Review and Growth Prospects of Renewable Energy in Luxembourg: Towards a Carbon-Neutral Future

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***Abstract*—This paper presents an comprehensive review of the renewable energy landscape in Luxembourg, focusing on the evolution and potential growth of photovoltaic (PV) and wind installations. The study considers the increasing prevalence of prosumers—households that produce their own renewable energy and the growing electric vehicle market. By examining historical and current data, this paper evaluates the possibility of Luxembourg meeting its ambitious goals of a 55% reduction in emissions by 2030 and carbon neutrality by 2050. The analysis reveals trends, potential growth areas, and challenges in renewable energy production and consumption. The paper concludes with a discussion on the likelihood of meeting emission reduction targets and the pathway towards a sustainable, carbon-neutral future for Luxembourg. The implications of these findings suggest a promising but complex trajectory requiring strategic planning and policy support.**

***Index Terms*—Renewable Energy; Exploratory Data Analysis; Luxembourg; Carbon Neutrality.**

I. Introduction

The Earth's temperature has been on a consistent rise. Between 2011 and 2020, the global average temperature surged by 1.09°C compared to the baseline period of 1850-1900. Should we maintain our 2020 pace of CO2 production, projections suggest a rise of 1.5°C by 2032 and 2°C by 2041, compared to the baseline [1].

A recently published study by *Jacobson et al.* argues for the viability of a complete transition to wind-water-solar (WWS) systems, suggesting this would not only meet global energy demands but also prove to be more energy efficient, economical, and employment-generating than our current energy paradigm [2]. Luxembourg is considered in their analysis, which proposes a full renewable transition by 2050. However, since their study covers a wide spectrum of nations, certain generalizations might not hold true in specific scenarios due to reasons ranging from local regulations to grid designs and infrastructure limits. We will try to clarify those points in our review.

Luxembourg's energy trajectory is distinctive. Over the last decade, its population grew from 493,500 in 2009 to 643,941 in 2021 with two-thirds of the workforce being non-nationals. Yet, its electricity consumption remained fairly stable as seen in Figure 2d. The nation lacks major power plants and thus, imports dominate its electricity sourcing (81.5% in 2021 [3]). Also the industrial energy consumption pattern is unique, with the steel industry consuming nearly 40% of the national electricity [4]. Lacking fossil fuels, Luxembourg depends on external energy imports, be it oil or natural gas, making it reliant on a robust and competitive European energy market.

In 2005, CO2 emissions in Luxembourg, arising from fossil fuels and industry, stood at 12.09 Mt [5]. By 2021, this figure reduced to 8.1 Mt, a 33% decrease. Still, in 2017, Luxembourg ranked fourth for CO2 emissions per capita among IEA member countries and first among EU countries [6]. It also ranked first among the IEA member countries regarding the energy consumption per capita, with 6.1 tonne of oil equivalent (toe) [6]. Although Luxembourg's government heavily invested in the roll-out of renewable energies by doubling the total supply from 2008 to 2018, it still lags behind most high GDP countries [6]. The particularity of Luxembourg in the aforementioned rankings and metrics is that they are significantly influenced by cross-border fuel tourism. As such, these rankings tend to overestimate the actual per capita consumption.

One advantage of a small, high-GDP country like Luxembourg is its agility: with a continuous government support and the right policy implementation, it can transition from a poorest performer to a leader in just a few years.

Luxembourg's Integrated National Energy and Climate Plan for 2021-2030 (NECP) embodies this ambition. It outlines the following primary, yet non-exhaustive, objectives for 2030 that we will consider in our analysis [7]:

1) A 55% reduction in Greenhouse Gas (GHG) emissions compared to 2005 levels (compared to 40% at EU level).
2) Ensuring 37% of the gross final energy consumption comes from renewable sources (compared to 32% at EU level).
3) Achieving an energy efficiency of 44% relative to the 2007 EU PRIMES model (compared to 32.5% at EU level).

The remainder of this paper is structured as follows. Section 2 details the existing renewable energy infrastructure in Luxembourg. In Section 3, we review the past decade's energy production and consumption trends in the country and provide an outlook based on the scenarios put forth in the NECP [7]. Section 4 delves into the impact of prosumers and electrified mobility on the electricity grid, and in Section 5, we discuss the roadmap towards net zero emissions by 2050 and how it can be achieved by the means of new technologies and policies, before providing a conclusion.

