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Creating a renewable energy-powered energy system: Extreme scenarios and novel solutions for large-scale renewable power integration

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HIGHLIGHTS

- Examines integration of large-scale renewables in Luxembourg, focusing on wind, solar, and vertical farming.
- Addresses challenges of renewable power curtailment and proposes power-to-heat solutions for energy system flexibility.
- Provides detailed energy simulations for Luxembourg, offering strategic insights for sustainable energy policy and planning.

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ABSTRACT

The large-scale integration of renewable power sources, such as wind and solar, is pivotal in achieving climate change mitigation goals and reducing dependency on fossil fuels within energy systems. This manuscript explores the integration of substantial wind and solar power capacities into Luxembourg's energy framework, addressing challenges like variability, intermittency, and curtailment. It delves into scenarios that include power-to-heat (P2H) and vertical farming (VF) technologies to improve system flexibility and promote the incorporation of renewable energy. Utilising a mixed-integer linear programming (MILP) algorithm, an energy balance model with hourly resolution optimises the system. This algorithm guides the operation of individual plants, ensuring optimal performance based on a variety of criteria. Notable findings underscore the significant influence of an appropriate mix of renewable power resources, indicating a potential increase in renewable power consumption by up to 50% within the system. Furthermore, curtailment management solutions are shown to enhance renewable power integration by as much as 30%, highlighting the importance of strategic, system-wide approaches. Additionally, vertical farming emerges as a promising avenue for significantly augmenting the utilisation of surplus solar power, potentially by up to 100%. While the integration of large-scale renewable power is demonstrably viable, it necessitates a meticulously crafted strategy that considers technological innovations and strategic planning.

1. Introduction

Many countries have intensified their international efforts in response to the climate crisis, setting more stringent environmental targets [1,2]. These include reducing emissions by 2030 and achieving net-zero emissions by 2050, in alignment with the objectives of the Paris Agreement [1,3]. This urgency is driven by projections indicating that global temperatures could rise 1.5 °C by 2040, a decade earlier than previously anticipated [4]. The International Energy Agency (IEA) underscores the critical need for a shift towards clean energy, particularly advocating for electric-based solutions in key economic sectors as essential steps towards achieving carbon neutrality [2,3], and emphasises the vital role of renewable power technologies. It suggests that tripling the global installed capacity of renewable power by 2030, with a focus on solar and wind energy, is crucial to limiting the global temperature rise to 1.5 °C [2,5].

Acknowledging these global ambitions for renewable energy expansion, we must also confront the practical challenges in realising these goals, particularly in integrating these energy sources into existing infrastructures. The integration of renewable power into energy systems is primarily challenged by its variability [6]. As the transition from fossil fuel-based systems to variable renewable energy (VRE) sources progresses, this shift demands greater grid flexibility to effectively balance supply and demand across various locations and times [7,8]. As a result, the operational dynamics of traditional power plants are undergoing

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Nomenclature

Abbreviations

DSM	Demand-Side Management
EVs	Electric Vehicles
IEA	International Energy Agency
MILP	Mixed-Integer Linear Programming
NECP	National Energy and Climate Plan
P2H	Power-to-Heat
P2X	Power-to-X
VF	Vertical Farming
VRE	Variable Renewable Energy Sources
O&M	Operation and maintenance cost
OPEX	Running costs
TIR	Third industrial revolution study
r_i^+	Increase in electricity output of a plant during a time step MW
r_i^-	Decrease in electricity output of a plant during a time step MW
$T_i^{start/Stop}$	Minimum time step before/after power plant start/stop
t	Time step
w^t	Wasted heat MW
$X_i^{+/-}$	Maximum/Minimum electricity output for power plant MW
x_i^t	Electricity output of power plant MW
Y_i^+	Maximum heat output for power plant MW
y_i^t	Heat output of power plant MW
z^t	Maximum curtailed power MW
θ_i	Combined heat and power plant ratio (how much nominal heat output is smaller than nominal power output) %

Symbols

b_i	Binary value for state of the power plant (1=on/2=starting up/3=shutting down/4=off) [1 2 3 4]
c^t	Power to heat MW
e^t	Delivered power to the demand side MW
$f^t_{\downarrow/\uparrow}$	Exported/Imported power MW
h^t	Delivered heat to the demand side MW
i	Power plant technology index MW
K	Coefficient of performance (COP)
P_i^t	Hourly renewable power production MW
$Q^t_{e/h}$	Hourly power/heat demand MW
R_i	Maximum ramping MW

significant changes, necessitating a collaborative approach between renewable and conventional energy systems for the foreseeable future [9]. One innovative solution is the power-to-X (P2X) technology, which convert electricity into various forms of energy, such as gas, heating, cooling, or electricity for electric vehicles (EVs) [7,10–14]. This not only increases flexibility in the energy system but also reduces dependence on fossil fuels and allows for the utilisation of excess renewable energy [12,13,15,16]. Additionally, demand-side management (DSM) plays a vital role in balancing energy supply and demand by adjusting usage patterns [15,17]. Strategies like load shifting, demand reduction, and demand increment offer significant opportunities for further integration of renewable energy [15].

As we consider the global and individual country efforts in renewable energy integration, it is essential to look at specific regional strategies. The European Union, for instance, has implemented comprehensive measures to address these challenges [18]. A critical milestone in this journey is the reduction of greenhouse gas emissions by at least 55% by 2030, relative to 1990 levels (‘Fit-for-55’ program), which aligns with the broader European green deal initiative aimed at transforming the EU economy for a sustainable future [3,10,18]. Consequently, The EU’s climate strategy is centred around the EU climate law and the ‘Fit-for-55’ program [3,10]. Adopted in 2021, the EU climate law sets a legally binding objective for the EU to achieve climate neutrality by 2050 [19]. To meet these targets, the ‘Fit-for-55’ package introduces a series of legislative proposals that modify and create new regulations across various sectors, such as energy, transportation, industry, and building infrastructure [18]. This comprehensive package is designed to ensure the transition towards a low-emission economy is equitable and competitive while encouraging innovation [10]. It involves initiatives like enhancing renewable energy usage, tightening vehicle emissions regulations, and broadening the scope of the EU’s emissions trading system [18]. The implications of these strategies for the energy sector are multifaceted [10]. For instance, the push towards renewable energy not only demands technological innovation but also necessitates significant infrastructural changes [3,10].

Shifting focus from the EU-wide strategies, individual member states are also making significant strides in sustainable energy practices. Luxembourg, for example, stands as a notable case in point. Luxembourg is at the forefront of the low-carbon urban energy transition [20]. Its integrated national energy and climate plan (NECP) for 2021–2030 sets ambitious targets for reducing greenhouse gas emissions and increasing the renewable energy share in the national energy mix [3]. However, as an example, just Luxembourg City, the capital, is currently heavily reliant on fossil fuels, accounting for over 70% of its primary energy consumption in 2020 [2,18]. This reliance on fossil fuels makes Luxembourg vulnerable to energy price shocks and contributes to climate change [10,18,21]. To achieve its ambitious targets for renewable energy deployment, the Luxembourg government will need to significantly increase the integration of renewable energy into the energy system [3]. This can be achieved through a variety of measures, such as investing in upcoming renewable energy projects, deploying energy storage technologies, modernising the grid infrastructure, and promoting energy efficiency measures [2,3,10,20,22]. Luxembourg is already making significant progress in integrating renewable energy into its urban energy system [22]. For example, in 2022, Luxembourg commissioned its largest wind farm to date, the Parc éolien de Roost [23]. The wind farm has a capacity of 38.4 MW and is expected to generate enough electricity to power 15,000 households [23].

Building on the theme of adapting to specific national circumstances, such as Luxembourg’s energy transition, we must also explore innovative solutions tailored for countries with unique geographical challenges. Countries with limited land resources, like Luxembourg and Singapore, stand to benefit significantly from vertical farming (VF) [24–26]. The challenges of constrained space and high population density make innovative solutions such as VF crucial for enhancing food security and sustainability in these nations [24,26]. Vertical farming, which involves cultivating crops in stacked environments, can increase food production in urban areas [24]. However, due to its reliance on artificial lighting, the energy consumption of VF needs careful consideration [24,26]. Integrating VF with energy systems requires exploring the dynamic relationship between a vertical farm’s power demand and the urban energy infrastructure, including the integration of renewable energy into VF systems [27].

Alongside exploring novel solutions like vertical farming in space-constrained settings, it’s equally important to address the broader implications of renewable energy integration in environments. This includes tackling challenges such as energy curtailment, a key aspect in the efficient management of renewable resources like solar and wind power [7,11,13,28]. Solar and wind power, as part of renewable energy integration, are often seamlessly incorporated into existing energy systems [29,30]. This integration, however, leads to curtailment during periods when renewable energy generation exceeds the energy system capacity including lack of transmission availability and system balancing challenges [29]. Managing curtailment in renewable energy systems is thus crucial [7,14]. Excess power during curtailment can be utilised in various ways, such as storing in batteries [16], converting to thermal energy for district heating or industrial processes [14], or charging electric vehicles during periods of surplus energy [31]. Comprehensive analysis of curtailment in energy studies, especially with large-scale renewable integration, is vital for maximising the benefits of renewable power integration and ensuring a sustainable and resilient energy infrastructure [7,29].

Given the complexity of renewable energy integration highlighted above, our research directly tackles the specific challenges and opportunities within Luxembourg's energy landscape. This manuscript presents an in-depth exploration of large-scale renewable energy integration, addressing gaps in the existing literature concerning power-to-heat (P2H) and vertical farming (VF) technologies as innovative solutions to enhance system flexibility and manage curtailment. Our unique contribution lies in the holistic approach to incorporating these technologies into Luxembourg's energy system, aiming to provide actionable insights and strategies for achieving sustainable energy transitions. This includes the development of custom strategies for energy system optimisation, using a MILP algorithm to improve operational efficiency and resilience. By aligning our research objectives with the identified state-of-the-art challenges, we aim to advance the field of renewable energy integration, offering a valuable case study for Luxembourg and serving as a model for similar efforts globally.

After exploring the intricate challenges and innovative solutions in renewable energy integration, such as curtailment management and the incorporation of vertical farming, we now turn our attention to the broader scope of this manuscript. This study aims to bridge critical knowledge gaps and propose actionable strategies for sustainable energy transitions.

This manuscript explores the integration of large-scale renewable energy in a national context, addressing previously unexplored gaps in current research. As countries worldwide grapple with the challenges posed by climate change, our focus is on presenting unique solutions through scenario-based studies that contribute to the urgent need for sustainable energy transitions. Despite the growing body of research on large-scale renewable energy integration in energy systems, we identify specific gaps in existing knowledge. For instance, there is limited research on the application of power-to-heat and vertical farming technologies to enhance energy system flexibility and support large-scale renewable energy integration. Additionally, the study emphasises the importance of tailoring curtailed variable renewable power to specific needs, such as those of the heating sector. This study, includes an extensive analysis of the energy system, highlighting the critical challenge of integrating variable renewable power and controllable power resources, a challenge not adequately addressed in existing national plans for Luxembourg. Additionally, we address VF as a new load on Luxembourg's power system, which is seen as a crucial element for developing a sustainable nation.

The unique contribution of this study lies in its holistic approach to integrating renewable energy into systems, specifically focusing on Luxembourg. Firstly, our exploration of VF within energy systems offers an innovative and underexplored perspective, potentially unlocking new pathways for sustainable energy system development. Secondly, our in-depth analysis of curtailment management in renewable energy systems, utilising hourly energy simulations, is poised to provide groundbreaking insights into optimising energy distribution in national energy system landscapes. Thirdly, the custom strategies developed for Luxembourg's energy system represent a unique case study, demonstrating practical solutions transferable to similar settings. Moreover, the use of a mixed-integer linear programming (MILP) algorithm for plant operation optimisation marks a significant methodological advancement, improving the precision and efficiency of energy management. Collectively, these elements significantly contribute to the originality of our research, offering valuable insights into the field of renewable energy integration and planning.

