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Towards a Sustainable Energy Future

A Case Study of Luxembourg’s Transition to Renewable Energy and Carbon Neutrality

by

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Climate change poses a significant threat to humanity, with devastating consequences already occurring. Transitioning to a low-carbon economy is crucial for mitigating the effects of climate change. High per capita energy consumption and emissions make this transition an urgency for Luxembourg. This study focuses on the sustainable energy transition in Luxembourg, examining challenges and opportunities through a case study. To accelerate the transition, policymakers must implement closer regulation of energy types and provide subsidies and tax reductions for renewable energy adoption. Accountability for energy consumption and emissions should apply to both industries and individuals, with incentives to encourage their participation. Transforming the transportation sector is crucial. Collaboration beyond national borders is necessary due to limited land availability and a stance against nuclear energy and carbon capture technology. Luxembourg's progress in renewable energy transition has been comparably slow. Achieving a successful transition within Luxembourg alone may be challenging by 2050. Integration of individuals into the transition is vital for its success. Changing the low tax rate on fuels to match neighbouring countries can significantly reduce fossil fuel consumption and incentivize electric vehicle adoption. By embracing renewable energy and engaging stakeholders, Luxembourg can contribute to mitigating climate change. However, more work is needed to ensure a sustainable energy future for the country.

Key words: Renewable energy, emissions, electric vehicles, carbon neutrality, mitigation

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1 Introduction

Climate change is among the biggest threats to humanity, and we will face its devastating consequences if we continue to do 'business as usual'. In fact, we are already experiencing some consequences of human induced global warming today. Temperatures are reaching new heights, glaciers and ice sheets are shrinking, sea levels are rising and we are experiencing an ever-growing number of droughts, wildfires and extreme rainfall. This is a direct consequence of greenhouse gas emissions, like carbon dioxide and methane, across the world, of which over 75% are accounted for by the burning of fossil fuels, deforestation and agricultural practices (Fawzy, Osman, Doran and Rooney, 2020). It is therefore imperative for humanity and human welfare on earth today that we make a change.

Mitigating climate change requires global efforts to reduce greenhouse gas emissions and transition to a low-carbon and sustainable economy. This involves adopting renewable energy sources, improving energy efficiency, transitioning to cleaner transportation systems and enhancing the resilience of communities and infrastructure. International agreements, such as the Paris Agreement, aim to coordinate these efforts and limit global warming.

Transitioning our energy systems away from fossil fuels and towards a system based on renewable energy provides one of the greatest opportunities to mitigate the impacts of climate change and to halt the rise in global temperatures. It is therefore crucial that countries around the world make efforts in transitioning their energy systems towards clean and green energy. In doing so, together with reducing the general consumption of energy, humanity will stand a chance against climate change and its devastating consequences. There are many countries around the world that have already begun this transition process, with some being more successful than others, or doing so at higher intensities than others. Among them is Luxembourg. Though it is small, Luxembourg's per capita energy consumption and emissions are among the higher echelon, highlighting the need for a transition towards renewable energy and mitigating emissions.

1.1 Research Aim

The aim of this study is to use Luxembourg as the basis for a case study to analyse its progress in transitioning to an energy system based on renewable energy sources and to achieving carbon neutrality withing the next three decades. This entails analysing past greenhouse gas emission trends in Luxembourg and identifying the main drivers of said emissions, as well as gaining insights into the sectoral structure of emissions. As such, the focus of this study is also going to be on the high emitting sectors in Luxembourg, analysing trends, identifying patterns, searching for explanations for these trends and patterns and to identify possible solutions or pathways that can be of aid in the transition towards renewable energy and carbon neutrality. Furthermore, the focus of the paper will also be on identifying constraints to such a transition. Both in general terms and also specifically for Luxembourg and its context. Successfully implementing such a transition without the use of carbon capture technologies and nuclear energy can especially be especially challenging, and since there is a general consensus among officials and the population in Luxembourg against these methods, especially against nuclear energy, exploring whether Luxembourg can be successful in its transition without the use of these methods will also be a focus of the study. Ultimately, the study intends to contribute to the currently scarce academic research and literature on Luxembourg's energy transition towards renewables by identifying patterns, discovering causes of certain trends and by making recommendations for further in-depth analyses for specific findings.

2 Relevant Background on Luxembourg

2.1 Energy Intensity and Carbon Intensity

Energy intensity is a measure of how much energy is required to produce one unit of GDP, i.e., it tells us how much energy was used to create a certain amount of output (Kander, Malanima and Warde, 2014, p. 25). It also serves to estimate an economy's dependence on energy and its energy supply vulnerability, both of which are important for policymakers (Bhattacharyya, 2011, p. 31; Weber, 2008). There is a difference between economic efficiency and thermodynamic efficiency. Thermodynamic efficiency focuses on the physical conversion of energy from one form to another, whereas the economic efficiency relates to turning energy into units of value, such as into euros or dollars (Kander, Malanima and Warde, 2014, p. 22). GDP intensity, which is energy intensity when determined on a national basis using GDP, can be defined by the use of primary or final energy consumption (Bhattacharyya, 2011, p. 31). Lower energy intensity is the desired goal, as it characterises an efficient allocation of energy resources to create wealth and a high quality of life (Martinez, Ebenhack and Wagner, 2019, p. 7). Energy intensity also serves as a comparative measure between countries. Increasing the efficiency of materials production and outsourcing the production of manufactured goods to other countries to then buy them can lower energy intensity as well as using advanced energy extraction and conversion techniques (Martinez, Ebenhack and Wagner, 2019, p. 7). The shift away from coal towards electricity is an example of how energy intensity can be reduced.

From 1965 up until the beginning of the 80s, Luxembourg's energy intensity, when measured as primary energy consumption per unit of GDP, has been significantly above that of its neighbouring countries (France, Germany and Belgium), as well as double that of the world average (Ritchie, Roser and Rosado, 2022). In 2018, energy intensity in Luxembourg was measured at 1.33 kWh (per 2011$ Purchasing Power Parity), positioning it at better places than its neighbours Belgium, but still far above most other European countries (Ritchie, Roser and Rosado, 2022). Luxembourg has made gradual process in reducing its energy intensity values from a high 7.01 kWh in 1965 to 1.33 kWh in 2018. Decreasing energy intensity measures show that progresses in reducing emissions have been made throughout that time (Ritchie, Roser and Rosado, 2022).

Another important metric in measuring a country's improvements in terms of emissions is carbon intensity of energy production, which is the ratio of carbon dioxide per unit of energy (World Bank, 2023c). The amount of carbon dioxide emitted per unit of GDP measures the carbon intensity of the economy (Roberts and Grimes, 1997; Rodriguez, Pansera and Lorenzo, 2020). From 1967 to 1990, where it peaked at 0.3 kg of carbon dioxide per kWh, Luxembourg experienced an increase in its carbon intensity. In the years between 1990 and 2021 this score dropped to 0.2kg of carbon dioxide per kWh, indicating progress in reducing their emissions. For comparison, the world average fluctuated between 0.22 and 0.26 kg of carbon dioxide per kWh in that timespan, and with Luxembourg's neighbouring countries generally scoring better in terms of carbon intensity of energy production. The indicators however also encounter limitations. Rodriguez, Pansera and Lorenzo (2020) argue that intensity indicators can be vastly misleading if they are being used uncritically and that they are often perceived as a measure of 'win-win sustainability' where economic growth can easily be decoupled from energy consumption, thus potentially misguiding policymakers. While this is beyond the scope of this paper, it is nonetheless important to be aware of the limitations. Table 1 shows a comparison of energy intensity and carbon intensity levels of Luxembourg and its neighbouring countries at two points in time. One can observe that while all countries have made improvements since 1965, Luxembourg records the steepest progress in terms of energy intensity, but has still not caught up with the majority of its neighbours. In terms of carbon intensity, improvements have been made, though Luxembourg still lags behind its neighbouring countries. This table simply serves to show how Luxembourg compares to its neighbouring countries, as well as to emphasise the improvements made up to 2018.

Table 1: Comparison of Luxembourg and its neighbouring countries in terms of energy intensity and carbon intensity.

	Year	Luxembourg	Germany	Belgium	France
Energy intensity (kilowatt-hours per 2011$ PPP)	1965	7.01	2.68	3.20	1.80
	2018	1.33	0.98	1.60	1.08
Carbon intensity (kg of CO2 per kilowatt-hour)	1965	0.29	0.32	0.26	0.28
	2018	0.21	0.20	0.14	0.12

Source: Ritchie, Roser and Rosado (2022).

2.2 Luxembourg's Energy Profile

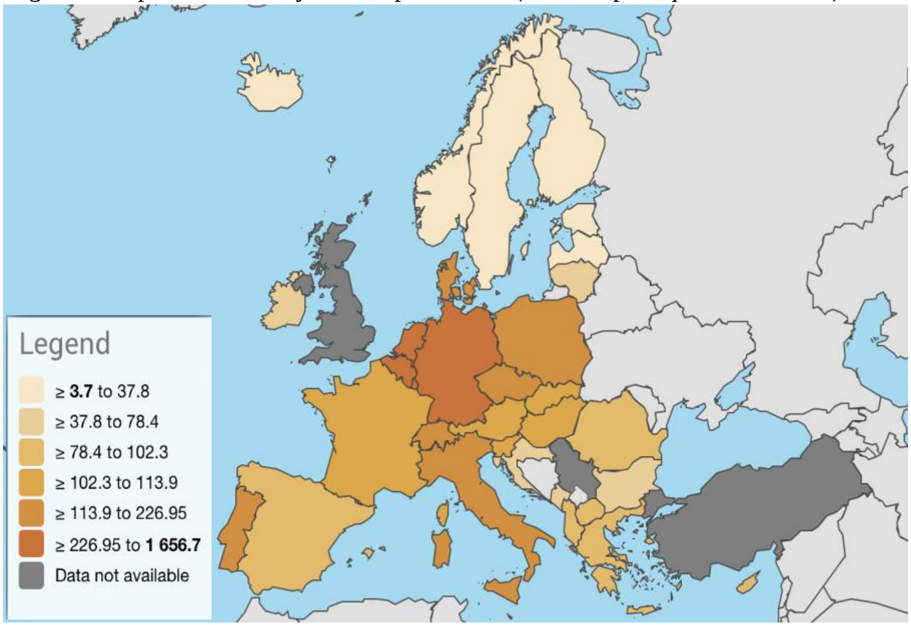
Luxembourg is marked by a high reliance on fossil fuel imports, with the country importing 95% of its energy supply in 2018, primarily from Germany and France (IEA, 2020). Between 2014 and 2019 energy imports increased, while exports decreased (IRENA, 2022a). Oil and natural gas are the dominant energy sources of the country, being used for transportation, residential and commercial heating, as well as industrial purposes (IEA, 2020). The use of coal, as a means of generating energy in Luxembourg, has been virtually abolished, and is primarily used for non-energy purposes (IEA, 2020). Energy coming from nuclear power has, according to data reaching back to 1965, never been part of Luxembourg's energy mix (BP, 2022). In terms of access to electricity and clean fuels for cooking, as a share of the population, Luxembourg records a rate of 100% (IRENA, 2022a) and between 95-100% (Ritchie, Roser and Rosado, 2022; IRENA, 2022a) respectively.

Despite recording a gradually declining per capita primary energy consumption, from 144833kWh in 1974 to 65830kWh in 2021, Luxembourg's per capita primary energy consumption is more than three times higher than the world average, and almost double that of the EU average (Ritchie, Roser and Rosado, 2022). Among the reasons for this comparably high energy consumption is the steel industry, which uses large amount of energy in their steel production, as well as fuel tourism for motor fuels, where non-residents make their way into

Luxembourg for the sole purpose of buying cheaper priced fuel (Enerdata, 2021). Additionally, Luxembourg's high population density (as can be seen in Figure 1 and more in detail in Table 2) is another factor playing into the high energy consumption (Zarco-Perinan, Zarco-Soto and Zarco-Soto, 2021) In terms of total energy consumption, which includes electricity, transport and heat, a different trend appears, with Luxembourg being one of the lowest total primary energy consumers (Ritchie, Roser and Rosado, 2022). This in itself can, however, be very misleading, given that Luxembourg is a much smaller country with only a fraction of the population of its neighbouring countries. Therefore, using per capita energy consumption data is a much better alternative for comparing energy consumption trends. Table 3 shows total and per capita energy consumption of Luxembourg and its neighbours. We can see that while Luxembourg's total energy consumption is much lower than that of its neighbours, its per capita energy consumption sits at the top.

An interesting finding is that total primary energy consumption has only changed slightly, compared to the large increases in its neighbouring countries. This is especially interesting when learning that Luxembourg's population has almost doubled in the same time span. This trend could be explained by a combination of factors, such as improvements in energy efficiency, economic changes, in the sense that Luxembourg transitioned away from being a heavy and mining industry and towards a more service-oriented industry (Harmsen and Högenauer, 2021).

Figure 1: Population density in Europe in 2022 (Persons per square kilometre)



Source: Eurostat (2023a).

Table 2: Population density in Europe in 2022 (Persons per square kilometre)

Country	Persons per square kilometre in 2022	Country	Persons per square kilometre in 2022
Malta	1656,7	Spain	94,3
Netherlands	512,8	Romania	81,6
Belgium	380,5	Greece	81,3
Liechtenstein	248	North Macedonia	78,4
Luxembourg	247,5	Ireland	73,3
Germany	235,5	Croatia	70,7
Switzerland	218,4	Bulgaria	62,5
Italy	198,6	Montenegro	45,5
Denmark	139,5	Lithuania	44,7
Czechia	136,1	Estonia	30,9
Poland	122,9	Latvia	29,8
Portugal	113,9	Sweden	25,6
Slovakia	111,8	Finland	18,2
Austria	108,5	Norway	14,8
France	106,9	Iceland	3,7
Hungary	106,4	United Kingdom	n/a
Slovenia	104,6	Serbia	n/a
Albania	100	Türkiye	n/a
Cyprus	97,7		

Source: Eurostat (2023a).

Table 3: Comparison of Luxembourg and its neighbouring countries in terms of total primary and per capita energy consumption.

