of national energetic self-sufficiency, this research aims at filling a gap in the current literature on potential renewable autarky and energetic efficiency.

2.1. Energy trilemma

Firstly, fossil fuels are one of the main contributors to greenhouse gases and pollution worldwide. Not only their consumption but also their extraction, transformation and transportation pose great risks to the environment. Secondly, in countries deprived of any easy-to-access fossil fuels, their procurement requires lengthy supply chains which in times of geopolitical instability may affect energy security. Renewables on the other hand can be produced in most regions locally, reducing foreign dependency. Hence, shifting away from a fossil fuel dominated energy production to renewables enables not only to reduce pollution to a great extend but also to foster a certain level of energetic self-sufficiency. (Wu et al. 2021) This can be analysed at various scales, from continental to national, regional or communitarian partial or full autarky. The following paragraphs will analyse the benefits and eventual throwback of self-sufficient energy production, by analysing the three main pillars of the energy trilemma (Wu et al. 2021): Energy affordability, energy sustainability and energy security. (Fig. 2.1)

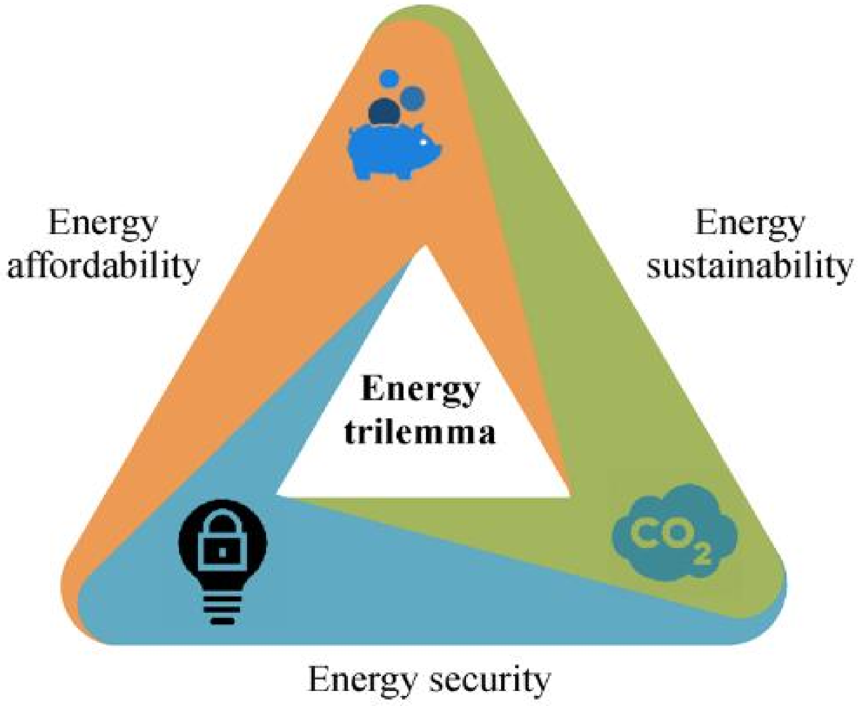

Fig. 2.1 Energy trilemma (Wu et al. 2021, 183)

2.2. Infrastructure

One of the main benefits of domestic energy production over imported electricity is the reduced need for transmission networks. Lengthy transmission and distribution grids are one of the main sources of inefficiency among centralised energy generation as considerable losses occur over distance. (Wu et al. 2021) Since wind turbines and photovoltaics are able to feed directly into the medium or low voltage grid, transmission losses are reduced which for instance occur by transmitting 380 to 220kV. A reduction in transmission losses translate into a higher efficiency and thus contribute to a more environmentally friendly energy generation. (Zens and Kalmes 2022)

In order to ensure 100 % access to electricity, grids have to be expanded. Especially in rural areas, where large distances have to be covered, this proves costly and problematic. Therefore, the rate of access to electricity is much higher in urban areas than in rural communities. The reason is that geographical barriers and the need of lengthy transmission, raise the marginal costs of granting universal energy access tremendously. Decentralised power generation is therefore the solution to electrify diffused populations in a cost-effective way. This enables them to develop their local economy and raise their living standards considerably. (Alstone et al. 2015) This does not only apply to remote areas in development but also in highly developed economies. Long distance, high voltage transmission lines, like those currently being built to transport offshore wind power from the North Sea to landlocked regions are costly and one of the main contributors of the increase of end consumer electricity costs. (Brauner 2019) Hence, in order to keep marginal costs at the lowest level possible, shortening the distance of transmission is crucial.

Besides reducing the losses occurring over distance transmission lines, the reduced need for grid expansion also reduces costs for the final consumer. (BNA 2011) Furthermore, the construction of high-voltage transmission lines also has considerable impacts on the environment. By generating energy locally, lengthy electricity transportation is not necessary. On the other hand, the capacity of local distribution grids still has to be expanded and maintained (Koirala et al. 2016) Especially if decentralised renewable production feeds into the national grid, capacities of distribution grids might be overloaded at solar or wind peak production. In order to mitigate this, a smart model has to be established using batteries or electric vehicles to relieve the national grid from an eventual electricity overflow. (Zens and Kalmes 2022)

Self-sufficient energetic production proves to be more efficient, less costly for the consumer and impacting the environment to a lesser degree. However, distribution grids still have to be adapted in order to be able to deal with the increased loads.

2.3. Energy security

Energy self-sufficiency guarantees vital energy supply. It reduces the dependency on lengthy supply chains or on authoritarian states which in case of geopolitical turmoil may affect energy supply. In order to conduct a coherent foreign policy, strategic energy autonomy is crucial. (Umbach 2012)

Furthermore, the relatively high reliability of renewables contributes to their advocacy for secure energy provision. In a large grid of renewables, if an outage in a solar panel or wind turbine occurs, the remaining installations continue to produce. Whereas, if an outage occurs in a centralised power plant, the whole grid might be affected. (Hirsch et al. 2018) On the other hand,despite individual cells being less vulnerable to issues in other parts of the system, the chance of a disruption in an individual cell is higher. (BNA 2011) McKenna sums this point up by stating that micro grids are more resilient towards external shocks, but internal shocks occur more frequently. (McKenna 2018) In case of an energy outage, the micro grids are supposed to be organised in such a way that the central grid provides the necessary emergency supply until the decentralised grid resumes its generation capacity. (Brauner 2019)

On the other hand, renewables, especially solar and wind, require appropriate climatic conditions to function, which can limit their use during seasons of low solar influx and low wind conditions. (McLellan et al. 2015) By spatially distributing the renewables, the average yield can be increased in order to guarantee a constant supply. (Sovacool 2009)

2.4. Social impact

Domestic energy production also has positive societal aspects such as promoting employment at the local level especially in grid organisation, expansion, and maintenance. (Koirala et al. 2016) Energy autarky thus has a beneficial impact on a local economy beyond simply guaranteeing energy availability. If organised in a decentralised manner, renewable electricity generation can generate a substantial income for energy communities. This can be done proactively by producing energy but also by so-called

"PV contracting," where unused surfaces are leased for solar installations for instance. (Brummer 2018) As consumers can pro-actively participate in the generation of energy, energy becomes more tangible for the average citizen. This has an educational impact as people become more aware of the various implications of energy generation. As a result, they tend to be more inclined towards more sustainable consumption habits and eventually reduce environmental pollution. (Wu et al. 2021) In addition, communal energy production may also have direct financial consequences as domestic production may alleviate energy costs for the producing community. (Boon and Dieperink 2014) Koirala et al. therefore argue that a decentralised energy production with active consumer participation is the most cost-effective way of reaching the necessary carbon targets. (Koirala et al. 2016)

Furthermore, it is also important to point out that societal acceptance is crucial for the expansion of renewables. Especially wind turbines and large-scale solar fields face several critics due to their appearance. (Wu et al. 2021) However, due to fluctuating energy prices and the rising public awareness of climate change, people become increasingly welcoming to the expansion of renewables. Furthermore, especially among rural communities, there is an increasing strive to become autonomous to become independent from large energy companies. (Bomberg and McEwen 2012)

As local energy production requires less infrastructure, it is more affordable for the end-consumer compared to offshore generated electricity transported over thousands of kilometres via high-voltage lines. In addition, it has a lesser impact on the environment and a higher efficiency. The absence of any foreign dependence as for instance with Russian gas proves that energy security is much higher. However, due to fluctuations in renewable production, a compromise between regional production and international interconnection is important.

2.5. Reactivity

The construction of renewables in a decentralised grid is much faster. Especially solar installations, which are mostly prefabricated and arranged in modular setting, are very quick to set up (Sovacool 2009). Even in case of abandoning a project, the modular characteristics enable users to dismantle them and set them up somewhere else. This enables a country or energy community to constantly improve, extend, or adapt their system to the latest technology available. (Sovacool 2009) In Luxembourg, for instance, four older windmills have been recently replaced by a single wind turbine, which is much taller, and thus much more efficient. It is capable of generating around the same amount of energy but takes up much less space. (Turmes 2022)

2.6. Smart grids

One of the main challenges of decentralised energy production is to manage peak demand and peak supply. In order to mitigate this challenge, it is important to find a suitable compromise between regional autarky and international exchange. (Zens and Kalmes 2022) International connectivity enables a country or a region to export electricity during peak production times to regions where less electricity is produced at that time in order to relieve the regional grid. In addition, it also enables to import electricity in times of low production to avoid an energy shortage. According to a study conducted in Denmark, smart managing of energy loads results in an increased potential of usable wind power from 20 % to 40 % of the total electricity demand. This is only possible by exchanging surplus renewable production, such as during a phase of strong winds, with neighbouring Germany. Since the domestic demand at times of high renewable energy production was not sufficient, this surplus electricity would have to be stored or would be lost. However, by connecting the Danish grid with the German grid, the Danish grid was not overloaded and the wind power potential increased. (Lund and Münster 2006) Besides interconnecting national grids, smart managing of grids also proves to be very fruitful. Smart grids optimise demand and supply and hence prioritise crucial demands during peak hours and hence smartly share the available electricity. Washing machines, for instance, can be equipped with a timer and can be launched automatically by the system when general demand is relatively low. Electric vehicles can be charged over a longer lifespan over the night if their direct need is not required. Interconnected communities balance each other's energy demands out. In addition, by smartly controlling demands and prioritising imminent energy demands over others, peak demands can be reduced to a maximum (Kefayati and Baldick 2012).

2.7. Storage

In order to mitigate daily and seasonal fluctuations of renewables, storage is necessary. Shortterm storage varies from hourly over daily to weekly period and is easily available. However, long-term seasonal storage is more challenging. (Koirala et al. 2016) Storage enables decentralised energy production to withstand peak demands with the highest possible share of renewables without having to make use of the centralised grid. Additionally, storage capacity also enables attenuated power distribution in order not to overburden distribution grids at peak generation times. The decentralized utilization rate of locally generated renewable energy can be increased through storage of surplus electricity or surplus heat. The increased use of electric cars is beneficial for storage options as they can function as a vehicle-to-grid storage possibility. In addition, old car batteries can be recycled as local storage facilities in household buildings. (Brauner 2019)

Grid overloads can be mitigated by introducing variable electricity tariffs. In combination with accumulators, these enable to relieve grids. Variable tariffs operate in function of energy offer. In times of peak renewable production, the surplus of electricity generated feeds into local batteries or electric vehicles. (Brauner 2019) A stagnation in electricity generation at times of peak demand can be mitigated through peak shaving. This means that energy-intensive industrial processes can either operate with storage capacities that are used in times of general peak demand and low offer or by temporal phasing of processes. (Brauner 2019)

2.8. Sector coupling

Besides storing surplus energy in battery, sector coupling proves an important alternative. During peak time renewable production, the surplus electricity can be transformed regionally into other forms of energy in order to use it in other sectors. (Brauner 2019) The most common sector coupling is power-to-heat, which transforms surplus power into heat. Power-to-gas proves to be an interesting method for long-term storage, as surplus electricity can be transformed into hydrogen at an efficiency rate of 60 %. By synthesising hydrogen with carbon dioxide, methane can be produced, which is easy to store and can be transferred and stored in the same infrastructure as natural gas. In addition, hydrogen and methane are both usable to fuel electric mobility. Power-to-liquid can be used efficiently in heavy industrial processes. (Brauner 2019)

2.9. Combined Heat and Power

Furthermore, in order to further raise the potential efficiency of micro grids, instead of separately generating electricity and heat, the combined heat and power approach maximizes the potential utility. In the United States, this method proved to reach around 65-75 % efficiency compared to a national average of 45 % of the centralised grid which generates electricity and heat separately. Furthermore, as the combined heat and power approach needs to be located in close vicinity of the area of consumption, transmission and distribution losses are minimised and the investments in the respective domains are reduced. (US Department of Energy 2012) Especially in industries requiring large amounts of heat, the potential for cogeneration is very high as it can improve overall efficiency gains significantly up to 75%. Furthermore, a reduction in transmission losses affects carbon intensity considerably. (Benjamin McLellan et al. 2015)

3. EU Energy directives

In 2019, the EU designed a framework to implement the commitments signed under the Paris agreement and replace polluting fossil fuels with sustainable renewable energy production. A legal framework consisting of eight points has been launched in order to achieve the Union's long term environmental goal of reaching carbon neutrality by 2050. (European Commission 2019)

- Since buildings are one of the main polluters and have among the highest share of energy consumption in the EU, the Energy Performance of Buildings Directive (EU 2018/844) was introduced. (European Commission 2019)
- In order to foster the development of renewables on the European continent, the EU published the Directive on Energy Efficiency (EU 2018/2002). This directive is a legally binding instrument fixing a minimum of 32 % renewables in the EU's energy mix by 2030. (European Commission 2019)
- The same directive also functions as an instrument to promote energy efficiency by a minimum of 32.5% by 2030, in comparison to current levels. Promoting efficiency works twofold as. on the one hand. it reduces greenhouse emissions and, on the other, reduces the consumer's expenses for energy. (European Commission 2019)
- The EU also aims to fundamentally reform national governance concerning energy policies. Hence every member state has to formulate a ten-year national energy and climate plan (NECP) for the period of 2021-2030. The regulatory framework for these can be found in the Regulation on the Governance of the Energy Union and Climate Action (EU 2018/1999). (European Commission 2019)
- In order to facilitate the Union-wide exchange of electricity an increased participation of the Agency for the Cooperation of Energy regulators has been called for. This will increase the flexibility and reform the energy market in a way that enables it to adapt better to the energetic transition. (European Commission 2019)
- Further policy directives by the EU were developed, especially in regard to coal-producing regions and isolated regions such as islands. In addition, measures to combat energy poverty in Europe have been launched. (European Commission 2019)
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In order to achieve these supranational goals, Luxembourg decided to reduce its greenhouse gas outputs by 55 % until 2030 and is supporting the EU´s ambition to achieve net zero emissions by 2050. In addition, the Luxembourgish government is advocating for a complete halt of nuclear and fossil fuels. Therefore, it was one of the few countries who opposed the labelling of nuclear and natural gas as renewable energy sources in the EU taxonomy scheme to promote green investments. (Rankin 2022) Especially greenwashing nuclear energy is a no-go for Luxembourgish decision makers, who perceive this form of energy production as a direct threat to the national security. Hereby it should be noted that Luxembourg city is the European capital closest to a nuclear power plant. The French nuclear power plant Cattenom is located at around 25 km from the capital. Another French nuclear power plant, Chooz, and the Belgium nuclear power plant Tihange are both located at less than 120km from the capital of Luxembourg. In case of a serious accident in any of these facilities, Luxembourg's territorial integrity would be put at risk as most of the country would have to be evaded and resettled. This would not only create a humanitarian disaster but also endanger the existence of Luxembourg as a sovereign nation state and risk the preservation of the national culture. Hence, promoting the use of nuclear power plants contradicts Luxembourg's national interests. (Gouvernement du Grand-Duché de Luxembourg 2018)