II. Renewable Energy Landscape in Luxembourg

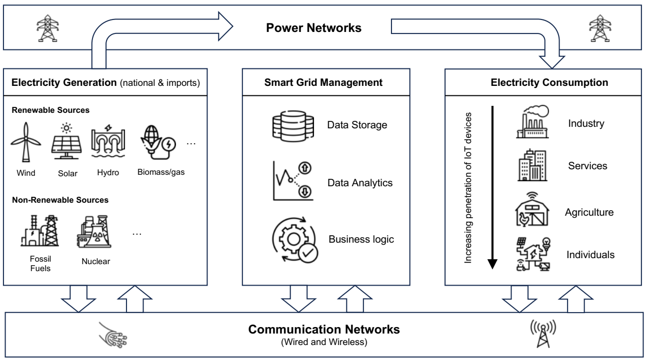

Fig. 1: Typical Architecture of a Smart Energy Grid.

Figure 1 depicts the typical architecture of a smart energy grid. It is divided into three main building blocks: (1) electricity generation, (2) electricity consumption, and (3) smart grid management. Regarding the electricity generation, Luxembourg still heavily relies on imports to meet its energy demand. In 2021, 81.5% of the electricity needs were imported. The remaining 18.5% were produced domestically, of which a majority, constituting 65%, originated from renewable sources [8]. The ambitious goal is to triple the share of renewables to reach 37% by 2030 [7]. Table I lists the current and projected future electricity generation capacity in Luxembourg for different energy sources. Already today, the majority of the capacity comes from renewable sources, including solar, wind, hydro, biogas, and biomass, totaling a maximum installed generation of 553 MW (471 MW for solar and wind) [4]. Over the coming years, the solar and wind capacities will be significantly expanded. The NECP considers two scenarios: (1) the *reference scenario*, based on current policies and strategies, and (2) the *target scenario*, which necessitates additional measures to achieve the net zero emissions goal by 2050. For solar and wind combined, the projected generation capacity in 2040 is estimated at 1,357 MW for the reference scenario and 2,350 MW for the target scenario, representing a three to five-fold increase from the current capacity, depending on the scenario [4]. Beyond national efforts, cross-border cooperation is essential for planning the strategic expansion of renewable energy production across the greater region and beyond [7].

Not all renewable energy sources are controllable. Especially, the generation from wind and solar energy can fluctuate heavily with changing weather conditions, diurnal cycle, and seasons. The same unpredictability applies on the consumption side. It is, therefore, important to monitor and manage the energy grid to guarantee that production, imports, and consumption are in equilibrium. In this context, data is key. The increasing penetration of smart meters (more than 95% of the households are equipped in Luxembourg [7]) and IoT devices provide vast amounts of data that can be used to build accurate production and consumption forecasts, helping to balance the grid, avoid peak demands, and optimize the use of the existing infrastructure. An essential tool that will allow involving end users in grid management is dynamic electricity tariffs that, once applied, will provide valuable input to design new tariffs to optimize the operation of the grid. A recent European directive stipulates that all member countries should offer dynamic tariffs to their citizens [9]. Luxembourg has transposed this directive and made dynamic tariffs for electricity legally mandatory through a law passed in June 2023.

Finally, over the coming years Luxembourg will strengthen its ties to the North Seas Energy Cooperation (NSEC), supporting the development of the offshore grid (primarily to expand wind power). This initiative aims to account for 12% of the EU's electricity consumption by 2030 [10].

	Capacity (MW)				
Energy Source	**2022**	**2040***	**2040****	Renew.	Contr.
Solar	305	857	1.800	✓	×
Wind	166	500	550	✓	×
Cogeneration	55	79	14	×	✓
Biogas and Biomass	48	100	110	✓	✓
Hydro	34	43	40	✓	×
Waste burning	21	21	21	×	✓
Total	**629**	**1.600**	**2.535**		

TABLE I: Current and future national electricity generation capacity by energy source. The future projections include the NECP reference* and target** scenarios for 2040 [4].

III. Energy Production and Consumption Characteristics in Luxembourg

In this section, we conduct an exploratory data analysis on Luxembourg's energy production and consumption trends over the past decade, emphasizing on renewable energies. Our data sources include the ENTSO-E Transparency Platform [3] and Luxembourg's statistics portal [11].

The ENTSO-E platform offers continuous, free access to pan-European electricity market data across categories such as load, generation, and transmission. In contrast, the statistics portal provides official data on Luxembourg, including topics like population, employment, economy, and energy.