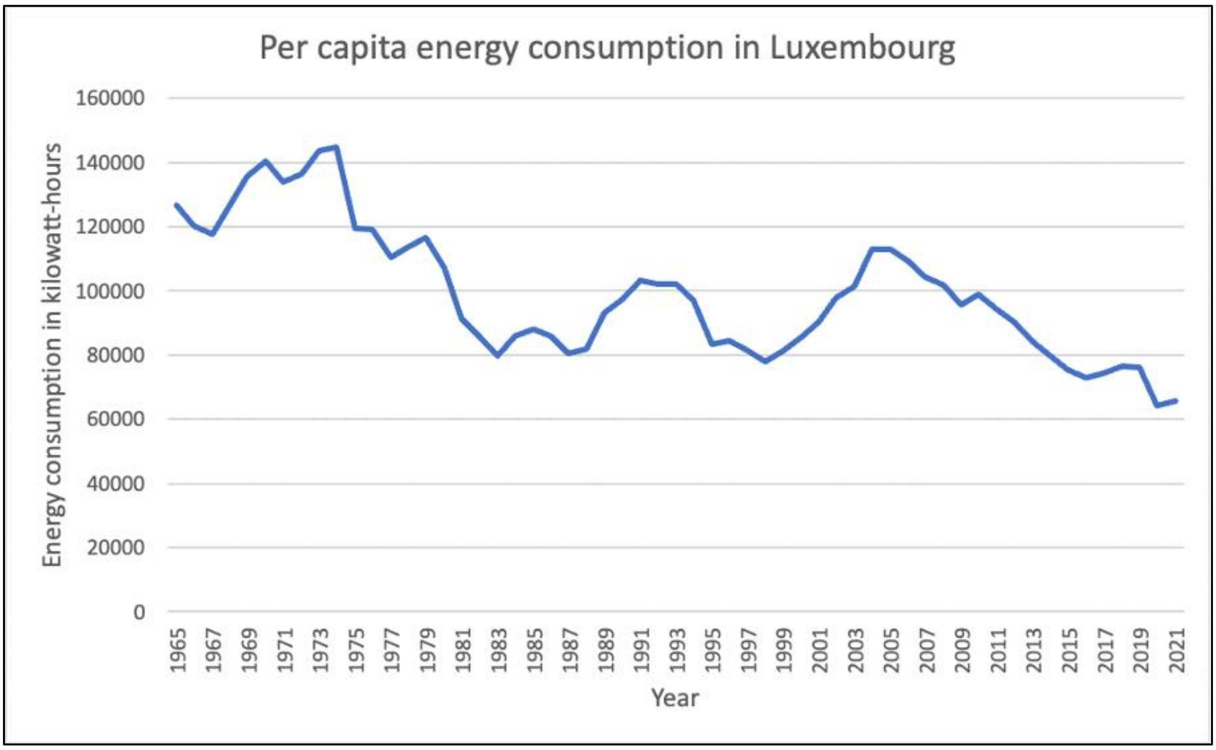
	Year	Luxembourg	Germany	Belgium	France
Total primary energy consumption (terawatt-hours)	1965	42	2969	413	1310
	2018	46	3793	726	2791
Per-capita energy consumption (kilowatt-hours)	1965	126758	39050	43873	27189
	2018	76382	45754	63411	43423

Source: Ritchie, Roser and Rosado (2022).

Other reasons for this could be government policies and regulations together with the integration of renewable energy. Despite the seemingly modest change in primary energy consumption, one can find a volatile trend over the last half a decade when looking at it in terms of the percentage change of consumption compared to the previous year. In 1975 for example, consumption dropped by almost 17%, with consumption reaching its peak in 1989 at almost 15% (Ritchie, Roser and Rosado, 2022). The drastic drop of energy consumption in the mid-seventies can in large part be explained by the energy price shock in 1973-1974 and its subsequent rise in oil prices, which followed the oil embargo imposed by Arab members of the Organization of Petroleum Exporting Countries (OPEC) (Mork and Hall, 1980; Ölund, 2010). Figure 2 shows the trend in per capita energy consumption in Luxembourg from 1965 onwards. We can observe a gradual decline in per capita energy consumption, as well as the effects of the energy price shock in the mid-seventies.

In terms of per capita electricity production, Luxembourg lags behind. Per capita electricity production in Luxembourg is almost half of that of world average, and significantly less than in Norway and Sweden for example. While per capita electricity production was at a little less than 2000 kWh in Luxembourg in 2021, Norway's and Sweden's per capita electricity production reached levels of almost 28000 kWh and 16500 kWh respectively (Ritchie, Roser and Rosado, 2022). When looking at electricity consumption by its own, one can spot a gradual decline in electricity consumption from 2006 onwards, where it peaked at 3.54 TWh and dropped to 1.19 TWh in 2022 (Ritchie, Roser and Rosado, 2022). In 2021, when electricity production was 1.21 TWh in Luxembourg, 1 TWh (roughly 82.5%) of this was generated from renewable energy sources (BP, 2022).

Figure 2: Per capita energy consumption in Luxembourg over time.

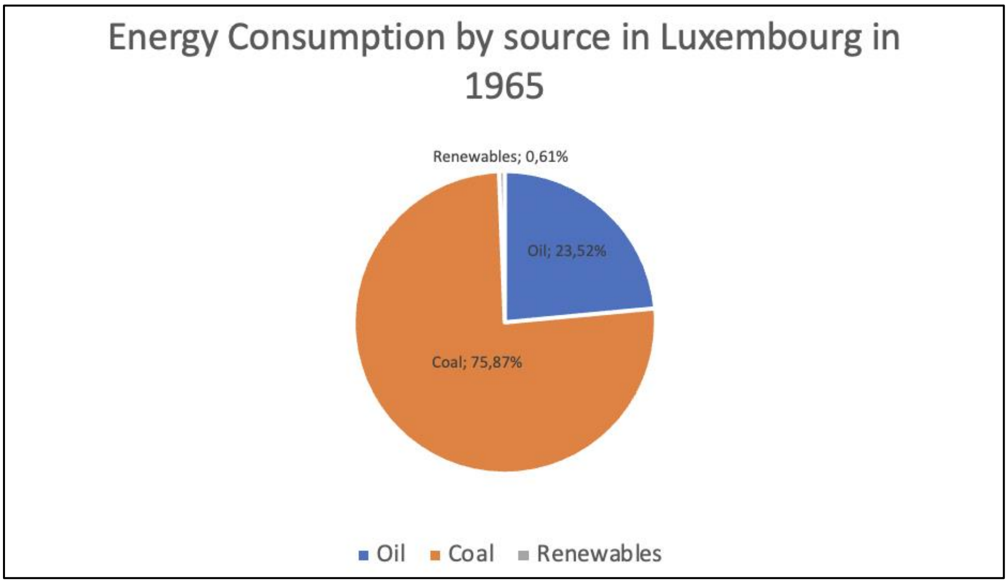


Created by the author using data from Ritchie, Roser and Rosado (2022).

Data from 1965 until 2021 shows that coal and oil together made up over 85% of Luxembourg's energy mix up until the 90s, with gas playing a small, and renewable energy sources playing an insignificant role in the country's energy mix (Ritchie, Roser and Rosado, 2022). While hydropower has been part of the energy mix since at least 1965, although seldomly accounting for more than 1% of total energy consumption, wind and solar energy have grown towards the end of the 90s, making up, together with hydropower and other renewables, a total of roughly 3.6% of Luxembourg's energy mix in 2019 (Ritchie, Roser and Rosado, 2022). Hydro, wind, solar, geothermal, as well as bioenergy, accounted for 83% of the country's total renewable energy supply in 2019 (IRENA, 2022a). Biomass and biofuels were primarily imported and used for transportation and heat and power plants, with wind and solar generated energy currently playing a small, but growing role (IEA, 2020). Between 2014 and 2019, renewable energy sources grew by almost 118%, as a share of total energy supply (IRENA, 2022a). Different sources however contend that renewable energy sources accounted for 13% of Luxembourg's total primary energy supply in 2019 (IRENA, 2022a), rising from 3.3% in 2008

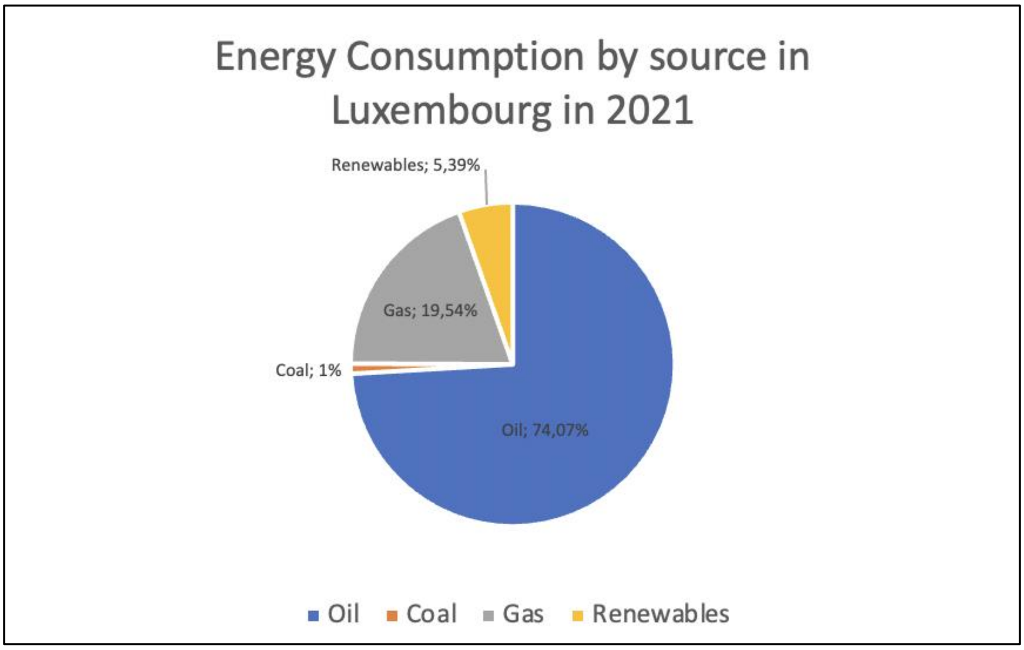
(IEA, 2020). Eurostat (2023b) found that Luxembourg's share of renewable energy sources were 7% in 2019, significantly below the EU average of 19.8%. According to this data, Luxembourg's share of energy from renewable sources has risen to 11.7% in 2021. Despite the progress made, Luxembourg remains at the bottom of the list of countries in the EU in terms of the share of energy that is coming from renewable sources. Figures 3 and 4 display Luxembourg's energy consumption by source in 1965 and 2021 respectively. The data used for these figures is taken from Ritchie, Roser and Rosado (2022), and puts the share of renewable energy in energy consumption at 5,39% in 2021. These figures serve as a visualisation of the changes in Luxembourg's energy mix and illustrate how coal has transitioned from being the dominant source in the mid-sixties towards playing a small and insignificant role in 2021. Instead, the role of oil has grown over threefold, currently making up roughly three quarters of energy consumption in Luxembourg. Furthermore, the figures highlight how gas has emerged from nowhere in 1965, to making up almost a fifth of Luxembourg's energy consumption.

Figure 3: Energy consumption by source in Luxembourg in 1965



Source: Created by the author using data from Ritchie, Roser and Rosado (2022).

Figure 4: Energy consumption by source in Luxembourg in 2021



Source: Created by the author using data from Ritchie, Roser and Rosado (2022).

When analysing the electricity mix specifically however, a very different picture of Luxembourg emerges. Oil and gas played a primary role in Luxembourg's electricity generation between 1990 and 2015, where these two sources alone accounted for between 60% and 95% of total electricity production (BP, 2022). Since 2015 however, bioenergy, solar, wind and hydropower have taken over and were responsible for over 85% of electricity generation in 2022 (BP, 2022). Table 4 depicts the share of renewables in electricity generation in Luxembourg and its neighbouring countries in 1990 and 2022 respectively. We can observe an overall trend in the growth of renewables, with Luxembourg having the highest share of renewables in electricity generation in 2022.

Table 4: Share of renewables in electricity generation (in % of total electricity generation)

Year	Luxembourg	Germany	Belgium	France
1990	12,9	3,49	0,79	13,37
2022	85,71	42,89	25,45	24,54

Source: Ritchie, Roser and Rosado (2022).

Note that nuclear energy is part of the energy mix in Germany, Belgium and France, but not include in these calculations. Though the process of electricity generation may be carbon neutral, it is not considered as a renewable energy. In Belgium, the share of nuclear energy made up nearly half of its electricity generation, almost two thirds in France and around 6% in Germany in 2022, all of which are lower than their respective shares in 1990.

Commuters, who do not live in Luxembourg, make their way into the country for work or to take advantage of its cheap gasoline and tobacco prices distort the true per capita energy consumption, which makes these national statistics misleading. The impact of commuters on per capita consumption becomes quite evident when learning that the growth rate of commuters is five times higher than the growth rate of the Luxembourgish population (Rugani, Marvuglia and Pulselli, 2018), thus driving up the number of per capita consumption statistics. The number of commuters coming from Luxembourg's neighbouring countries has increased by over 300% over the last 20 years, and is expected to grow further in the coming years (Rugani, Marvuglia and Pulselli, 2018). To put this into numbers, in 2010, Luxembourg had a population of roughly 507'000, and the number of commuters at that time was estimated to be over 150'000 (Rugani, Marvuglia and Pulselli, 2018), meaning that Luxembourg's population would grow by over 30% during the day. This undoubtedly has a big effect on energy consumption in the country, though it should not hide the fact that Luxembourg is a big energy consumer, but it does help in understanding just why it is so high.

3 Theory and previous research

This section will briefly provide an insight into previous research on energy and sustainable energy transitions, a theoretical understanding thereof, as well as an overview of related work for renewable energy and a sustainable energy transition on Luxembourg specifically. Underlying knowledge of the characteristics of (sustainable) energy transitions, as well as previous research in this field, will be helpful for analysing the case of Luxembourg.

3.1 Energy Transitions

Research on energy transitions in the last century has found a lot of interest in academia, with many scholars analysing these from a multitude of angles. Leach (1992) for example analysed the substitution of traditional biomass fuels by 'modern' energy sources (fossil fuels and electricity) in the household sector of developing nations, finding that this process of transition is highly dependent on urban size and household income, as access to 'modern' fuels is limited and costs related to their use are high. Some of the key insights of previous research on historical energy transitions include that they are relatively rare and take a long time, that they involve the introduction of new primary energy sources, that energy consumption has surged following energy transitions, that they are influenced by environmental and economic factors and that they have historically been national-scale transitions (Fouquet, 2016; Fouquet and Pearson, 2012; Solomon and Krishna, 2011; Sovacool, 2016; Grubler, 2012).