4. Energy in Luxembourg

4.1. 2030 Targets

According to the EU 2018/1999 Directive, all of the member states are required to develop a NECP (Gouvernement 2018) for the period 2021 to 2030 (Table 4.1). In this plan, every member state points out its individual strategy in order to adhere to the EU´s 2030 climate, renewable energy, and efficiency targets. The goals formulated by the EU are based on the thresholds defined at the Paris Climate Conference (COP21). The most important threshold defined at the COP21 is to keep global warming below 2°C compared to preindustrial levels. The actual aim is to limit it to around 1.5°C maximum increase in global temperatures. (Gouvernement 2018)

Table 4.1: 2030 National Energy Targets (Gouvernement 2018)

Subject	Principal targets
Greenhouse gas (GHG) emissions	- 55 % reduction of greenhouse gases until 2030 (in relation to the 2005 levels of emissions)
Renewable energies	- Minimum share of renewables in the final national energy consumption mix: at least 25 % by 2030 - Fostering of international cooperation at EU-level
Energetic efficiency	- Increase of energetic efficiency by 40 % to 44 % by 2030 - Newly constructed buildings will be powered without fossil fuels - Promote energetic renovations of existing buildings - Creation of renewable thermal networks - Expansion of public transportation - Reach 49 % of electric mobility by 2030 - Emergence of an energy efficiency market for the industry, medium and small sized private companies, and office buildings
Energetic security	- Reduction of import dependency by expanding domestic renewable energy production - Assuring flexibility by creating an Energy Data Hub - Increase regional cooperation for natural gas and electricity procurement

Subject	Principal targets
National energy market	Natural gas: - No infrastructure expansion on the national level, neither for transportation nor for distribution - Strengthening of the common gas market with Belgium Electricity: - Modernisation of the existing grid - Sector coupling of electricity, heat and transportation
Research, innovation and competition	- Aim to become a pioneer in successful national energy transition with the main pillars being: zero carbon emissions, circularity, renewable energies and energy-efficient buildings with energy storage capacities - Promote sustainable urban development - Becoming a global hub for climate solutions - Reach 20% of green financial flows by 2025 in order to become a leading global financial centre of green energy

4.1.1. Greenhouse gas emissions

In order to reach the above-mentioned goals (Table 4.2), the Luxembourgish government has introduced a number of policies in order to reach the 2030 targets. Concerning greenhouse gases, the government is aiming to introduce a legal climatic framework and to develop individual pacts with municipalities to strengthen their capacities to adhere to the energetic transition. Additionally, a carbon tax will be introduced which will affect fuels such as gasoline and diesel. (Gouvernement 2018)

4.1.2. Renewables

Regarding renewable energies, the government aims at increasing the national share of photovoltaics and wind parks tremendously. In order to realise this, the current strategy is to promote large-scale photovoltaic installations and to support private investments by subsidising them. The share of wind power will be increased by investing into large-scale wind parks in- and outside of the country. (Gouvernement 2018) To give an example, one of the projects currently being funded are so-called energy island off the Danish shore. These are large-scale wind parks connected to floating islands generating electricity for the mainland. (Gouvernement, 2021a) In general, the Luxembourgish government is aiming at fostering international cooperation in order to establish a large network of renewable energy production. This applies also to the procurement of raw material of biomass. The government is aiming at sourcing sustainably produced wood from the so-called Grande Région which includes the German states of Rheinland Pfalz, Saarland, the French department Lorraine, and the Belgian French- and German-speaking regions.

In addition, a solar and wind register will be created for the entire country. This crucial tool will enable policymakers to effectively track the best suited locations for future investments. Furthermore, the government also aims at advocating renewables to heat by promoting the private use of heat pumps and investing into district heating and geothermal energy. (Gouvernement 2018)

4.1.3. Efficiency

Concerning energy security, Luxembourg aims at increasing regional cooperation in order to reduce dependency on energy sourced from outside the EU. Hence, the existing grid capacities have to be increased, on a national and regional level. Additionally, the mobility sector has to be reorganised in order to shift from combustion engines to electric motors. (Gouvernement 2018) This will strongly reduce the dependency on fossil fuel imports but significantly raise electricity demand. Gas infrastructure will not be expanded on a national level and newly constructed buildings will not be connected to the gas network, but solely dependent on electricity for heating and cooking purposes.

Table 4.2: Comparison of 2020 and 2030 targets (Gouvernement 2018)

Targets	GHG reduction	Renewables	Efficiency
2020	20 % (vs. 2005)	11 %	max. 49.3 TWh
2030	50-55 % (vs. 2005)	23-25 %	max 35.6 TWh

The Luxembourgish strategy for 2030 demonstrates the government’s willingness to reduce the dependency on fossil fuels and shift from fossil-fuel generated energy to electricity generated by renewable sources, such as solar, wind, and biomass. (Table 4.2) This will create a massive increase in electricity demand, for which transmission lines have to be adapted. Private investments to either renovate housing units or to install heat pumps or photovoltaics will be incentivised with financial support such as subsidies. The use of fossil fuels will be gradually discouraged by introducing a carbon tax.

4.2. 2020 Energy mix

As can be observed on Fig. 4.1, Luxembourg's energy mix has always been and is still strongly characterised by petroleum. This is largely due to the very low taxes on petrol, which stimulate a regional tank tourism. From an economic point of view, this is very lucrative for the Grand-Duchy. Besides attracting inhabitants from the neighbouring countries, it is also attracting a considerable amount of logistics companies. (Beyer 2009) The share of solid fuels has strongly decreased over the past years, but imported natural gas remains a major source of energy.

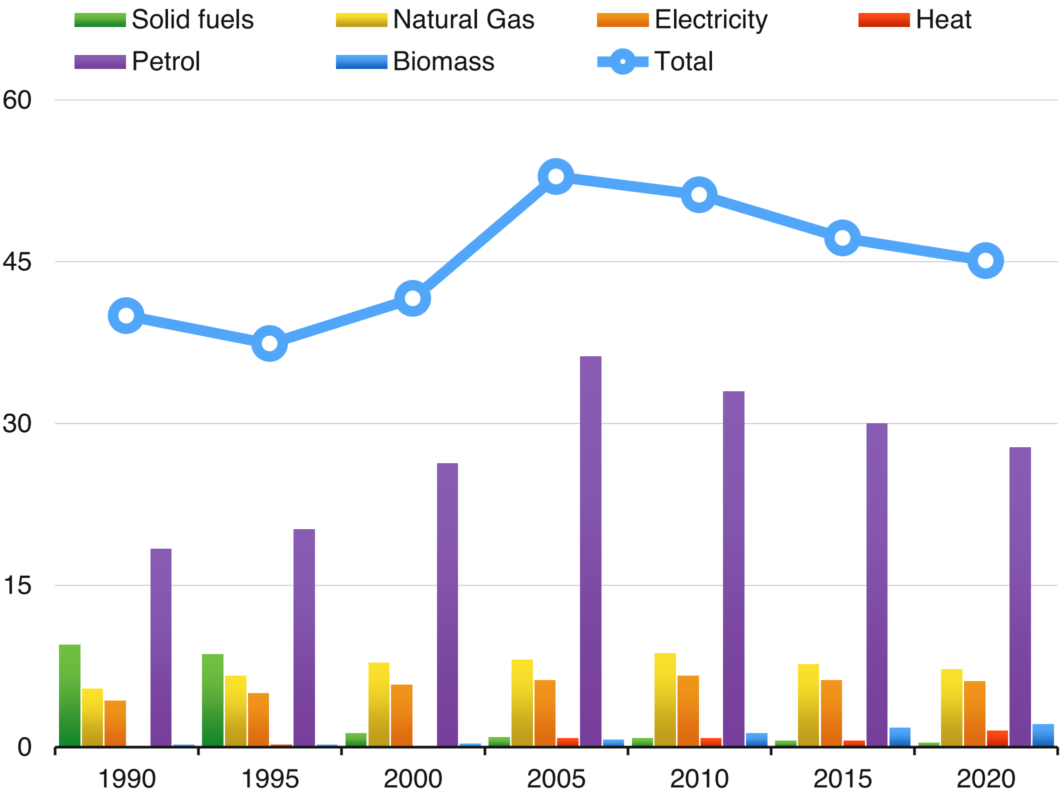


Fig. 4.1: Evolution of Luxembourg's energy mix (in TWh/a) (Statec 2020a)

Domestic renewables have a very marginal share of around 3 %. However, the actual share is much higher, as around 80 % of the electricity is imported. Most of the electricity is imported from Germany, which has a relatively high share of renewables. And since Germany is aspiring to achieve zero emissions by 2045, this will subsequently impact the electricity exports to Luxembourg. (Turmes 2022)

In the following analyses, 2019 will be chosen as comparison. Instead of opting for more recent data, 2019 reflects the national consumption best as both subsequent years were strongly impacted by lockdown measures due to the Covid-19 pandemic.

4.2.1. Greenhouse gas emissions

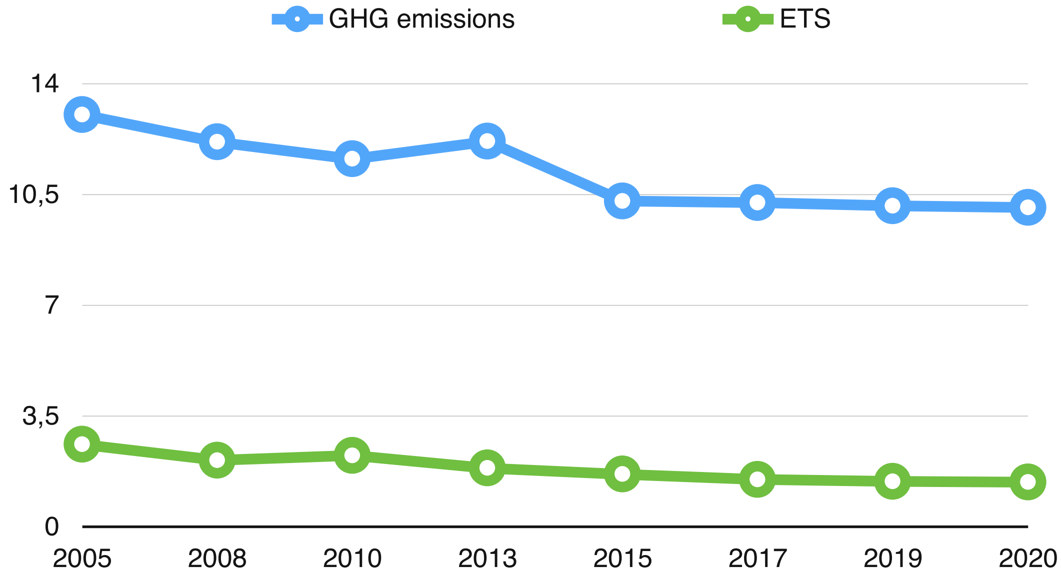


Fig. 4.2: Evolution of Greenhouse gas emissions (in million tons of CO_2) (2005-2020) (Gouvernement du Grand-Duché de Luxembourg, 2020, 31)

Luxembourg's target to reduce its Greenhouse gas emissions (GHG) by 20 % by 2020 compared to the emissions emitted in 2005 was reached. They managed to reduce them by 22.5 %, which surpasses their set goal of a 20 % reduction. (Fig. 4.2) However, by closely analysing, this was only possible due to the European Trading Emissions scheme (ETS), which allows states to trade emission allowances. (European Commission 2022) By subtracting the share of ETS, Luxembourg did not reach their 2020 goal, as they only reduced their GHG by 16.7 % over the 15 years period. (Fig. 4.2) For 2030, the Luxembourgish government set as a target to reduce their GHG by 50 % to 55 %, with 2005 as a baseline. (Table 4.2) This ambitious target exceeds the EU's goal which foresees a 40 % GHG reduction by 2030. In order to reach this target, considerable efforts have to made in the coming years.

4.2.2. Renewables

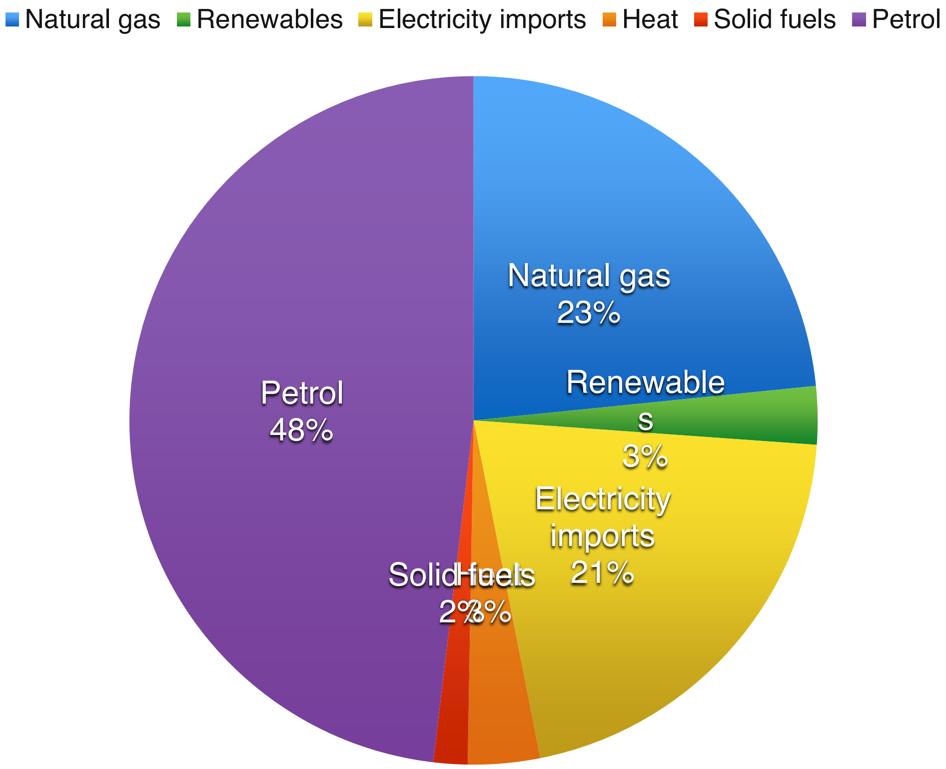


Fig. 4.3: National energy consumption 2019 (in % of total share) (Statec 2021a)

Regarding renewables, Luxembourg has made considerable efforts since the start of the century. However, domestic renewables only amount to around 3 % of the national energy mix in 2019. (Fig. 4.3) By taking into account the share of renewables among electricity imports, Luxembourg achieved their goal and reached 11.7 % of renewable energy production in their national consumption in 2020. However, the goal of 11 % is substantially lower than the European average of 22.1 %. (Eurostat 2022a) In order to reach the 2030 goal of a minimum of 23 %, substantial efforts have to be taken -either by drastically reducing the share of fossil fuels or by expanding renewable energy production.

4.2.3. Efficiency

The third pillar of the climate targets set out by the EU refers to energy efficiency. In order to measure this, the Luxembourgish government set a threshold of maximal energy consumption, equal to a maximum of 49.3 GWh in 2020. Luxembourg reached this goal, as the 2020 energy consumption equalled 45.1 GWh. (Fig. 2) However, in order to reach the 2030 goal, which assumes a reduction of further 21.1 % in energy consumption, significant changes have to be made. Either by reducing consumer behaviour or by strongly enforcing energy efficiency by shifting from fossil fuels to electrification of the transport sector.