We summarise the explained knowledge gaps and detail our contributions to addressing them as novel elements of our research:

- Tailored Integration Strategies: Our research uniquely addresses the need for customised integration strategies for renewable energy within Luxembourg's specific energy framework. This involves a detailed examination of the applicability of mixed renewable power sources (wind and solar) in varying ratios, specifically tailored to enhance both the flexibility and penetration of renewable energy in a system with distinct climatic and infrastructural characteristics.
- Advanced Curtailment Analysis: We delve into the complex issue of renewable power curtailment, a topic that has not been extensively studied in the context of its detailed impact on both the power and heating sectors. Our approach includes proposing innovative solutions that utilise curtailed energy for electrified heating, thus enhancing the efficiency of energy utilisation and presenting a novel strategy for managing excess power.
- Vertical Farming Integration: Perhaps most significantly, our study explores the integration of seasonal vertical farming with large-scale renewable energy systems. This aspect of our research examines how agricultural demands can be aligned with energy production, thus addressing the intermittency issues of renewable sources and providing a novel perspective on sector coupling. This is particularly groundbreaking in the context of Luxembourg, where such integrative approaches have not yet been explored.

To complement the research objectives, the subsequent section outlines our methodological approach. We utilise an energy balance model with 1-h resolution for macro-scale energy system optimisation, supplemented by micro-level optimisation of individual plant operations via MILP algorithm, considering various criteria and constraints. This dual-level approach is poised to offer invaluable insights to policymakers and energy planners, shaping strategies for the integration of large-scale renewable energy into energy systems. The paper's structure facilitates a comprehensive understanding of our methodology and findings: Section 2 outlines the methodology, Section 3 presents the results, Section 4 engages in discussion, and Section 5 concludes the paper.

2. Method

This study models the national-level energy system with multiple energy production technologies mainly through time series and an optimisation model (see Fig. 1). To solve the applied optimisation case (as core of the energy simulation), the MILP technique was employed [11–13]. The MILP technique is a potent optimization tool, capable of handling both discrete and continuous data points, which makes it particularly effective for managing the complex operations of power plants [12]. In this case, each power plant's power production is portrayed by continuous variables, and each plant's on/off phase is described by discrete variables. This model's reliability has been consistently confirmed across several studies [11,32]. It is important to emphasie that the first step in investigating sustainable energy integration strategies for Luxembourg involves applying MILP. The results presented stem directly from the MILP optimisation process, showcasing a range of energy system configurations based on various scenarios. These include energy balances with renewable energy integration, all optimised based on the minimised cost function (MILP application).

The model operates on an hourly basis, identifying the most cost-effective solution that satisfies energy demand requirements. The

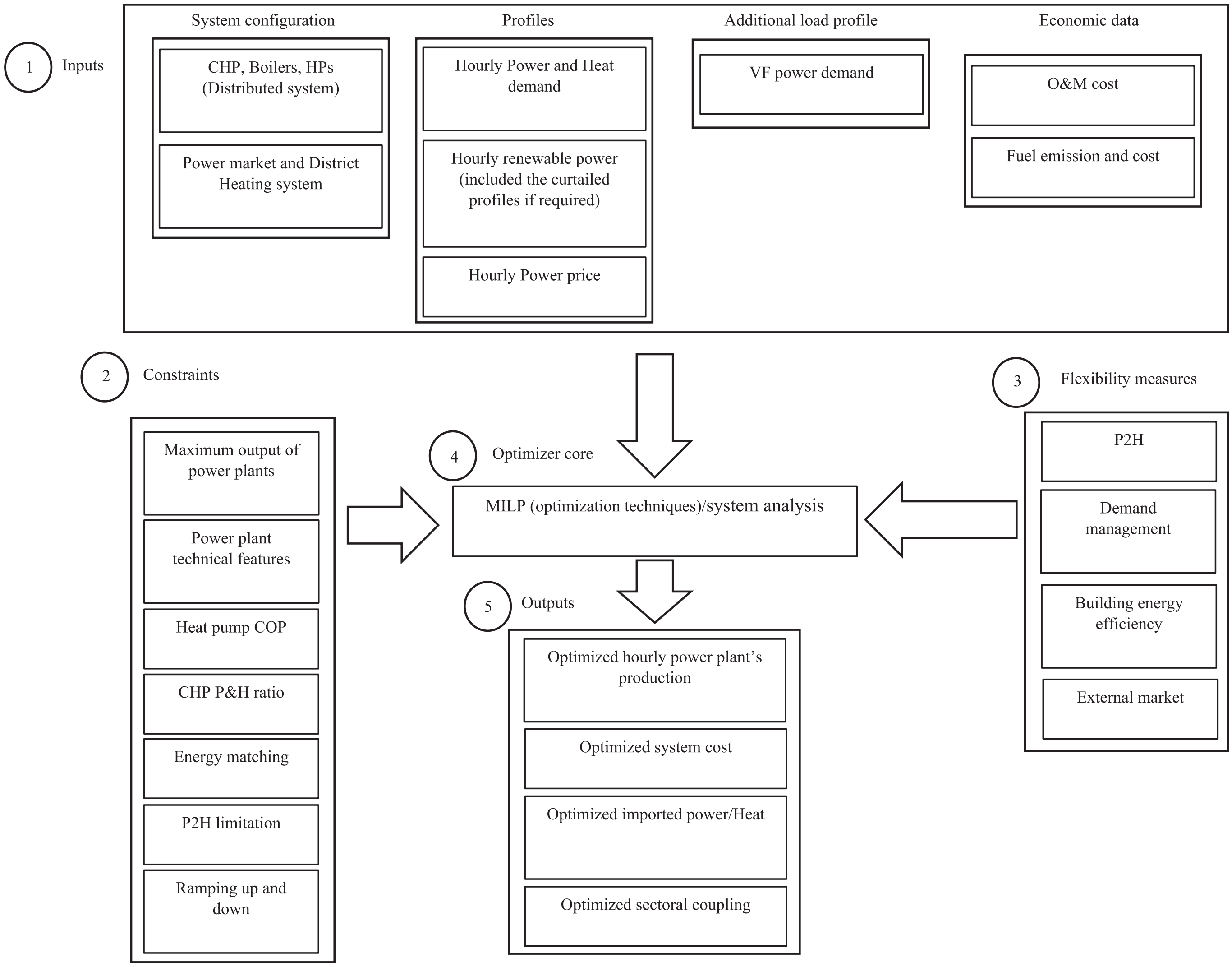

Fig. 1. The applied dynamic energy system model approach [12].

optimal option is found by considering technological constraints in energy balancing, energy production plants, and flexibility technologies. As inputs, (Point #1 in the Fig. 1) energy consumption profiles (electricity and heat) and VRE production time series are provided. These data are incorporated into the optimisation problem's boundary conditions to ensure that energy supply always matches energy demand. Other inputs include system configuration, which includes characteristics of each power plant's maximum and minimum energy outputs, ramp rates, and fuel expenses. The term "ramp" for a power plant refers to the rate at which its energy output changes. This reflects the plant's ability to quickly adjust to variations in demand or renewable energy generation while maintaining grid stability. Hourly profiles provide information on the expected hourly power output of renewable energy sources, power prices, and hourly energy demands. These profiles will be discussed in more detail in the following sections. Other input data include economic data in the energy model, which encompass financial indicators such as revenue projections from exporting surplus power and operation and maintenance (O&M) costs to reflect ongoing expenses for energy system upkeep. Fuel emissions/costs are also considered to evaluate the environmental impact and fuel implications of the energy system.

(Point #2): Technical limitations of energy production plants and energy networks are included to ensure technical viability. Restrictions are implemented to maintain energy equilibrium at each time step, guaranteeing that the total power generated, and energy demanded are equal. Power plants have maximum and minimum energy outputs, and the model keeps the power plant's energy output variation rate below its allowed ramp rate range. It is considered in the model that each power plant must maintain sufficient fuel reserves to satisfy its power requirements [11,12]. (Point #3): Energy system flexibility technologies such as power-to-heat conversion (P2H), heating storage, demand-side management, and building energy efficiency levels are incorporated into the model. (Point #4): The optimisation challenge goal is defined by the optimised energy system operation. The objective is to minimise the cost of producing energy. If necessary, the running cost also covers the price of importing power from the external market [12]. The objective function of the optimisation is the following [12]:

Minimise annual running costs (OPEX):

$$\sum_{t=1}^{time}\sum_{i=1}^{tech}\left(\text{Fuels}_{t,i} + \text{Emission costs}_{t,i} + \text{O\&M}_{t,i} - \text{Revenues from sales}_{t,i}\right) \tag{1}$$

where t is time and i denotes the energy generation technologies employed. The model minimises the operating expenditure (OPEX) in the presence of variable renewable electricity (VRE) technologies. The running cost does not include thermal storage or the cost for P2H. The model provides hourly profiles for both the production and demand sides with a resolution of one hour. As an output, the model generates the optimal series of power plant operation and technological flexibility, as well as the expenses and profits from supplying the energy demand.

Even though the optimisation algorithm produces optimal time series for the entire optimisation horizon at each time step, only the values of the first-time step of the horizon are used in the output profiles, as the rest of the time steps are updated during the optimisation of the next time steps. We implement specific constraints to account for the technical properties of power plants, particularly combined heat and power (CHP) plants, as well as their ramping, startup, and shutdown behaviours. Eq. 2 restricts the power output of the power plant within a defined range, considering its maximum production capacity and operational state (e.g., startup or continuous running) [12]. Eq. 3 applies a similar principle to the heat output of the power plant. Eq. 4 regulates the interconnection between power and heat production in CHP plants [12]. Eqs. 5 to 9 address various aspects of power plant operations: Eq. 5 covers general ramping, Eq. 6 focuses on positive ramping, Eq. 7 on negative ramping, Eq. 8 on starting up energy production, and Eq. 9 on shutting down energy production [12]. It's important to note that a plant must have been shut down for at least T_i^{start} time steps before it can start up again. A similar rule applies to the shutdown process, where a plant must have been started up for at least T_i^{start} time steps before it can be shut down [12].

$$\left(b_{1,i}^t + b_{4,i}^t\right) X_i^+ \leq x_i^t \leq \left(b_{1,i}^t X_i^+ + b_{4,i}^t\, X_i^-\right) \tag{2}$$

$$0 \leq y_i^t \leq Y_i^+ \tag{3}$$

$$(1-\theta_i) x_i^t \leq y_i^t \leq (1+\theta_i) x_i^t \tag{4}$$

$$x_i^t - x_i^{t-1} = r_i^+ - r_i^- \tag{5}$$

$$\left(b_{4,i}^t\right) X_i^- \leq r_i^+ \leq \left(b_{1,i}^t R_i + b_{4,i}^t\, X_i^-\right) \tag{6}$$

$$\left(b_{2,i}^t\right) X_i^- \leq r_i^- \leq \left(b_{1,i}^t R_i + b_{2,i}^t\, X_i^-\right) \tag{7}$$

$$\left(b_{4,i}^t\right) T_i^{start} \leq \sum\nolimits_{t=t-T_i^{start}}^{t-1} \left(b_{2,i}^t R_i + b_{3,i}^t\right) \tag{8}$$

$$\left(b_{2,i}^t\right) T_i^{stop} \leq \sum\nolimits_{t=t-T_i^{stop}}^{t-1} \left(b_{1,i}^t R_i + b_{4,i}^t\right) \tag{9}$$

where x_i^t is electricity output of power plant (MW), y_i^t is heat output of power plant (MW), V_i^t is variable renewable power (MW), r_i^+ is increase in electricity output of a plant during a time step (MW), r_i^- is decrease in electricity output of a plant during a time step (MW), $b_{1,i}^t \ldots b_{4,i}^t$ are operational state of a plant (binary variables): $b_1 = on$, $b_2 = Shut\ down$, $b_3 = off$, $b_4 = Start\ up$. θ_i is ratio between power and heat output of the CHP, R_i is maximum ramping for power plants, T_i^{start} is minimum time a plant must be off before starting up (time steps), T_i^{stop} is minimum time a plant must be on before shutting down (time steps). We also examine the hourly balance in both the power and heating sectors. Boundary conditions 10 and 11 ensure that supply and demand are always balanced [12]. The electricity delivered to the demand side must equal the total produced electricity (comprising VRE and power plants' production), adjusted by flexibility measures such as Power-to-Heat (P2H), curtailment, and import/export [12]. The heat balance condition, as outlined in Eqs. 12 and 13, considers P2H and any wasted heat [12].

$$e^t = Q_e^t \tag{10}$$

$$e^t = P_i^t + \sum_i x_i^t - c^t - z^t - f_\downarrow^t + f_\uparrow^t \tag{11}$$

$$h^t = Q_h^t \tag{12}$$

$$h^t = Kc^t + \sum_i y_i^t - w^t \tag{13}$$

where Q_e^t is total power demand (MWh), P_i^t is hourly renewable power production, Q_h^t is total heat demand (MWh). $f_\downarrow^t$ and $f_\uparrow^t$ are the power imported and exported respectively. z^t is the curtailed renewable power (MW), c^t is P2H (MW), e^t is power from energy system to demand side (MW), h^t is Heat from energy system to demand side (MW), K is coefficient of performance (COP), and w^t is wasted heat (MW). Our model is described in greater detail and has undergone thorough testing and evaluation in multiple studies [11,12,14,26].