A transition in itself simply refers to the process of moving from one condition or action to another. The meanings of energy transitions have steadily varied over time. In the 1930s, for example, it was considered a change in energy states that occur with molecular dissociation, whereas in the 1970s it focused on fuel substitution and resource limitations (Semenoff and Shecter, 1930; Robinson, 1976; Wishart, 1978; Araujo, 2014). Nowadays, the focus has shifted towards emphasizing the way that developments in technology, information and practices can change the way that energy is used (Araujo, 2014). While there is no generally accepted hierarchy of meanings, the term 'energy transition' is most commonly used to describe "the changing composition (structure) of primary energy supply" (Smil, 2017, p. ix), i.e., "the gradual shift from a specific pattern of energy provision to a new state of an energy system" (Mazzone, 2020, p. 320). The transition from traditional biomass, such as charcoal, wood and crop residues, towards fossil fuels, coal for example, has been universally experienced and is the most example of such a transition process (Smil, 2017, p. ix). It can be argued that there have been three typical energy transitions globally: the above-mentioned replacement of wood with coal as the main energy source, the transition where oil replaced coal as the dominant energy source, and finally the latest energy transition, where there is global commitment to use renewable energy to replace fossil fuels (Kabeyi and Olanrewaju, 2022). The first two mentioned historical transitions have mostly lasted over centuries to achieve and were stimulated by high labour costs, resource scarcity and technological innovations (Solomon and Krishna, 2011). The current energy transition towards renewable energy however does not have the luxury of time and will need to occur at a much faster rate than previous transitions, given that an unsuccessful global transition can have devastating consequences for our climate and humanity (Solomon and Krishna, 2011).

A sustainable energy transition simply refers to the transition away from current energy systems and practices, which are, on the global scale, predominantly based on fossil fuels, and towards an energy system built on renewable energy sources. This is also often referred to as a transition towards renewable energy. The drivers of energy transitions are numerous and can differ from transition to transition. Some observed drivers include political and institutional interventions on energy, energy technology pathways and technological interventions, social practices and values for energy, the availability of alternative energy sources, as well as economic considerations (Edomah, 2018). Any of these factors can, depending on the local context, influence and drive an energy transition. Among the key drivers for the energy transition towards renewable sources is the global effort to limit the effects of climate change, especially through emissions cutting (Bogdanov et al., 2021). Transitioning to renewable energy as the primary source of energy is believed to hold the key to tackling both the current global energy crisis, which began in 2021 following the pandemic and escalated quickly in early 2022 as a result of the Russian invasion of Ukraine, and the climate crisis (IRENA, 2022c; IEA, 2023). Additionally, renewable energy also provides a means through which countries can reduce their energy dependence and ensure energy security, which has become a growing concern for the EU in recent years (Ozturk, 2013; Boehm and Wilson, 2023).

Academic interest and research into energy transitions towards renewable energy sources is currently very high as there is growing concern worldwide about environmental degradation stemming from current energy systems, concerns about the energy security and energy dependence of nations, prospects of the benefits of renewable energy on the economy and the environment, as well as technological advancements in the efficiency of renewable energy and related infrastructure (York and Bell, 2019; Al-Shetwi, 2022). Bogdanov et al. (2021) for example analysed how the fundamental structure of the global energy system can shift from low efficiency to high efficiency through the use of low-cost solar, wind and other natural energy sources. Khoie, Ugale and Benefield (2019) analyse the role of renewable energy for the case of the United States and find that its use can significantly reduce greenhouse gas emissions and improve energy security. Brodny, Tutak and Bindzar (2021) analysed the direction of renewable energy developments in European countries. Gernaat et al. (2021) analyse the impact of climate change on renewable energy supply. Over the past few years, a great deal of attention has also been placed on the societal and economic effects of renewable energy. The findings of recent studies vary greatly, ranging from the negative effects of renewable energy on social welfare, to the positive effects on job creation, local employment, health, community development, consumer choice and wealth creation (Ahn, Chu and Lee, 2021; Kumar, 2020; Ram, Aghahosseini and Breyer, 2020; Caruso, Colantonio and Gattone, 2020; Madaleno and Nogueira, 2023).

3.2 Previous research on the sustainable energy transition in Luxembourg

A decent amount of academic research relating to the transition towards renewable energy, or aspects of sustainability, in Luxembourg has been conducted, though there appears to be a gap in the literature that specifically focuses on the renewable energy transition in Luxembourg, how it has developed so far, what its potential is and how the transition can be undertaken.

Arababadi, Leyer, Hansen and Arababadi (2021) have investigated the energy use in residential buildings, both in terms of quantity and source of energy, in Luxembourg. Their research was theory driven and highlighted future concerns. One significant finding of this study was the limited effectiveness of the strategy aimed at increasing the proportion of renewable energy sources to reduce dependence on conventional fuels and lower the carbon footprint.

Furthermore, this study revealed that in Luxembourg, construction activities play a crucial role, with energy efficiency schemes being highly reliant on the construction sector. Thus, addressing energy concerns at a macro level should be approached as a function of construction activities rather than as an independent endeavour. In a study that investigated public consideration of the energy transition towards renewable energy in Luxembourg, Arababadi, Leyer, Hansen, Arababadi and Pignatta (2021) surveyed people in Luxembourg. The results indicated that people did not imagine their future differently and that there was a lack of optimism in the future, which the authors found concerning. As such, the findings confirmed that the need of an energy transition is relatively far from people's considerations.

Faller and Schulz (2018) investigated the interplay of several actors in the biogas and building industries in Luxembourg who are efficiently producing and/or using renewable energies, as well as how their practices changed over time. The study identifies two aspects of the transition process: the advanced state of changes in the biogas sector, leading to the emergence of a new industry, and the early stage of development in the green building sector in Luxembourg, characterized by the emergence of new practices and actor configurations. Changes in the biogas sector, including shifting actor constellations and new practices, contribute to the establishment of a new sector and shape the regional context. In the green building sector, public policies, regulations, incentives, and transformative actions by corporate agents play a significant role, while the civic sector has limited influence.

Cucchiella et al. (2021) analysed the energy transitions of Western European countries, including Luxembourg. They find that Luxembourg's energy policy seems to be the most successful of cases studied (Austria, Belgium, France, Germany and the Netherlands), with initially starting the transition at lower levels than other studied cases but exhibiting the largest growth in renewables. Their policy recommendations for the Luxembourgish government include an introduction of carbon pricing tools, reducing duties and barriers to entry for renewable energy sources, as well as taking political measure in favour of electric mobility, especially in cross-border travel with its neighbouring countries. More generally, Cucchiella et al. (2021) find that the yield in renewable energies has been higher in countries where energy policy is not fragmented, and that growth is higher in countries with various forms of subsidies.

3.3 Theoretical Framework

Sustainability transition theory is an emerging scientific field that examines complex and long-term processes of transformation. It emphasises the transformative process required to switch from conventional energy systems, based primarily on fossil fuels, to sustainable alternatives. It recognises that transforming the energy system towards renewable energy encompasses a fundamental transformation of current energy systems. By recognising the multidimensional nature of sustainability transitions, sustainability theory offers a comprehensive understanding of the intricate interconnections of differing factors. These processes involve a comprehensive integration of technical, organizational, economic, institutional, social-cultural, and political changes (Hermans 2018). Sustainability transition theory thus offers an insight into the factors shaping and influencing transitions, including institutional arrangements, policy frameworks and social dynamics (Smith, Voß and Grin, 2010). The concept of sustainability transitions has become a core concept used to bridge different scientific disciplines and societal challenges, and has become increasingly universal, comprising a large range of sectors, domains, as well as societal issues (Loorbach, Frantzeskaki and Avelino, 2017). Within the context of Luxembourg, sustainability transition theory assists in identifying institutional actors and their role in promoting renewable energy, it helps in analysing policy measures aimed at guiding the transition towards renewable energy and gives insights into policy instruments, financial incentives, as well as regulatory frameworks. Furthermore, it can aid in following trends of social acceptance of renewable energy projects, the role of social movements and public engagement.

The Innovation Systems Approach concentrates on the role that innovations play in influencing sustainable developments. Researchers in various fields contend that technological development should not be considered as isolated phenomena, but should rather be studied as part of a wider system, an ‘innovation system’ (Bergek, 2011). Such systems are considered very important determinants of technological change, with changes in existing systems evolving together with the process of technological change (Hekkert et al., 2007). While the aim of an innovation system is to develop, diffuse and use innovations, few innovation systems have been created for that purpose, with actors within the same system being driven by personal goals rather than overarching system goals (Bergek, 2011). While there is a variety of definitions of innovation systems, and consequently different interests, Lundvall (1992) focuses on the production, use and diffusion of new, as well as economically useful, knowledge more generally. In this system, the direction and rate of innovations are influenced by regulations and standards (Bergek, 2011). As such, one can assume that governments can directly influence the creation of new innovations, as well as the rate and speed of diffusing these innovations into society. By adopting this perspective, the intention of the innovation systems approach framework is to explore and better understand the innovation dynamics within Luxembourg, and more specifically in the energy and transport sector. It furthermore aims to examine the adoption and diffusion of renewable energy and carbon neutral technologies.

Social Practice Theory is a theoretical framework that focuses on understanding social practices affect, and are affected by institutions, individuals and wider socio-cultural contexts. It provides a conceptual framework for observing, analysing and understanding social phenomena, and represents an exclusive perspective on, in this case, green consumption behaviours (Sadovnikova and Pujari, 2017; Ali, 2021). It shows that the behaviour of consumers is more dependent on existing practices, rather than interpreting information that has not yet been practiced upon (Ali, 2021). The theory outlines that, in the context of green (sustainable) purchase behviour, consumers are more inclined to purchasing products that they have previously engaged with and of which they already have an understanding of the environmental effects (Ali, 2021). As such, by studying social practices in the context of sustainable energy transitions, this theory offers valuable insights into the social aspects of the transition process. It furthermore helps identify already existing energy-related practices within households and communities, but also highlights the role of social interactions and networks in driving a transition to renewable energy. By analysing the trend of Luxembourg's transition towards renewable energy through a social practice theory perspective, one can gain a better understanding of the role that individuals and networks play, whether it is in driving the transition or blocking it.

The theoretical framework comprises the sustainability transition theory, the innovation systems approach and the social practice theory, all of which are required to provide a comprehensive understanding of Luxembourg's energy transition towards renewable energy. By integrating these three theoretical approaches into the framework, a deeper analysis of the barriers to-, drivers and dynamics of the transition process can be facilitated. This foundation will guide the empirical investigation and analysis that will be undertaken in the case study, and as such provides valuable insights into the specific context of Luxembourg's sustainable energy transition.

4 Methodology and Data

The following section will explain the methodological choices that were made for this study, as well as the data and sources that were used throughout the study. The Case study was chosen as the methodological foundation of the study as it allows for in-depth understanding of phenomena.

4.1 Research Design

A qualitative approach was chosen for this study as it was deemed the most appropriate method to conduct an in-depth analysis of Luxembourg's progress in its transition to renewable energy as well as in its target of reaching carbon neutrality. While previous academic research in the field of sustainable energy transitions in Luxembourg has been limited, especially when compared to other countries, the research methods have been of both quantitative and qualitative kind. A qualitative method was chosen to contribute to the already existing research in this field and to complement it with new findings. The objective of qualitative research is to comprehend a particular social situation or event, and is largely an investigative process, in which the scholar progressively makes sense of a social phenomenon through comparing, contrasting, replicating and classifying the object of the study (Locke, Spirduso and Silverman, 1987; Miles and Huberman, 1984). Its advantage lies in the fact that it focuses on a single case, and therefore enables the researcher to intensively analyse the phenomena. Qualitative research distinguishes itself from quantitative research through several unique characteristics. It is based on assumptions that are different from quantitative research, with no establishment of theories or hypotheses per se; data collection is primarily done by the researcher, and the emerging data is of descriptive kind, rather than in numbers (Marshall and Rossman, 1989, p. 92). Unlike quantitative research, qualitative research enables researchers to examine the 'why'' and 'how' of phenomena, it can give them an understanding of how and why specific things occur. A qualitative case study can provide researchers with a means of interpreting their research results (Jackson, 2009, p. 86).

Some of the previous research in this field has been primarily focused on individual sectors in Luxembourg, such as the residential buildings and bio energy sectors. Previous research has also identified means through which the transition towards renewable energy may be accelerated in Luxembourg. The aim of this study is to assess some of these findings and to analyse how they can be implemented and what their implications could look like, based on theoretical knowledge, as well as empirical findings. Theoretical and practical research results from other case studies will also be assessed and compared with the case of Luxembourg in order to observe whether the findings can be applied to Luxembourg or whether they are context specific.

As such, the study is conducted as an explanatory qualitative case study analysing the sustainable energy transition in Luxembourg. The benefit of an explanatory case study lies in its ability to develop an understanding of the phenomenon of interest, as well as to develop design options that can be used in a more focused and in-depth subsequent study, as well its capacity to answer 'why' and 'how' questions (JRSA, 2021). The method of comparable analysis is used to address the research question, with a focus on Luxembourg as the primary case study, but including other cases for the purpose of comparison. Additionally, pattern matching is made use of, as it allows an analysis of how trends match their respective theory. A qualitative comparable analysis, established by Mill (1843), can be used to establish causal relationships through systematic comparisons and can be used to identify common causes or effects of a specific phenomenon (Roig-Tierno, Gonzalez-Cruz and Llopis-Martinez, 2017). Ensuring validity and reliability of the case study are necessary for high quality research. Halperin and Heath (2012, p. 174) contend that a successful qualitative study is both internally and externally valid. While there is no one set of measures to ensure validity in a qualitative study (Hayashi, Abib and Hoppen, 2019), attempts have been made to promote validity. Generalisability of research results is one such indicator for validity (Golafshani, 2003).

4.2 Case selection

Selecting a case is often understood as a particularly delicate and demanding step (Leuffen, 2007). Seeing as cases in small n-samples are usually not chosen at random, researchers can be in big jeopardy of introducing selection bias (Leuffen, 2007). Selection bias, if not reduced to a maximum, can severely undermine the validity of the research (Collier and Mahoney, 1996).

Halperin and Heath (2012, p. 175) provide a way through which selection bias can be reduced. This approach entails identifying the population that the researcher is interested in, and to then define precise selection criteria to reduce the pool of potential cases. The final step is to identify and pick the case (or cases) that will be subject to investigation. As such, the first step was to identify the population of interest. Given that the research focus is to analyse sustainable energy transitions, countries that are in the process of such a transition have been shortlisted, as there would not be any significant research results if a country was chose that had not yet begun its transition towards renewable energy. The second step was to establish clear selection criteria to ensure a systematic and unbiased process. These included factors like economic growth and population dynamics, both of which are relevant to such a transition. I then performed an initial screening of potential countries based on their relevance to the research focus and meeting the selection criteria. The results of this screening process generated a shortlist of countries for further evaluation. The next step was to conduct a comparative analysis of the selected countries, considering indicators such as renewable energy policies, energy consumption patterns, carbon emissions, and existing infrastructure. This process left me with a number of potential cases, which underwent an in-depth assessment of their renewable energy efforts, their national renewable energy and emission targets, initiatives, as well as investments. This assessment provided valuable insights into Luxembourg's potential as a case study. Lastly, after considering all the gathered information, an informed decision was made, and Luxembourg was chosen as the subject of this case study. Luxembourg was chosen due to its notable economic growth, its distinct population dynamics, as well as its ongoing transition towards renewable energy sources.