4.3. Sectorial energy demand

The following table divides the national energy demand into three sectors: Households, industry. and the tertiary sector. Households and industry represent a quarter of national energy demand, respectively, whereas the tertiary sector, the most energy devouring sector, consumes nearly half of the national energy demand. This table does not include the sale of petroleum products to non-residents, but only includes national energy consumption. This was chosen on purpose, as both 2020 and 2021 were strongly impacted by national Covid-19 lockdowns and border closures. Thus, the data for these two years is not representative as especially the tertiary sector has a much lower proportion of energy consumption. In addition, energy sales (mainly petrol and a tiny fraction of bioenergy) to non-residents have been subtracted in order to reduce the statistical distortion, which can be observed on Fig. 4.1.

Table 4.3: Energy demand by sector (in TWh) (Statec 2020a)

2019	Households	Industry*	Tertiary	Total
% Share	25	26	49	100
Buildings	5.358	7.186	6.184	18.728
Transport	2.285	708	8.812	11.805
Total	7.643	7.894	14.996	30.533

4.4. Sectors

4.4.1. Households

Household constitute a quarter of the national energy demand. (Table, 4.3) Approximately two thirds are spent for buildings and housing applications and one third for transportation. By taking into account the relatively small national population of 613,900 in 2019, the national domestic per capita consumption is around 12 MW per year. The largest chunk of the energy used, 82.2 %, is used for space heating, 7.8 % are used for water heating, and 7.4 % for lightning and appliances. (Eurostat 2019) Concerning transportation, Luxembourg has the highest car per capita ratio in Europe. (Eurostat 2021) Due to the low penetration of electric cars, the household transportation sector has a relatively high efficiency improvement potential.

4.4.2. Industry

The Luxembourgish industrial sector is mainly dominated by a crumbling steelmaking industry and the aviation sector. Despite the shrinking importance of the heavy industry, total industry energy demand accounts for around 26 % of national energy demand. (Table 4.3) However, this image is relatively distorted, as the actual energy demand of the industry is much higher, but due to the EU's emissions trading scheme (ETS), they are not registered as part of Luxembourg's energy demand. The total energy consumption which is therefore not taken into account amounts to 14,500 GW per year. These are approximately 7,500 GW consumed by the industry and 7,000 GW by international aviation. Cargolux, one of the world's largest cargo airlines, is responsible for most of the energy demand and emissions in the aviation sector.

4.4.3. Tertiary

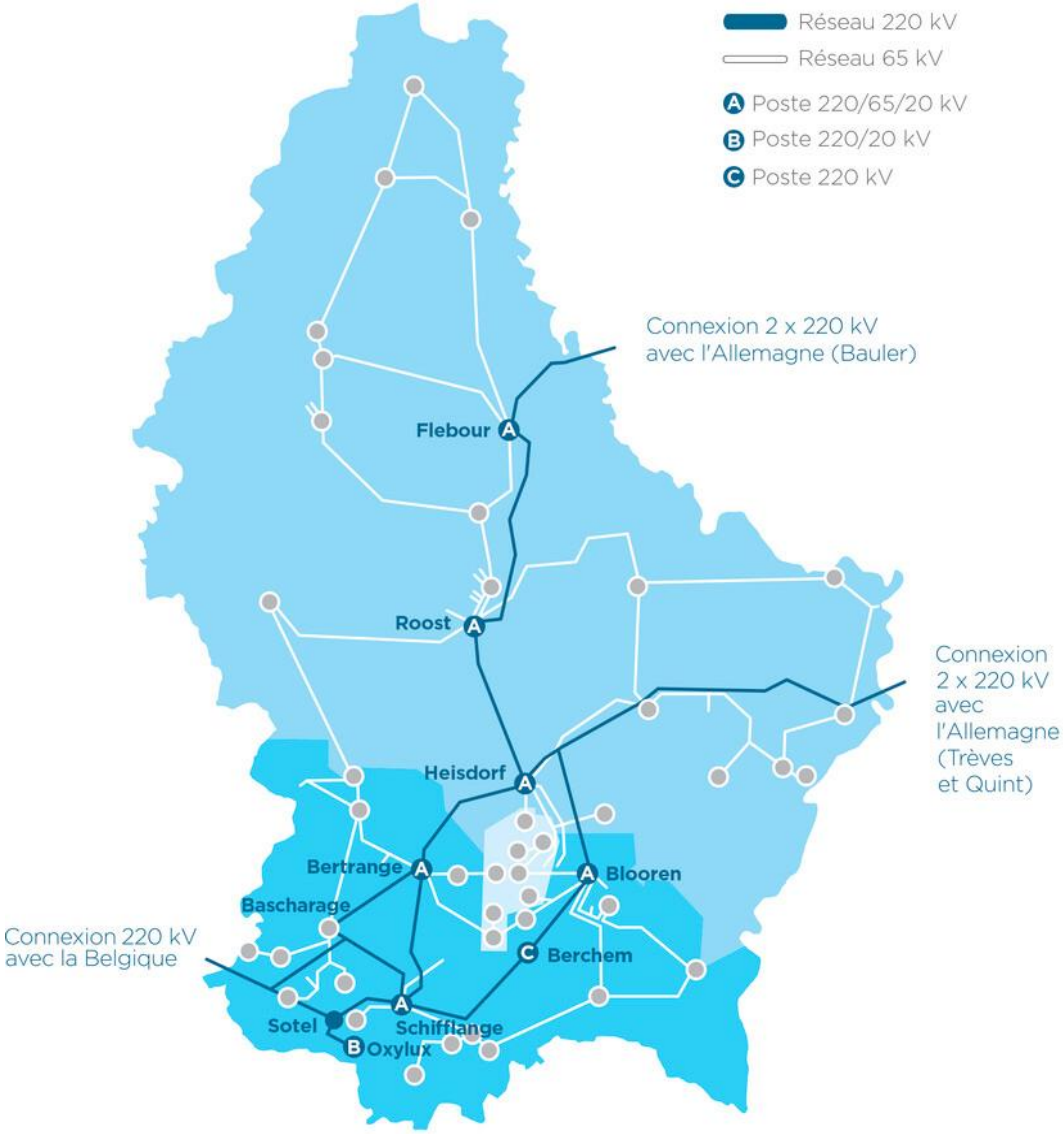
Luxembourg's tertiary sector is mostly dominated by financial institutions and consulting firms. The total energy demand of the tertiary sector is around 24 %. (Table 4.3) By comparing the energy demand to the economic output, the tertiary sector outruns the industrial sector easily. However, in the coming decades, a substantial increase in energy demand can be expected from the tertiary sector due to planned realisation of data centres. Their activities are extremely energy intensive but generate very little employment, thus their realisation remains questionable. (RTL 2019)

4.4.4. Agriculture

Despite not being listed as a separate sector here, agriculture has a prominent role in the energy transition. The energy demand of the sector is relatively low but is a major contributor to greenhouse gas emission due to cattle breeding. In addition, farmers play a considerable role in the energy transition, as they are able to shift from alimentary crops to energy crops in order to produce biomass for the production of biofuels or biomethane. Furthermore, due their vast land possessions, they are able to install photovoltaic installations or wind turbines amid their cattle breeding grounds. (Turmes 2022)

4.5. National grid

Fig. 4.4: Electricity grid (Creos 2022)



In Luxembourg, CREOS is the sole transmission system operator and is also responsible for the distribution grids. Besides CREOS, four distribution grid operators exist. Additionally, SOTEL operates a separate grid supplying the heavy industry in the southern part of the country. Whereas CREOS imports most of its electricity from Germany, and since 2017 a smaller share from Belgium, SOTEL is connected to the

Belgian grid but imports a substantial amount of its electricity from France. To this day, there is no interconnection between CREOS and SOTEL. (ILR 2021) Currently, the Luxembourgish grid is connected via two double lines at a voltage level of 220 kV each to the German transmission operator Amprion. The maximal transmission capacity equals 1960 MVA. However, CREOS is currently expanding its connection to the German grid by replacing one of the 220 kV with a 380 kV line. This project will be realised by 2026. (CREOS 2020a) Since 2017, another transnational 220 kV connection to the Belgium transmission operator Elia exists. The maximal capacity of this line is 720 MVA. The Luxembourgish pump storage plant Vianden is directly connected to the German grid. (ILR 2021) This installation enables to storage energy surpluses and generate electricity during periods of low supply. The full generation capacity of this installation totals 1096 MW. (SEO 2022a)

Wind turbines and photovoltaic installations directly feed into the medium or low-voltage grid. A total of 312,815 consumers are connected to the Luxembourgish grid, of which 248,861 are households. The total number of connections is expected to increase to 427,069 by 2033. (Ministère de l'économie 2018) One of the major challenges of the grid operator is to balance electricity demand and supply around 50 Hz. If the balance is not maintained due to an increase in supply or demand, an emergency measure may lead to a disruption in electricity supply to avoid damaging the lines.

Luxembourg's electricity supply mainly depends on imports (Table 4.4). In 2016, the gas and steam power plant Twinerg was closed down for economic reasons. After the closure of the sole major power plant, only a waste incineration plant remains, whose output represents only 7 % of national renewable production. (Turmes 2022)

Table 4.4: Net electricity imports (GWh/a) (Statec 2021b)

GWh	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Import	7280	7096	6732	6852	6961	7519	7718	7567	7553	6818	6543
Export	3216	2614	2622	1908	2067	1919	1420	1389	1392	939	1079
Net import	4064	4482	4110	4944	4894	5600	6298	6178	6161	5876	5464

4.6. Electricity tariffs

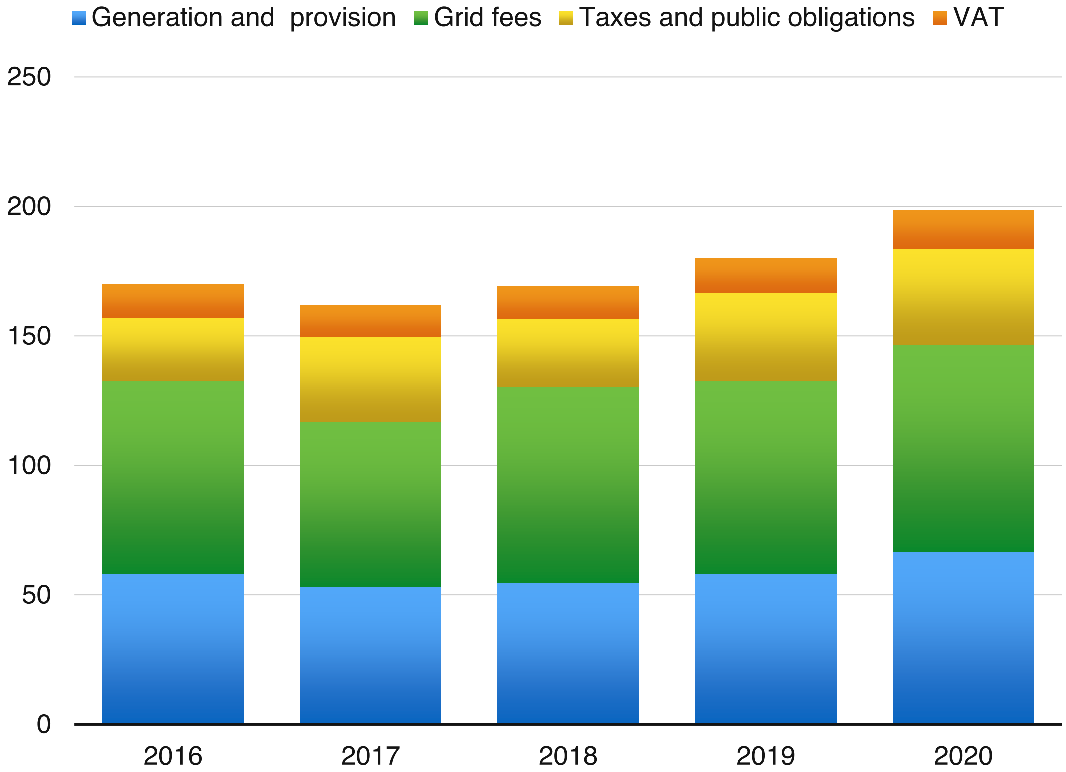


Fig. 4.5: Electricity cost development (€/MWh) (IRL 2021)

The comparably low electricity prices in Luxembourg are composed of the following factors: (Fig. 4.5)

- Generation and provision, which equal the total costs of the energy supplier
- Grid fees are the costs of the electricity grid usage
- Taxes and public obligations are public taxes to finance feed-in tariffs of renewables
- The value added tax (VAT), which in Luxembourg is at 8 % for electricity (ILR 2021)

In the second half of 2021, the European average electricity costs for households were 0.2369 €/kW and in the Eurozone at 0.2474 €/kW. In 2021, Luxembourg’s final electricity consumer costs were at 0.1989 €/kW and thus relatively low compared to other Western European countries. The main reason for this observation is the comparably low Luxembourgish VAT. (Eurostat 2022b) In addition, the relatively high consumer purchasing power of Luxembourgish inhabitants means that electricity costs only represent a small fraction of their expenses. This is beneficial to combat energy poverty nationwide, but detrimental for the functioning of transition measures such as the feed-in tariff, which is currently around 0.20 €/kW. (Turmes 2022) This means that the relatively low energy prices produce little incentive for households to produce renewable electricity by installing solar panels on their roof for instance. Again, the high purchasing power further alleviates any pull incentives, as electricity expenses only represent a very marginal fraction of household expenses. In a country with higher electricity prices and lower purchasing power, such as Germany, higher proportional household electricity expenditures and more attractive feed-in tariffs incentivise a wider social participation in the energy transition. (Eurostat 2022b) Urban rooftop photovoltaics coupled with battery storage options are therefore developed in a very limited manner.

5. Renewables in Luxembourg

5.1. Current state

The national electricity production covers less than 20 % of national electricity demand. The main components are wind turbines and photovoltaics. (Fig. 5.1) (Statec 2020b)

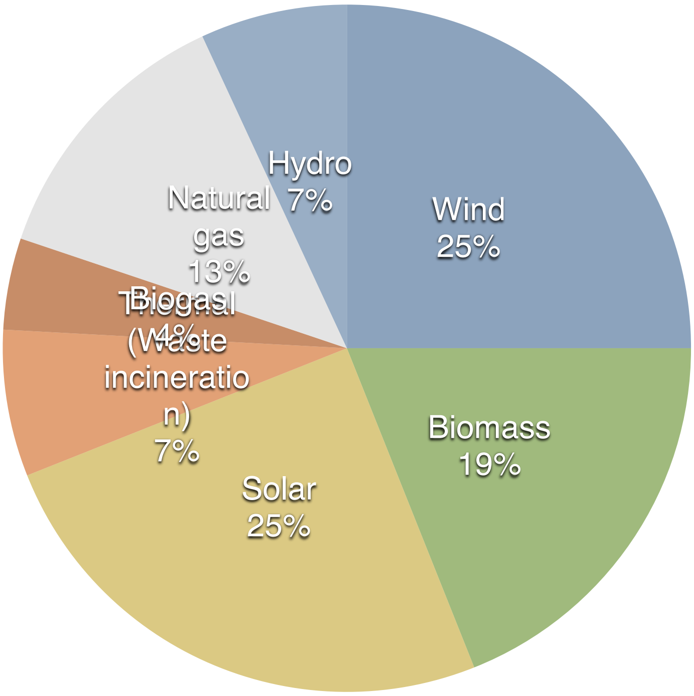


Fig. 5.1: Domestic renewables (in % of total share) (IRL 2021)

5.2. Current state and limitations

Apart from Malta, the Grand-Duchy is the smallest national territory of the EU. The territory has a size of 2,586 km², which compares to around 6.2 times the size of Vienna. (Statec 2022a) Hence, territorial availability for surface-intensive renewable energies remains relatively limited. In addition, a full reliance on wind and solar might create shortages between January and February, which often experience periods of low wind and solar influx. (Turmes 2022) Hence it is important to have adequate storage capacities or connectivity to international grids.