2.1. *Luxembourg energy landscape*

European climate targets and national environmental goals heavily influence future energy system needs [19]. The EU green deal aims for major greenhouse gas reductions by 2030 and climate neutrality by 2050 [2]. This necessitates EU member states to develop and adopt national energy and climate plans (NECPs) for 2021–2030 [18]. In spring 2020, Luxembourg's ministry of energy and spatial planning released its national energy and climate plan (NECP-LU) [18]. It sets specific targets for reducing greenhouse gases, increasing renewable energy, and improving energy efficiency [1,18]. NECP-LU aligned with the Paris agreement, the EU climate and energy framework for 2030, and the European green deal roadmap [1,18]. The country aims at:

- Reduce greenhouse gas emissions in non-ETS sectors by 55% by 2030 (from 2005 levels).
- Increase renewable energies share from 11% in 2020 to 25% by 2030.
- Reduce end energy consumption by 40% to 44% compared to the 2007 EU-Primes Baseline projection.

These targets are considered sufficiently ambitious and exceed the country's expected contribution [10]. NECP-LU outlines an ambitious vision for reducing electricity consumption across key sectors [1,18,33]. In Luxembourg's residential areas, the focus is on promoting energy awareness and using efficient electric devices, including modernising homes and advocating for innovative living styles [1,18,22,33]. Offices aim to reduce electricity usage through energy-efficient designs [1]. The industrial sector faces mixed expectations, with scenarios ranging from increased electricity usage due to automation to significant energy use cuts [1]. The transport sector receives a separate assessment for its transition to electric solutions [1,3,22]. Between 2010 and 2019 (Table 1) energy consumption remained stable, with a slight rise of 1.34%, despite economic and population growth [1]. The COVID-19 crisis impacted energy consumption, particularly in tertiary and household sectors, but a long-term increase in electricity use is expected, especially in residential areas [1]. This increase offsets declines in the industrial sector, notably the steel industry [1]. Luxembourg's grid,

Table 1
Monthly power demand for Luxembourg for period 2015 to 2022 (GWh) [34].

Month	2015	2016	2017	2018	2019	2020	2021	2022
Jan	9	13	15	16	15	13	13	13
Feb	10	13	15	15	15	15	15	12
Mar	10	13	14	15	16	16	16	14
Apr	10	11	12	13	15	16	16	15
May	13	11	12	14	15	16	16	15
Jun	13	13	13	9	14	16	16	15
Jul	13	14	14	12	13	14	14	16
Aug	12	14	14	14	15	13	13	14
Sep	12	14	14	14	15	15	15	13
Oct	10	14	13	13	15	16	15	15
Nov	10	12	12	14	15	16	15	15
Dec	12	11	11	13	15	16	15	15

managed by Creos, has seen a steady increase in peak demand, highlighting the challenges of erratic power demands and the need for efficient grid management [1,3].

It is worth mentioning that the Luxembourg's government opposes nuclear power as a solution to reducing greenhouse gases [3]. Luxembourg seeks to exclude nuclear energy from sustainable investments and supports the EU's decision to exclude it from "green finance" [3]. New low-energy or passive houses will have reduced energy needs, and positive energy buildings might even produce their own energy through solar systems, contributing excess electricity to the grid [1,3,22]. This shift could turn consumers into "prosumers" (producers and consumers), and lead to local or renewable energy communities. These communities aim to reduce their collective impact on electricity grids by using smart systems and energy storage [1,3,10].

2.2. Luxembourg wind and solar power generation

The Creos grid's installed power capacity in Luxembourg has increased from 229 MW in 2010 to 629 MW by the end of 2022, with renewable energy sources—mainly solar and wind—accounting for 86% of total capacity [1]. Wind turbines are predominantly in the north, while solar installations are widespread, with the largest capacities in the north, east, and west [1,18]. CHP units are mainly around the capital and the south [1]. Despite the capacity growth, domestic generation's contribution to peak power demand remains small, varying between 13% and 19% over the past decade, with most of the peak power still imported [1,18]. Peak demand times often coincide with low or no wind and solar activity [1]. Wind power is variable, sometimes low in winter and often in summer [1]. Solar PV output peaks with higher solar radiation in spring and summer. The highest power generation typically occurs in spring rather than winter when peak demand is highest [1]. The regional distribution maps (see Fig. 2) depict solar and wind power production across Luxembourg. The majority of wind turbines and farms are predominantly situated in the northern part of Luxembourg, owing to favourable wind conditions in that region. In contrast, solar installations are more evenly spread throughout the country, reflecting the broader accessibility and applicability of solar technology in varying geographical locations [1].

Notably, a 4 MW windmill in Luxembourg can achieve the same energy output as a solar installation spanning 10 to 12 ha, underscoring the efficiency of wind energy in the Grand Duchy's geographical context [35]. However, the expansion of wind farms is somewhat constrained by stringent noise regulations, which are stricter in Luxembourg than in neighbouring Germany and Belgium [35].

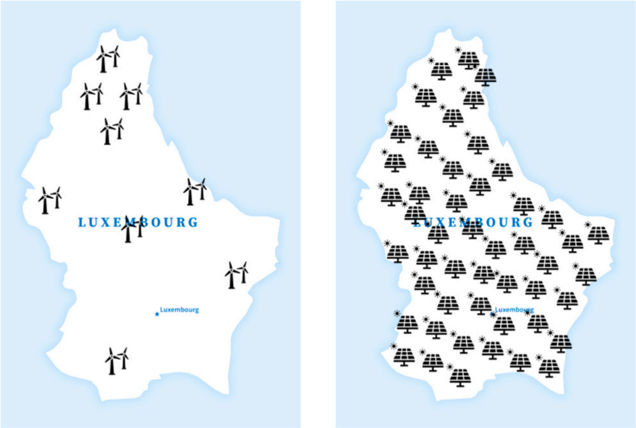

Fig. 2. Wind and solar power distributions in Luxembourg [1].

2.3. Energy demand scenarios for Luxembourg

Luxembourg is firmly dedicated to sustainability as it grows, with its population projected to rise from today's figures to 752,000 by 2030, 870,000 by 2040, and over a million by 2050 [1,18]. Accompanying this growth is an optimistic economic forecast, with an expected 3% yearly GDP growth from 2025 [1]. The country's energy strategy focuses on renewable electricity for everything from electric vehicles to energy-efficient heating in homes [1,18]. In this study, we examine data from two major plans available for Luxembourg: the National Energy and Climate Plan (NECP) and the Third Industrial Revolution (TIR) strategy. The energy plan presents two paths: a "Reference scenario" and the "Target scenario" aligns with the Paris Agreement's goals [1]. In brief, the mentioned scenarios are:

- Reference scenario (NECP): Luxembourg's electricity consumption is projected to increase by 8% from 2015 to 2040
- Target scenario – Paris Art. 2.1a (NECP): The national electricity demand rises slightly more, about 10% between 2015 and 2040.

The 2016 3rd industrial revolution (TIR) study predicts a substantial drop in Luxembourg's energy needs by 2050, with a shift towards efficient electricity and heating use [1]. TIR study presents two scenarios:

- STATEC scenario (TIR): Electricity consumption in Luxembourg is projected to rise by 17% from 2015 to 2050.
- Energy efficiency scenario (TIR): Luxembourg's electricity demand is expected to decrease by 1% from 2015 to 2050.

Despite STATEC's projection of population surpassing one million, electricity demand is expected to increase only by 17% to 6.9 GWh from 5.9 GWh in 2015, due to greater electrification across sectors [1]. Conversely, heating demand is anticipated to slightly decline by 2% to 13.0 GWh from 13.3 GWh in 2015, thanks to more efficient buildings and heating systems [1].

The "Energy efficiency" scenario anticipates a significant cut in energy use [1]. Electricity demand is nearly steady at 5.8 GWh, down just 1% from 2015, indicating that despite efficiency gains, demand persists due to the digital economy's needs [1]. In contrast, heating demand is projected to drop by 37% to 8.3 GWh, thanks to building retrofits, new efficient construction, and a shift to renewable heating [1]. This scenario reflects Luxembourg's strong commitment to energy efficiency, focusing on reduced heating needs while ensuring sufficient electricity for its growing population and economy [1]. Adding to this, Luxembourg's population was 552,000 in 2015 and is projected to reach 1,027,000 by 2050 [1]. The annual power demand in Luxembourg in 2015 was 2000 GWh for services and 753 GWh for residential houses [1]. In the STATEC scenario for 2050, the annual power demand is expected to be 2900 GWh for services, 1200 GWh for residential houses, and 2700 GWh for industry [1,18]. A summary of the discussed scenarios is presented in

Table 2
Comparative Overview of Projected Electricity and Heating Demand Across Various Scenarios for 2040 and 2050 [1,18].

Scenarios	Reference (2015)	TIR / Rifkin STATEC (2050)	TIR / Rifkin Energy efficiency (2050)	NECP Reference (2040)	NECP Target scenario (2040)
Electricity demand (TWh)	5.9	6.9	5.7	6.4	6.5
Heating demand (TWh)	13.3	13	8.1	13.2	5.5

Table 2.

In this study, we focus on the "TIR STATEC" (2050) scenario to examine the integration of renewable energy sources into Luxembourg's energy system. In a STATEC scenario for 2050, the power and heat demands have been addressed separately (see Table 3). This scenario is particularly important due to its comprehensive projection of a 17% increase in electricity demand by 2050, amidst significant population growth and economic development. The STATEC scenario is a great fit for our research because it offers a thorough sector-by-sector examination of energy demand, which provides a solid framework for assessing and developing hourly energy demand profiles [11].

The following sectors' energy demands are included in the applied hourly profiles for power and heating demand: Residential, Service, Industry, and Electric transportation [1]. Our energy consumption data comes from real recorded data provided by energy producers. We then adjusted the recorded data with projected values for 2050 heat and power demands using a range of modelling techniques. This analysis uses forecasts for 2050 and historical data (2015–2023) to create an hourly power consumption profile. The average hourly demand was estimated by combining hourly data into a single matrix. Then, we normalised this average to match the 2050 annual power demand prediction of 6.9 TWh as specified in the STATEC scenario. We used a combination of physical and data-driven approaches to develop a model that accurately develops the heat demand for every hour [36]. The applied model was tested against cases in Helsinki and Vantaa, Finland, demonstrating its utility in aggregated load analysis and predicting changes in hourly heat demand patterns [36]. The applied approach uses measured hourly heat demand data for a district heating system and ambient temperature to derive model parameters [36,37]. For the residential sector, considering the building heat loss/gain dynamics, the model focuses on space heating for energy-efficient and passive buildings, domestic hot water (DHW) demand, and thermal and circulation losses in district heating (DH) networks. The hourly demand for both the service and industrial sectors is mainly calculated based on the temperature, operational and seasonal patterns and predicted annual heat demand for each of the sectors [36,37]. The applied hourly energy demand profiles can be found in the supplementary material. The applied profiles for energy demand and VRE production have been presented in the supplementary material section (see Figure S1 and Figure S2).