4.3 Data

For the purpose of this study, and its aim to analyse the transition towards renewable energy sources in Luxembourg, both qualitative and quantitative data was used. The case study solely relies on secondary data, and no primary data was collected in connection to this study. Gathering primary data for this would have been very time consuming and costly, and not needed as the required data had already been made available. The use of secondary data was deemed appropriate and sufficient for the scope of this study. A benefit of using secondary data is that the researcher can make use of any data collected in the past, when giving credit to the original owner of the data (Kumara, 2022). On the other hand, using secondary data, researchers have no means of correcting the data for errors, which is why it is essential for researchers using secondary data to evaluate the data collection process wherever that is possible (Kumara, 2022). Additionally, secondary data may suffer from missing data and may not provide all the information that is required by the researcher (Kumara, 2022). For a case study, any type of data can be considered and used. Additionally, the availability of the data did not impact the, or change the formulation of the research questions, ensuring that limitations on data did not alter the initial aim of the study. A wide range of different sources was used in an attempt to both reduce bias in data and to be as thorough as possible with the analysis. The quality of the data was closely evaluated before being used, checking the reliability of its sources in order to improve the reliability of the study. For the theoretical aspect of the thesis, data was primarily taken from reputable journals and sources. The selection bias in sources for this aspect of the thesis was minimised, with the sole criteria being the contents relevance to the research. As such, data containing relevant information concerning the studied context were prioritised over a stringent selection criterion. With that in mind, qualitative data stemming from academic literature and reports will be used as provided, which in turn cannot guarantee appropriate data collection methods. This implies that certain data may be biased or unreliable. As such, it is important to remain cautious when interpreting this data. This is especially important when using data from political organisations or organisations with a political agenda, as this may have an influence on the reliability of the data and its bias towards their agenda.

The quantitative data used in this study was collected from reputable and known national, as well as international organisations, agencies, platforms, as well as from academic literature. These sources include, but are not limited to the World Bank, the European Automobile Manufacturers' Association, BP, NASA, Climate Watch, Eurostat, the Global Carbon Project, the International Energy Agency, the European Parliament and Statec. Using data from large and reputable organisations has the advantage that they are commonly transparent in their data collection process and how the collection process is financed, increasing the likelihood of reliable data (Halperin and Heath, 2012, p. 177). One must however remain mindful as data from these sources is not guaranteed to be perfectly reliable, seeing as errors may be entrenched in the data, therefore requiring a thorough inspection of the data prior to its use. The data that was taken from these sources was primarily used for graphs, tables and statistical comparisons throughout the thesis. As such, these quantitative sources provided data on economic indicators, such as GDP per capita and tax revenues, population size, the number registrations of new vehicles, the otal vehicle fleet size, energy consumption, the share of renewable energy, emission levels and specific data on sectoral emissions in Luxembourg. This type of data was selected depending on availability and completeness of datasets.

Throughout the process of collecting secondary data for this study, primarily with respect to quantitative data, a lack of consistency in datasets could be observed. There were some cases of missing values and addition errors. It proved difficult to collect a wide range of data on Luxembourg within the same timeframe, as some of the datasets only began several decades after the others. As a result of this, some comparisons and visualisations of data have had to be produced for a shorter time frame than was initially planned. Additionally, finding recent data, i.e. data covering the years 2022 and 2023, on Luxembourg also proved difficult. In general, there were instances where data on Luxembourg was limited, while data on other countries like Germany and Belgium was available. That made the comparative approach in this study more difficult than initially expected. Finding data on the share of newly registered electric vehicles in relation to total new car registrations in Luxembourg in the past decade was extremely difficult, neither the National Institute of statistics and economic studies of the Grand Duchy of Luxembourg, nor Eurostat, nor the World Bank, nor the Luxembourgish Ministry of Mobility had any of this data available. Relating this back to the lack of consistency, data, depending on the source it was taken from, differed greatly at times, despite supposedly showing the same. An example for this is the share of renewable energy sources in Luxembourg’s energy consumption in 2019, where, depending on the source, the share of this ranged from 7% to 13%. While this significantly impacts the reliability in parts of the study, it was addressed in the study when such inconsistencies were discovered. Overall, while qualitative data sources proved to be more reliable in terms of access and information, quantitative data for this study was at times difficult to come by and at times inconsistent.

5 Luxembourg Case Study: Advancing Renewable Energy in Luxembourg – overcoming constraints, achieving carbon neutrality and expanding transitions beyond borders

5.1 General and specific constraints to the transition

Countries undertaking such a transition are subject to a plethora of constraints. Social, technological and regulatory barriers have strongly impacted renewable energy deployment, with economic factors significantly influencing it indirectly (Seetharaman, Moorthy, Patwa, Saravanan and Gupta, 2019). Social barriers include the 'not in my backyard syndrome', where people, although generally advocating for renewable energy, oppose projects on grounds of the impact on the landscape and the resulting environmental degradation (Nasirov, Silva and Agostini, 2015). Economic barriers include tough competition from fossil fuel, government grants and subsidies, as well as fewer financing institutions (Seetharaman et al., 2019; Ansari, Kharb, Luthra, Shimmi and Chatterji, 2016). Technological and regulatory barriers can appear as limited availability of infrastructure and facilities, a lack of research and development capabilities, inadequate fiscal incentives, as well as ineffective policies by governments (Seetharaman et al., 2019).

5.1.1 Financial constraints

One of these concerns is linked to the financial capacity constraint of countries to support such transitions (Bolano et al., 2022; Amigues, Kama and Moreaux, 2015). An unwillingness to finance renewable energy projects, limited financial resources, as well as a lack of access to capital markets are among the constraints. A report estimates that around USD 4 Trillion need to be invested globally into renewable energy until 2030 in order to reach the goal of net-zero emissions by 2050 (Markandya et al., 2016). For comparison, in 2020, roughly USD 5.9 Trillion were spent on subsidising the fossil fuel industry (Markandya et al., 2016). A recent study at

Oxford University found that a fast transition towards clean energy is cheaper than a slow, or no transition (Way, Ives, Mealy and Farmer, 2022), with renewables-based electricity becoming the most affordable energy option in the world (IRENA, 2022b). The study concluded that countries around the world can save more than USD 12 Trillion, compared to a continuation of current fossil fuel usage levels, when transitioning to a decarbonised energy system by 2050 (Way, Ives, Mealy and Farmer, 2022). Each of these differing estimates suggest a win-win scenario. However, the true costs of the net-zero transition are difficult to ascertain. In a 2022 report by the Mc Kinsey Global Institute, the cost of a successful transition to net-zero emissions by 2050 was put at $275 trillion, which would amount to an average of $9.2 trillion per year. This would mean a $3.5 billion annual increase in capital spending today (McKinsey Global Institute, 2022). To put this into perspective, these $3.5 trillion alone are the equivalent to approximately one quarter of total global tax revenues (McKinsey Global Institute, 2022). Additionally, the McKinsey Global Institute estimates that an additional $1 trillion of today's yearly spendings will need to be reallocated from high-emissions assets to low-emissions assets. This study substantially increases the estimated cost to previous assessments. In Europe, for example, additional yearly investments of about €260 billion are needed to achieve the goals of the Paris Agreement (Ministry of Energy and Spatial Planning, n.d.).

The financial factor of expanding green renewable energy has been pinpointed in Asia as the single major factor determining whether countries can and choose to opt for such energy (Peimani, 2018). The market alone will not be able to direct the required capital flows, which is why other means of financing are needed (Majid, 2020). To begin with, supportive regulatory and policy frameworks, together with appropriate financial tools and a sustainable energy finance ecosystem, are needed to attract and mobilise capital (Majid, 2020).

An IEA (2020) report finds that Luxembourg has generous support programmes for renewable energy and energy efficiency, but that the low taxes imposed on fossil energy represent a barrier to investments needed in renewables and energy efficiency. Luxembourg, together with neighbouring Germany, have the lowest level of environmental taxes in the European Union, amounting to merely 4.4% of total tax revenue (Jensen, 2021). This poses as a barrier to incentivising efficiency measures (Jensen, 2021). In 2019, Luxembourg introduced a carbon price of 20€ per tonne of carbon dioxide in its national energy and climate plan (NECP) (Jensen, 2021). As of February 2023, this price has reached 100€ as part of the EU's Emissions Trading System, in which manufacturers, airlines and power companies are to pay for each tonne of carbon dioxide emissions that they create (Twidale, Abnett and Chestney, 2023). There is not yet an available assessment of Luxembourg's overall investment needs, nor information regarding the financial sources that are to be mobilised (European Commission, 2019), as Luxembourg's NECP is currently being updated (Ministry of the Environment Climate and Sustainable Development, 2023). Additionally, Luxembourg is known for being a wealthy country, with a per capita income of $133590,1 in 2021 (its neighbours Germany, France and Belgium had a per capita income of $51203,6; $43659; $51247 respectively in 2021) (World Bank, 2023a). The financial constraint of a transition towards renewable energy may not be as significant in Luxembourg.

5.1.2 Limited land endowments

When determining whether a transition towards renewable energy is feasible in countries, both physically and financially, it is necessary to evaluate whether a country has the land resources to facilitate this transition. Luxembourg for example is the second smallest country in the Europe Union, with a land size of a mere 2586 square kilometres. Gross (2020) finds that coal or natural gas fired power plants require ten times less land per unit of power produced than wind and solar generation. Furthermore, the locations in which renewable energy is generated are dependent upon where its resource availability is the greatest, instead of where it is most needed, also owing to the fact that the generated energy cannot be transported in the same way that fossil fuels can be transported (Gross, 2020). This implies that a far greater amount of land is needed in order for countries to facilitate a transition towards renewable energy, which can be perceived as a barrier by countries with small territories. MacKay (2009, p. 44) contends that there is not enough land available that make biofuels a viable option for a sustainable energy future, and that wind and solar power would require a great deal of land, huge battery backups and that they would be very costly. However, he does not rule out renewable energy sources altogether, emphasizing that there is a need for a careful and quantitative analysis of the numbers behind different energy technologies. For the case of biofuels, one can distinct between first-, second- and third-generation biofuels. While the former comes from biomass that is also a food resource, second-generation biofuels mainly come from non-biomass (Datta, Hossain and Roy, 2019). As such, the first-generation biofuels would entail a trade-off between energy generation and producing food for consumption by people. This poses a dilemma, seeing as hunger remains a major problem in the world (Datta, Hossain and Roy, 2019). The main issue for second-generation biofuels is that they compete with food production in terms of land use, which, again, poses a dilemma (Datta, Hossain and Roy, 2019). Third-generation biofuels may however be an alternative, as they do not compete relating with food (Datta, Hossain and Roy, 2019). Nonetheless, the issue of limited land availability remains, especially in Luxembourg, and using land for biofuels instead of food production can have negative effects on populations and health.

As such, deciding whether to use this land for renewable energy or for other purposes can be regarded as a trade-off. Furthermore, MacKay (2009, p. 167) uses the example of Great Britain for analysing land use. He finds that solely using nuclear energy to power Britain would amount to 0.2% of total land, whereas wind farms would need 500 times the space to generate the same amount of energy that nuclear power plants need, making up 10% of land. Using biomass to produce roughly 12% of the required national energy would take up land up to three and a half times the size of Britain (MacKay, 2012). In this example, even a mix of all these different energy sources would not amount to the required energy at the time. Additionally, this does not consider social opposition to such a deployment of energy infrastructure, nor the conflict of land use. While this exemplifies the advantage of nuclear energy in terms of land use, it does not serve as an alternative for Luxembourg, due to its opposition to nuclear energy.

Land use of technologies however can vary within a single technology (Ritchie, 2022). Solar panels for example can easily be added to existing rooftops and infrastructure.. Luxembourg has called upon its citizens to generate their own electricity through renewable energy sources and has supplemented this with financial incentives, such as returns on investments, as well as guaranteed market premiums.

In contrast to those arguing that extensive land use is a barrier to the transition to renewable energy, Farrell (2011) challenges this by looking at the examples of Germany and California, where new space needs to be used and that existing rooftops can be utilised for this. He debunks Bryce’s (2011) myth that wind generation requires 128 acres per megawatt, instead stating that 80% of wind farms in the United States use less than an acre per megawatt (Denholm, Hand, Jackson and Ong, 2009), arguing that over 99% of a wind farm is actually just the space left between turbines to avoid collisions. While challenges land availability as a constraint, available land continues to affect countries to different extents and will be case specific. While Luxembourg is restricted in terms of land upon which it can deploy renewable energy infrastructure, the example of Germany has proven that such technologies can be deployed on existing infrastructure. Doing so can be extremely interesting in Luxembourg, seeing as

Luxembourg has more single-family houses than the European average (Arababadi, Leyer, Hansen and Arababadi, 2021).

Therefore, the issue of limited land availability, and its entailed trade-offs, can pose as a significant constraint in Luxembourg's attempt to transition to a renewable energy system.

5.1.3 Social Acceptance

Despite there being a general acceptance of, and support for renewable energy systems, social acceptance has proven to be a significant barrier in the implementation of renewable energy systems (Segreto et al., 2020). More specifically, while people are largely proponents of renewable energy, the actual implementation of these projects is often met with local resistance and low levels of local acceptance (Segreto et al., 2020). This type of behaviour is often termed NIMBY ('Not in my Backyard'), which describes the opposing sentiment of residents concerned about the potential impacts of new developments on their neighbourhood or locality (Hubbard, 2009). NIMBY does not only reflect opposition to renewable energy infrastructure, but rather that it comprises all types of unwanted or hazardous infrastructure, be it a new prison, a landfill site, rehabilitation centres or power plants (Hubbard, 2009). Voiced concerns include noise pollution, visual disturbances and decreasing property values (Jarvis, 2022). The term NIMBY itself has been criticised by scholars, arguing that it inaccurately and unfairly describes local opposition (Burningham, 2000; Wolsink, 2005; Devine-Wright, 2010), which is worth a discussion in itself, but beyond the scope of this paper.

For example, a study analysing the effects of wind turbines on property values in the United Kingdom has found that residential property values, in a proximity of 2 kilometres from a wind turbine, have decreased by an average of 4-5% (Jarvis, 2022). Jarvis (2022) contends that in a community with no wind turbines and an unhindered view on its surroundings, the economic cost of the first wind turbine, in terms of depreciating property values, is much bigger than in communities where there are already existing wind turbines. As such, the first wind turbine is much more 'costly' than any of the following ones (Jarvis, 2022). Solar projects have proven to be less controversial and less influential on property values (Jarvis, 2022). Some argue that the NIMBY phenomenon played a factor in the development of offshore wind farms, despite being more costly and technologically more challenging than onshore farms (Devine-Wright, 2010). Therefore, social acceptance, or in this case social rejection of renewable energy infrastructure can greatly affect the pace, success and effectiveness of the rollout of renewable energy.