5.2.1. Hydropower

Among the total domestic produced electricity, hydropower generates around 7 %. (Fig. 5.1) The hydroelectric power stations are mainly located along the Mosel and the Sauer River. Their total capacity potential amounts to 37 MW. (SEO 2022b) The largest is located in Esch-Sauer, for which a dam has been constructed. This led to the flooding of an entire valley, destroying ecosystems and resettling entire villages. Due to territorial limitations and environmental concern, hydropower is very difficult to develop further in Luxembourg.

5.2.2. Wind power

Energy generated via onshore wind turbines consists of a quarter of the domestic electricity production in Luxembourg. (Fig. 5.1) By national law, wind turbines are required to be located at least 300 meters away from any inhabited community and the height of the entire construction has to be the minimum distance to any paved road and non-inhabited agricultural construction. However, municipalities are free to decide on more stringent conditions. (Weber 2012) Despite these regulations being less strict than in Austria, for instance, where the most lenient state prescribes 800 meters minimum distance to any inhabited community, a large-scale expansion of wind turbines remains difficult to realise, especially in the densely populated southern part of the country. (Brauner 2019) The northern part of the country still has a lot of potential to construct wind turbines. The main factor opposing the further expansion is public acceptance of wind turbines. People have environmental concerns and are afraid of audible nuisance generated by the turbines. However, with the improved efficiency of taller wind turbines, their output can be increased by keeping the expansion at an acceptable level. On Pafebierg, for instance, 4 older installations of 500 kW each, have recently been replaces by a single turbine generating around 4.2 MW. (Turmes 2022, Wind Power 2020) The recent and future improvements in technology will enable this technology to be further expanded while remaining publicly accepted.

5.2.3. Biomass

Regarding biomass, spatial compromises have to be taken, creating economic and environmental trade-offs. It is important to distinguish between residual biomass from forestry or agriculture which are by-products and agrarian biomass, which is produced with the sole purpose of using it as an energy source. (Brauner 2019) In order to make biomass viable for energy production, residual biomass is not sufficient. This can only be done by either increasing the productivity of land or by increasing the surface of production at the expense of other crops or non-agrarian or forestry surface. Hence, there is a first trade-off between an increase in the volume of production, investments into fertilisers to increase the productivity, and land use. (Schmidt et al. 2012) The second major trade-off concerns the use of the agrarian output if the agrarian output is designated to be used as fuel source or as source of nutrition. (Choi et al. 2018) The answer to this question purely depends on the revenue and costs for the farmers of either one. In the case of Luxembourg, expanding the land for fuel production seems relatively difficult due to the spatial limitation. Increasing the productivity and a substitution of food production could be an option, but only if the economic reward for fuel production allows it.

On the one hand, compared to other sources of renewable energy, biomass requires additional efforts in growing and subsequent treatment and is therefore less cost-efficient. However, the potential of biomass is interesting due to its wide array of applications. It can be used directly as source of heat or transformed into liquid or gaseous products which can be used as fuel for cars for instance. The main advantage of biomass compared to other renewables is its storage ability (Brauner 2019). It can thus compensate low production periods of weather-dependent photovoltaics and wind production. Despite its limitations, biomass consists therefore an important aspect of the energy transition.

5.2.4. Photovoltaics

In Luxembourg, electricity from photovoltaic installations currently generates around a quarter of the domestic production (Fig. 5.1). There is no minimum distance that has to be considered when construction photovoltaics, but creating large solar parks have to be done at the expensive of agrarian land or urban areas. This leads to a socio-economic trade-off between generating power at the expense of agricultural production and/or living areas. As the country is already facing a major housing crisis, dedicating an increased share of constructible areas to energy generation might be difficult. (Paccoud et al. 2021) The most recent solar park inaugurated consists of floating panels on a cooling lake on site of a former industrial plant. (Enoblog 2021) This project successfully circumvented the spatial limitations but affects the local lake biotope. In addition, this project lacks scalability, as the amount of water surfaces is limited. It is producing 3.05 GWh per year, which is roughly the yearly consumption of around 3200 people. (Enoblog 2021)

5.2.5. Infrastructure

Besides biomass, renewable energy generation does not require any fuels, therefore marginal costs are close to zero. Generating energy at full capacity or not at all involve the same costs. This means that the energy price is mostly dependent on infrastructure investments and maintenance costs. Hence, renewable energies with the lowest investment and maintenance costs have the highest economic potential. Investments costs for photovoltaic installations have been rapidly falling over the past years and are sought to continue to decrease. (See 6.3.1) A similar trend can be observed with wind power generation. However, offshore wind power will remain the most expensive renewable energy source due to its dependence on expansive grids. (IRENA 2021)

Besides territorial complications, the expansion of renewable energy generation also challenges existing infrastructures and especially grid capacities. The Luxembourg-funded offshore wind park close to Denmark is therefore questionable, as the sustainably sourced energy has to be transported over roughly 1000 kilometres to the consumer. Firstly, setting up such lengthy power lines is very costly, both in building and maintaining, and, secondly, the environment is impacted by the power lines. Underground power lines heat up require digging and heat up when transporting at high capacity, which affect biotopes. (Brauner 2019) Overland lines require space and have to fulfil environmental and safety regulations creating trade-offs similar as with large-scale on-land solar parks. It is therefore questionable if investments into an offshore wind park off the Danish coast are cost-efficient for the Luxembourgish end-consumer.

6. Energy economy

As the energy transition is only realisable if it proves feasible from an economic perspective, the costs of generating electricity from fossil fuels, nuclear and renewables will be assessed in the following paragraphs. The levelized cost of energy (LCOE) refers to the average cost of electricity generation by taking into account the costs and expenses that the construction, maintenance, and eventual disposition of possible waste materials would incur. (Ueckerdt et al. 2013)

6.1. Fossil fuels

The LCOE of fossil fuels such as natural gas and coal are mostly driven by raw material costs. In general, fossil fuel powered plants have high initial investment costs but relatively little operating costs. The international agency for renewable energy estimates that globally, a total capacity of over 800 GW coal plants is not competitive anymore, in comparison with renewable electricity production. (IRENA 2021) In Germany, power plants running on lignite are deemed not profitable and their suspension proves being more economic than their renovation and subsequent operation. (Öko-Institut 2017) This is not solely due to global resource prices nor labour wages but also due to the estimated benefits and health savings of reduced air pollution. Research from India demonstrated enormous economic losses due to air pollution. (Pandey et al. 2020).

Natural gas remains the most cost-efficient fossil fuel due to its relatively cheap extraction and transportation. In addition, compared to lignite or other coal products, natural gas does not emit any particulate matter and thus does not have the same human health repercussions as discussed earlier. However, the price of natural gas may be highly volatile, depending on the global supply and demand. (IEA 2020)

6.2. Nuclear

Since nuclear power does not directly emit any greenhouse gases, a number of countries have heavily invested into nuclear power plants in order to generate “clean” energy. Another advantage is the possibility to continuously generate a baseload independent of climatic factors. (Kepper and Cometto, 2061) However, the disposal of the radioactive waste and the construction and the dismantlement of the power plant raise the LCOE to a level that is not profitable in comparison to renewables. (Zens and Kalmes 2022) Moreover, the unconceivable potential costs in case of a nuclear accident are not taken into account. The Japanese government estimated in 2016, five years after the nuclear meltdown in Fukushima, that the disaster-related costs amounted to 188 billion US$, in addition to the death of 15,000 people. (Obayashi and Hamada 2016)

6.3. Renewables

6.3.1. Solar

The global average LCOE of solar photovoltaic installations fell by over 85% since 2010. Whereas 1 kWh of solar generated electricity costed on average 0.381 USD, the rate was only around 0.057 USD for a kWh in 2020. (IRENA 2021) In addition, efficiency of the modules has risen continuously over the past two decades. Today, the most efficient modules are built from multi-crystalline silicon. Their efficiency has reached over 20% in the past few years. (Benda and Černá 2020) Furthermore, the introduction of tandem solar cells, also called multi-junction solar cells enabled to reach even higher levels of efficiency, lately their efficiency reached around 25 % to 31 %. (Fig. 6.1) Their key to success are multiple layers of semiconducting materials which allow the absorption of a broader range of wavelengths. (Werner et al. 2016)

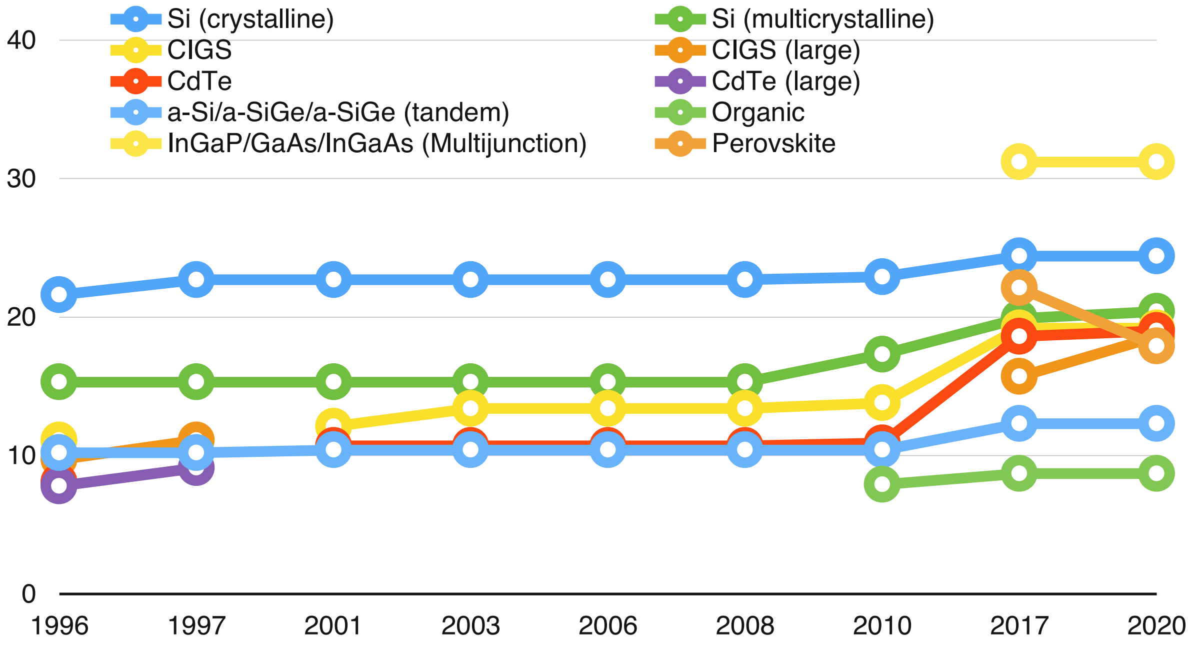


Fig. 6.1: Efficiency development of Photovoltaics in % (Emery 1996, Green et al. 1997, Green et al. 2001, Green et al. 2003, Emery 2006, Emery 2008, Green et al. 2010, Green et al. 2017, Green et al. 2020)

Table. 6.1: Abbreviations (Emery 1996, Green et al. 1997, Green et al. 2001, Green et al. 2003, Emery 2006, Emery 2008, Green et al. 2010, Green et al. 2017, Green et al. 2020)

Abreviation	Meaning
Si	Silicon
CIGS	CuInGaSe
a-Si	Amorphous silcon
a-SiGe	Amorphous siicon/Germanium/Hydrogen alloy
InGaP	Indium/Galium/Phosphorus
GaAs	Galium/Arsenic

The global photovoltaic market has risen tremendously over the past two decades. Total global photovoltaic installed power has reached 707 GWp, of which 127 GWp have been installed in 2020. (IRENA 2021a) The main driver for this enormous growth is not solely linked to environmental factors but can be mainly traced back to economic reasons. Photovoltaic modules have experienced a significant price reduction. Crystalline modules tariffs dropped from 430 €/kWp in 2018 to 310 €/kWp in 2020. (EuPD Research) However, while the prices for PV modules decreased massively, the costs of inverters and balance of system components did not decrease at the same rate. (Fig. 6.2) Hence, nowadays, their proportion of the end price of a PV installation are larger than the modules themselves. In addition, global supply chain disruptions due to Covid-19 and the ongoing chip shortage have taken their toll on the sector. The lacking availability of semiconductors have contributed to a recent global surge in module and BOS tariffs. (Eckhouse 2021)

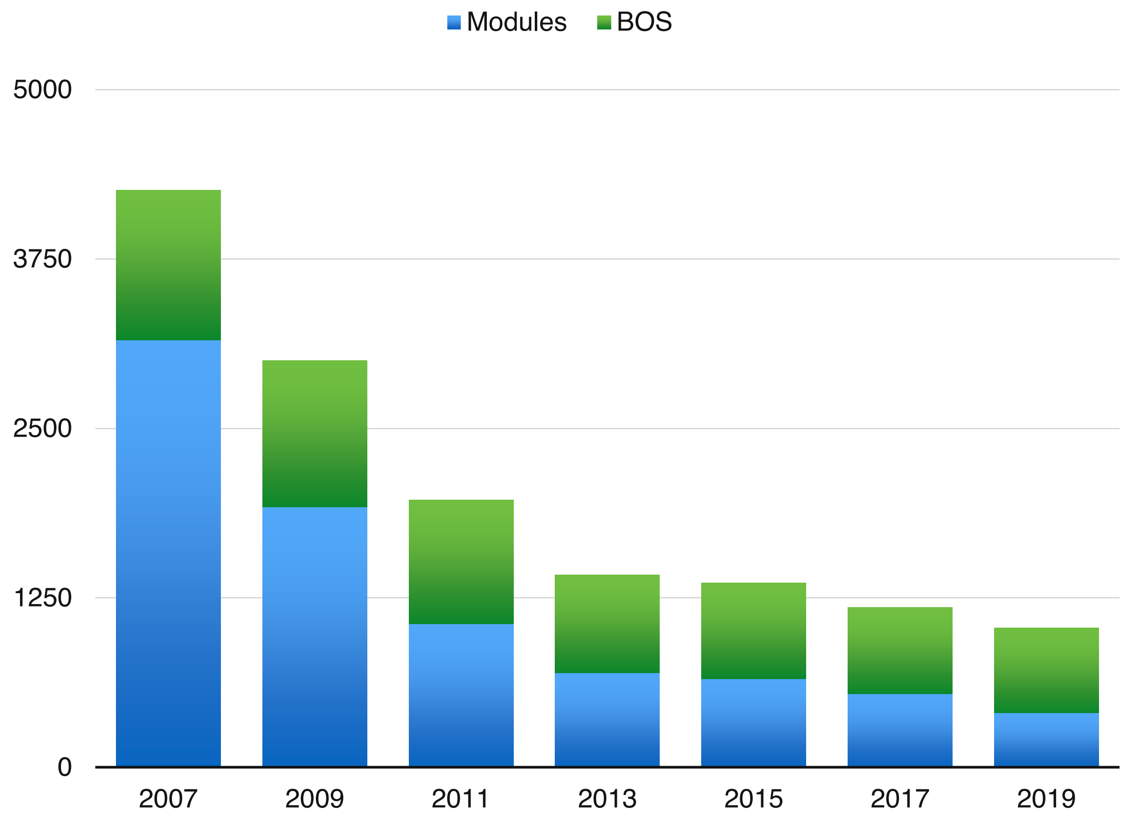


Fig. 6.2: Price constellation of Photovoltaic installations (€/kWp) (Fraunhofer 2022)

In the future, it is expected, that a further general cost reduction in solar power will occur as not only mass production increases but also the efficiency of modules. (Wirth 2021) In addition, the commercialisation of bifacial modules, which significantly increase the yield per module, is expected to further impact the cost-efficiency balance positively. (IRENA 2021) Another important factor is lifetime. The longer the lifetime, the cheaper the investment per kW produced. Currently manufacturers such as Meyer Burger offer warranties from 25 to 30 years, depending on the module. In addition, they also offer performance guarantees that the efficiency of the module will not decrease by more than 8 % over the first 30 years of use. (Meyer Burger 2021) Other manufacturers offer performance warranties of 85 % performance efficiency after 25 years. (Axitec 2022)

In general, photovoltaic modules are continuously becoming more affordable while continuously gaining in efficiency and lifetime.