2.4. Vertical farm power consumption

In this study, we explore the integration of Vertical Farming (VF) as a proposed solution to utilise surplus power generation, predominantly from solar sources, in reducing exports. We examine various sizes of cultivation areas for vertical farming within Luxembourg (100 ha–500 ha). Agriculture has long been a significant part of Luxembourg's economy [38]. According to the Ministry of Agriculture, the agricultural sector in Luxembourg contributes to the Europe 2020 strategy by addressing new societal challenges, including economic, social, environmental, climatic, and technological issues, thereby fostering smart, sustainable, and inclusive growth [38]. Farmers in Luxembourg must continually adapt their practices to meteorological conditions and the ever-changing market for agricultural products [38]. Given the high building land prices in Luxembourg, it's not surprising that the average prices for arable land in the country are among the highest in the European Union [39]. Currently, the average national price for a hectare of arable land in Luxembourg is approximately €47,290 in 2022 [39]. Considering that VF can significantly reduce the need for cultivation area and water usage, it forms the primary motivation for our choice of VF as a strategy to enhance the utilisation of renewable power in Luxembourg.

Here we simulate the power demands for growing wheat, tomatoes, soybeans, and lettuce in the context of vertical farming (see Table 4). Our study explores the lighting schedule for VF which provides lighting based on selected crops where lights are on until the daily lighting period is reached (e.g. for 12 h, lights are on for soybeans). The proposed lighting system control prioritises using available variable renewable power in a vertical system. The study's choice of model species is influenced by the crucial role of wheat as a primary source of energy, the global importance of soybeans for oil and protein, and the broader significance of tomato and lettuce in agricultural contexts [26,40]. In our simulation, we consider specific details regarding the varying light requirements for each crop, considering the photosynthetic photon flux density (PPFD) and daily light integral (DLI) values. Additionally, by estimating energy demands for each crop based on their lighting needs taking into account-PPFD values of 150 for lettuce with 18 h daily light period, wheat (PPFD 500, photoperiod 18 h), tomato (PPFD 300, photoperiod 18 h), and soybean (PPFD 350, photoperiod 12 h)-the applied model provides hourly power demand profile throughout the year [26].

In this study, we explore the operational strategy of a vertical farm exclusively during the spring and summer seasons, coinciding with periods of surplus solar power production (see Fig. 3). This approach is designed to maximise the utilisation of renewable energy resources, specifically solar power. By aligning the operational schedule of the vertical farm with the availability of excess solar energy, we aim to enhance the efficiency of renewable energy usage. This strategy not only ensures the vertical farm's energy sustainability but also mitigates the need to export surplus solar power out of the system. Consequently, this aligns with broader goals of optimising renewable energy utilisation and reducing reliance on non-renewable energy sources. For more explanation, in Fig. 3, the upper graph shows the conventional power demand pattern against the available variable renewable energy (solar power generation). The lower graph represents a modified demand curve, which has been strategically increased during mid-year (via seasonal vertical farming). The approach shown in Fig. 3, incorporating seasonal vertical farming, is a practical example of demand-side management (DSM) [7,13]. DSM is the modification of consumer demand for energy through various methods [7]. This strategy, especially when renewable energy production is high, optimises energy usage and reduces exports. In this case, vertical farming acts as a controllable load, increasing demand during periods of high solar output.

In addressing the integration of VF into the energy system, our model primarily focused on the daily lighting requirements of selected crops, identified as the principal energy demand factor for VF operations. Recognising the significant but less variable energy demands for heating and cooling in VF systems, we employed a pragmatic approach to estimate these demands. Specifically, we increased the calculated lighting power demand by 33%, a figure derived from empirical observations in a current VF project in Finland [26]. This method allowed us to incorporate a comprehensive estimate of total power demand for VF operations into our simulation, capturing the essential energy dynamics of VF

Table 3
Projected electricity and heating demand by sector in Luxembourg for 2015 and 2050 based on STATEC scenario [1].

Sectors	Residential		Service		Industry	
Year	2015	2050	2015	2050	2015	2050
Electricity demand (TWh)	0.7	1.2	2	2.9	3	2.7
Heating demand (TWh)	5.7	6.6	2.9	1.9	4.6	4.4

Table 4
Required intensity and daily lighting period for different crops [26,40].

Crop	Intensity $(\frac{\mu mol}{m^2 s})$	Daily light period (hour)	Production $(\frac{ton}{ha})$	Calorie $(\frac{Kcal}{100gr})$
Soybean	350	12	25	374
Lettuce	150	18	500	13
Wheat	500	18	70	350

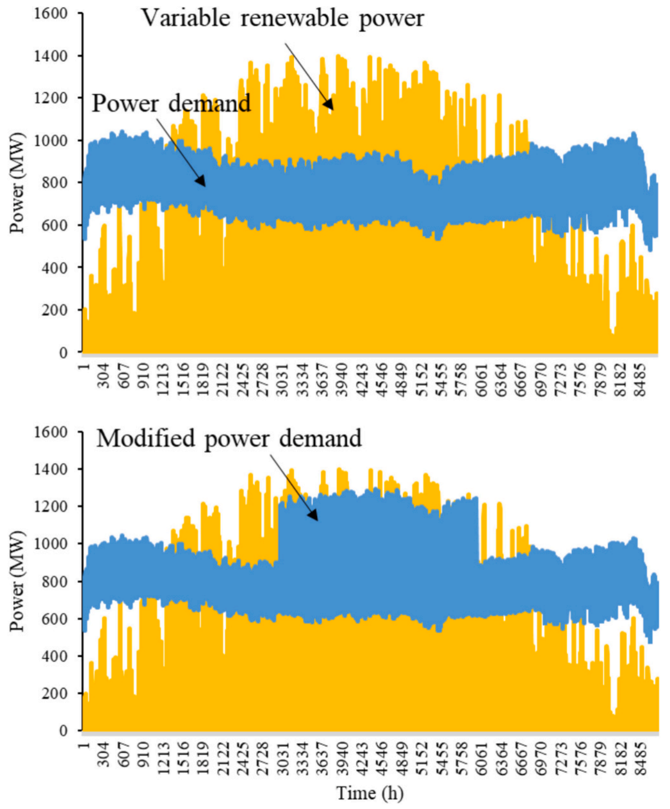

Fig. 3. Seasonal alignment of vertical farm operations with surplus solar power production (for whole year). Conventional power demand profile (top) and modified power demand with seasonal vertical farming (bottom).

systems without complicating the model with intricate heating and cooling schedules. This approach reflects our commitment to accurately simulating the energy requirements of VF, ensuring our study's findings provide a realistic picture of VF's potential impact on and contribution to the energy system.

Our study primarily explored the technical integration of VF with renewable energy systems, without delving into VF's maintenance costs due to our focus on energy dynamics. Recognising the importance of these costs, future research will extend our analysis to include economic considerations, enriching our understanding of VF's role in sustainable systems.

2.5. Studied scenarios

In this section, we present the proposed scenarios for transitioning Luxembourg's energy system towards sustainability, backed by justifications based on current trends and practices. The study investigates two principal configurations.

The first configuration advocates for a renewable-only system, primarily dependent on solar and wind power, complemented by an external power market. Our justification for this scenario stems from Luxembourg's significant shift towards renewable energy, where the share of electricity generation from renewables has escalated to 88% [1,18].

In the second configuration, we propose integrating a Combined Heat and Power (CHP) plant within the renewable framework. This scenario is justified by Luxembourg's strategic use of controllable sources, particularly CHP plants, to effectively manage peak power demands. The rationale behind including CHP plants is their role in providing stability and flexibility in energy supply, especially during periods with lower renewable energy outputs, such as winter months [1,18]. Notably, similar scenarios have been explored in multiple studies to decarbonise energy systems [11,14,28]. The main hypotheses applied in this study are as follows:

- For power-to-heat, we assume a constant coefficient of performance (COP) of 3. This value is typical for most commercially available technologies, which usually range from 3 to 5. However, in extreme conditions, such as cold weather, COP values may drop to 2 or lower. Considering Luxembourg's climate, a COP of 3 is a reasonable assumption based on historical temperature data.
- In some simulations, we consider a high level of renewable energy production, even surpassing current Luxembourg energy scenarios. This approach helps us investigate extreme conditions that the energy system might encounter, identifying potential challenges and areas for improvement. Notably, we maintain a total renewable power production of 2 TWh in scenarios, in line with Luxembourg's future energy goals.
- Despite Luxembourg's current emphasis on solar power, we explore diverse combinations of renewable energy sources. Luxembourg faces strict noise regulations and technical challenges for wind power. However, we examine the potential for technological progress and distributed wind generation, including microgrids and energy communities. Our scenarios also investigate solar-dominated cases and solutions for integrating large-scale solar power.
- For vertical farming, we assume seasonal operation, mainly during mid-year when surplus renewable power, primarily from solar energy, is available. The use of vertical farming depends on factors like food market demand and resource availability. We presume that the produce from vertical farms can be marketed or stored for future use.
- We use hourly national power consumption data from platforms like ENTSO-E [34] for demand profiles. Access to real-time heating sector data is limited. While real-world data poses challenges for academic and research endeavours globally, we rely on a valuable model validated and tested with real data. Our main assumption for applying this model in Luxembourg is the extensive use of district heating systems, heat pumps, and energy-efficient buildings, consistent with Luxembourg's NECP [18] and other energy scenarios [1].
- We assume a curtailment rate of 30%, which is comparatively high. Renewable energy curtailment has decreased in many countries due to grid improvements. However, the shift to a system with numerous consumers and prosumers introduces significant uncertainties. Our assumption of high curtailment reflects a critical scenario where the grid system and infrastructure are under substantial strain. This allows us to evaluate the potential of electrified power in utilising curtailed renewable energy.

To ensure the study's analytical clarity and relevance, we employed uniform increment steps of 25% for the capacity of the Gas CHP systems across selected scenarios. This methodological choice was driven by the need to reach a balance between the granularity of the analysis and computational feasibility, reflecting strategic decision-making benchmarks commonly used in energy system planning and infrastructure development [11,14,26,32,36,41–43]. By adopting this approach in the "Gas CH" and "Limited Energy System" scenarios, we conducted a structured sensitivity analysis, effectively illustrating the impact of various levels of CHP integration on the energy system's efficiency, resilience, and alignment with sustainability targets. In contrast, for the "Vertical Farm Integration" scenario, we presented results from a specific CHP capacity (sized at 50% of the peak power load) to minimise computational costs and to simplify the visual representation of our analysis results. This decision allows us to explore a broad spectrum of potential futures in a manner that is both detailed and pragmatically aligned with the increments typically considered in energy policy and system development.

2.5.1. *Scenario: Full renewable*

In the “Full Renewable” scenario, solar and wind power are the sole on-site power sources for the energy system. This model anticipates a total renewable power generation capacity of 2 to 8 TWh/year, meeting the system’s energy needs. To boost efficiency, a large electrified heating system (via HP or electrical boilers) is integrated into the system. Additionally, the system maintains a connection to the external power market, offering increased flexibility. The “Full Renewable” scenario acts as a key benchmark in our study, providing a comparative reference for other models.

2.5.2. *Scenario: Gas CHP*

In contrast to the ‘Full Renewable’ scenarios, the ‘Gas CHP’ scenario introduces a significant element to the energy system: a natural gas-powered Combined Heat and Power (CHP) plant, working in conjunction with a large array of variable renewable energy sources. This CHP plant can adjust its output, ranging from 25% to 100% of the system’s peak power load. It efficiently provides both electricity and heat to the energy system. Additionally, this scenario maintains a connection to the external power market, ensuring a supplementary power supply when needed. In this model, the gas used is emission-free, potentially sourced from environmentally friendly options like biogas or synthetic gas (such as power to gas, SNG).

2.5.3. *Scenario: Limited energy system (Curtailment)*

The “Limited Energy System (Curtailment)” scenario evaluates the impact of pre-emptively reducing renewable power generation by up to 30% due to grid limitations, a strategy known as “Renewable-following” [42,43]. Before explaining this scenario, we will describe our proposed curtailment strategy. Curtailment is one of the main challenges in increasing penetration of renewable energy sources, particularly wind and solar power. There are a variety of reasons for curtailment, including transmission congestion, system balancing challenges, and voltage control issues. Transmission congestion occurs when the physical capacity of transmission lines is insufficient to carry the amount of renewable energy generated [2,29,44]. System balancing challenges arise when there is a mismatch between the supply and demand of electricity [29].