A. *Energy Production and Consumption*

Figure 2a depicts the evolution of renewable energy production from 2015 to 2022 for the four relevant sources available in Luxembourg. Over that period, the compound annual growth rate (CAGR) amounts to approximately 13.7%. If we project the CAGR to 2030 and 2040, we obtain 2,230 GWh and 7,952 GWh respectively. Assuming the CAGR remains consistent over the next few years with steady consumption, a 25% renewable share is projected for 2027, and 37% by 2031. If this trend is further accelerated by forthcoming governmental policies, the target of achieving a 37% renewable share by 2030 (Objective 2) appears attainable [7].

However the scenarios outlined in the NECP do not consider a continuation of this trend on the long term. For the reference scenario, the renewable electricity production is projected to reach 1,900 GWh in 2030 and 2,448 GWh in 2040. For the

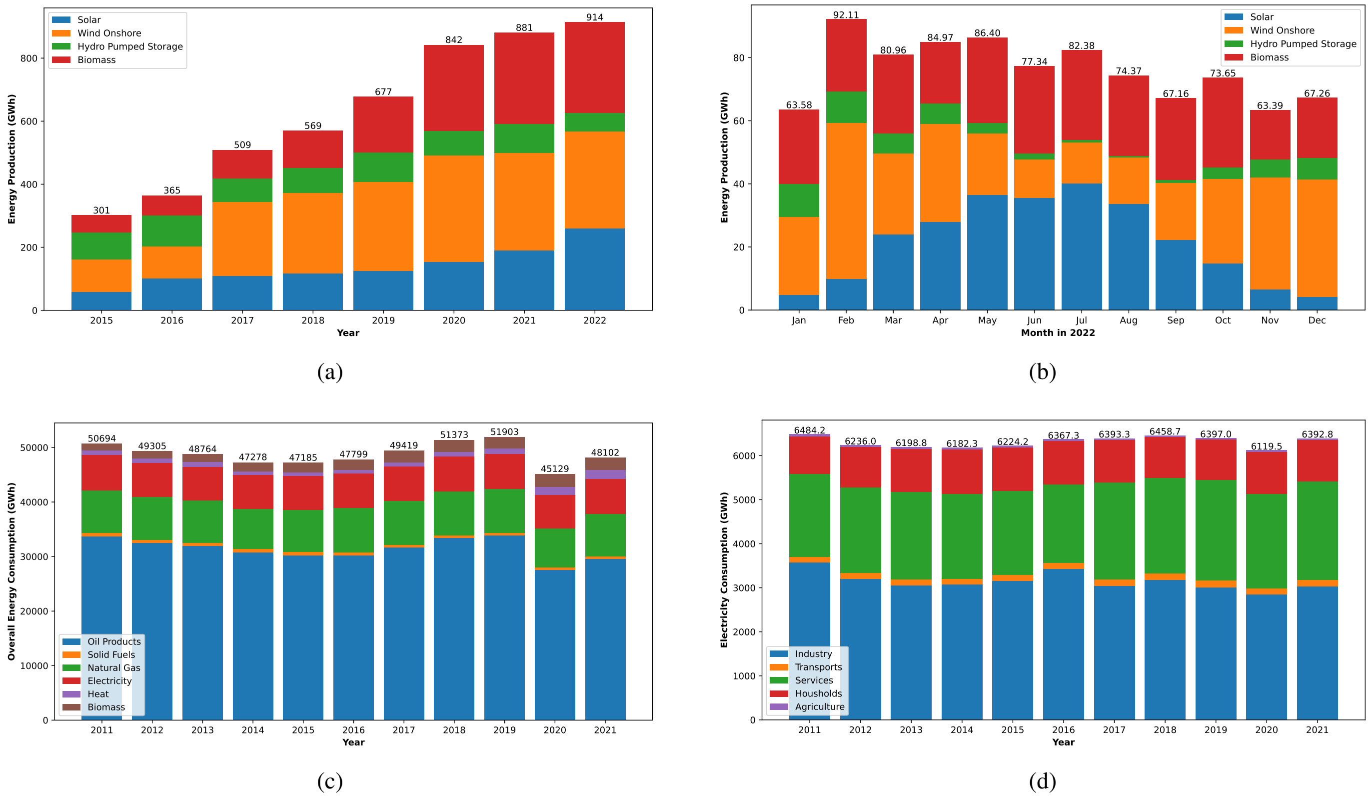

Fig. 2: Energy production and consumption in Luxembourg: (a) Evolution of renewable energy production from 2015 to 2022, (b) renewable energy production in 2022, (c) total annual energy consumption by source from 2011 to 2021, (d) total annual electricity consumption by sector from 2011 to 2021.

target scenario, the energy production is estimated at 3,029 GWh in 2030 and 4,793 GWh in 2040 [7].