6.3.2. Onshore wind

Between 2010 and 2020, the global LCOE of onshore wind decreased from 0.083 €/kWh to 0.036 €/kWh, representing a net decrease of 56 % in 10 years. Two main factors are driving this substantial price reduction: Firstly, the steadily decreasing turbine prices which is strongly induced by mass production, especially in China. An increasing number of producers is raising competition among manufacturers, which lower their margins in order to remain as competitive as possible. (IRENA 2021) Secondly, the efficiency of wind turbines improves continuously due to technological advancements. Currently, the main drivers of innovation are larger and more durable turbines. In addition, wind turbines are becoming increasingly taller in order to improve their yields. (IRENA 2021) With turbines growing to become increasingly affordable, their installation and maintenance are becoming the main cost-decisive factors.

6.3.3. Offshore wind

Between 2010 and 2020, the global LCOE of offshore wind decreased from 0.151 €/kWh to 0.078 €/kWh, marking a net decrease of 48 % in 10 years. The LCOE of offshore wind electricity generation is mostly influenced by the same factors as onshore wind. A few more factors prevail regarding offshore wind, namely product standardization, regional manufacturing hubs and an increased experience in the domain. (IRENA 2021) Hence, offshore wind generation is being expanded at a rapid rate. From 2010 to 2020, the total global turbine capacity has been raised from 3.1 GW to 34.4 GW, thus multiplied by a factor of 11. The installation of floating energy islands and the introduction of specialised maintenance ships have contributed to an improved cost-efficiency balance. However, generating electricity further away from the mainland requires lengthy transmission cables and increases the costs of maintenance significantly. Thus, offshore electricity remains more expensive than onshore, despite the increased average yield. (IRENA 2021)

6.3.4. Biomass and hydropower

Regarding hydropower, it is very difficult to make any generalized cost assumptions as the cost-efficiency depends highly on the project itself. (IRENA 2020)

Concerning bio energy, the economic competitiveness strongly depends on the energy crop chosen and its use. If it is sourced as by-product or as an energy crop, being transformed into methane or directly used as source of heat strongly affects the costs. The large demand for land, fertiliser and manual labour, are the main driving factors for biomass. (Domac et al. 2005; Kranzl and Haas 2009)

As the global demand for renewable energies continuously grows, so does the offer. The rising market increases competition which, on the one hand, pushes prices down and, on the other hand, increases investments into innovation and research. This increases efficiency and lifetime which both have a positive impact for the consumer. Especially solar panels and wind turbines experienced relatively large drops in costs. Installation and maintenance are expected to become the main price components of these two renewables rather than the technology itself.

In comparison, fossil fuels are increasingly becoming unprofitable. Firstly, the construction of large powerplants demands high investments costs. Secondly, the reliance on fuels whose price is determined by global market prices are not profitable on long term. In addition, the financial costs of the resulting pollution, especially in the sanitary sector, cause a discrepancy between costs and utility. As natural gas emits less pollution, and is relatively cheap in transportation, its cost-effectiveness simply depends on the market price. Nuclear is relatively expensive in construction, maintenance, and waste disposal. In addition, the reliance on fuels creates dependency on market prices. Furthermore, the costs of an eventual accident, make this technology unprofitable.

If current trends continue, renewable energy sources prove being the most cost-utility-efficient energy form. In addition, after installation, their non-dependence on fuels does not create any dependence on world markets but simply on climatic conditions.

7. Efficiency potential

7.1. Buildings

Currently, the energy demand for buildings represents around a third of the national energy demand. Buildings consumed in 2019, 5,358 GWh annually, the tertiary sector 6,184 GWh and the industry 7,186 GWh. However, the national statistics include the energy demand of the industrial process in the category building energy demand. (Table 5)

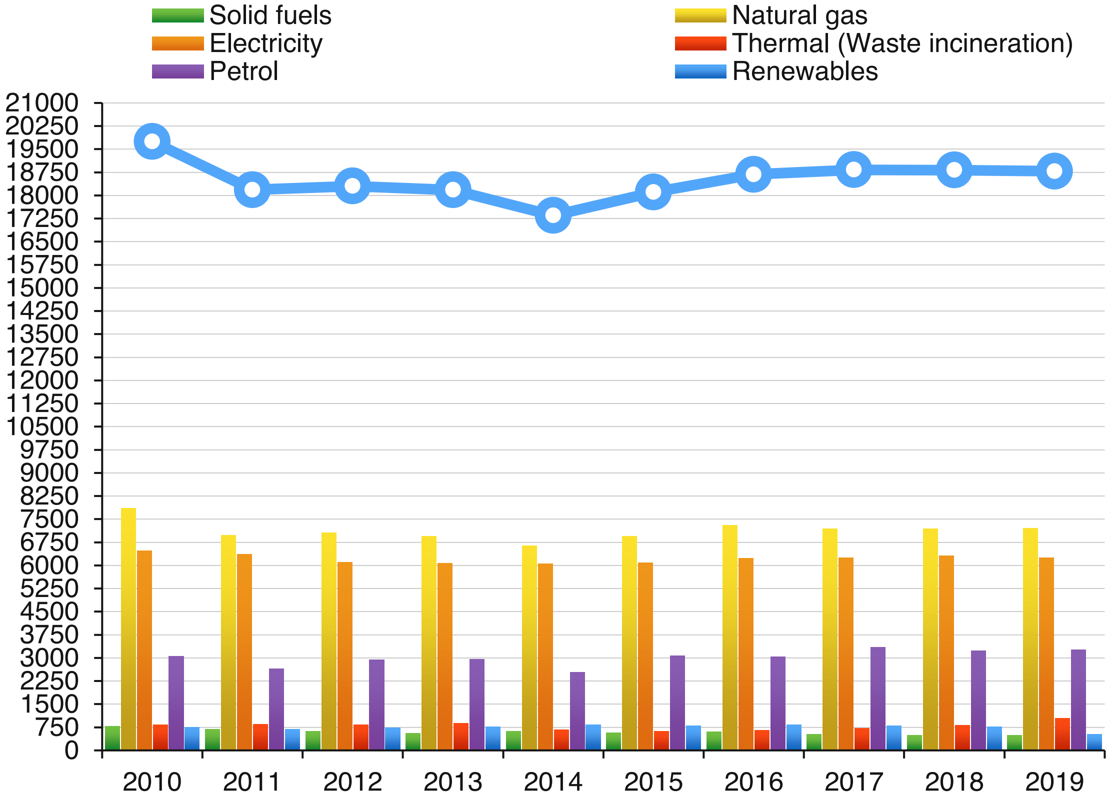


Fig. 7.1: Development of building’s energy mix (in GWh/a) (Statec 2020a)

The majority of household use fossil fuels to heat their homes. Natural gas and petrol are the dominant energy forms used for domestic heating. Only 3 % use electric heating and another 3 % use heat pumps. (Fig. 7.1) This means that there are enormous efficiency improvements that can be made in this field. In order to reach the EU’s 2030 targets, not only new constructions but all buildings, private and public alike, have to be equipped with heat pumps, electric heating or at least switch from petroleum heating to natural gas. In addition, isolation has to be improved in order to reduce heat losses at maximum. The national climate plan predicts that heat pumps will generate 276 MWh of thermal energy and 73 MWh of electricity by 2030. (Gouvernement du Grand-Duché de Luxembourg 2018) Over the past years, total energy consumption of buildings has remained relatively stable despite a continuous increase in living units. Hence energy efficiency of buildings must have improved. (Fig. 7.1, Table 7.1) This can be due to technical developments such as improved isolation but also due to increased consumer awareness or climatic effects such as milder winters.

In order to calculate the potential reduction in energy demand through the installation of heat pumps, three factors have to be taken into consideration: the yearly heating and warm water demand, the capacity of the installation, and the annual performance factor. The annual performance factor (APF) is an approximation of the heat pump's efficiency. Water-to-heat or water-to-water are the most efficient heat pumps with an average APF of 4 to 5, compared to Air-to-heat or Thermal heat-to-heat pumps with an APF of 2.5 to 4. (Entega 2022) For this approximation, a relative conservative APF of 3.5 will be chosen for heating water generation, which is a relatively low efficiency. The annual heating hours will be estimated at 2,190 hours for heating which equals a quarter of the year. This is a relatively generous approximation, as usual approximations are rather between 1600 and 2,000 full load hours. Warm water generation will be estimated at 1,500 yearly hours and an APF of 2,8. (Table 7.2)

Table 7.1: Average heat pump consumption (own calculations)

	Heat	**Warm water**
APF	3.5	2.8
Time (hours)	2190	1500
Energy demand (kW)	5	5
Yearly demand (MW)	3.1	2.7

In this model it is assumed that 90 % of household energy demand is spent on room and warm water heating. (See 4.4.1) By fully equipping current Luxembourgish households with heat pumps, Luxembourgish households could save around 3,101 GW annually. (Table 7.3) In addition to heat pumps, co-generation of heat could have a potentially significant impact to cover heat demand of buildings.

Table 7.2: Heat pump efficiency potential (Peltier 2015; Klein and Peltier 2017)

	Amount (2017)	Share (%)	Heating demand (GW)	Amount (2030)	Share (%)	Heating demand (GW)
Houses (isolated)	53,337	22,8		59,338	20	
Houses (serial)	65,034	27,9		74,173	25	
Apartment units	115,304	49,3		163,181	55	
Total	233,675	100	4,822	296,692	100	1,721
Population	590,700			750,000		

Among the tertiary sector it is more difficult to assume how much of the building energy demand is dedicated to heating as data centres and financial institutions consume a considerable amount of energy. Also, there is currently no data on the exact size of private companies' buildings available. The same applies to the public sector. By electrifying and sector coupling the entire tertiary sector, significant efficiency improvements can be made. Therefore, it is safe to assume that the energy demand of the tertiary sector can be reduced by a third until 2030.

Concerning the industrial sector, it is even harder to calculate potential efficiency improvements. Firstly, the current data does not precise whether energy is spent on industrial processes or on heating appliances. As mentioned under 4.2, Luxembourg's industry is dominated by steelmaking. According to predictions formulated by the EIA, efficiency improvements in the sector could lead to a reduction of around 10 % of the energy demand in the sector until 2030. (EIA 2016) In order to further maximise efficiency measures in industrial processes, mechanical energy has to be electrified to a maximum. Process heat is still largely dominated by fossil fuel. However, these could be substituted with electrode boilers which can be coupled to other sectors in order to use surplus electricity. Biomass also has high potential for industrial applications as it can substitute fossil fuels in the form of methane, hydrogen, or biogas. (Brauner 2019)

7.2. Transport

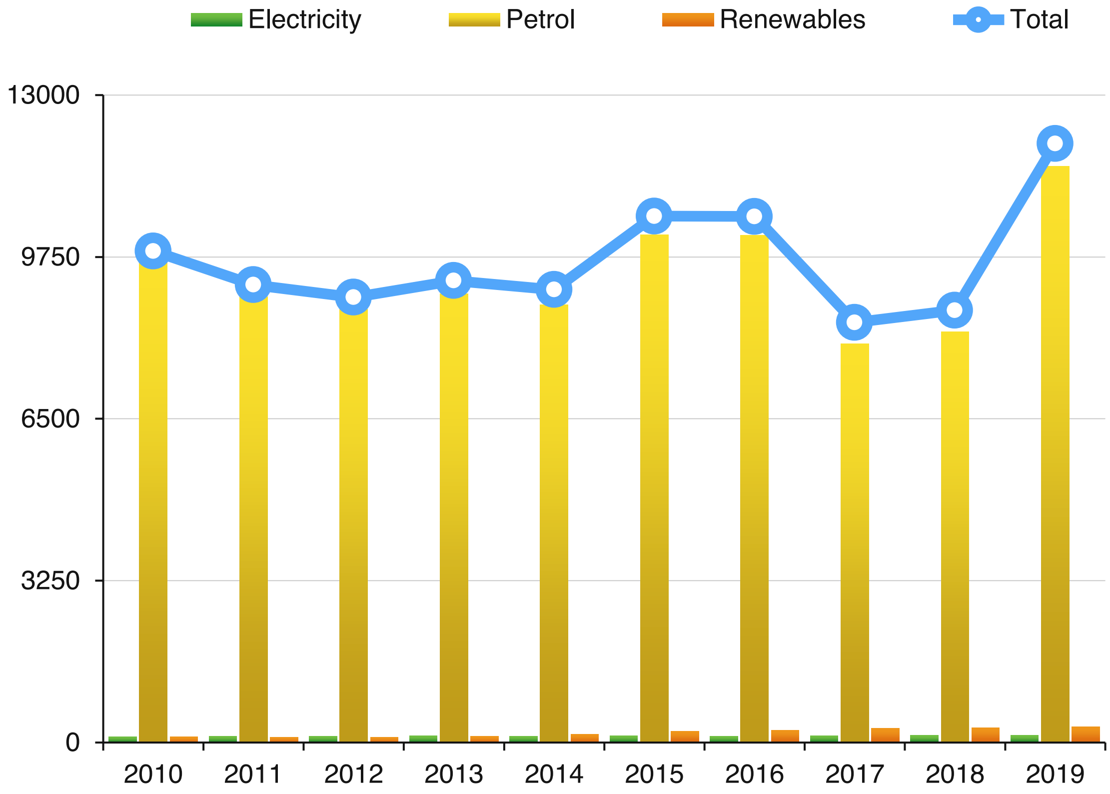


Fig. 7.2: Development of transport’s energy mix (in GWh/a) (Statec 2020a)

As figure 7.3 demonstrates, electric mobility is rapidly increasing over the past decade. Whereas in 2011, only 42 electric cars were registered, the total number of electric or hybrid vehicles registered in Luxembourg increased 5,034 in 2019. From 2017 to 2019, the number of electric vehicles nearly four-folded. This is mostly due to two factors. Firstly, the national and international charging grid has been strongly expanded, enabling users to be more flexible and drive longer distances. Secondly, the Luxembourgish government is strongly subsidising the purchase of an electric vehicle. The government contributes by up to 8,000 € for the purchase of an electric vehicle, if the consumption of the car in question does not trespass 180 W/km. (Administration de l’Environnement 2022)