Voltage control issues can occur when the variability of renewable energy sources causes fluctuations in grid voltage [16,29,31]. Curtailment can be caused by a combination of these factors, and the specific reasons for curtailment vary depending on the location and the time of day. In some cases, curtailment may be a necessary measure to maintain grid stability and reliability [16,29,31]. However, curtailment also represents a loss of potential renewable energy generation, which can have economic and environmental consequences. Curtailment reduces the available renewable energy for consumers, potentially raising energy prices [29]. It negatively impacts developers by limiting the sale of their produced energy [29,44]. Additionally, curtailment may be necessary to comply with grid regulations, which can limit the flexibility of renewable energy operators [29,31,44,45]. Here we focus on the proactive curtailment which is a more strategic approach to managing renewable energy, where decisions are made in advance to avoid wasting curtailment in the first place. We consider the curtailment as high as 30% (see Fig. 4). It simulates a critical situation that includes:

- The grid infrastructure needs to be able to handle the variability of renewable energy. If the grid is not up to the task, then renewable energy will have to be curtailed.
- Renewable energy resources need to be managed carefully to ensure that they are used efficiently. Renewable energy will have to be curtailed in cases of poor forecasting data, un-optimised dispatch, and ineffective demand response programs that fail to shift consumption patterns.

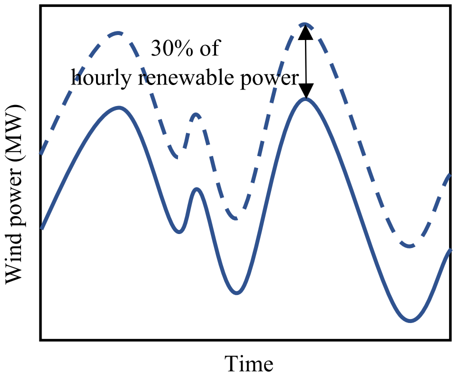

Fig. 4. Renewable power curtailment strategy “Renewable following” curtailment level 30%. The dashed line is the original renewable power profile, and the solid line is the curtailed renewable power.

So, in general, we simulate an extreme scenario in accepting renewable power production. The scenario also proposes utilising the curtailed renewable energy for Power-to-Heat (P2H) applications to maximise resource efficiency. This approach aims to enhance the reliance on renewables, considering the non-dispatchable nature of the resulting heat supply. Proactive curtailment, as part of this scenario, is a preventive measure to ensure grid stability and efficiency. It involves forecasting, grid analysis, curtailment decisions, implementation, and real-time adjustments. While this method helps in balancing the grid, it also faces challenges in forecasting accuracy, requiring a balance between proactive and reactive measures. This approach is crucial for integrating variable renewable sources like wind into the electricity grid, promoting a sustainable energy future.

2.5.4. *Scenario: Vertical farm integration*

This scenario focuses on integrating seasonal vertical farming into Luxembourg’s energy system, examining various configurations to understand their feasibility and impact. We consider different vertical farming cultivation areas, ranging from 100 ha to 500 ha, growing wheat, soybeans, and lettuce paired with distinct energy systems. These include a system powered entirely by solar energy, another solely reliant on wind power, and two hybrid systems. The first hybrid system combines 100% solar power production (6TWh) with a CHP plant, sized at 50% of the peak power load as its maximum nominal power output (520 MW). Similarly, the second hybrid system merges 100% wind power production (6TWh) with a CHP plant of the same capacity. The logic behind these configurations is rooted in the assumption that these energy systems have surplus variable power. Moreover, they face flexibility issues that vertical farming could potentially mitigate.

Table 5 summarises different scenarios applied in a study for a power system with renewable power, heat pump, exogenous power market connection, gas CHP, building energy efficiency improvements, gas boiler, and renewable power curtailment.

3. Results

Here, we explore creative and extreme approaches to solving Luxembourg’s 2050 energy systems, presented by a detailed hourly energy system simulation. The power demand for vertical farming (VF), various shares of solar and wind energy, renewable power curtailment, and the effectiveness of electrified heat via heat pumps in heating applications are aspects that are carefully evaluated by the simulation. We actively evaluate outcomes based on the system’s ability to maximise the usage of renewable energy sources. Our analysis places a strong emphasis on each scenario’s energy balance, paying close attention to the dynamics of power import and export. The import and export shares are important for energy system interaction with the power market, but we also want to intentionally lower them to boost the system’s resilience and

Table 5
The brief description of applied scenarios in this study.

Scenario	Renewable Power (TWh)	Power to heat	Gas CHP	Renewable Power Curtailment	Share of wind and solar
Full Renewable	2–8	Yes	No	No	Wind/Solar [0–100%]
Gas CHP	2–8	Yes	Yes (25%–100% of peak power load)	No	Wind 75%solar25%
Limited energy system (Curtailment)	2–8	Yes	Yes (25%–100% of peak power load)	30%	Wind75%solar25%
Seasonal vertical farm integration	6	Yes	Yes (50% of peak power load)	No	Solar100%

maximise the amount of energy that may be derived from renewable sources. In this manuscript, we examine the potential for integrating large-scale renewable power, specifically 2 TWh, 4 TWh, 6 TWh, and 8 TWh, into Luxembourg's energy system. Although these figures exceed Luxembourg's current renewable energy projections, even for 2050, this approach is instrumental in exploring the full potential and limitations of renewable energy in the country. Such an analysis is crucial for understanding the energy system's capacity, considering possible future technological advancements and policy shifts. Section 2.5 explains the simulated scenarios in this section. The code is structured in MATLAB to ensure reproducibility of the results and the key parameters, and the model used has been applied in a wide range of studies before.

3.1. Scenario full renewable

In our study of Luxembourg's energy system, we assessed various simulation cases to evaluate the renewable power integration. Fig. 5 presents the power balance in Luxembourg's energy system for varying levels of renewable power production, from 2 to 8 TWh, with different mixes of solar and wind. The scenarios are presented across different scales of total renewable power production, from 2 to 8 (TWh), and the mix of solar and wind energy varies from 100% of solar power share to an even split or 100% of wind power. It visually summarises the relationship between renewable integration and the energy system's import-export dynamics, highlighting the key findings from our analysis.

Due to the inherent mismatch between renewable power generation and energy demand, a portion of the generated renewable power cannot be directly utilised within the energy system. The successful integration of significant renewable power into the energy system requires careful assessment. It is evident that the scenarios where exported and imported power are at their minimum offer insights into better renewable power integration. Lower imports and exports suggest a more self-sufficient and renewable energy-dependent energy system, reflecting greater integration of renewables.

For instance, when looking at the 2 TWh scenarios, all generated renewable power is being utilised within the system, indicating a potentially well-matched supply and demand. However, imports remain relatively high across all 2 TWh scenarios, constant at 9.3 TWh (2 TWh less than the imported power in the reference case), suggesting that regardless of the renewable mix, there is a reliance on energy imports (exogenous power market) to meet demand. As we increase the scale to 4 TWh, the scenario with higher wind power share stands out, where the export is at a minimum (0–0.1 TWh), indicating that almost all the renewable power produced is consumed within the system. Moreover, the import decreases significantly in the 4 TWh scenarios as compared to the 2 TWh scenarios, suggesting better self-sufficiency.

Notably, at the 6 TWh scale, export is minimised (0.28 TWh) with a 75% wind and 25% solar mix. This could be an indicator of an optimal mix for 6 TWh renewable power production, balancing the variability of wind with the steadiness of solar energy to meet demand. At the highest

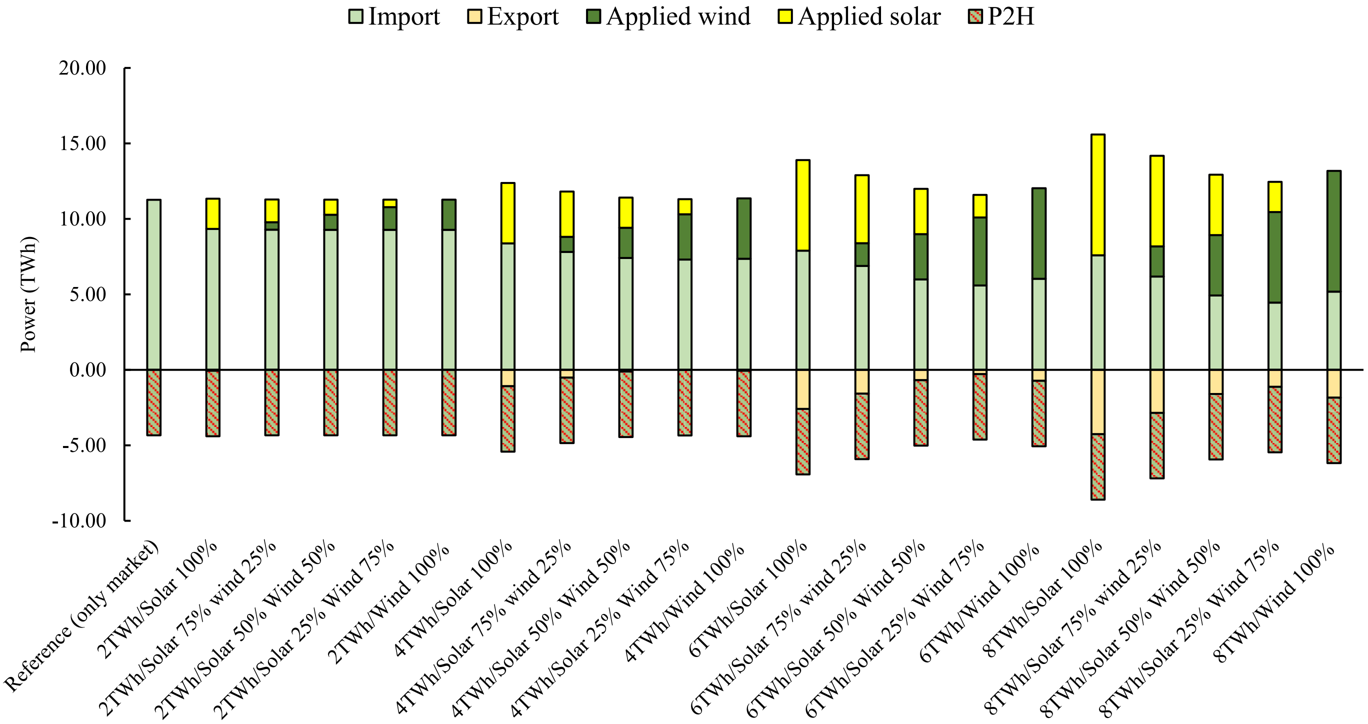

Fig. 5. Power balance for Luxembourg energy system with renewable power (2TWh-8TWh). The share of both the solar and the wind power production ranging 0–100%.

scale of 8 TWh, we see that the import values are the lowest across the simulated cases, which could be due to a larger base of renewable generation reducing the need for external energy sources. At the same time, the export values are somewhat higher here, which might suggest the limitations of the energy system in integrating renewable power.

The annual power demand of Luxembourg after adding power to heat via a large HP will increase from 6.9 TWh (suggested by the "STATEC" scenario [1]) to 11.2 TWh. This increment in yearly power demand at 4.3 TWh, will be used by HP to cover the heat demand for Luxembourg at 13 TWh. The analysis of Luxembourg's energy system data indicates that adopting a composition of 75% wind and 25% solar power not only leverages the complementary nature of wind and solar energy but also ensures efficient integration into the national grid. We selected this specific mix to further explore the integration of renewable energies within Luxembourg's energy framework in subsequent scenarios.