Figure 2b illustrates the renewable energy production in Luxembourg for the year 2022. It is evident that both wind and solar exhibit seasonal patterns; they complement each other so well that their outputs nearly neutralize each other's fluctuations. The monthly output varies from a low of 63.39 GWh in November to a peak of 92.11 GWh in February, reflecting a near 50% surge. On average, monthly energy production stands at 72.07 GWh with a standard deviation of ± 8.46 GWh.

Figure 2c displays the total energy consumption for Luxembourg from 2011 to 2021, segmented by different energy sources. As observed, approximately two-thirds of the total energy consumption is derived from fossil fuels (both solid and liquid). This trend is characteristic for Luxembourg, given that liquid fuel prices have historically been lower in Luxembourg than in neighboring countries, thereby attracting many fuel tourists. Electricity accounts for roughly 12% of the overall energy consumption, a figure that has remained relatively stable over the years. However, there was a minor decline during the COVID-19 pandemic due to a sharp reduction in individual mobility. The goal is to diminish the overall energy needs to 35.5 TWh by 2030 to achieve the 44% efficiency increase (Objective 3). The NECP anticipates that by 2040, the total energy requirement will further decrease to 27.4 TWh. Realizing this will necessitate a significant reduction in the consumption of fossil fuels [12].

In Figure 2d, the electricity consumption is further delineated by activity sectors. The data reveals that nearly half of the consumption is attributed to the local industry (primarily steel). Households and transport combined account for about 20% of the total electricity usage. This percentage has remained surprisingly consistent over the years, even when acknowledging that the population of Luxembourg grew by 25% during this span [13]. Taking this population growth into account, the per capita electricity consumption declined by over 20% and 5% overall.

Multiple factors contribute to this observed trend. Firstly, there's the emergence of more efficient electrical appliances accompanied by the introduction of new regulations, such as LED lighting and low/zero energy housing. Secondly, there's a growing public awareness about climate change, emphasizing the need for sustainable lifestyles and energy savings. Lastly, off-grid electricity production, which is not entirely captured in national statistics, such as individual solar and wind installations.

Consequently, even with its robust economic and demographic growth, Luxembourg has shown signs of decoupling its energy needs from GHG emissions [6]. This is a positive indicator that economic growth and the energy transition can coexist harmoniously.

B. Peak Power Demand

The electricity grid needs to support a rapidly increasing peak power demand, which has increased by over 73% of the last 30 years. It is important to note that for grid dimensioning the peak power demand is more relevant than the actual electricity consumption [4]. In 2022 the peak reached 828 MW [4]. This rapid evolution can be explained by the ever increasing deployment of high-power infrastrucrure, including but not limited to, fast chargers for EVs (up to 350 kW in Luxembourg) and the operation of data centers (16 MW peak in 2022 [4]).

The surge in power needs over brief intervals and unpredictable consumption patterns will likely result in reduced usage hours in the future. This widening gap between electricity consumption and peak power demand might result in a rise in peak power needs, even if the overall electricity consumption remains constant.

In 2022 the highest absoute power generated was 352 MW, which amounts to almost 56% of the maximum installed capacity. At that time the overall demand was about 689 MW which still requires 337 MW (48%) to be imported [4].

In projections for 2040, the estimated generation during peak demand stands at 580 MW for the reference scenario and 700 MW for the target scenario [4]. On the other hand, the actual maximum generation capacity is projected to be around 75% of the installed capacity. This translates to approximately 1,200 MW for the reference scenario and 1,900 MW for the target scenario. However, it's important to note that these maximum generation times might not coincide with peak demand periods.

The surplus energy generated can be utilized in various ways, such as exportation or conversion to different carriers. Potential conversion methods include, but are not limited to, batteries, hydrogen, synthetic fuels, and pumped-storage hydroelectricity, often referred to as *Power-to-X*. One of the primary objectives is to decrease imports during times of peak demand.

Future projections also factor in the influence of battery systems. It's anticipated that these systems will reduce both peak demand and peak generation values by 5% in 2030 and by 10% in 2040 [4].