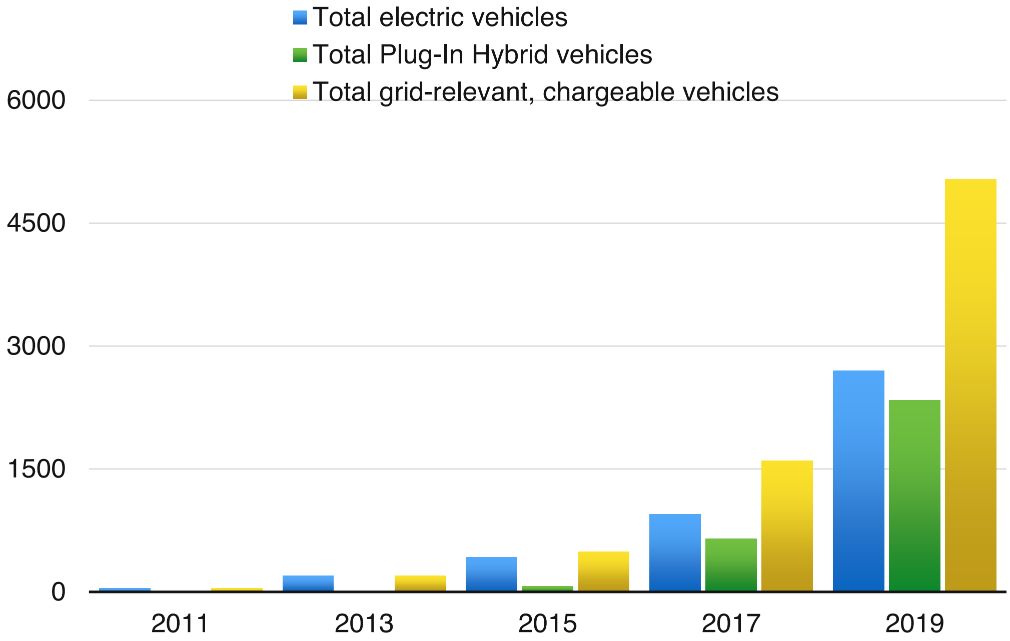


Fig. 7.3: Development of electric vehicles in Luxembourg (Creos 2020b)

However, electric cars currently represent less than 2 % of the total vehicle fleet. Hybrid vehicles represents around 4 % of total registered cars in Luxembourg. (Fig. 7.4) Vehicles running on petrol or diesel represent more than 92 %. (Fig. 7.2) Thus, large efficiency savings can be made by replacing vehicles with combustion engines with electric vehicles. In the following simulation, privately-owned vehicles are assumed to drive 18,000 km per year. Company-owned petrol-cars are assumed to drive 30,000 km per year. Company-owned diesel vehicles are assumed to drive 80,000 per year. This relatively high assumption can be traced back to the large number of logistic companies operating from Luxembourg. Since, in the following step, no differentiation will be made between cars and trucks, the relatively high yearly distance, equalling nearly thousand times the length of the country, is supposed to compensate this.

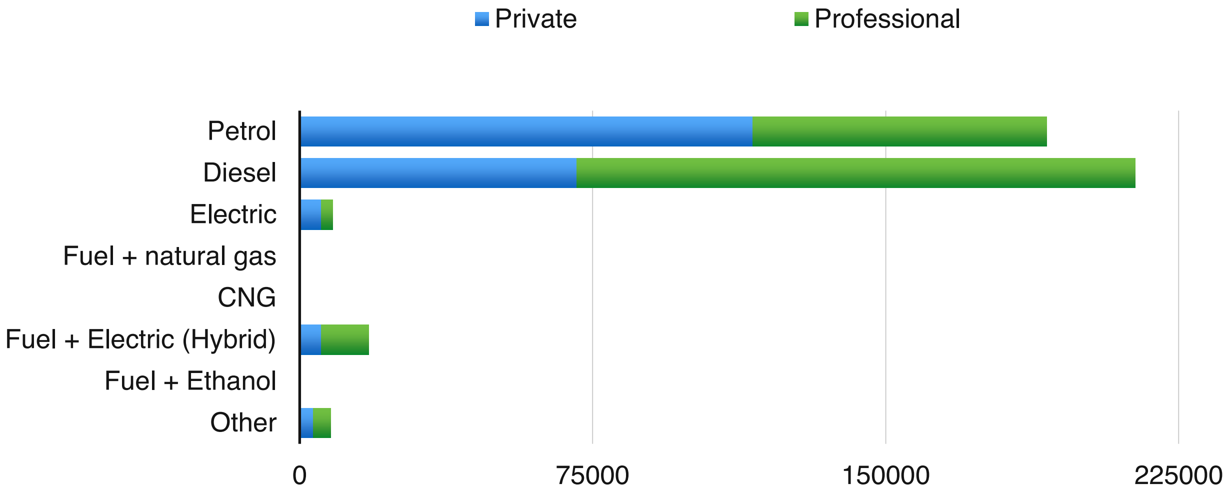


Fig. 7.4: Total registered vehicles by type of propulsion (Statec 2022b)

In order to estimate the approximate efficiency potential in the mobility sector, it is assumed that an electric engine consumes between 19-21 kWh per 100 km driven. (Creos 2020b) The electricity consumption greatly varies in accordance with the speed driven. (Brauner 2019) Currently, the Luxembourgish state only subsidises electric vehicles with a maximum consumption of 18 kWh per100 km. For the following calculation, the mean value of 20 kWh will be used, as especially utility vehicles might have a higher consumption.

Table 7.3: Vehicle electrification potential (own calculations)

GWh	**Combustion engines demand**	**Full electric propulsion demand**
Private vehicles	2285	672
Utility vehicles		
Petrol - electric	3180	452
Diesel - electric	6340	2288
Annual energy consumption (GWh)	**11805**	**3412**

Following this calculation, by fully electrifying the current fossil fuel driven vehicle fleet, the energy demand in the mobility sector could be reduced to a third to 3,412 GWh per year. (Table 7.4)

Besides electrifying the currently existing vehicles, a change in consumer behaviour is essential in order to reduce the energy needs of the mobility sector. Luxembourg has currently the highest number of cars per capita in the EU, accounting to 681 cars per 1000 inhabitants. (Eurostat 2021) This value is slightly distorted as a number of people, especially cross-border commuters, register their cars in Luxembourg due to the favourable tax conditions. However, the number of cars has to be decreased, and the number of rides as well. The Luxembourgish government is supporting this by offering free public transportation for residents and non-residents and increasing the current offer, by expanding railway connections. (Gouvernement 2021b)

Furthermore, due to Luxembourg's relatively small size and the comparably high population growth, urban growth is unavoidable. This unavoidably contribute to the public transportation usage if the offer exists. This shift from private cars to public transportation will be mainly driven by lengthy commuting hours due to frequent traffic jams and a lack of parking spaces rather than an active change in consumer awareness. (Brauner 2019)

Table 7.4 shows that by installing heat pumps in every building and electrifying the entire vehicle park, substantial energy savings can be made.

Table 7.4: 2030 Energy demand by sector (in TWh/a) (own estimations based on calculations)

2030	Households	Industry*	Tertiary	Total
% Share	18	39	42	100
Buildings	2.3	6	4.2	12.5
Transport	0.7	0.5	2.8	4
Total	3	6.5	7	16.5

8. Renewable energy potential

8.1. Photovoltaic potential

The following analysis will analyse the potential of decentralised urban rooftop photovoltaics in Luxembourg.

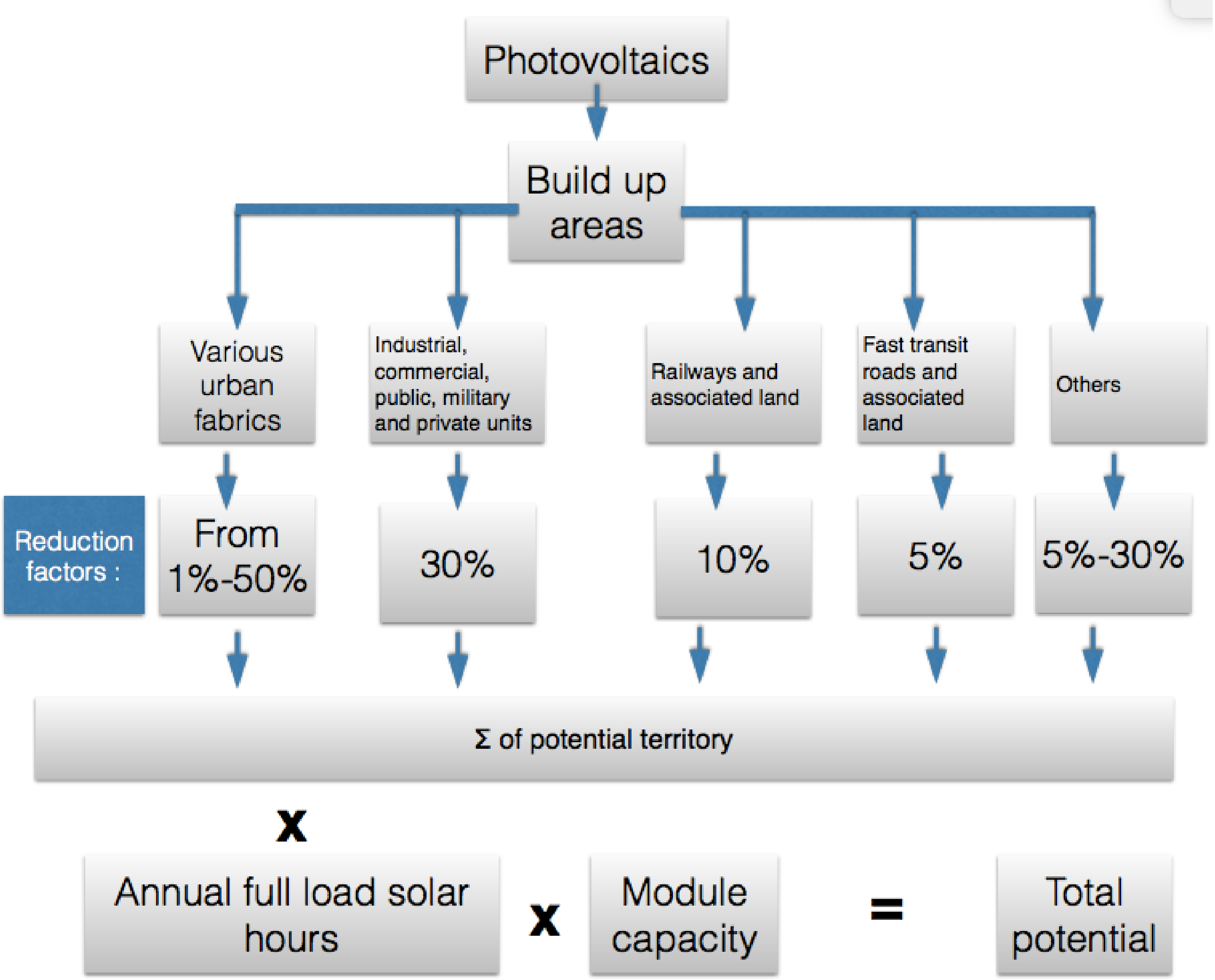


Fig. 8.1: Urban photovoltaic potential methodology (graphic by author)

In order to assess the potential of Photovoltaics in Luxembourg, the territory will be categorised in various spatial subdivisions according to the 2018 Copernicus Urban Atlas. This will enable to clearly identify the total surface of urban conglomerations and deduct the total rooftop potential for solar installations.

Table 8.1: Urban subdivisions (Copernicus Urban Atlas 2018)

Urban surfaces	**Total Surface (km^2)**	**Percentage usable (%)**	**Usable surface (km^2)**
Continuous urban fabric (> 80%)	8,2112	50	4,1056
Discontinuous dense urban fabric (50% - 80%)	72,6040	30	21,7812
Discontinuous medium density urban fabric (30% - 50%)	42,3089	15	6,3463
Discontinuous low-density urban fabric (10% - 30%)	3,8720	5	0,1936
Discontinuous very low-density urban fabric (< 10%)	0,8801	1	0,0088
Industrial, commercial, public, military and private units	71,4609	30	21,4383
Total			**53,8738**

The total theoretical potential for urban photovoltaics totals 53,8738 km^2. (Table 8.1)

Theoretical potential takes into account solely the total rooftop surfaces, whereas the technical potential assesses the actual usable parts of the roof. The surface of chimneys and windows have to be taken out. In addition, the surface of the roof-oriented northwards receives less sunlight than the southern oriented. According to a Swiss study conducted by Solardach, the average proportion of the total surface is around 50-70 %, depending on roof size. (Portmann et al. 2019) In addition, tilted rooftops have a higher surface than flat roofs, where they can be tilted artificially in order to maximise the yield. In addition, east-west roofs have the highest yield on average as they have the longest sun exposure. But according to specialists, even north-facing solar panels are efficient. For the following approximation, 50 % are assumed. The following formula is used to estimate the technical potential.

$$\textit{Technical potential} = \textit{Theoretical potential x reduction factor}$$

In addition to rooftops, other surfaces such as in between train tracks or highways, on sonic barriers along highways, on football stadium, swimming halls and airports, photovoltaics can be installed. Hence another 4,1093 can be added to the technical potential of photovoltaics in Luxembourg. (Table 8.2)

Table 8.2: Additional potential subdivisions (Copernicus Urban Atlas 2018)

Additional surfaces	**Total Surface (km²)**	**Percentage usable (%)**	**Usable surface (km²)**
Fast transit roads and associated land	6,5551	5	0,3278
Railways and associated land	5,9786	10	0,5979
Sports and leisure facilities	13,4135	5	0,6707
Isolated structures	4,3452	30	1,3036
Airports	4,0309	30	1,2093
Total			**4,1093**

$$\Sigma\ \textit{potential surface} = \textit{Technical rooftop potential} + \textit{additional potential surfaces}$$

After having evaluated the usable roof size, we have to evaluate the solar radiation reaching the Luxembourgish ground. As the size of the national territory is relatively small, this thesis will use the average solar radiation of the past 7 years which totals 860 yearly solar hours. The mean solar hours were evaluated by dividing the electricity output generated in each year with the installed capacity of that year. (Fig. 8.2) Compared to other Western European countries, Luxembourg has a relatively medium solar influx.

$$\Sigma\ \textit{produced solar power year } X / \textit{installed solar capacity year } X = \textit{Year } X \textit{ Full solar hours}$$

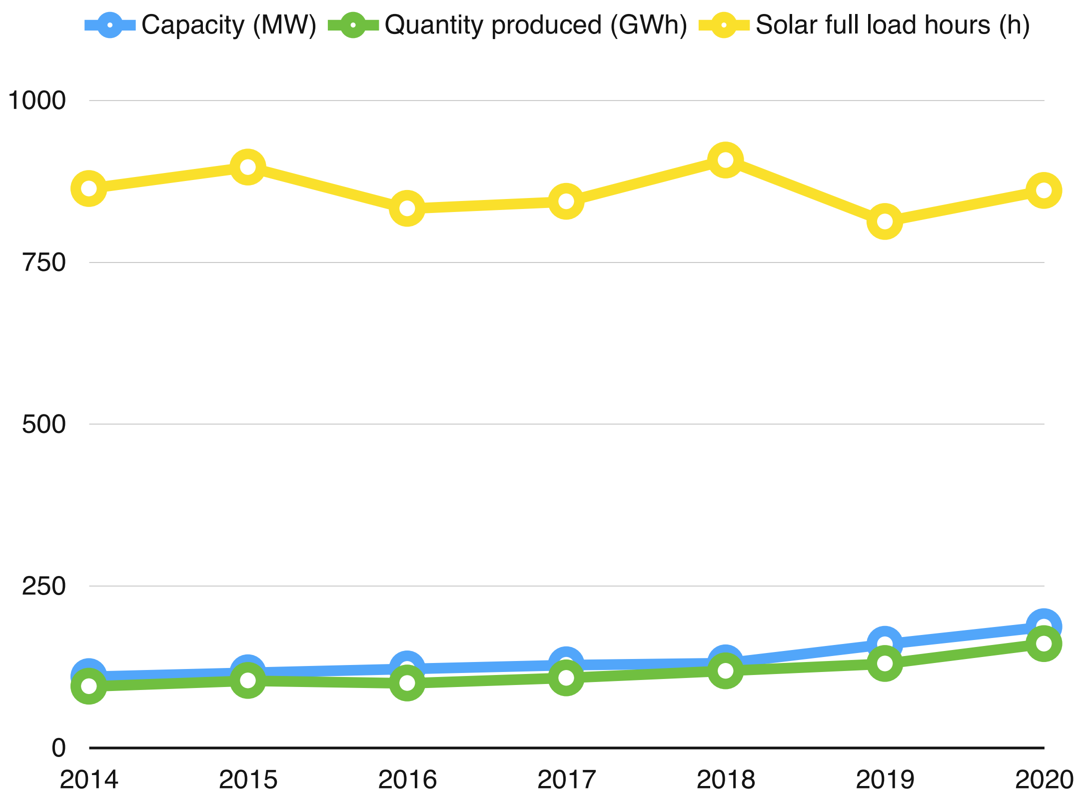


Fig. 8.2: Solar full load hours (Statec 2020b, Gouvernement 2021c)

For the following analysis a single model of solar cells, a 320 Wp, the size of 0,990 m x 1,650 m will be used. (Axitec 20220)

Σ installable modules = Σ available Rooftop Size / solar cell size

A total of 19,005Wp modules can be installed.