Devine-Wright (2010) notes that following a path in which active public engagement and dialogue is promoted can reduce local opposition. Here, public dialogue would engage the public with more systemic aspects of future energy systems (for example the mix of energy sources and quotas for carbon), which would ultimately create a kind of ‘social contract’ on technological change (Devine-Wright, 2010). Barry and Ellis (2010) are among those advocating for this type of dialogue, arguing that imposing local carbon reduction targets would oblige residents to engage in the dialogue, while simultaneously providing autonomy in deciding on the most appropriate ways by which these targets can be met. While this might work efficiently at local level, it needs to be ensured that local and national levels are appropriately integrated (Devine-Wright, 2010), given that big projects have outcomes that transcend localities (Owens, 2002).

Reforming local political control is an alternative solution to address the perceived problem (Jarvis, 2022). It involves making the decision about new infrastructure locations a political matter. This can be done by empowering local governing bodies to represent private local interests. One approach is to impose stricter rules on local planning officials through national planning guidelines. Another option is to give national planning officials a more prominent role, shifting decision-making to the national level. In Sweden, there is a discussion about limiting local municipalities' right to veto wind farm construction, which would reduce opposition from NIMBY. However, this may also reduce local autonomy. To mitigate this concern, increasing community engagement is crucial to ensure locals' desires are acknowledged. (Jarvis, 2022)

Lastly, the final approach focuses on the economic aspect of the opposition, such as opposition arising on grounds of decreasing property values. Here, residents would be compensated for the loss in property value and reap rewards from the new project (Jarvis, 2022). The financial capacity of municipalities for this however is not guaranteed. Jarvis (2022) notes that providing residents with a share in the new projects would offer a solution to this issue. A present-day example of this can be found in Denmark, where, since 2011, a minimum of 20% of community ownership of new wind farms is mandatory (CMS, 2017).

There are a few select cases where local opposition in Luxembourg has affected the expansion of energy infrastructure. One of those concerns itself with the construction of a single 230 metres high wind turbine in Bürden in northern Luxembourg. The planned wind turbine would generate up to 14.6 million kWh annually, covering the yearly consumption of roughly 13'000 people (Lamberty, 2020), which is equivalent to 2% of Luxembourg's total population. Despite this, local residents have voiced their concerns over the construction of the wind turbines, arguing that it may emit infrasound waves, which, despite being under the hearing threshold, will still be perceived by the human body (Lamberty, 2020). Other concerns for local residents were that this would be the highest wind turbine in Luxembourg, the depreciation of their property values, as well as the approach of the developers, who did not provide much information about the project (Infalt, 2023). In response to the concerns the minister of the environment at the time, Carole Dieschbourg, stated that the sound impact of the wind turbine was within the legal boundaries, that the minimum distance to the town border was complied with, and that the shadow cast of the wind turbine would, in the worst-case scenario, only amount to 10% of the allowed 30 hours per year (Lamberty, 2020). The planning for the wind turbine began in 2018, with local opposition voicing their concerns in 2020. Now, in 2023, the wind turbine is still not built, with local residents continuing to oppose the project, as well as taking legal steps against the construction, with legal proceedings beginning in January 2024 (Infalt, 2023).

Nuclear energy is another example where local opposition in Luxembourg hindered the deployment of energy infrastructure. In 1973, plans emerged for the building of a nuclear power plant in Remerschen (Luxembourg) and Cattenom (France). In response to this, the citizens' initiative 'Biergerinitiativ Museldall' comes to life, with its purpose being the fight against the two nuclear power plants. Several manifestations with several thousand participants occurred in the following years (Meco, 1993). Partly as a result of the concerns voiced by local residents, as well as accidents in other nuclear power plants (Gundremmingen in Bavaria in 1975 for example), participants in the Special Congress for a Moratorium on Remerschen Affairs voted against the building of the nuclear power plant in Luxembourg (Meco, 1993; Michels, 2015). Despite further efforts against the building of the French power plant (which is located only 46 kilometres from the Luxembourgish capital), as well as protests that were attended by up to 30'000 people, the nuclear power plant in Cattenom was completed in 1986. Nowadays, the rejection of nuclear power is considered a national consensus in Luxembourg and is backed by all parts of the population (Michels, 2015).

The here presented constraints are merely a selection of constraints that countries may face when wanting to transform their energy systems into ones based on renewable energy. Other constraints, which are not being addressed in this paper, include political constraints, where, for example, many access points for powerful status quo veto players significantly slow the diffusion of renewable energy (Bayulgen and Ladewig, 2016), physical resource constraints, such as wind turbines and batteries for electric vehicles (Klimenko, Ratner and Tereshin, 2021), as well as market constraints (Adeniyi, 2019). It becomes evident that these factors have an influence on whether a country is able to do the transition and, more importantly, how countries facing these obstacles can overcome them. This may be especially challenging for small, densely populated and import dependent countries, such as Luxembourg. It may therefore be challenging for Luxembourgish policymakers to find the appropriate ways through which the transition to renewable energy, as well as net-zero carbon emissions by 2050, can be achieved.

5.2 Path to carbon neutrality: Examining Emission Trends, Sectoral Challenges and Progress Achieved

In response to the ongoing climate crisis, countries around the world committed to the Paris Agreement in 2015, whose overarching goal lies in "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels […]" (United Nations, 2015, p.3). More than half a decade after the signing of the Agreement, signs of 'too little, too late' have started to show, with countries having missed initial targets already (Buchholz, 2021). Countries and institutions all around the world will need to undergo economic and social transformations for the success of the agreement (UNFCCC, n.d.). The EU and its member states adopted national energy and climate plans (NECPs) for the period of 2021 up until 2030 as part of their energy and climate legislation for 2030 (Jensen, 2011). Here, Luxembourg targets a greenhouse gas reduction of 55% by 2030. As mentioned, nuclear energy will not be considered an option for this, as well as coal, fracking and the capture and storage of carbon dioxide (Ministry of Energy and Spatial Planning, n.d.). This makes the land constraint an even more pressing issue.

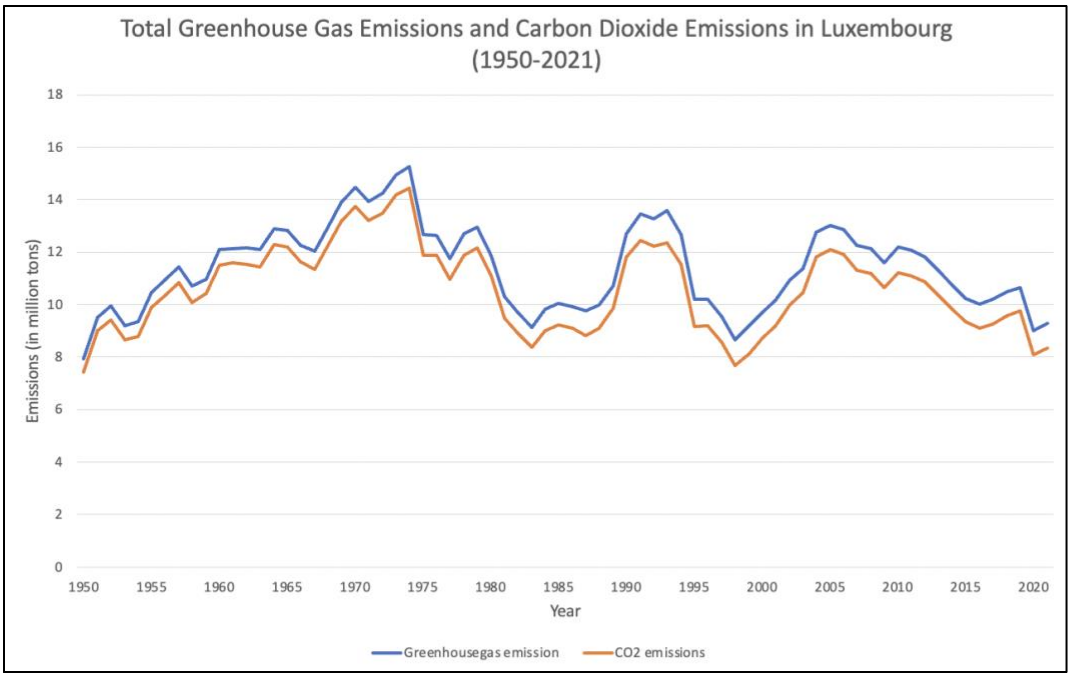
Luxembourg's climate and energy policies are effectively based on improving energy efficiency, promoting more sustainable public and individual mobility, as well as promoting renewable energy (Ministry of Energy and Spatial Planning, n.d.).

Greenhouse gases and the greenhouse effect are the main drivers of climate change, with a large part coming from the burning of fossil fuels (Candanosa, 2021). In 2018 for example, fossil based and land use related carbon dioxide emissions amounted to 74% of total global greenhouse gas emissions (Fawzy, Osman, Doran and Rooney, 2020). With its 2050 long term strategy, the EU aims to be an economy with net-zero greenhouse gas emissions, making Europe the first climate-neutral continent on earth (European Union, 2019). In its vision, the EU outlines seven main strategic building blocks. These include maximising the benefits of energy efficiency, maximising the deployment of renewable energy and of electricity to fully decarbonise Europe's energy supply, embracing clean, safe and connected mobility, the circular economy as a significant enabler to reduce greenhouse gases, developing a smart network infrastructure, creating crucial carbon sinks and reaping the benefits of bioeconomy, as well as overcoming the remaining carbon dioxide emissions with the help of carbon capture and storage facilities (European Union, 2019).

This raises an especially interesting question concerning Luxembourg, which is whether they can achieve carbon neutrality by 2050 without the use of nuclear energy and carbon capture and storage technology. Scholars are doubtful that carbon neutrality can be achieved without industrial carbon capture, removal and storage, as we will still be dependent on fossil fuels in the near future (Chen, 2021). The focus will now shift to emission trends in Luxembourg to answer the question.

Luxembourg's annual total greenhouse gas emissions, as well as carbon dioxide emissions, have fluctuated slightly in recent years, but have generally declined since 2005. Figure 5 shows the trend of greenhouse gas emissions, as well as carbon dioxide emissions in Luxembourg from 1950 until 2021. The figure clearly shows that carbon dioxide emissions account for a considerable amount of total greenhouse gases in Luxembourg. Using data for the years 2015-2019, one can find that carbon dioxide emissions in the energy sector have accounted for over 95% of total greenhouse gas emissions in Luxembourg, with industrial processes and agriculture playing minor roles (Statec, 2023a).

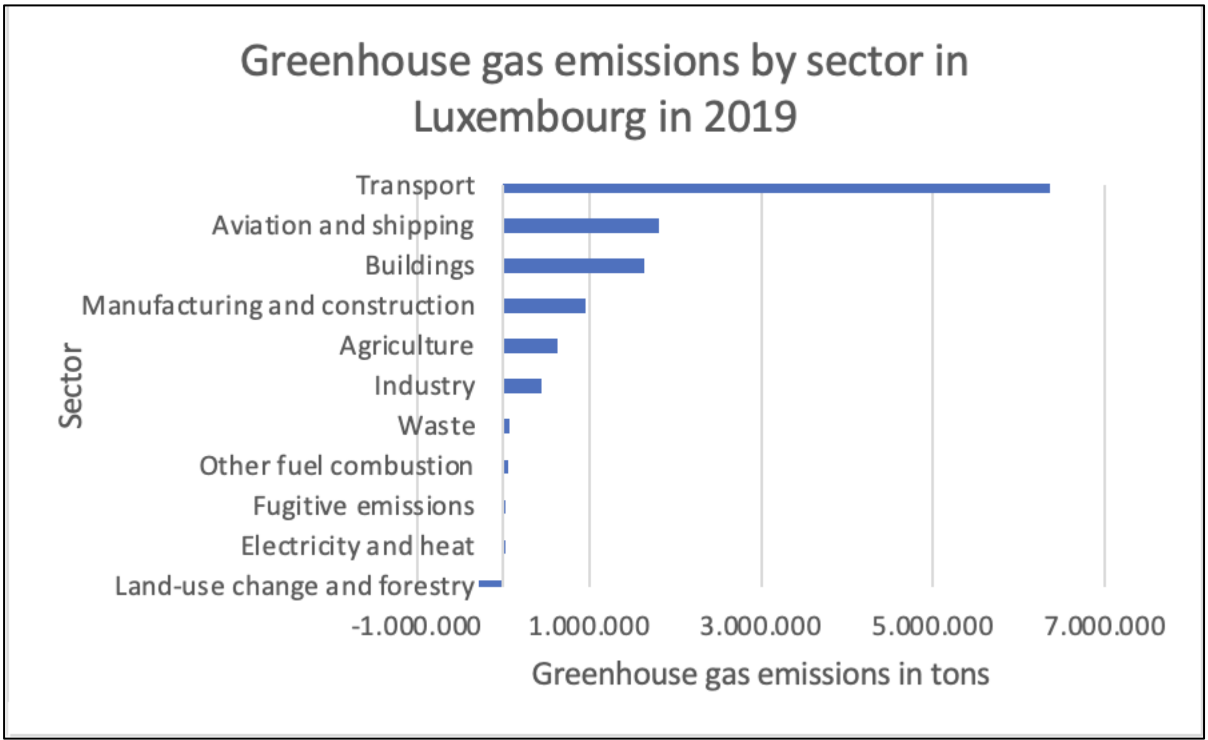
Figure 5: Total Greenhouse Gas Emissions and Carbon Dioxide Emissions in Luxembourg (1950-2021).



Created by the author using data from Jones et al. (2023) and Global Carbon Project (2022).

However, when looking at that specific dataset (Statec, 2023a), the transport sector is not listed specifically, which could very well mean that it is included in the energy sector, as different data (Climate Watch, 2023) suggests that the Transport sector accounted for roughly 53% of total greenhouse gas emissions in Luxembourg in 2019. Figure 6 visualises the total greenhouse gas emissions by sector in Luxembourg in 2019, with the energy sector not being explicitly listed in this graph apart from electricity and heat. When looking at the figure it becomes evident what a significant role the transport sector in Luxembourg plays, and that a transformation in this sector is required to achieve carbon neutrality by 2050.

Figure 6: Greenhouse gas emissions by sector in Luxembourg in 2019.