IV. The Role of Prosumers and Electric Vehicles

The energy crisis triggered by geopolitical instabilities has accelerated the adoption of electric vehicles (EV) and the proliferation of photovoltaic (PV) installations in Luxembourg. This acceleration was supported by a number of subsidies for the aquisition of EVs and PV installations [14, 15]. By the end of 2022, Luxembourg had a total of 10,329 solar installations. Nearly 50% of these have a capacity of less than 10 KW (typical for individual homes), and 0.5% with a capacity of more than 500 KW (consistent with industrial plants) [16]. As per SolarPower Europe, Luxembourg currently ranks fifth in the EU concerning solar capacity per capita, achieving 629 W in 2022, up from 435 W in 2021 [17].

As of January 2023, 3.1% (13,949) of all cars in Luxembourg were electric and 2.7% plug-in hybrid (11,896) [4]. From 2018 to 2022, EV registrations doubled annually [4]. By September 2022, 23% of new cars registered in Luxembourg were electric [18]. This surge in EVs is part of the drive to meet the efficiency target of 44% (Objective 3), requiring 49% share of electrified vehicles by 2030 [6], reducing significantly the GHG emission of the transport sector, currently responsible for more than half of all emission (Objective 1) [19].

It is important to contextualize the role of the transport sector in the energy landscape. In 2017, this sector accounted for 66% of energy-related GHG emissions, a figure that was amplified due to fuel tourism. However, goals have been set for the transport sector to source 25.6% of its energy from renewables by 2030 and reaching 54.3% by 2040. This encompasses both synthetic fuels and the increasing e-mobility initiatives [6].

As of July 2023, there are 757 public charging stations in Luxembourg [20], and by the end of 2023, 17 ultra-fast charging sites, including chargers with up to 350 kW, will be operational. These chargers can replenish 80% of the battery capacity in less than 30 minutes, depending on the vehicle model.

During 2022, 22,656 vehicles utilized ultra-fast chargers, consuming a total of 634 MWh, which represents 0.01% of the total national electricity consumption in 2021 [20]. This figure does not include the use of the other public chargers or the significant number of private chargers. As of mid-2022, around 11,000 private chargers were operational [4], and many households charge their smaller EVs and plug-in hybrids from standard power outlets.

As of January 2023, EVs made up about 14% of all public transport buses [4]. If the entire bus fleet were to transition to electric, the estimated annual energy consumption would be 132 GWh [4], equivalent to 14% of the 2022 renewable production.

Considering the projected numbers, if EV adoption continues at its current pace, by 2040, there could be as many as 477,000 EVs on Luxembourg's roads. This would mean an increased peak capcity of up to 695 MW [6], underscoring the significance of the shift towards sustainable transportation.

V. Discussion and Conclusion

The need for energy will increase in the future. The total power demand in Luxembourg will most likely double over the next 20 years, mainly driven by the increasing electrification of the transportation sector [4]. At the same time, we need to lower GHG emissions to avoid a global climate catastrophe. The NECP set forth by the Luxembourg government has ambitious but realistic objectives for 2030. Electricity import, although reduced, will remain an important element in the energy supply for Luxembourg. In the following, we summarize the three main objectives of the NCEP and how, based on our analysis, we believe they will be achieved. We then discuss the net zero roadmap until 2050 and list the most important tools already existing today that will be crucial to reach this goal before concluding the paper.

A. Summary of the Objectives for 2030

The NCEP encompasses a plethora of measures to reduce GHG emissions, enhance the share of renewable energies, and improve energy efficiency. All these measures and the objectives are interconnected. Our view is that one cannot be achieved without the others. In the following, based on the author's insights, we outline the key measures to realize the three objectives mentioned in the introduction:

- **Objective 1** – 55% reduction in Greenhouse Gas (GHG) emissions compared to 2005 levels: To meet this objective, there will be a substantial decrease in the use of fossil fuels, subsequently impacting fuel tourism. It will be essential to have a high penetration of EVs and to transition from combustion heating systems to heat pumps. Another way to reduce emissions in the transportation sector is to systematically implement flexible working times and encourage working from home. Additionally, major indutrial players must decrease their reliance on fossil fuels by shifting to machinery powered by electricity, green hydrogen, or synthetic fuels.
- **Objective 2** – Ensuring 37% of the gross final energy consumption comes from renewable sources: With the current plan to install PV installations and wind turbines, it is reasonable to assume that the 37% share of renewables can be achieve by 2030. The current policies provide reasonable incentives for individual households to become prosumers by investing in PV systems. More attractive policies, including prepayment for installations, are currently being discussed and will contribute to further accelerating this trend. In the short term, the increasing number of prosumers will disrupt the distribution network and energy management, heightening the complexity of the grid. As such it will be important to implement efficient and fair electricity markets for prosumers that will lead to an ubiquitous distributions of clean energy [21]. Finally, a cross-border collaboration will be essential to plan for a strategic expansion of renewable energies beyond Luxembourg.
- **Objective 3** – Achieving an energy efficiency of 44% relative to the 2007 EU PRIMES model: One important measure to reach this goal is to make existing buildings more energy efficient through renovations and technological upgrades (e.g., central heating systems). The plan is to reduce their current consumption of 50 TWh to 35.5 TWh by 2040. This can be achieved by systematically installing heat pumps in both existing and new buildings [4]. Another pivotal measure is the massive deployment of IoT devices to make buildings smarter and more energy-efficient. Smart meters combined with machine-to-X interfaces play a critical role in providing the right information to the right person or device at the appropriate time [22, 23]. Lastly, digital platforms, such as digital twins of the energy grid [24] and geographic information systems (GIS) [25], offer valuable insights on optimizing grid efficiency, for instance, by providing solar and wind maps.

B. Beyond 2030 and the Net Zero Target in 2050

The roadmap to 2030 is clear and the objectives are realistic. It will require some additional efforts to reach the net zero emission goal in 2050. We summize our view on the most important measures below:

- **Increasing R&D Efforts:** The research conducted today will be reflected in production systems in a few years. Therefore, it is vital to support R&D activities now. Several initiatives have already been launched between the research actors, energy companies, and grid operators in Luxembourg. Additional research proposals are currently being evaluated. Relevant topics include, but are not limited to, energy demand and production forecasting using machine learning (ML) [26, 27], smart grid management techniques [28], and digital twins as decision making tools for planning energy systems [29].
- **Investments in Energy Transformation and Storage:** No produced electricity should be wasted, for instance, during times of low demand and high production. Three types of energy transformations need further considerations: (1) pumped-storage hydroelectricity, (2) battery systems, and (3) electrolysis to produce green hydrogen.
- **Investments in Hydrogen:** Hydrogen has multiple use-cases and only produces water as an emission when transformed into electricity. It can serve as fuel for hydrogen vehicles and can be used in many industrial applications.
- **Improving Flexibility:** Increased flexibility is crucial. It will allow for: (1) a 10% to 30% reduction in peak demand caused by all electric vehicles by 2040, (2) the implementation of industrial load management systems that could reduce peak demand by 15% by 2040, (3) reduced peak power demand in the residential sector due to better control of heat pumps, and (4) the rollout of feed-in management systems could help reduce future peak generation by 5% to 15% [4].
- **Introducing New Mobility Concepts:** Autonomous mobility on demand will considerably decrease the number of vehicles on our roads, subsequently reducing the overall energy needed for transportation. It is estimated that a 90% penetration of autonomous vehicles could reduce traffic congestion by 60% [30].
- **Roll-out of Carbon Capture and Storage Technologies:** A net zero balance can only be reached by relying on carbon capture and storage (CCS) technologies, which allow for the trapping of CO2 emissions from, for example, heavy industries like steel and cement that cannot completely avoid emissions [31]. Further ideas include the rollout of vertical farming, which not only enables local food production in urban environments but also helps absorb carbon emissions.

- **Continuously Adapt Policies:** Policies need to be continuously adapted to the evolving environment. New policies for businesses, sustainable finance, housing, mobility, and society as a whole need to be proposed to guide the energy transition and ensure fairness for everyone.

C. Conclusion

This paper aims to provide a comprehensive insight into the current and future energy system of Luxembourg, with a focus on renewable energies and their evolution in the coming years. We reviewed the ambitious yet realistic plan of the Luxembourg government to significantly reduce GHG emissions by 2030. We also discuss additional measures that will be needed to achieve the net zero goal by 2050. The good news is that the technologies required to meet these objectives are already available today and will become more efficient and affordable over time. The behavior of end-users (all of us) plays a crucial role in the overall equation. The right policies to incentivize the transition will be key to initiating a behavioral change, which is necessary to achieve the end goal and avoid a climate disaster.

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