Σ Potential Solar Energy = Σ installable modules x Average annual full load hours

Luxembourg's total urban photovoltaic potential equals approximately 5,230 GWh per year.

According to the calculation, more than a quarter of Luxembourg's projected 2030 electricity demand can be covered solely by rooftop photovoltaics. By considering that Luxembourg has the highest population growth in the Europe in 2020, mainly due to migration, it is expected that rooftop surfaces will increase in the coming decade. In order to calculate the additional rooftop surfaces in 2030, a proportional estimation in accordance with population growth is too simplistic, as urban conglomerations will become more densely populated. In the coming decade, the proportion of apartment inhabitants will increase at the expense of people residing in single family houses. In order to take this into account, the population growth expected for 2030, equalling 750,000 people will be multiplied by a reduction factor called *urban growth factor* hereafter.

Urban growth factor = Urban growth / population growth

2021 solar rooftop energy per capita / 2030 solar rooftop energy per capita x urban growth factor

2021 urban solar energy per capita: (5,230/ 634,700) = 0.00824 GWh/a

2030 urban solar energy potential: (0.00824 GWh/a x 750,000) = 6180.60 GWh/a

Δ urban solar energy production: 950.16 GWh/a x urban growth factor = 570 GWh/a

2030 total urban solar energy potential: 5230.43 + 570 = 5800 GWh/a

The total projected urban photovoltaic potential for 2030 equals 5,800GWa. However, this estimation does not consider potential efficiency improvements until 2030, hence the expected urban photovoltaic potential is expected to be even higher.

8.2. Wind potential

The following analysis will determine the wind harvesting potential in Luxembourg.

Due to legal regulations and spatial limitations, it is relatively difficult to estimate the potential of wind turbines in Luxembourg. Therefore, the full wind hours will be calculated.

Σ produced wind power year X / installed wind capacity year X = Year X Full wind hours

Table 8.3: Wind full load hours (Statec 2021a, Gouvernement 2021c)

	2015	2016	2017	2018	2019	2020
Produced energy in GWh	102	101	235	255	281	251
Installed power in MW	63,79	63,79	119,69	122,89	135,79	152,74
Average wind hours	1599	1583	1963	2075	2069	1640

Yearly wind hours may vary from year to year, but in the following calculations, an average of 1650 yearly wind hours will be taken.

8.3. Biomass potential

The following analysis will estimate the potential of biomass in Luxembourg.

In Luxembourg, the most potent surface for biomass is arable land which represents approximately a quarter of the national territory. In order to use the full potential of the total arable land in terms of biomass, a comparison with the Austrian output will be made. In Austria, arable land equals 13,770 km² and could potentially produce 44.5 TWh/a. (Kranzl et al. 2009) This means that on average 1 km² produces approximately 3.25 GWh/a.

$$\Sigma \text{ arable land / biomass potential factor} = \text{Arable land biomass potential}$$

625.82 km² x 3.23 km² / GWh/a = 2021.4 GWh/a

The total biomass energy output of arable land in Luxembourg equals 2021 GWh/a.

Remaining natural surfaces without forests and green urban areas

650.60 km² x 3.23 km² / GWh/a = 2021.4 GWh/a

Additionally, animal manure could be taken into account to estimate the full potential of biomass.

9. Energy self-sufficiency potential

Today, electricity represents around 13,5 % of the entire energy demand or 24 % if only national consumption is analysed (by subtracting petrol sales to non-residents). By progressively phasing out fossil fuels and electrifying the transport, household demands and the industrial sector, electricity demand will strongly grow until 2030 while fossil fuel demand will decrease. Today, a total of 30,818 GWh/a is consumed, which in the following scenario will be reduced by a third to approximately 20,000 GWh/a. This can be only achieved by a massive increase in efficiency through electrification and smart consumption.

9.1. Scenario 1

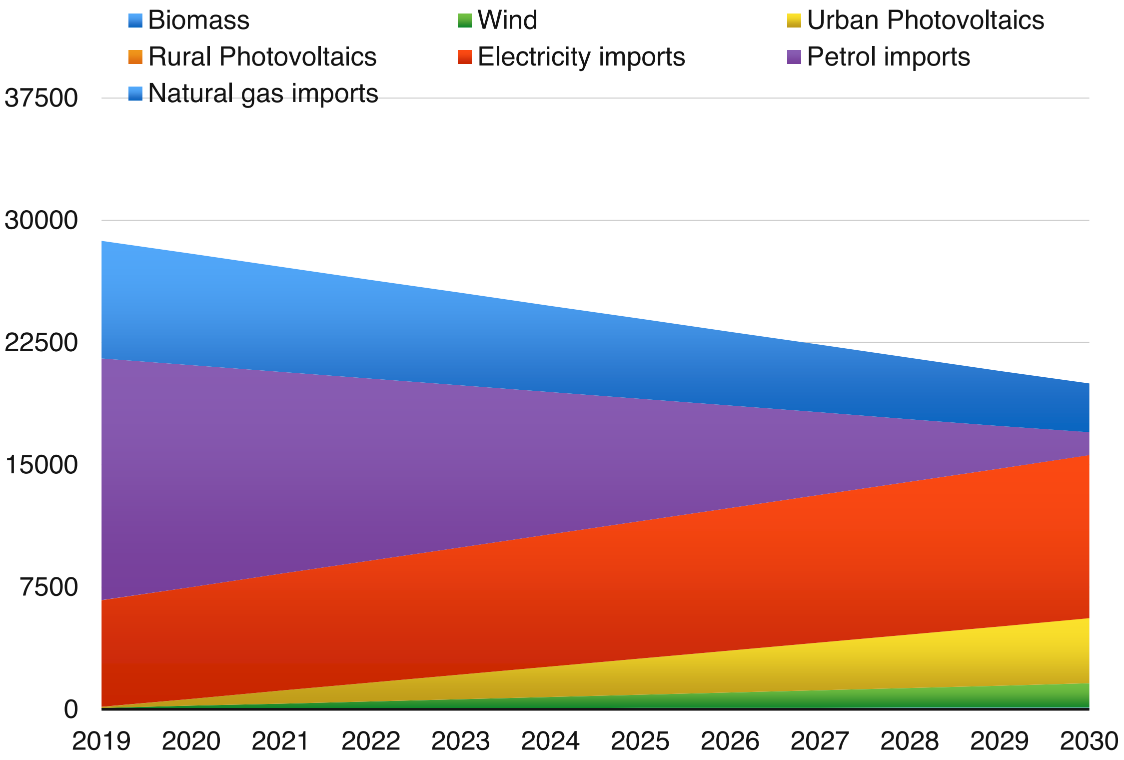


Fig. 9.1 : Scenario 1 : Minimum energy autarky: 33 % domestic renewables – 33 % imported renewables – 33 % fossil fuels

In the first scenario, Luxembourg will reduce its national energy demand by a third. This will be mainly driven by an improvement of building's isolations and the installation of heat pumps. This will strongly reduce heat demand which to this day was covered by two thirds by fossil fuels such as petroleum and natural gas. In addition, the electrification of the car park to 90 % will strongly reduce the need for fossil fuels which will be substituted by a relative strong increase in electricity imports. In addition, domestic renewable production will be increased to sustain the energy need.

- Due to the limited availability of biomass, this form of energy production will only increase by 5 GW per year. Due to the interconnectivity with the grid and the remaining import of electricity and fossil fuels, there is little need for the storage capabilities that biomass offers. In order to limit biodiversity loss and promote local food production, biomass' share of the national energy mix will remain limited by 2030.

- Wind will be expanded at an annual rate of 131 GW, which equals an increase of approximately 24 MV wind turbines annually (at 1,650 yearly full wind hours).

- Photovoltaics will experience the strongest growth among domestic renewables. By 2030, they will reach nearly 80 % of their total rooftop potential. This means that every year, the total output of photovoltaics will be increased by 357 GW, which equals a surface of approximately 2.1 km². However, as this surface will be entirely covered by residential rooftops or public buildings, no environmental compromises have to be taken.

- Despite the relatively large reduction in total energy demand, the maximum reduction potential has only been achieved by 71 %. However, the governments and the EU's efficiency target will be met. In addition, since over a third of the final energy consumption will be covered by renewable energy sources, the second target is also met. The pollution reduction target has not particularly been measured in this case, but it is relatively safe to assume that the over 85 % substitution rate of petrol, reduced pollution to a level far below the specified target of reducing greenhouse gases by 55 % compared to 2005.

9.2. Scenario 2

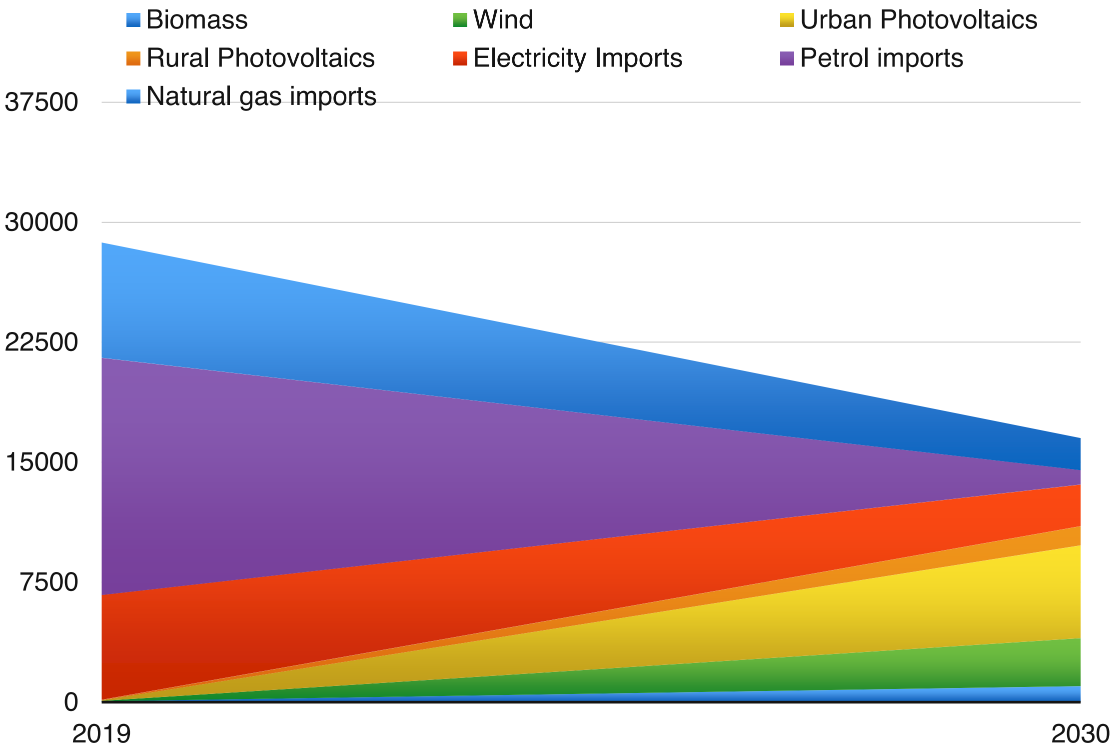


Fig. 9.2 : Scenario 2 : Optimal energy autarky – 66 % domestic renewables – 33 % imports

In the second scenario, the Luxembourgish energy demand will be reduced to the maximum that efficiency measures allow, without compromising on current living standards. This scenario requires that 100 % of buildings will be renovated in order to have state-of-the-art isolation and to have them either generating heat with heat pumps or being connected to district heating. Household buildings will therefore reduce their heating demand by 57 % (Table 7.3), while the tertiary sector reduces their energy demand by one third. Through the electrification of the entire car park and replacement of old-fashioned boilers, household fossil fuel demand will be reduced to zero. Mechanical industrial applications will be electrified, and sector coupling will improve the efficiency of energy use drastically, hence a reduction of 15 % of energy use (from 7,100 GWh/a to 6,000 GWh/a) will occur. However, process heat is still reliant on fossil fuels such as natural gas, hence natural gas imports will not be reduced entirely but limited to nearly a quarter of the natural gas imports in 2019. Petrol imports, although reduced to a maximum through the large-scale electrification of vehicles, will still be needed for certain heavy-weight transportation and utility machinery.

- Biomass will play a crucial role to reduce natural gas and petroleum products in the industry. Due to its conversion abilities and storage options, it's production will strongly increase. A yearly increase of 86 GW will require 26,6 km² of energy plants to be grown additionally each year.
- In order to cover the growing electricity demand, the expansion of wind turbines will be necessary. Hence, every year, 41 new turbines generating each 4 MW will have to be installed. In total, they will produce 3000 GW by 2030 and thus cover around 18 % of national energy demand.
- Photovoltaics will be producing the largest share of electricity. In order to reach this, a yearly increase of 630 GW is needed, which requires around 3,7 km². The largest share will be places in urban areas. They will be installed on 100 % of buildings with additional units being placed between railway tracks and along highways. The total output by 2030 of urban photovoltaics will equal 5,800 GW. However, in order to satisfy total electricity demand, an additional output of 1200 GW generating modules will have to be places in rural areas.
- In this scenario, 100 % of the efficiency potential of Luxembourg has been achieved. However, current technologies do not allow a full abandoning of fossil fuels. Especially in the industrial sector, they still prove to be crucial for process heat, but reduced to a fraction of today's consumption. The large substitution of food production for the energy plants raises concerns, as food imports are required to a larger degree. The large expansion of wind turbines also slowly raises public concerns.
- This scenario is feasible from a territorial perspective but might be challenged by public opinion.