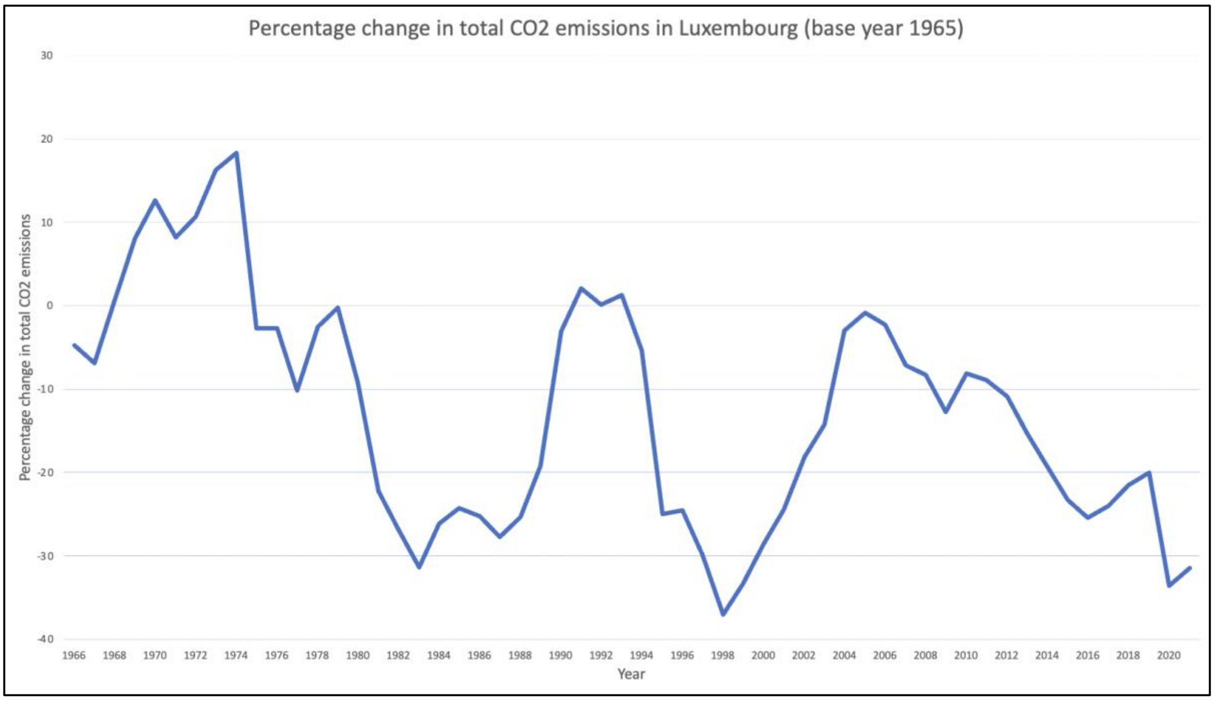
Created by the author using data from Climate Watch (2023).

The Kaya Identity is a mathematical framework used to assess the factors contributing to human related greenhouse gas emissions by decomposing changes in these emissions into underlying factors (Feron, 2016, p. 3; Shimoda et al., 2020). It creates a relationship between population growth, per capita value added, energy per unit of value added and carbon dioxide emissions per unit of energy on one side of the equation, with total carbon dioxide emissions on the other side:

$$CO_2 = (CO_2/E) * (E/GDP) * (GDP/P) * P$$

where P represents the population, E the energy consumption and GDP the gross domestic product or value added (Nakicenovic, 1997). In this framework, changes in carbon dioxide emissions can be explained by changes in these four factors, of which two increase and two decline at the global level (Nakicenovic, 1997). Economic growth and population growth are the main factors that influence greenhouse gas emission trends, with energy intensity being another important river of greenhouse gases that measures energy efficiency, and where a higher energy efficiency results in lower associated greenhouse gases (Streimikiene, 2022). Lastly, the carbon intensity of energy supply is the most significant driver of greenhouse gas emissions related to energy, seeing as it expresses the low carbon energy transition trends, with an increasing share of renewables being the primary reason for decreases in the carbon intensity of energy consumption (Streimikiene, 2022). Using this formula, we can calculate the total carbon dioxide emissions for Luxembourg, which can be found in the Appendix. Figure 7 depicts these results in terms of percentage change, with the year 1965 as the base level. Here we can see that, despite there being volatility in total carbon emissions, the general trend is a reduction in carbon dioxide emissions.

Figure 7: Percentage change in total carbon dioxide emissions in Luxembourg with 1965 as the base year

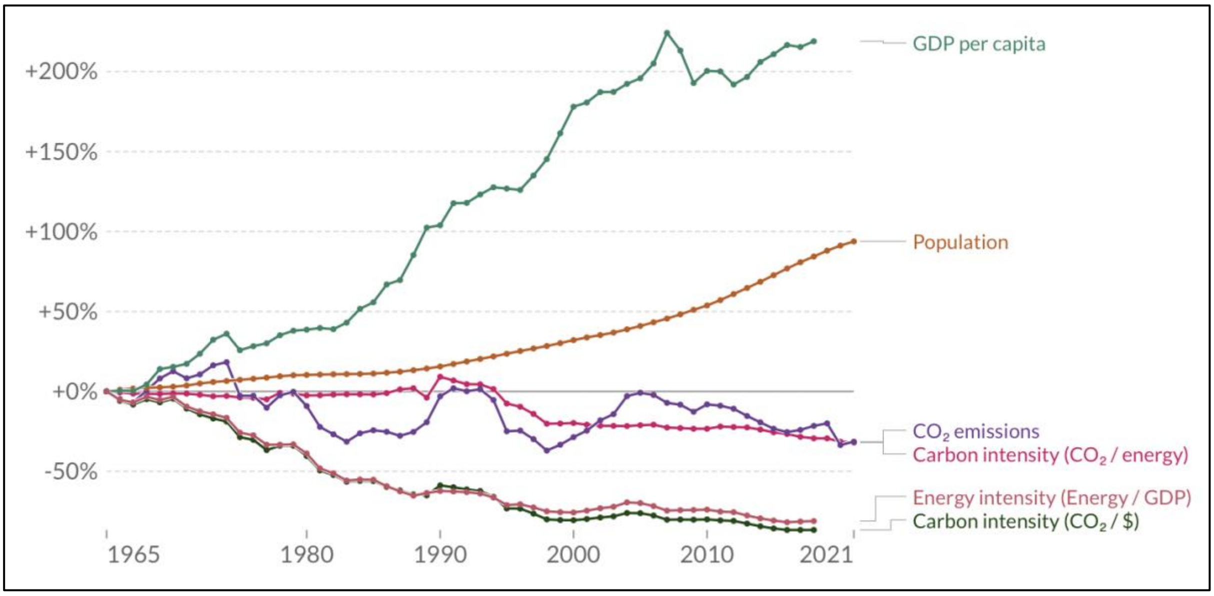


Created by the author using data from BP (2022); Global Carbon Project (2022); World Bank (2023a); World Bank (2023b).

Figure 8, taken from Ritchie and Roser (2020), shows a graph of the Kaya identity with the drivers of carbon dioxide emissions in Luxembourg from 1965 onwards. Here we can see that GDP per capita and Population have constantly increased over time, while energy and carbon intensity have decreased. Furthermore, we can detect that the carbon dioxide emissions line did not follow the trend of GDP per capita and population, but rather that it followed a similar pattern to energy and carbon intensity. These findings may be indicative that improvements in these two areas have been a driver of reductions in carbon dioxide emissions in Luxembourg, which is in line with Streimikiene's (2022) findings that improvements in energy and carbon intensity are the two primary ways through which anthropogenic greenhouse gas emissions can be reduced. Lastly, one may assume that the improvements in energy and carbon intensity have been able to offset the increases in emissions caused by population growth and increases in

GDP per capita, which have been shown to be a significant driver of greenhouse gas emissions, given that the emission pattern did not follow that of population and GDP per capita (Trang, Hanh and Thanh, 2019).

Figure 8: Drivers of carbon dioxide emissions in Luxembourg; percentage changes in the four parameters of the Kaya identity (base year 1965).



Source: Ritchie and Roser (2020).

Now that we have got a slightly better understanding of the trends in emissions in Luxembourg over the last decades, we can begin analysing the reduction in emissions so far achieved and whether Luxembourg is on track to meet its goal of carbon neutrality by 2050.

Despite being among the countries in the EU that have recorded one of the steepest reductions in their per capita emissions levels (by 34% between 2005 and 2019), Luxembourg remains as the highest per capita emitting country in the EU (Jensen, 2021). In the same period, total emissions have declined by 12%, well below the EU wide goal for that period of reducing emissions by 19% (Jensen, 2021).

In 2020, the Luxembourgish government brought to life its climate law, which targets a 55% emissions cut at the national level by 2030 compared to the 2005 level (FEDIL, 2021). The law defined five specific sectors (energy and manufacturing industry and construction, transport, residential and service sector buildings, agriculture and forestry, waste and wastewater treatment) that are not part of the EU's emissions trading system (ETS) (FEDIL, 2021). Together, these five sectors are mandated to reduce emissions by 55% by 2030 compared to the 2005 level (FEDIL, 2021). The ETS is an EU carbon market based on a system of cap-and-trade of emissions allowances for energy-intensive sectors (aviation and power generation sector) (European Council, 2023). In late April 2023, the European Council adopted new laws that will allow the EU to reduce greenhouse gas emissions in the main sectors of the economy. As part of these new laws, maritime transport emissions have been included in the EU ETS, while buildings, road transport and additional sectors (mainly small industry) are now included in a new ETS (European Council, 2023). This change comes as decarbonisation in these sectors has thus far proven to be difficult, and will ensure cost-efficient emissions reductions, which will assist the EU in its goal of reducing greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, and climate neutrality by 2050 (European Council, 2023).

Efforts towards the mitigation of the effects of climate change will further drive significant emission reductions. This, together with a continuing growing population, which is believed to grow well beyond 2050 will further reduce this high per capita emissions indicator (Jensen, 2021). A 2020 IEA report found that additional measures seem to be necessary in order for Luxembourg to reach its goal of 10% renewable energy in the transport sector (IEA, 2020).

The EU's Effort Sharing Regulation sets out national targets for reductions in greenhouse gas emissions by 2030 in the domestic transport (excluding aviation), buildings, agriculture, small industry and waste sectors (The European Parliament and the Council of the European Union, 2023). These sectors are not covered by the current EU ETS but make up a large part of total EU economy emissions. In total, across all member states, this covers almost 60% of total domestic EU emissions. Therefore, including these sectors will now enable the EU to reduce emissions in most of the EU economy. While the Regulation was initially adopted in 2018, it was amended in 2023, and will collectively contribute to an emission reduction at EU level of 40% compared to 2005 levels (The European Parliament and the Council of the European Union, 2023). Table 5 shows the initial and revised national targets for Luxembourg and its neighbouring countries. Here we can see an increase in the target for emissions reduction of at least 10% for all 4 countries. Luxembourg, together with Germany, Sweden, Denmark and Finland all have the highest target of reducing greenhouse gas emissions by 2030 in relation to 2005 levels, at -50%. The financial ability to support these emission reductions, as well as progress made to this point may be among the reasons for why these countries have the highest goals.

Table 5: Initial and revised targets for national greenhouse gas emission reductions by 2030 in relation to their respective 2005 level.

Year	Luxembourg	Germany	Belgium	France
2018	-40%	-38%	-35%	-37%
2023	-50%	-50%	-47%	-47,5%

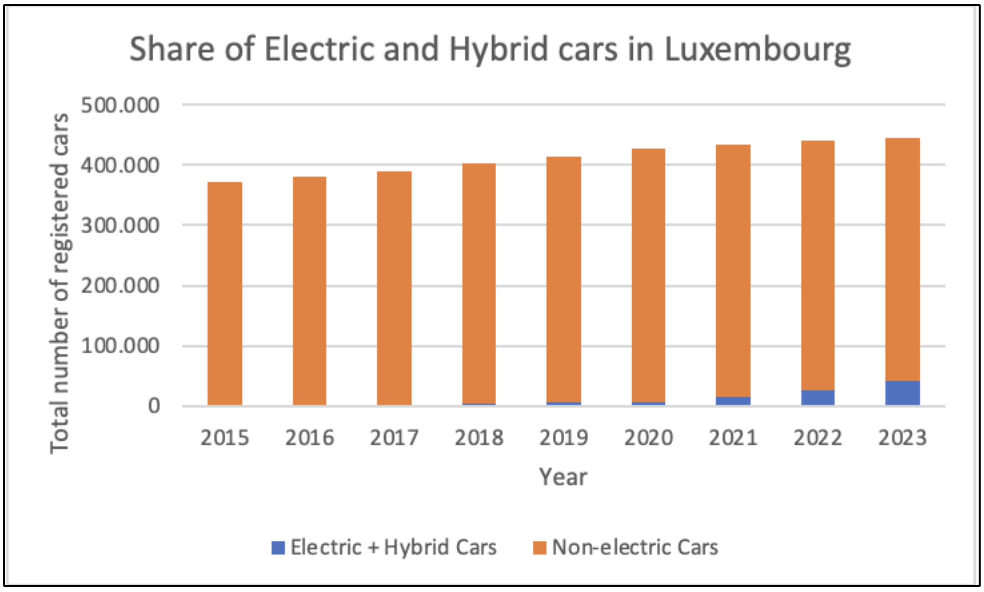
Source: The European Parliament and the Council of the European Union (2023)

5.3 Transport sector in Luxembourg

Given that the transport sector is the largest emitting sector of greenhouse gases in Luxembourg, a transition towards low emitting technologies is required to realise carbon neutrality by 2050. Among the options to largely reduce emissions are electric vehicles, emitting zero greenhouse gases when used and with an energy consumption close to eight times lower than non-electric vehicles (Hoekstra, 2019; Teixeira and Sodré, 2018; Ghosh, 2020). One could argue that electric vehicles are destined for the transition towards a climate neutral and more sustainable transport sector, but simply stating this would disregard the nature of electric vehicles. When debating the climate neutrality of electric vehicles, opponents (or sceptics) would often turn their focus towards the production process of these vehicles, arguing that they are not as clean when one considers their total life cycle. They are, admittedly, not necessarily in the wrong for bringing this up, given that greenhouse gases are emitted into the atmosphere during the extraction (extracting and refining raw materials) and production process (Hoekstra, 2019), but the same can be said about the production process of non-electric cars, perhaps to a different extent though. It is therefore that the production process of batteries for electric vehicles is sometimes regarded as their 'Achilles heel' (Hoekstra, 2019), showing that they are not carbon neutral in their entire lifecycle. While it can be argued that the production of electric vehicles may potentially be more polluting than the production of non-electric vehicles, studies addressing this issue have found that hybrid and electric vehicles, with regards to total life-cycle emissions, reduce emissions by up to 89% compared to internal combustion engine vehicles, as such making them the overall cleaner and more appropriate option for reducing emissions in the transport sector (Buberger, Kersten, Kuder, Eckerle, Weyh and Thiringer, 2022).