3.2. Scenario Gas CHP

A gas-fired CHP plant with a nominal power output of 25% to 100% of the peak load (0.2 to 1 TW) has been integrated into the energy system to increase the diversity of energy generation sources and strengthen the resilience of the energy system (see Fig. 6). This illustration quantifies the impact of combining a consistent renewable mix of 75% wind and

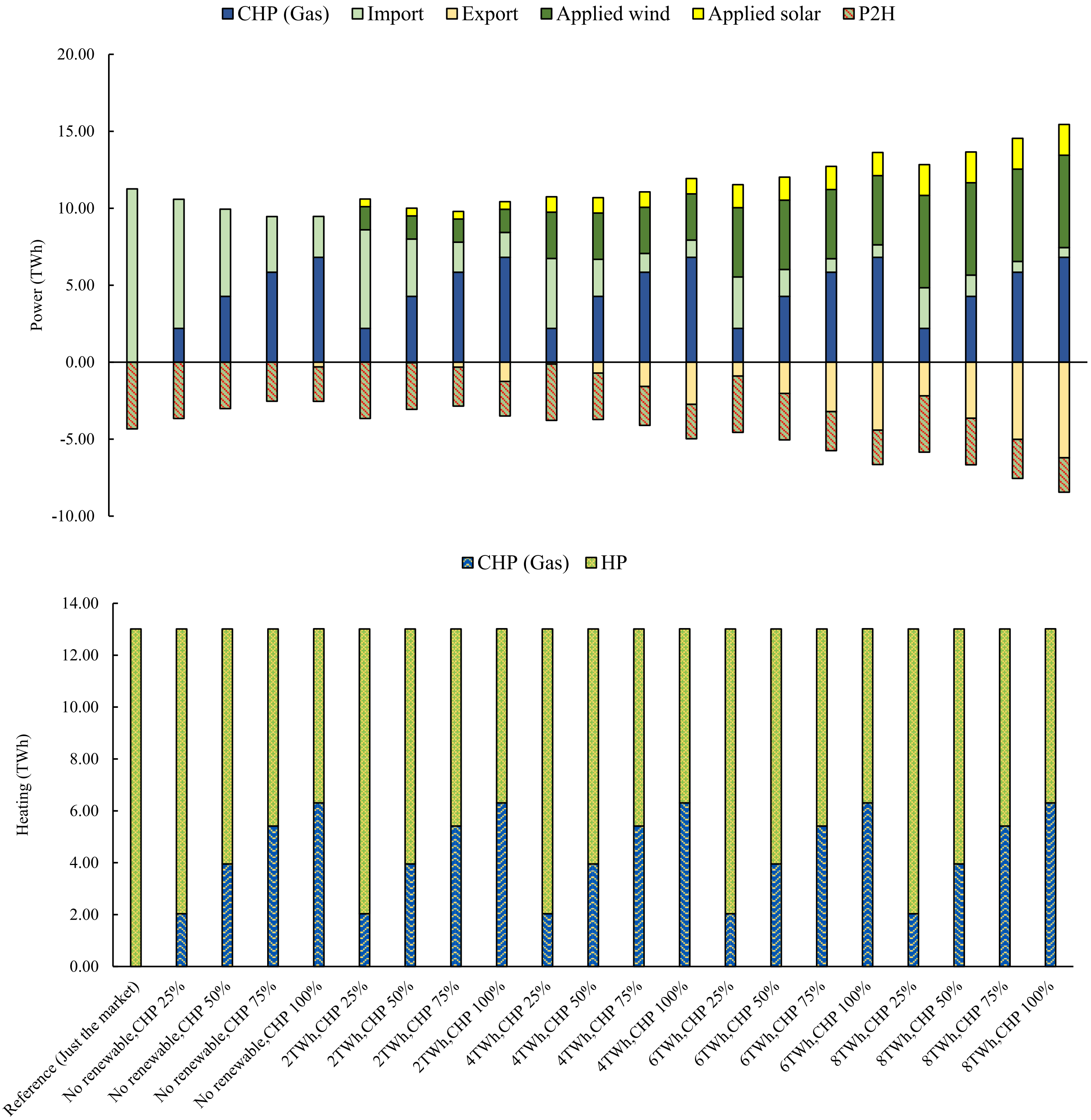

Fig. 6. Energy balance for Luxembourg energy system with renewable power production (2TWh-8TWh) and Gas-CHP with nominal power output 25% to 100% of power peak load. The mixture of the renewable power production is solar 25% wind 75%.

25% solar with flexible CHP system sizes on the system's reliance on imports and the handling of excess generation. Fig. 6 displays the energy balance in Luxembourg's energy system, factoring in both renewable power production and the integration of Gas-CHP at varying outputs from 25% to 100% of peak power load. The amount of renewable energy used is still the same as in the earlier scenario ranging from 2 to 8 TWh/year.

Our analysis reveals that the integration of CHP systems and renewable energy sources can significantly reduce dependence on imported power. Specifically, CHP systems catering to 25%, 50%, 75%, and 100% of peak power demand—corresponding to annual productions of 2.2, 4.3, 5.8, and 6.8 TWh respectively—can decrease imported power by 20%, 50%, 68%, and 76% (in comparison with reference case). Notably, even a CHP system fulfilling 100% of peak demand efficiently utilises over 96% of the generated power within the system. Complementing this with a renewable energy mix of 75% wind and 25% solar power enhances system efficiency further. For instance, integrating 2 TWh of such renewable power with a CHP system sized up to 75% of peak demand, or 4 TWh of renewable power with a 25% peak demand-sized CHP, results in highly efficient operations with minimal export and significantly reduced import requirements. Overall, in a system that incorporates CHP along with substantial variable renewable energy sources, the export can be as high as 34% of the total system production, which includes power generated from CHP as well as solar and wind.

When the CHP system and renewable power sources operate simultaneously, the exported power primarily originates from unmatched and surplus renewable energy. Due to their dependence on environmental conditions, renewable energy sources such as wind and solar can exhibit unpredictability in their power output; in contrast, the Combined Heat and Power (CHP) system provides a more controlled and reliable output, offering stability to the energy system. By integrating CHP with renewable sources, we can ensure a consistent energy supply. The ability of CHP to simultaneously produce heat and power enhances exported power in energy systems. Due to this, CHP continues to generate heat even when there is sufficient renewable power available. As a result, this reduces the need for electrified heating powered by renewable power, subsequently decreasing the consumption of renewable energy. For instance, in the simulated case with 2 TWh of renewable power, the exported power reaches 1.2 TWh with a CHP system sized at 100% of peak power demand. Similarly, for a scenario with 4 TWh of renewable power, varying scales of CHP systems can elevate the exported power, potentially as high as 2.7 TWh when the CHP system matches 100% of the peak power demand. In the heating sector, as the CHP contribution to the peak power load rises from 25% to 100%, a corresponding increase in total CHP heat generation is observed, rising from 2.03 TWh to 6.31 TWh. Conversely, the heat pump's production exhibits a decreasing trend, diminishing from 10.98 TWh (CHP's 25% of power peak) to 6.71 TWh (CHP's 100% of power peak).

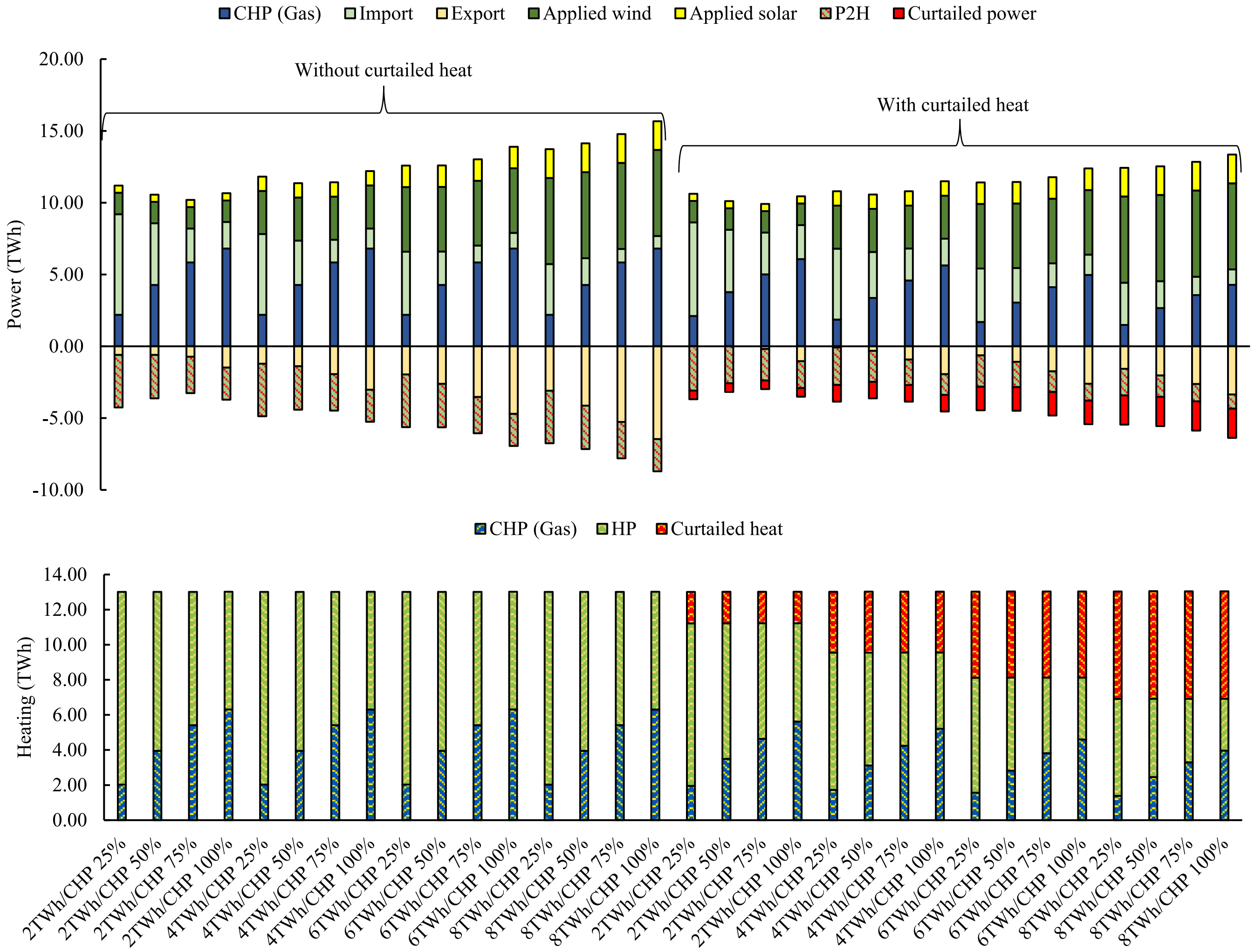

Fig. 7. Energy balance for Luxembourg energy system with 30% curtailed renewable power production (2TWh-8TWh) and Gas CHP (25% to100% peak power load). Two series of simulation's results with curtailed heat (left) and without curtailed heat (right).

3.3. Scenario limited energy system (Curtailment)

In this scenario, we explore the concept of using curtailment and power-to-heat (P2H) to increase flexibility in energy systems with a high share of wind and solar power. It's important to clarify that we define "curtailment" as any reduction in wind and solar power production. The key idea is that intentionally directing curtailed wind and solar power to P2H systems could enhance the integration of these renewable sources and prevent the unnecessary discard of variable renewable power. Fig. 7 depicts the impact of managing 30% curtailed renewable power in Luxembourg's energy system through Gas CHP integration and P2H strategies. The figure contrasts scenarios with and without the redirection of curtailed power to heating, illuminating the trade-offs between increased system flexibility and reliance on external energy imports. This visualisation is key to understanding how strategic management of excess renewable energy can optimize the energy system's performance.

The results of this scenario provide insight into two energy systems, both experiencing curtailments, with one key difference: the allocation of curtailed power to the heating sector. In the first part, the system is simulated with the curtailment of variable renewable power without utilising the "curtailed P2H" approach. In the second part, the curtailed renewable power is redirected to the heating sector, which we refer to as "curtailed P2H". The scale of CHP applied is consistent with the previous scenario, ranging from 25% to 100% of the power peak load. We chose an energy system with CHP for this study to examine the effects of curtailment in a more challenging scenario. This choice is based on insights from a previous scenario, which showed that CHP can lead to greater mismatches between variable renewable power supply and demand.

As expected, power imports in this scenario increase compared to the "scenario CHP," because of curtailed power and less integrated variable renewable power. Implementing a 30% curtailment level can lead to a rise in imported power, varying from 9% to 20%. This variation depends on the scale of the CHP and the amount of variable renewable power applied.