9.3. Scenario 3

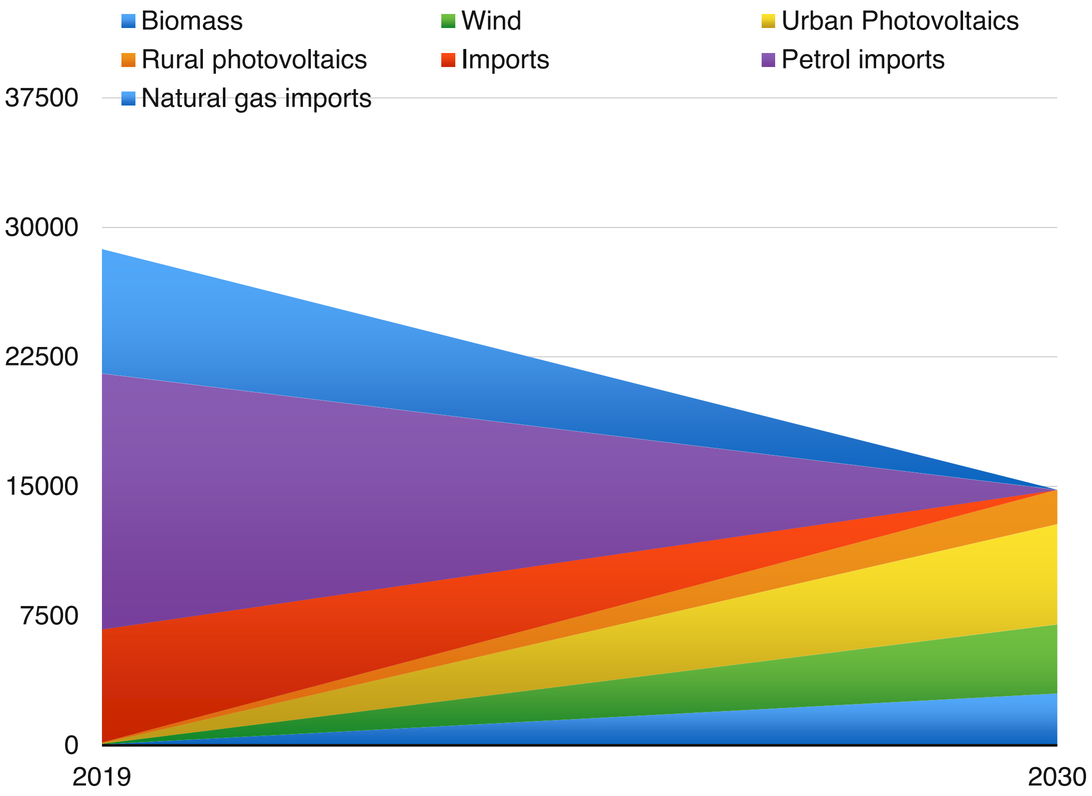


Fig. 9.3: Scenario 3: Radical renewable energy autarky – 100 % domestic renewables

In this scenario, a radical approach of full autarky will be taken. Hence the total imports have to be substituted by domestic renewables. This is only possible by a further reduction in energy consumption. Complete energy autarky in the Luxembourgish case is only possible by fully exploiting the efficiency potential and an additional shift in consumer behaviour. Additionally, some of the heavy industry, which is very energy intensive, will have to be outsourced. This will allow total energy demand to drop to nearly half of the 2019 energy demand. Electricity imports are being compensated with domestic electricity production by urban and rural photovoltaics and wind power. Since there is limited storage possibility for these, biomass will be the main energy form to generate the base load. In addition, in order to continue generating the necessary process heat for industrial applications, biomass has to be expanded tremendously.

- Biomass will be expanded to its full potential in order to generate 3,000 GWh/a. This will require a yearly increase of 82.9 km² of energy plants. However, this is only possible by using the entirety of arable land, pastures, permanent crops, and green areas for biomass production. This will have several negative effects. Firstly, food production will be entirely dismissed, as the entirety of farmable land will be used to generate energy plants. This means that full energy autarky leads to nutritious dependence as no arable land will be left for domestic food production. Secondly, the dedication of the entire farmable land for biomass production will create massive monocultures which will strongly affect local ecosystems and biodiversity.

- In order to cover the growing demand in electricity, every year 554 MW wind turbines will have to be constructed in order to reach a maximum output of 4000 GWh/a in 2030.
- Photovoltaics will experience the largest expansion. In addition to urban rooftop photovoltaics, an increase of 2000 GW rural photovoltaic installations will be necessary. In total this will require a minimum of 5.2 km² increase in photovoltaics annually.
- In the case of Luxembourg, this scenario will be difficult to realise. The limited territory of the country will lead to difficulties in reaching complete energy self-sufficiency. The massive expansion of biomass production will lead to food import dependency. In addition, citizens will oppose the massive increase in wind turbines. At peak production, national grids will be completely oversaturated without large battery storage capacities. Hence large investments have to be made in order to maintain the loads. However, these investments will not be cost-effective as most of the time, the grids will not be used to their full extent.

Table 9.1: Scenario comparisons (own calculations)

	Scenario 1		**Scenario 2**		**Scenario 3**	
Photovoltaics	357 GW	2.1 km²	630 GW	3.7 km²	884 GW	5.2 km²
Wind	131 GW	20 turbines	270 GW	41 turbines	361 GW	55 turbines
Biomass	5 GW	1.55 km²	86 GW	26.6 km²	267 GW	82.9 km²
Yearly increase	**493 GW**		**911 GW**		1.512 GW	

10. Discussion

The various scenarios depicted in table 9.1 demonstrate that it makes little sense for Luxembourg to become fully self-sufficient on an energetic level because of a number of reasons:

- Electricity grids

National grids will be oversaturated during peak time solar production. Hence an immense expansion of the grids has to take place, which is not cost-efficient as most of the time they will not transport electricity not even at close range to their full capacity. Due to limited storage capacities, it is therefore highly recommendable to have interconnections with neighbouring grids in order to favour energy exchanges either due to phases of overproduction or during periods of insufficient electricity supply. Interconnected grids also offer the possibility to spatially distribute renewable energy production, which firstly increases the average yield and thus requires less installations on average and, secondly, reduces the impact on the environment.

- Environmental concerns

The difficulty to store renewables such as solar and wind in the long term raise the need for biomass, of which the majority is generated via energy plants. Due to the sheer necessity of biomass, in case of full autarky, most of the national crops would have to be exchanged with biomass generating energy plants. Firstly, this would create massive monocultures, which is extremely detrimental to biodiversity and favours the outbreak of pests. Secondly, by substituting the entire domestic food production with energy plants, food sovereignty would be entirely annihilated. Luxembourg would then have to entirely rely on food imports as domestic production needs to entirely shift to fuel production. This would be counterproductive as food imports are extremely energy intensive in packaging, transporting, and cooling. The balance between energy self-sufficiency and environmental protection does not only concern biomass production but also other renewables such as hydro-generated electricity, wind turbines, and photovoltaic installations. As mentioned before, the expansion of hydropower plants is not further possible in Luxembourg, as damming rivers has detrimental effects for the ecosystem and has already been exploited to the largest extent possible. Wind turbines and photovoltaics also impact the environment if they are installed in rural areas. Hence it is important to keep the necessary balance uphold.

- Social concerns

By becoming fully energy self-sufficient, the expansion of renewable energy sources would not only have detrimental repercussions for the environment but also raise concerns among society. Changes are high that the public would disregard the government's efforts to reach energy autarky and eventually oppose the expansion of renewables. As citizens are crucial elements in the energy transition, losing their support would be detrimental to any further efficiency efforts. Furthermore, the energy transition should not solely be instigated by central decision makers but also be accelerated by local, decentralised elements such as energy communities.

Hence it makes little sense for a country the size of Luxembourg to achieve complete energy autarky. However, the research has also shown that a partial energy self-sufficiency is fruitful for several reasons. It reduced the need for transportation grids, which are inefficient and account for a major fraction of the energy costs. Additionally, it increases energy security and is more environmentally friendly. Luxembourg should therefore instigate the expansion of renewables at a rate that is not detrimental to the environment nor raise public concerns. According to the scenarios visualised in Chapter 8, the optimal rate of self-sufficiency lies between Scenario 1 and 2. Scenario 1 does not fully exploit the efficiency measures as presented in Chapter 6. Scenario 2 fully adapts the efficiency measures and reduces the import of energy by a significant level. However, the expansion of renewables, especially solar and wind seem are taking place in an environmentally friendly manner. Solely the expansion of biomass production might pose a threat to biodiversity and/or domestic food sovereignty. This could be countered by constructing additional storage capacities or by solely maximising wind and solar production and expanding grid connectivity with Germany. This would reduce the need for seasonal storage capacities as the overproduction can simply be transferred to the German grid during periods of low domestic production, and the necessary energetic supplies can be transmitted to Luxembourg.

The potential efficiency measures analysis conducted in the frame of this research pointed out that the energy demand can be significantly reduced solely by adopting efficient heating and mobility applications. Especially households can contribute a large share by improving the isolation of their homes and adopting heat pumps instead of old-fashioned heating installations running on fossil fuels. By electrifying the privately-owned car park, additional large energy economies can be made. In total, households can reduce their energy demand by 61 % without having to drastically change their consumption habits. (7.1) This refutes the popular opinion that the energy transition is solely possibly by drastically changing our consumer behaviour.

Through electrification of the car park and installation of heat pumps, the tertiary sector is also capable of conducting extensive reductions in energy demand. The total energy savings possible in this domain have been estimated at a third of the energy demand in 2019. The industry is the sector having most difficulties to adopt to electrification, as large amounts of peak time energy are necessary. However, through sector coupling and electrification of mechanical applications, around 15 % of the industries energy demand can be reduced. Regarding the energy intensity of the tertiary sector and the industry, it is important to elaborate on how durable their existence is. On the one hand, the survival of the Luxembourgish heavy industry is questionable in an environment of increasing global competition and continuously increasing costs. On the other hand, a domestic industry is important in terms of employment and in terms of self-sufficiency. Additionally, outsourcing energy intensive and polluting industries will not lead to an improvement in the sector but rather to the pollution being outsourced and probably worsened due to lower environmental standards in the receiving country. What is questionable, however, is the establishment of data centres in Luxembourg. Firstly, they are very resource intensive and, secondly, they do not generate much employment. Thus, energy transition does not only translate into improving the sources of energy but also questioning the consumers of energy.

In total, the energy consumption of the Grand-Duchy can be reduced from 30.5 TWh/a in 2019 (Table 4.3) to 16.5 TWh/a in 2030 (Table 7.4). This reduction in energy demand simply by the means of efficiency measures result equals a reduction of nearly 50 %. Hence, the governments milestone set for 2030 represents a reduction close to 30% in contrast to 2020. (Table 4.2) Despite, this threshold incorporating the energy demand by non-residents (mainly petrol), the efficiency potential analysis has demonstrated that this target is feasible solely by introducing the necessary mechanisms as outlined in Chapter 7.

The potential analysis conducted in the frame of this research has proven that especially the expansion of urban photovoltaics has a relatively high potential to cover a relatively large fraction of domestic electricity needs without severely affecting the environment. The potential of urban photovoltaics reaches over 5,000 GWh per year which would in an optimal efficiency scenario cover more than a quarter of national energy demand. (8.1) The expansion of biomass production proves more difficult. The territorial availability and the resulting trade-offs between energy and food sufficiency challenge the expansion. As transformed products from biomass such as biofuels or biomethane could replace fossil fuels in industrial applications that are difficult to electrify, biomass production would need to be produced differently than solely from energy crops. Additional, possible sources could be animal manure, human faeces, and other organic waste products.

In general, reaching the government´s target for 2030 of 23 % to 25 % domestic renewables of the final energy consumption is feasible. (Table 4.2) Scenario 1 (Fig. 9.1), the most conservative model, already surpasses this target. In this model, solar photovoltaics are being expanded by 2.1 km² annually, which can be covered entirely by rooftop installations. Wind and biomass have to be expanded continuously but at reasonable rates from an environmental perspective.

11. Policy recommendations

The Luxembourgish government should therefore not only enact pull factors such as subsidies but also actively implement push factors in order to accelerate the energy transition. In February 2020, the city of Hamburg introduced the §16 HambKliSchG, which denotes a photovoltaics rooftop obligation. From 2023 onwards, every newly constructed house has to be equipped with rooftop solar panels. From 2025 onwards, every renovated roof has to be furnished with photovoltaics. (Hamburger Senat 2020) The city of Berlin has decided on a similar legal concept. (Senatsverwaltung für Wirtschaft, Energie und Betriebe 2022) These provisions could work as examples for

Luxembourg, which, to this day, has only enacted demand-side incentives such as subsidies but has not yet formulated any legal ramifications. Despite the governmental financial aid, the expansion of photovoltaic installations on private roofs remains very limited. One of the potential reasons could be that energy expenses represent a very marginal share among the total expenses of Luxembourgish households. This is firstly due to the comparably low electricity prices and secondly due to the relatively high purchasing power. (4.4.1) Hence in order to incentivise the expansion of private rooftops, the government should introduce other push factors such as increasing electricity costs. With higher electricity costs and a stable long-term feed in tariff, people would have more incentives to use their roofs for electricity generation. In addition, by raising energy taxes, tank tourism would be reduced. Finally, an increase in fuel prices, would push people to rather buy an electric vehicle instead of a combustion engine. Hence raising taxes on energy products could have an overall positive effect. The government or national energy suppliers could also develop a PV contracting model, where private roofs are being leased, in exchange for free electricity for instance. The contracting company could feed with the installed panels into the national grid. This model accelerates the quantity of installed panels as private households might lack the necessary funds and thus contribute to a faster shift to renewable energy generation. Simultaneously, in order to phase out combustion engines, taxes on private cars running on fossil fuels should be raised tremendously. Electric cars are not only more efficient but also serve as critical elements in the energy transition. By increasing domestic urban photovoltaic generation, current distribution grids risk to be oversaturated during peak load production. Thus, electric vehicles are capable of relieving grids and feed the stored electricity back into the grid during periods of low electricity generation. The electrification of the car park is therefore not only necessary in order to reduce energy demand but also in order to increase storage options as seen in chapter 2.7.

12. Conclusion

This research has demonstrated various aspects in the frame of the energy transition. Firstly, it evaluated the potential reduction in energy demand by shifting from fossil fuels to electricity in transportation and domestic heating. Results show that the total energy non-ETS consumption can be reduced quite significantly by more than a third in comparison to Luxembourg´s 2019 energy demand. In addition, the energy potential of urban rooftop photovoltaics has been analysed, before assessing the full potential of biomass production. Subsequently, three scenarios of various degrees of energy self-sufficiency have been elaborated and thoroughly discussed. Hereby it became clear that full energy autarky for Luxembourg makes little sense for a number of reasons. Firstly, entire domestic production would either require an enormous increase in storage capacities or demand an immense expansion of grids which in both cases does not prove as being cost-efficient as capacities would have to match peak demand or supply which only occurs a fraction of total use. Secondly, due to Luxembourg's relatively small size and comparably high energy use per km², full autarky would lead to energy plant monocultures and the destruction of natural habits in order to produce electricity. Food sovereignty would be put at risk as crops would be replaced by energy plants which would be counterproductive. Thirdly, chances are high public opinion would oppose the growing visibility of the power-generating infrastructure. Hence, in order to mitigate these issues, an optimal degree of energy self-sufficiency between 30 % and 60 % has been identified. In the case of Luxembourg, connection to larger international grids is crucial in order to secure future energy supplies and not overload national grids. The expansion of national grids and social partaking in the energy transition by mounting solar panels on private houses have both been identified as crucial steps in order to guarantee a quick and efficient energy transition.

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