Since 2017, Luxembourg has installed over 700 charging stations for electric and hybrid vehicles, and is dedicated to installing a total of 1600 charging points for electric mobility (The Government of the Grand Duchy, 2023a). In response to the increasing demand for electric vehicles and to further encourage the adoption of electric and 'soft' mobility options, the government has introduced a new subsidy for the purchase and installation of new private electric vehicle charging stations, covering 50% of the cost (excluding VAT) (The Government of the Grand Duchy, 2023a). Figure 9 shows the share of electric and hybrid cars registered in Luxembourg (with the percentage in the graph pertaining to the share of electric and hybrid cars). Despite only showing slow growth in the number of electric vehicles in Luxembourg between 2015 and 2020, there has been an explosion like increase in the last three years. The share of electric cars among new registrations has grown from roughly 6% at the end of 2020 to almost 20% at the end of 2022 (Statec, 2023c). For comparison, the EU wide share of electric cars in new car registrations grew from 10.7% to 17.8% between 2020 and 2021, with each country seeing an increase in their respective share (EEA, 2022). Interestingly, while the total number of registered cars in Luxembourg has constantly increased throughout the timeframe used in Figure 9, the absolute number of non-electric vehicles has decreased by more than 15000 cars between 2020 and 2023, while electric and hybrid cars have continued to grow exponentially in that same timeframe. This could be an indicator that an increasing number of people have started to switch their cars from non-electric to electric or hybrid cars. The sudden surge in new electric car registrations may very well be connected to the subsidies that the government has offered to its citizens, such as the subsidy for the purchase and installation of new electric vehicle charging stations, as well as the subsidy of up to 8000€ for new electric vehicles bought between 2019 and 2024 (The Government of the Grand Duchy, 2022). The Luxembourgish State has awarded around 37€ million in State subsidies for electric cars over the past three years (The Government of the Grand Duchy, 2023b).

Figure 9: Share of Electric and Hybrid cars in Luxembourg (2015-2023)

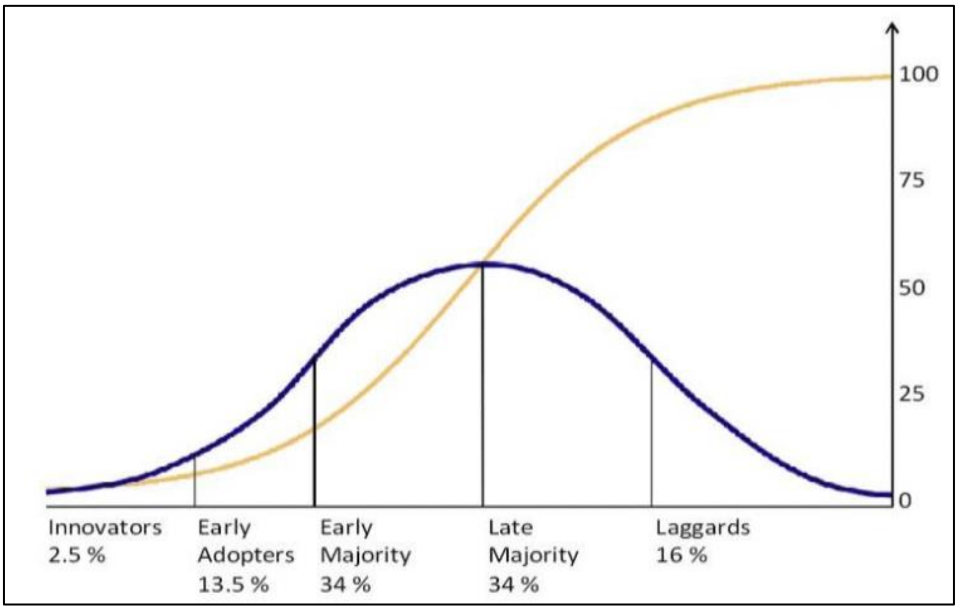


Created by the author using data from Statec (2023b).

While subsidies for electric vehicles in general may incentivise people to purchase them instead of carbon dioxide emitting cars, there are scholars that argue that such subsidies encourage additional consumption of motor vehicles, which in turn adds to external costs connected to government-funded road infrastructure, congestion and accidents (Freebairn, 2022). Nevertheless, the EU sees electric vehicles as an important means to reduce carbon dioxide emissions, as, currently, one fifth of total EU emissions come from road transport, and are as such an important factor in achieving carbon neutrality by 2050 (European Parliament, 2023). As such, the European Parliament supported the European Commission's proposal of zero emissions from new cars and vans by 2035, ultimately banning the sale of new carbon dioxide emitting cars (European Parliament, 2023). While the deal was essentially agreed to by European countries in October 2022, Germany has been negotiating with the EU for an exception in the 2035 ban on internal combustion engines, demanding that cars running on carbon-neutral synthetic fuels (more generally e-fuels, which can be produced by captured carbon dioxide from the air and renewable energy, and as such, on balance, considered to be carbon neutral as they offset the created emissions in their production process) are to be allowed past 2035 (Le Monde, 2023; Frost, 2023; Abnett, 2023). Finally, on March 28th 2023, the EU approved legislation ending sales of new carbon-emitting cars by 2035, allowing the sale of internal combustion engine cars that run on e-fuels (Economist Intelligence, 2023). This decision marks a significant step towards carbon neutral mobility in the European Union by 2050 and highlights the importance of electric cars in this process. Diffusion theory can help in understanding patterns of technology adoption, electric vehicles in this case.

Diffusion of innovation theory concerns itself with the way in which an innovation is adopted by a society. Diffusion can be defined as “the process by which an innovation is communicated through certain channels over time among the members of a social system” (Rogers, 1995, p. 5). This counts for any type of innovation, whether it is a new technology or a new idea. The process of diffusion can be very difficult, challenging and lengthy, despite some innovations having obvious advantages over older innovations (Rogers, 1995, p. 10). Any new product that comes on the market goes through this, where its adoption takes some time before it is widely adopted. The rate of adoption is the relative pace with which an innovation is adopted by members of society, usually measured as the number of individuals that have adopted said innovation (Rogers, 1995, p. 206). The rate and speed of adoption typically differs from innovation to innovation but usually follows the same trend, and can be influenced by its relative advantage, its compatibility, complexity, trialability and observability (Wigand, 2003). A successful diffusion results from many adoption decisions over time by agents, with the cumulative share of adopters representing the diffusion curve (Fleiter and Plötz, 2013). Figure 10 depicts such a diffusion curve. The diffusion curve is commonly s-shaped, with its shape coming from the rate of adoption, which is initially small. Given that information is initially limited, and that only a few agents can spread information about it, it takes time for more members of society to know about it and to adopt it themselves (Fleiter and Plötz, 2013). Over time, more and more agents will adopt the new innovation, resulting in the steep rise of the curve, before it ultimately flattens out again when the majority of agents have adopted this innovation, with the x axis representing time. The blue curve shows the trend of adoption, with low adoption rates at the beginning and end and higher adoption in the middle. When wanting to analyse the changes in prices, one can imagine a cost curve that is the inverted version of the s-shaped curve. Here, prices are initially high and drop over time. It is at the point where costs drop sharply that more people adopt a new innovation; in this case electric vehicles. Costs of electric vehicles decline as technologies mature and as supporting infrastructure is made available (Muratori et al., 2021).

Figure 10: The Diffusion of Innovation Curve and the S-shaped Curve



Source: Briscoe, Trewhitt and Hutto (2011).

There are alternate versions to this diffusion curve, some being steeper or flatter depending on the speed of diffusion, but with the overarching logic staying the same. Evidently, the adoption and diffusion of electric vehicles follows that same trend. Their adoption takes time, and depending on customer satisfaction, as well as the information that is transmitted regarding electric vehicles influences the range and success of the diffusion. There are of course, like with most other innovations, ways through which its adoption can be enhanced and incentivised.

Policy support, as well as environmental factors influence the spread of electric vehicles. More specifically, they argue that an effective policy tool for the adoption of electric vehicles exists, but that the blend of policy measures is significant for the diffusion of electric vehicles (Yong and Park, 2017; Brückmann and Bernauer, 2020). The factors that affect the scale of market penetration of electric vehicles are as follows: type of policy support (such as subsidy payments and tax benefits), economic status of the country and status of charging infrastructure for electric vehicles (Yong and Park, 2017). The composition of these factors dictates the speed and rate of the diffusion of electric vehicles in any given country. Yong and Park (2017) give the examples of India and China, which both have a similar proportionally low GDP per capita, and both offer tax exemptions or subsidy payments, but the market penetration of electric vehicles is severely different, with India having a low market penetration rate while electric vehicles have become somewhat popular in China.

The difference between the successful and unsuccessful market penetration of electric vehicles in these cases came down to the available charging infrastructure, with which China was better equipped at that point. This is not to say that the market penetration and diffusion rate of electric vehicles solely depend on the extent of charging infrastructure in a country, seeing as, at the time of Yong and Park's analysis, Sweden and Iceland experienced a high supply of electric vehicles without having well developed charging infrastructures. Instead of pinpointing one factor in this mix as the decisive one, it is a mix of these factors that enables a successful diffusion of electric vehicles. Countries need to make efforts in spreading charging infrastructure, together with tax exemptions and purchase subsidies, if they seek to promote electric vehicles and the use thereof. Taking these steps is much easier than changing the economic status of a country, and it is also achievable in a much shorter timeframe.

Yong and Park (2017) used Luxembourg as an unsuccessful example despite its high GDP per capita, arguing that the lack of tax exemptions and purchase subsidies resulted in a relatively low penetration rate of electric vehicles. This has since changed, with Luxembourg offering purchase subsidies on electric vehicles since 2019. Using what we have just learned, we can optimistically assume that the diffusion of electric vehicles in Luxembourg should continue at an increasing rate and speed, given high GDP per capita, an ever-expanding charging infrastructure, as well as purchase subsidies. If we look back at figure 9, we can see that the share of electric and hybrid vehicles in Luxembourg is growing, and accounting for an increasing share. We can also see that the share of electric vehicles was growing relatively slowly from 2015 to 2021, but has grown exponentially since 2021. Assuming that the trend continues, we can confidently argue that the diffusion of electric vehicles in Luxembourg will occur at an increasing rate over the next years, and that it follows the s-shaped curve that is used to depict diffusion trends of innovations. When looking at the s-shaped curve, based on the experienced trend so far, with the diffusion of electric and hybrid vehicle experiencing a slow start in Luxembourg, but increasingly fast in recent years, it would not be unreasonable to believe that Luxembourg is currently situated somewhere in between 'early adopters' and 'early majority', indicating that we will experience a surge in electric and hybrid vehicles in Luxembourg in the coming years, assuming that the charging infrastructure will be further developed and that the purchase subsidies will get prolonged, rather than seeing them end in 2024 as is currently planned. It is noteworthy, however, that Yong and Park (2017) do not see subsidies and tax exemptions as a long-term strategy, but rather as an enabler of early market creation in the early stages of a diffusion process, seeing as an endless continuation of such policy tools would be undesirable from the viewpoint of sustainable growth of the market. As such, stopping the subsidies as planned in 2024, may have given the market enough time to boost demand for electric vehicles, and will, if successful, not require further subsidies or tax exemptions. Sweden for example abruptly stopped its subsidies for electric vehicles in early November 2022, reasoning that electric vehicles have reached price parity with diesel and gas cars (Regeringskansliet, 2022). As this happened recently, the effects of this decision are not yet clear.

Seeing as the subsidies in Luxembourg have already been extended by two years (Schnuer, 2022), we will have to wait and see whether this will be enough time or whether additional subsidies or tax exemptions will be necessary. Additionally, it is very important to understand that electric vehicles are only as sustainable as the electricity used to charge them, meaning that switching to electric vehicles alone will not be enough to reduce emissions. The shift away from cars running on fossil fuels will provide an incredible opportunity to meet the surging demand with electricity from clean energy sources, such as wind and solar power (Oguz, 2023). Additionally, renewable energy technologies have advantages such as flexibility in type and scale, as well as enhancing energy security (Ölz, Sims and Kirchner, 2007). Renewable energy, if adopted domestically, enhances energy security by decoupling the country from parts of imported energy. Luxembourg, a net energy importer, would thus improve energy security and reduce dependence on other countries. A shift towards electrification and sustainable electricity generation must thus occur simultaneously.

Relating this discussion back to the EU's decision to ban carbon emitting vehicles from 2035 onwards, we can confidently believe that the diffusion of electric vehicles will reach new heights, either before 2035, with people adapting in anticipation of the upcoming law, or at the latest in the years following the new law, seeing as people will then be unable to buy carbon emitting cars. This will without a doubt give (further) rise to electric vehicles across the European Union. Furthermore, while cars running on synthetic fuels are allowed to be sold past 2035, the extent of their market share will be questionable, given that such fuels are currently 50% more expensive than regular fuels (Transport & Environment, 2023). This will undeniably add up to become very expensive very quickly, and thus making it only available to the wealthiest drivers (Transport & Environment, 2023). Synthetic fuels are produced artificially and can be made using captured carbon dioxide, water and hydrogen (Willauer and Hardy, 2020). When asked about what types of carbon neutral cars most people will be driving, Dutch member of the European Parliament Jan Huitema (who is responsible for drafting the report about the revision of the EU's carbon dioxide standards for new cars and vans) sees the trend moving primarily towards battery-electric vehicles (European Parliament, 2023). This is because the total cost of ownership of these vehicles is lower than that of alternatives, also because the production of synthetic fuels is much more expensive given that it requires a lot of electricity (European Parliament, 2023).

Another important and interesting factor in this is the average lifespan of cars, which is around 18 years in Western Europe, while it is only 6.7 years in Luxembourg (Held, Rosat, Georges, Pengg and Boulouchos, 2021; ACEA, 2022). This highlights the consumerism in Luxembourg and respective impacts on the diffusion of electric vehicles post 2035. Depending on the diffusion pattern up to 2035, one could reasonably expect that there will be an influx of electric vehicle registrations around 6 to 7 years post 2035. This means that one can expect the Luxembourgish car fleet to turn towards electric vehicles by 2041-2042 at the latest, assuming that consumption habits and the average lifespan of cars in Luxembourg stays the same. Seeing as the production of renewable electricity is four times more efficient than producing synthetic fuels (Searle, 2020), it could be reasonable to assume that the majority of the market demand will go towards electric vehicles rather than cars with an internal combustion engine, which will seemingly only be accessible to wealthier people. This estimation is based on current knowledge, and may well be challenged in the future when technology has advanced to new stages.

Synthetic kerosene can also be used in existing aircrafts, though it is roughly seven times more expensive than regular kerosene, with the cost gap further increasing for near net zero emissions aviation (Hieminga and Luman, 2023). A switch would therefore be very costly for any party involved, but is arguably required to reduce emissions and to achieve carbon neutrality by 2050. As we have seen in Figure 6, aviation and shipping account for the second highest greenhouse gas emissions in Luxembourg and will thus also need to undergo a transformation process in order to severely limit the emissions coming from this sector. Furthermore, a discussion on the viability and cost effectiveness of cars running on synthetic fuels must consider the demand arising for synthetic fuels from aviation. Seeing as there are technological limitations for the expansion of some synthetic fuels (Ram and Salkuti, 2023), on top of its comparably high price tag, there will be an ever-increasing demand for such fuels if cars running on synthetic fuels will become widely adopted. There is reason to believe that the high demand from the aviation industry, combined with the demand from the transport sector, could be a strain on limited supply, thus, through economic mechanisms, further increasing the price of synthetic fuels. This is merely a thought to consider when discussing synthetic fuels, seeing as other modes of transports, such as ships, planes and heavy-duty vehicles, are unlikely to be able to use heavy batteries, and instead see synthetic fuels as the most appropriate substitute for lowering their emissions (European Parliament, 2023).