Curtailment not only increases the operation but also the share of CHP in both the power and heating sectors (in comparison to "scenario CHP"). Consequently, the system still exports renewable power from solar and wind sources. This is due to the higher contribution of CHP in both sectors and the reduced opportunities to match renewable power from solar and wind with the demands in the power and heating sectors. For example, integrating 2 TWh of renewable power with a 30% curtailment level in a CHP system sized up to 75% of peak demand, or integrating 4 TWh of renewable power with a 30% curtailment level in a 25% peak demand-sized CHP, results in exporting variable renewable power at rates of 0.41 TWh and 1.12 TWh, respectively.

To address the issue of wasted energy, we chose to redirect the curtailed renewable power to the heating sector, utilising a Heat Pump (HP). Notably, the second system shows the utilisation of 0.60 TWh to 2 TWh of curtailed power for heating, marking a strategic shift towards using excess power that would otherwise go unused. In the scenario where curtailed power is redirected to the heating sector, the redirection of curtailed power to heating purposes effectively reduces the amount of surplus energy available for export. This is because a portion of the heating requirements, which would traditionally be met by CHP systems, are now being satisfied by curtailed heat. In the simulated cases incorporating "curtailed P2H", exports decreased by a range of 30% to 100% compared to the cases without "curtailed P2H". Generally, the exported power constitutes 3 to 34% of the total system's production. The second system captures the utility of what would be curtailed power; as 1.8 TWh to 6.1 TWh of heat is derived from curtailed power, emphasising the benefit of repurposing curtailed power, which contributes to a more sustainable and efficient heating sector.

However, this reallocation does not completely offset energy demand. Consequently, the decrease in system power production, primarily due to the reduced power output from CHP systems, necessitates the increased import of energy. For instance, in the simulated case featuring "curtailed P2H" we observed an increase in power imports ranging from 1% to 42%, compared to the simulated cases without "curtailed P2H". This scenario suggests a dependence on exogenous power sources to compensate for the deficit created by using curtailed power for heating needs. The increase in imports may also reflect a strategic decision to maintain energy reserves or to ensure a consistent energy supply, considering the variability and unpredictability associated with renewable energy sources like wind and solar.

In the heating sector for systems without power redirection, the gas-driven CHP units contribute 2 TWh to 6 TWh, which decreases to 1 TWh to 4 TWh when curtailed power is used for heating, indicating a more efficient use of energy and possibly a reduction in natural gas consumption via CHPs. HP which is powered by system production also shows a decrease in usage from the range (6.7–11 TWh 3–11 TWh), suggesting that when curtailed power is redirected to provide heating, the demand on heat pumps is lessened. Generally, the power exported from the system, which includes both CHP and variable renewable sources, ranges from 17% to 52% of the total system production. These results are particularly significant when we consider that such a level of mismatch occurred even with a smaller proportion of renewable power in the system (30% curtailed). This degree of mismatch, along with the curtailment of renewable power, signifies a substantial loss and waste of variable renewable energy (please see Fig. 6).

3.4. Scenario: Vertical farm integration

Fig. 8 shows the power balance of Luxembourg's energy system enhanced with VF, showcasing the effect of integrating a 6 TWh solar power production and a Gas CHP system at 50% peak power load. It highlights the impact of VF cultivation areas ranging from 100 to 500 ha growing soybeans, wheat, and lettuce on power import and export dynamics, underlining the potential of VF in optimising energy use and adding resilience to food production. In this scenario, we implemented seasonal vertical farming (VF) strategies to modify the power demand profile and enhance the absorption of renewable energy, specifically from solar. Our experiments tested VF scales ranging from 100 to 500 ha of cultivation area, primarily active during spring and summer to coincide with peak solar power production. Typically, in systems lacking vertical farm integration, excess solar power would be exported to external power markets due to a mismatch between renewable power production and demand. Our strategic approach is designed to enhance the flexibility of power demand by systematically altering the demand profile to better align with variable renewable energy production.

We selected three crops for cultivation in these vertical farms: wheat, soybeans, and lettuce. Each crop impacts the power demand differently, depending on their required light intensity and duration. For instance, a 100-ha vertical farm growing soybeans, wheat, and lettuce would consume approximately 0.26 TWh, 0.56 TWh, and 0.17 TWh of power annually, respectively. Increasing the cultivation area generally reduces power exports but necessitates power imports, as the VF's energy demands exceed the surplus from solar production.

Soybeans, in particular, efficiently reduce power exports with minimal increase in imports. For example, a 100-ha soybean farm could lower power exports by 10% while only marginally increasing imports by under 1%. At a maximum cultivation area of 500 ha, soybeans could be entirely supported by variable renewable power, reducing exports by up to 50% compared to a system without VF. Wheat and lettuce show less potential in this regard. Wheat, requiring high light intensity (500 $\mu mol/m^2s$) and longer lighting periods (18 h), can minimise exports but increase dependence on external power by up to 20%. Lettuce, with its 18-h lighting requirement and 150 $\mu mol/m^2s$ intensity, has the least impact on reducing exports and utilising renewable power. However, lettuce cultivation leads to a low reliance on external power markets, similar to the increase in imported power for soybean vertical farming.

Additionally, we explored the integration of VF in systems operating

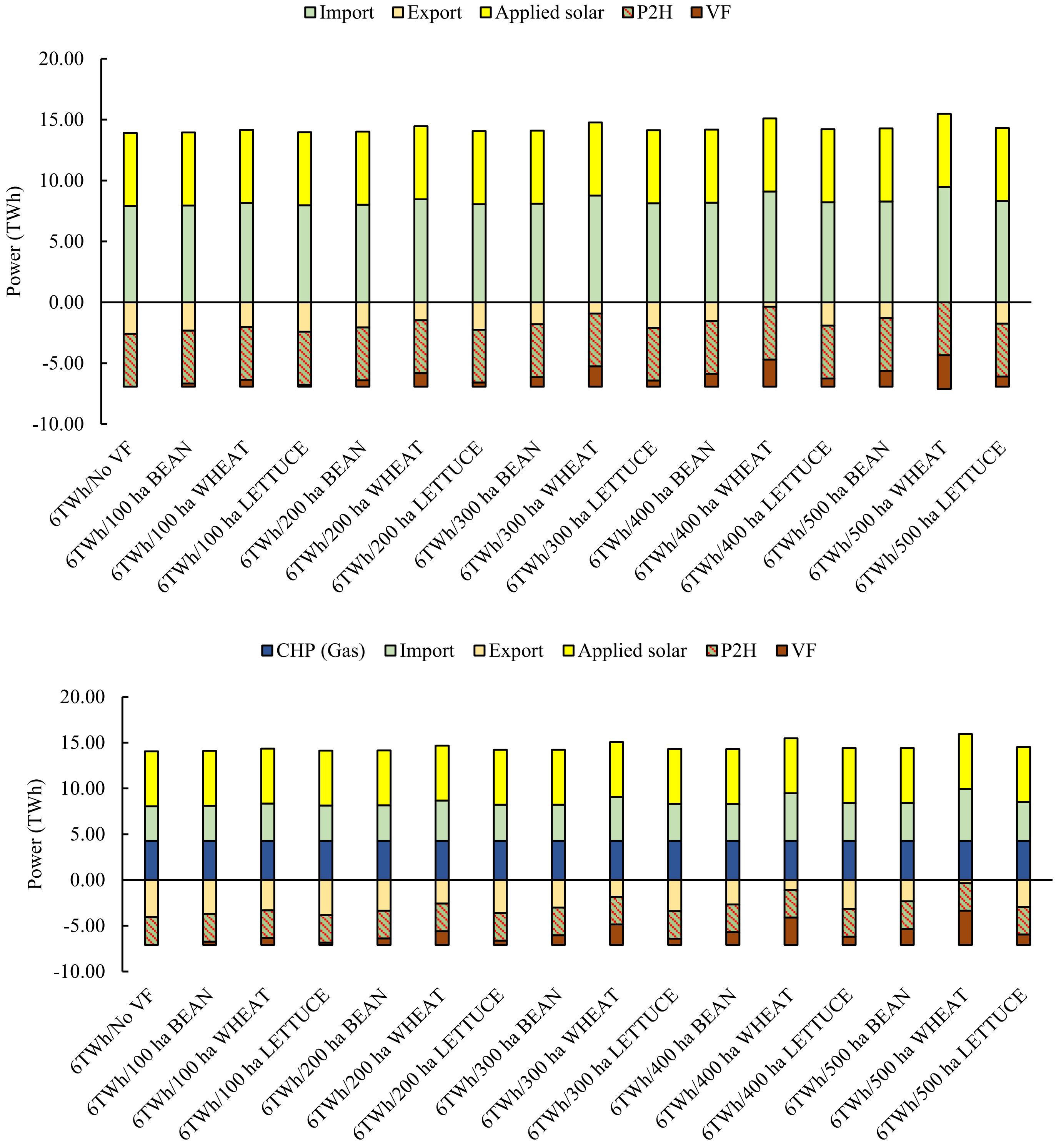

Fig. 8. Power balance for Luxembourg energy system with 6TWh solar power production (up) and Gas CHP with nominal power output 50% peak power load (down).The system including vertical farming growing soybean, wheat, and lettuce ranging 100 ha to 500 ha.

CHP units, with a nominal power output of 50% of the peak load (520 MW). The trend is like systems without CHP, but the increase in imported power is more significant. For instance, a 100-ha soybean farm in a solar-only system could cut exported power by 10% with a less than 1% increase in imported power. In contrast, in a CHP-inclusive system, the same farm reduces exports by 8%, and a 500 ha wheat farm could lead to a 90% reduction in exports but at the cost of a 50% increase in imported power. In conclusion, seasonal vertical farming not only boosts the utilisation of surplus variable power production in energy systems but also adds a resilient food production aspect.

4. Discussion

In this study, we have conducted a comprehensive analysis of Luxembourg's energy system transition towards renewable energy paradigm. The detailed simulations explored diverse scenarios: "Full renewable", "Gas CHP", "Limited energy system (Curtailment)", and " Vertical farm integration" each exploring the integration and efficiency of variable renewable energy sources, particularly solar and wind, in Luxembourg's unique context. In our study, we examined two primary energy system configurations. The first is a highly flexible system characterised by extensive renewable power production and an electrified heating system. This configuration is designed to maximise the use of renewable energy sources and enhance system adaptability. The second configuration focuses on the integration of controllable power plants, such as CHP systems. This approach introduces more variety into the energy system and improves its resilience [1]. However, it has a lower potential for flexibility compared to the first configuration. Transitioning from the theoretical frameworks of energy system configurations to practical applications, we find these energy system configurations particularly relevant to Luxembourg's energy strategies. These systems reflect Luxembourg's existing energy mix and strategies. The first emphasises the nation's growing reliance on renewable sources, while the second offers a pragmatic blend of renewables and CHP plants, ensuring consistent energy availability (mainly during the peak periods) and system resilience throughout the year.

In the Results section, the direct outcomes of the MILP optimisations are evident in the detailed simulations of Luxembourg's energy system. These results illustrate how MILP has been instrumental in identifying optimal operational strategies and configurations under diverse scenarios. By using MILP, we were able to explore the intricate dynamics of energy system flexibility, and the potential impacts of renewable energy integration at scale.

First, let's discuss Luxembourg's plan to develop power generation from solar and wind. The Integrated National Energy and Climate Plan (NECP) of Luxembourg outlines an ambitious strategy for the expansion of renewable energy sources, with a particular focus on solar and wind power [10]. While the plan foresees moderate growth in biomass generation, it places a stronger emphasis on the development of solar and wind energy by 2040–2050, aligning with the country's strategic priorities. In the NECP "Reference" scenario, solar power is projected to produce 1.5 TWh annually, and wind power is expected to generate 1.3 TWh/year [1,18]. The NECP "Target" scenario is more ambitious, estimating annual solar production at approximately 2.6 TWh and wind at 1.3 TWh [1,18]. In contrast, the TIR/Fraunhofer (scenario for 2050) predicts lower outputs, with annual solar and wind productions at 0.8 TWh/year and 1.2 TWh/year, respectively [1].

Moving from available Luxembourg's scenarios projections to our approach (using renewable power 2 TWh to 8TWh), we aim to surpass these targets. Our applied renewable power production significantly exceeds the projections outlined in Luxembourg's NECP, as we focus on the future potential, especially considering the rapid technological advances in the field of renewable energy. Our projections, ranging from 2TWh to 8TWh, anticipate a future where efficiency and capacity in solar and wind power are much greater than current levels. This is in line with the global shift towards more aggressive renewable energy targets, reflecting an optimistic yet realistic vision for the growth of renewable energies. By setting our sights high, we are aligning with the potential global trends and breakthroughs in green technology. Additionally, conducting an extreme study in this field offers significant benefits. It pushes the boundaries of current thinking, encourages innovation, and may lead to unforeseen advancements in renewable energy technologies. This approach not only prepares us for a more sustainable future but also positions us as leaders in the renewable energy sector.

Our forward-thinking approach in renewable energy leads us to address key challenges like the mismatch between renewable power generation and demand, emphasising the need for strategic management of intermittent energy sources like solar and wind. A key issue identified is the mismatch between renewable power generation and energy demand, highlighting the need for strategic engagement with renewable resources to manage imbalances. Renewable energy sources like solar and wind power are intermittent, with their output varying based on weather conditions. This intermittency can make it challenging to match renewable energy generation with demand, especially during peak hours when sunlight may be limited and wind speeds lower. One of the study's key findings is the identification of an optimal mix for renewable energy integration. The observation that scenarios with a higher proportion of wind power outperform those dominated by solar underscores the importance of wind energy in enhancing self-consumption and reducing power exports. The study suggests that a combination of 75% wind and 25% solar power is particularly efficient for Luxembourg's energy system. This mix takes advantage of the complementary nature of wind and solar energies, ensuring a more consistent and reliable energy supply, crucial for a small yet economically significant country like Luxembourg. Our analysis demonstrates that Luxembourg's energy system can effectively integrate and utilise up to 6 TWh of variable renewable power, ensuring maximum consumption with minimal waste. This capacity aligns closely with Luxembourg's climate action goals and the strategic objectives outlined in the national energy plan extending beyond 2030. When one looks at Luxembourg's climate action, there is a higher capacity of solar power compared to wind power capacity. This disparity is due to the feasibility of solar power, which has fewer environmental and technical requirements.

In Luxembourg's future energy plan, the role of the CHP is not significant, but it will be a part of the future energy system to maintain resilience and sustainability. Another significant insight from our research is the role of CHP systems in reducing reliance on imported power. The integration of CHP systems can potentially decrease imported power by up to 76% in certain scenarios, demonstrating the importance of diversifying energy generation sources. CHP plants typically operate at a fixed heat-to-power ratio and can affect overall system flexibility and variable renewable power self-consumption. Such observations, reported in literature references [7, 12, 28, 42], suggest that careful consideration is required to balance CHP benefits against potential limitations in renewable power integration. This finding is crucial for enhancing the resilience of Luxembourg's energy system and reducing its carbon footprint. Our results show that, under specific conditions, a combination of 2 TWh of variable renewable power and a CHP sized at 75% of peak power load, or 4 TWh of variable renewable power with a CHP sized at 25% of peak power load, would be suitable for Luxembourg's energy system if the target is to consume all the variable renewable power within the system.

Our study also explores the strategy of using curtailment and Power-to-Heat (P2H) systems to increase flexibility in the energy system. Redirecting curtailed power to heating needs, as shown in the "Limited energy system (Curtailment)" scenario, leads to a more efficient use of renewable energy. Adequate curtailment and its proper management significantly reduce exported surplus renewable power. This approach not only potentially reduces reliance on CHPs but also decreases the demand for heat pumps or electrical boilers (plant infrastructure for electrified heating system), indicating a more sustainable and efficient use of resources. Across all scenarios, the study underscores the critical balance between renewable energy integration, system efficiency, and resilience. By diverting excess power to heating applications, the surplus energy for export is significantly decreased. In scenarios featuring 'curtailed P2H', we observed a reduction in exports ranging from 30% to 100%, relative to scenarios without 'curtailed P2H'. The findings demonstrate that Luxembourg can significantly reduce its dependence on external energy sources while maximising the usage of renewable energies. This balance is crucial for the nation's move towards a sustainable energy future.

Our study's exploration of curtailment and P2H systems for energy flexibility seamlessly leads into the investigation of seasonal vertical farming (VF). This shift from efficient heating energy use to aligning agricultural demand with solar production exemplifies diverse strategies for optimising renewable energy use and minimising external power reliance. In our study, we implemented seasonal vertical farming (VF) strategies, primarily active during spring and summer, to enhance solar energy utilisation. This approach was designed to tackle the prevalent issue of excess solar power being exported due to a mismatch between production and demand. We investigated the effects of cultivating wheat, soybeans, and lettuce in these vertical farms, noting that each crop influences power demand according to its specific lighting requirements. A key finding was that, while larger cultivation areas generally reduced power exports, they also increased the need for power imports. However, by carefully selecting the type of crop, VF can maximise the use of renewable power within the energy system while minimising reliance on external power markets. Soybeans were particularly effective in decreasing power exports with only a slight increase in imports. In contrast, wheat and lettuce were less impactful in reducing exports and heightened dependency on external power sources. Furthermore, integrating VF with Combined Heat and Power (CHP) units resulted in a greater need for imported power compared to systems relying solely on solar energy.

Regarding the novelties mentioned in our introduction, our revised manuscript will further explain how these innovative approaches are not only theoretical but also practically significant. We explore tailored integration strategies specifically designed for Luxembourg's energy system (illustrated in “Scenario Full renewable” and “Scenario Gas CHP”), demonstrating through detailed simulations how different combinations of wind and solar energy optimize energy flexibility and penetration, given Luxembourg's unique climatic and infrastructural challenges. Additionally, our in-depth analysis of curtailment management (“Scenario Limited energy system”) introduces new strategies for utilising excess energy in electrified heating, thereby enhancing system efficiency. The integration of vertical farming to stabilize energy demand throughout the year (“Scenario: Vertical farm integration”) marks a pioneering step in aligning agricultural demands with energy production. Each of these elements reflects a strategic advancement in managing renewable energy resources, highlighting our study's contribution to both the theoretical and applied aspects of energy system optimisation.

There are several challenges and drawbacks associated with the practical implementation of our proposed scenarios. The primary issues include the integration and maturity of technologies such as large-scale vertical farming and power-to-heat systems, which are not yet ready for widespread commercial use. Another significant drawback is the economic feasibility of implementing these technologies and updating infrastructure, which can be considerable without adequate financial and policy support. In the context of vertical farming, adjusting lighting and power consumption also comes with limitations related to the optimal growth conditions of different crops, which can further complicate implementation. Regulatory and policy barriers also present considerable hurdles, as adapting existing laws and policies to accommodate new energy systems can be a complex and time-consuming process. Moreover, enhancing the grid's infrastructure and stability to manage high levels of variable renewable energy requires substantial investment.

Despite these drawbacks, it is both feasible and crucial to consider these scenarios as potential solutions for sustainable energy transitions. Highlighting these innovative possibilities not only acknowledges the current limitations but also encourages further research and development, helping to overcome the obstacles and bringing us closer to realising these advanced systems.

Our research outlines versatile strategies for integrating renewable energy, such as “Full Renewable”, “Gas CHP” and “Limited Energy System (Curtailment)” complemented by Vertical Farming (VF) to enhance energy system flexibility. VF is particularly beneficial for countries with scarce land and water, efficiently matching agricultural needs with surplus renewable energy. These cross-sectoral strategies not only propel decarbonisation efforts but also offer a blueprint for creating sustainable, resilient, and low-carbon societies globally. Our proposed scenarios, including those such as “Gas CHP” and “Full Renewable”, have been outlined in similar studies and have been recognized as viable options among various potential scenarios for different countries [11,14,26,32,36,41–43]. This highlights the universal relevance of these approaches and offers actionable insights for nations aiming to harness their renewable energy capabilities and foster sustainable development through innovative, cooperative solutions.

This study has several limitations. First, the study only considers a limited number of scenarios for transitioning Luxembourg to a sustainable energy system. Additional scenarios could be examined to provide a more comprehensive understanding of the potential options available. Second, the study does not account for the potential impact of future technological advancements. New technologies could emerge that could make it even more feasible to achieve a sustainable energy system in Luxembourg. Third, in our analysis, we concentrated on the technical exploration of integrating large-scale renewable power with energy systems, without conducting detailed cost assessments, including, for example, maintenance costs. This approach was driven by our objective to investigate the implications for the operational energy balance and the technical feasibility of such integrations. We recognise the importance of economic considerations in evaluating the viability of technologies like VF and other renewable energy solutions. Future research will build on this foundation, incorporating extensive economic evaluations to provide a holistic understanding of the benefits and challenges associated with these innovative integrations. Fourth, the study does not consider the potential social and economic impacts of transitioning to a sustainable energy system. These impacts would need to be carefully considered before implementing any specific measures. In our study, access to real power demand profiles was readily available through ENTSO [34], but obtaining accurate heating demand data was more challenging. The absence of direct access to comprehensive heating consumption data required the use of modelling approaches. This dependency on models, due to heating demand data not being publicly released by energy producers and companies, often for proprietary or competitive reasons, introduces certain assumptions and estimations. These factors can impact the precision of our findings related to heating demand, as the data is often guarded due to commercial sensitivities or regulatory restrictions. Despite these limitations, the study provides valuable insights into the potential options for achieving a sustainable energy system in Luxembourg. Further research is needed to address the limitations of this study and to provide a more comprehensive understanding of this complex issue.

5. Conclusion

Our comprehensive study has provided a detailed exploration of Luxembourg's transition towards a renewable energy system, examining a variety of scenarios that range from full reliance on renewables to the strategic integration of vertical farming (VF). The scenarios were specifically designed to reflect both current capabilities and visionary approaches to energy management, emphasising the importance of diversity in energy sources and system configurations for achieving a robust, sustainable energy infrastructure.

Key findings from our study include:

- Renewable Energy Integration: A strategic mix of 75% wind and 25% solar power substantially enhances system stability and self-sufficiency, reducing dependency on imported power by up to 50%. This blend exploits the complementary dynamics of wind and solar energies, ensuring a more reliable energy supply that aligns with peak demand times and varying weather conditions.
- Gas-fired CHP Plants**:** While these plants can significantly decrease reliance on imported power, enhancing energy independence, they tend to limit the flexibility and self-consumption of renewable resources. Our findings suggest scenarios where CHP integration can inadvertently increase power exports by up to 34%, highlighting a potential trade-off between energy resilience and renewable integration efficiency.
- P2H and Curtailment Strategies**:** These strategies have shown potential in decarbonizing heating sectors and improving the

integration of fluctuating renewable sources. Curtailment management, when combined with P2H systems, can transform excess renewable electricity into a stable, utilizable heat supply, potentially enhancing the utilisation of renewable energy by up to 34%.
- Seasonal Vertical Farming: Aligning VF operations with periods of high solar power production maximizes the use of renewable energy, with the potential to increase surplus solar power usage within the system by 50% to 100%. This strategic alignment demonstrates the importance of adaptive demand-side management in enhancing the efficiency of renewable energy systems.

Our research highlights the necessity for adaptive strategies and the importance of maintaining flexibility to respond to evolving energy needs and technological advancements. This study not only informs policymakers and stakeholders involved in Luxembourg's energy planning but also provides a framework that can be adapted to other regions with similar energy profiles. Moving forward, further research should address the limitations noted in our scenarios, particularly the exploration of more diverse configurations and the potential impacts of future technological advances. It is essential to continue refining these models to better understand and exploit the synergies between different energy sources and system components. Additionally, economic analyses incorporating the operational and maintenance costs of systems like VF and CHP should be integrated to provide a more holistic view of the feasibility of these energy solutions. By expanding the scope of future studies to include these dimensions, we can offer more comprehensive guidance for the development of sustainable energy systems that are not only technically feasible but also economically viable and socially beneficial.

CRediT authorship contribution statement

Vahid Arabzadeh: Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Raphaël Frank:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Vahid Arabzadeh reports financial support was provided by University of Luxembourg, Interdisciplinary Centre for Security, Reliability and Trust (SnT). The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2024.124088.

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