An important factor, especially for the case of Luxembourg, that should be considered when analysing the diffusion of electric vehicles is the cost of fuel and the taxes thereof. Fuel prices are important because they affect those with non-electric cars and thus their consumer behaviour. Rising fuel prices can have numerous effects on consumers, among them being a reduction in the consumption of their vehicles, i.e. rising fuel prices can lead people to driving their cars less (Du and Lin, 2017). Additionally, increases in the price of fuel can change purchase intentions of people, especially those of high-income consumers, and lead them towards choosing lower emitting cars (Du and Lin, 2017). Hu, Wang and Li (2020) also found that purchase subsidy policies can promote the diffusion rate of electric vehicles to 60%. They furthermore found that high oil prices and low electricity prices enhance the diffusion rate by 70% and 60% respectively (Hu, Wang and Li, 2020). This highlights how the cost of fuel, and the taxes thereof, can influence the diffusion process of electric vehicles.

Luxembourg and Switzerland are the countries in Western Europe with the lowest gasoline taxes (Sterner, 2007). In this, Luxembourg is a special case as its low fuel taxes attract a large number of consumers from neighbouring countries that come to Luxembourg for the sole purpose of filling up their vehicles with cheap fuel (Sterner, 2007). By doing so, Luxembourg attracts people from its neighbouring countries and generates high tax revenues despite having low taxes on fuel prices (Nerudova, Dobranschi, Solilova and Schratzenstaller, 2018). These low taxes mean that consumption in Luxembourg has been significantly higher than it would be if the tax rates were matched with neighbouring countries, ultimately leading to unproportionally high per capita consumption levels in national statistics, as has been previously addressed. When comparing the consumption to other countries, Luxembourg consumed as much diesel in 2014 Malta, Estonia, Cyprus and Lithuania combined (Nerudova et al., 2018), underlining the incredibly high consumption, and with it emissions, that arise from these low taxes. As such, seeing as higher oil prices lead to a greater use and consumption of electric vehicles, an increase in the tax rate of fuel in Luxembourg will be a way through which the Luxembourgish government can accelerate the diffusion rate of electric vehicles in Luxembourg. In addition to this, raising the fuel tax rate would also have significant positive impacts on cutting emissions. Shafiei, Davidsdottir, Fazeli, Leaver, Stefansson and Asgeirsson (2018) contend that an additional tax on petroleum fuels in Iceland will result in the largest reductions in carbon dioxide emissions. Assuming that this also holds for the case of Luxembourg, imposing an additional tax on fuels, or raising the current fuel tax significantly to level it with the tax rates of its neighbouring counties, Luxembourg could both significantly reduce its carbon dioxide emissions in the transport sector, which we have learned is the largest emitter in Luxembourg, as well as simultaneously spurring the diffusion of electric vehicles in the country. In doing, Luxembourg would seemingly be able to make significant progress towards the 2050 goal of carbon neutrality.

However, in raising the fuel tax rate, the Luxembourgish government would potentially lose out on a significant share of their tax revenue, which will have to be weighed against the benefits to the environment and health that will come with carbon neutrality (Milner, Hamilton, Woodcock, Williams, Davies, Wilkinson and Haines, 2020). Making such a decision however is not as straightforward as it may seem. The IEA (2020) estimated that total tax fuel revenues amounted to €1 billion in Luxembourg in 2017, roughly 5% of government revenues. This makes up a significant share of the governments revenues and thus requires careful consideration. By raising the tax rate on fuel to levels matching its neighbouring countries, the Luxembourgish government may potentially not be able to provide its people with the infrastructure and services to the same extent that it has been able to do in the past. Its function as a welfare state may very well be limited through this significant reduction in revenues. Seeing as Luxembourg has an extensive welfare system, comprising social security, health and pension funds, its decision on changes in the tax rate on fuels in the transport sector may not solely depend on the environmental benefits that will arise from such a change, but will depend on the country's ability to further finance and develop its welfare system if this revenue stream is lost. As such, while the reduction in consumption and emissions in the transport sector, through an increase in the tax rate on fuels, may be desirable, it can very well have adverse effects on the Luxembourgish welfare system and the states' ability to provide for its people. Though this also begs the question as to how sustainable such a reliance on fuel tax revenues really is, and how this loss in revenue, which will arise when no or few fuel based cars will be driven in Luxembourg, will eventually be compensated.

In addition to this, one could argue that if Luxembourg were to increase its tax rate on fuels in the transport sector to levels matching its neighbouring countries, overall consumption and emissions would not necessarily decrease, but rather be shifted away from Luxembourg towards Belgium, France and Germany, seeing as people will now not choose to go to Luxembourg to fuel up their vehicles anymore, but instead do so in their respective countries. Simultaneously, this could also be a motivating factor for these people to switch to electric vehicles, though this depends on their consumption behaviour.

Of course, as we have previously seen, higher fuel taxes in Luxembourg could lead to less consumption as people would rather take public transport or invest into emission free vehicles, though that depends on the consumption behaviour of the people. Therefore, such a change, though it may be beneficial to Luxembourgish emission and consumption statistics, would not necessarily have any desired effects on Europe wide emission and consumption levels, but rather just a statistical shift from one country to another. So, when looking at it this way, it appears to be a lose-lose situation, given that Luxembourg loses a significant source of income, and because overall emission and consumption levels will not necessarily be reduced following such a change. Therefore, it comes down to weighing the benefits to the disadvantages again, and I Luxembourg’s case, keeping this revenue stream alive could be more beneficial, in terms of Luxembourg’s capacity to be a welfare state and because it can use this revenue to invest into renewable energy projects like the ones in Denmark and in the North Sea, than it can do harm. However, an increase in taxes is one of the best ways to accelerate the adoption of electric vehicles and as such mitigate the effects of the transport sector on the climate. Making this decision will affect the lives of many people and as such needs to be carefully considered. This paper is unable to make any estimations or suggestions about this, seeing as this is a giant task where there are numerous factors that need to be considered and evaluated, given the scope of effects that any decision can bring with it. Increasing the tax however provides a great opportunity to accelerate the adoption of electric vehicles, reduce emissions in the transport sector and as such move closer to the goal of carbon neutrality by 2050.

5.4 Transitioning beyond national borders

As previously mentioned, the limited land availability in Luxembourg may not be as big of a concern to achieving zero net greenhouse gases by 2050 and the deployment of renewable energy as has been contended by scholars, given that there are other ways through which this can be achieved. Luxembourg's commitment to achieving these goals goes beyond its territorial borders, as shown by the following examples.

The Luxembourgish government announced in February 2023 that they have conclude a cooperation agreement with Denmark to accelerate the energy transition (The Luxembourg Government, 2023). As a result of this agreement, Luxembourg will act as a financier to Denmark until 2025. Luxembourg is expected to invest between 33 and 66 million euros into the project, depending on the demand for statistical transfers (Chambre des deputes du Grand Duché de Luxembourg, 2023). The finances will in turn be invested, by the Danish government, into a planned energy island in the North Sea (the world's first of its kind), as well as into other renewable energy project like offshore wind farms and green hydrogen projects (The Luxembourg Government, 2023). The energy island will be connected to hundreds of offshore wind turbines and is expected to generate green electricity to millions of European households at an unprecedented scale (The Government of the Grand Duchy, 2021). This cooperation agreement came to live as a result of Luxembourg's limited land availability, as well as its lack of open waters, which restricts them from implementing offshore wind farms or energy islands within their territorial boundaries. While the generated energy will not be physically transported to Luxembourg, the outcome of Luxembourg's financing will be a statistical data transfer. Such statistical transfers are only permitted when they come from newly installed renewable energy sources (Klessmann, Lamers, Ragwitz and Resch, 2010). Instead of receiving any physical energy, Luxembourg will be able to write off part of the generated renewable energy as their own and thus integrate them into national statistics. The EU Renewable Energy Directive allows for this type of transfer as it helps countries to achieve their national renewable energy targets (The Luxembourg Government, 2023). While Luxembourg is one of the strategic partners, together with Germany and Belgium, the details of how the benefits will be shared among them have not yet been made available and can therefore not be discussed. Such mechanisms are especially important for and interesting to landlocked countries with limited land size, as it gives them an alternative way through which they can invest into renewable energy projects despite not being able to do so within their borders.

Another example is The North Seas Energy Cooperation (NSEC), which is an offshore grid that links the nine member countries (Belgium, Denmark, France, Germany, Ireland, Luxembourg, the Netherlands, Norway and Sweden) in the North Seas Region. The goal of this cooperation is to promote renewable energy and to boost economic growth (European Commission, n.d.). The NSEC came to life following a joint political declaration that aimed at facilitating the cost-effective deployment of offshore renewable energy and to promote the interconnection of the countries in the region (European Commission, n.d.). The cooperation aims at generating 120 gigawatts of offshore wind energy by 2030 and a minimum of 300 gigawatts by 2050, which is larger than the existing generation capacity of any of the members at the national level (Politico, 2023). In addition to this, this project does not merely serve for the generation of clean energy, but also to reduce dependence on Russian energy imports through European value chains for green technology (Politico, 2023). The NSEC also promotes hybrid offshore wind projects, which will be directly linked to at least two member countries, thus enabling the transport of electricity generated in this wind farms, as well as promoting the mutual exchange of electricity (Federal Ministry for Economic Affairs and Climate Action, 2023). Such hybrid projects will have positive impacts on grid connection lines, costs, trade in electricity, nature conservation, security of supply as well as employment and public acceptance, thus making hybrid projects desirable and an important step towards achieving the EU's energy and climate targets (Federal Ministry for Economic Affairs and Climate Action, 2023).

These two examples provide an insight into how landlocked countries with limited land availability have to take on new initiatives that go beyond their territorial boundaries in order to achieve a transition towards renewable energy and carbon neutrality. It also highlights that Luxembourg's land constraint can make such a transition very challenging, as national interest must now also be aligned with those of other countries in order to embark on such projects. While little land is a real constraint to the renewable energy transition in Luxembourg, the fact that it is a very wealthy country enables it to undertake such projects outside of its territorial boundaries, and provides an opportunity for them to achieve their national goals, albeit it not necessarily being achieved on their territory. As such, the issue for Luxembourg is not necessarily the financial aspect of a transition towards renewable energy, but rather the issue of space, or in this case a lack thereof.

6 Conclusions

Transitioning global energy systems to renewable energy provides the world with an extraordinary opportunity to mitigate the effects of climate change. They are necessary if we want to halt global warming and avoid any more severe consequences of climate change. As we have seen, Luxembourg has already made significant improvements in the right direction, but there is still a lot left to do. While emissions have been reduced and the share of renewable energy in the energy mix has grown, Luxembourg still lags behind when compared to other European countries. Therefore, more precise action must be taken. The share of renewable energy in the energy mix is still far too little, policymakers therefore need to engage more actively, whether it be through closer regulation of permitted energy types or through subsidies and tax reductions for the purchase and use of renewable energy. This change must happen on both industrial and individual level. Companies and enterprises must be held accountable for their emissions and energy use, and they must be steered into the direction of renewable energies. Change must also happen on the individual level. As we have learnt, the sentiment to renewable energy is not especially strong in Luxembourg, with great resistance to large renewable energy infrastructure projects. It is therefore necessary to incentivise people to take greater part in the transition to renewable energy, be it through information campaigns, financial incentives or stricter regulation on what types of energy are allowed, though the latter might have negative economic consequences like the distortion of market competitiveness. Transforming the transport sector is among the biggest challenges and opportunities at the same time. Emissions here need to be significantly reduced or cut entirely. Incentives for this have already been introduced, like subsidies on the purchase of electric vehicles or free public transport aimed at motivating people to leave their cars at home. However, more needs to be done. A highly significant way through which this transformation towards renewable energy and carbon neutrality can be achieved is by changing the very low tax rate on fuels to levels matching their neighbouring countries. This will both reduce the consumption of fossil fuel as well as incentivise people to switch to electric vehicles, which have become increasingly price competitive with fuel driven vehicles. While this decision is up to the government citizens can take an active role in advocating for this measure to be taken to achieve their climate goals. The diffusion of electric vehicles has started slow but grew increasingly in the last year with further growth expected in the near future, and especially after 2035 when car sales are restricted EU wide.

Ultimately, Luxembourg's limited land availability acts as a constraint to the rapid deployment of renewable energy, as they are much more land intensive than fossil fuel energy. This, together with Luxembourg's stance against nuclear energy and carbon capture technology makes the issue of limited land availability even more significant. It requires for a thinking outside of national borders, as can be seen in the international projects that Luxembourg is participating in. This is a good starting point, and in order to achieve a transition to renewable energy without nuclear energy, more participation in such projects is required. Without the participation in such projects, the transition within its borders alone may not be achievable by 2050., as progress has been too slow and too small. As such, there is a lot of room for improvement in Luxembourg to successfully transition to renewable energy, but the integration of individuals into this transition is crucial and can be decisive for the success or failure.

An idea for future research could be to quantitatively analyse diffusion trends of electric vehicles in Luxembourg and to make projections of these trends, while incorporating different scenarios based on subsidies, tax exemptions, as well as the ban on fossil fuel driven motor vehicles in the EU from 2035 onwards. Additionally, further research could provide an in-depth analysis of changes in the tax rate of fuels, analysing different higher tax rates and their effects on the states capacity to act as a welfare state with the anticipated loss in revenue resulting from increased taxes on fossil fuels.

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Appendix A

Using the Kaya Identity to calculate Luxembourg's total carbon dioxide emissions since 1965, results:

Year	Total CO2 Emissions
1965	12192901
1966	11610355
1967	11350329
1968	12258972
1969	13182240
1970	13735355
1971	13194012
1972	13493196
1973	14175353
1974	14424045
1975	11863886
1976	11861830
1977	10953946
1978	11880833
1979	12162236
1980	11073563
1981	9485958
1982	8924177
1983	8364030
1984	9004226

1985	9236842
1986	9111157
1987	8812260
1988	9099730
1989	9846277
1990	11823353
1991	12443151
1992	12209723
1993	12354764
1994	11542475
1995	9151729
1996	9201614
1997	8553970
1998	7675949
1999	8127875,5
2000	8709963
2001	9207531
2002	9983685
2003	10459170
2004	11829091
2005	12087836
2006	11920357
2007	11317780
2008	11184473
2009	10638966

2010	11202164
2011	11102959
2012	10867476
2013	10325364
2014	9828191
2015	9347466
2016	9089235
2017	9261198
2018	9566671
2019	9751728
2020	8096513
2021	8354555