FlexBeAn

Flexibility Potentials and User **Be**haviour **An**alysis

The beating heart of the Luxembourgish energy transition

HOW FLEXIBLE ENERGY CONSUMERS CONTRIBUTE TO A RELIABLE AND LOW-CARBON ENERGY SYSTEM IN LUXEMBOURG

2022–2025

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How flexible energy consumers contribute to a reliable and low-carbon energy system in Luxembourg

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project FlexBeAn

Our energy system is within a transition process, facing the challenge of **integrating** high proportions of fluctuating **renewable energy sources** into the distribution grid. Additionally, the rapidly progressing electrification of sectors, such as heating and mobility, and the resulting increased demand for heat pumps and electric vehicles, **requires smart solutions**. Demand response is going to be one of the key enablers of this transition. The objective of the FlexBeAn project is to assess the **demand response potential** of the different consumer sectors of Luxembourg, from a technical, behavioural, and market perspectives.

WP1

Flexibility potential

How much demand response potential does Luxembourg have?

WP2

User behaviour

How does energy literacy affect flexibility provision?

WP3

Market development

How should electricity markets evolve to encourage demand response participation?

Definitions

For the purpose of this document , the following definitions[1] shall apply:

(1) *"Aggregation"* means a function performed by a natural or legal person who combines multiple customer loads or generated electricity for sale, purchase, or auction in any electricity market;
(2) *"Balancing"* means all actions and processes, on all timelines, through which TSOs ensure, in a continuous way, the maintenance of system frequency within a predefined stability range as set out in Article 127 of Regulation (EU) 2017/1485, and compliance with the amount of reserves needed with respect to the required quality, as set out in Part IV Title V, Title VI and Title VII of Regulation (EU) 2017/1485;
(3) *"Balancing market"* means the entirety of institutional, commercial and operational arrangements that establish market-based management of balancing;
(4) *"Balancing services"* means balancing energy or balancing capacity, or both;
(5) *"Congestion issue"* means a situation when the electric current flow through a physical asset exceeds operational limits applied by systems operators in line with their national framework;
(6) *"Conventional meter"* means an analogue or electronic meter with no capability to both transmit and receive data;
(7) *"Demand response"* means the change of electricity load by final customers from their normal or current consumption patterns in response to market signals, including in response to time-variable electricity prices or incentive payments, or in response to the acceptance of the final customer's bid to sell demand reduction or increase at a price in an organised market as defined in point (4) of Article 2 of Commission Implementing Regulation (EU) No 1348/2014 (17), whether alone or through aggregation;
(8) *"Downward flexibility"* means the capability of a consumer, producer, or storage unit to increase electricity consumption, reduce electricity generation, or charge storage in response to a external signal.
(9) *"Dynamic grid tariff"* means a grid tariff structure applied by the distribution or transmission system operator that varies over time, reflecting the actual or forecasted conditions of the power grid, including congestion levels, network losses, or system costs, with the aim of incentivising efficient use of the grid and demand-side flexibility.
(10) *"Dynamic retail tariff"* means an electricity supply contract between a supplier and a final customer that reflects the price variation in the spot markets, including in the day-ahead and intraday markets, at intervals at least equal to the market settlement frequency;
(11) *"Final customer"* means a customer who purchases electricity for own use;
(12) *"Flexible connection agreement"* means a set of agreed conditions for connecting electrical capacity to the grid that includes conditions to limit and control the electricity injection to and withdrawal from the transmission network or distribution network;
(13) *"Independent aggregator"* means a market participant engaged in aggregation who is not affiliated to the customer's supplier;
(14) *"Interoperability"* means, in the context of smart metering, the ability of two or more energy or communication networks, systems, devices, applications or components to interwork, to exchange, and use information in order to perform required functions;
(15) *"Metering point"* means a physical location where the withdrawal or injection of electrical quantities is measured or calculated.
(16) *"Smart metering system"* means an electronic system that is capable of measuring electricity fed into the grid or electricity consumed from the grid, providing more information than a conventional meter, and that is capable of transmitting and receiving data for information, monitoring and control purposes, using a form of electronic communication;
(17) *"Upward flexibility"* means the capability of a consumer, producer, or storage unit to decrease electricity consumption, increase electricity generation, or discharge storage in response to an external signal.

1 Key definitions are based on Article 2 of Directive (EU) 2019/944, 2019/943, 2016/1388, 2017/2195, and 2023/1162 of the European Parliament and of the Council.

Abbreviations

For the purpose of increased readability of this document, the following abbreviations shall apply:

BESS - Battery Energy Storage System

CO_2 - Carbon Dioxide

DSO - Distribution System Operator

ENTSO-E - European Network of Transmission System Operators for Electricity

EU - European Union

EV - Electric Vehicle

EWH - Electric Water Heater

HEMS - Home Energy Management System

HV - High Voltage

ICT - Information and Communication Technology

LV - Low Voltage

MV - Medium Voltage

NECP - National Energy and Climate Plan

PV - Photovoltaic

RES - Renewable Energy Sources

SME - Small and Medium-sized Enterprises

ToU - Time-of-Use

TSO - Transmission System Operator

V2G - Vehicle-to-Grid

1. Introduction

Luxembourg is on its way of **transitioning** to a low-carbon economy and society. In its integrated national energy and climate plan (NECP) for the period 2021-2030, among other things, Luxembourg has committed to rise the share of **renewable energy consumption to 35-37%** of final energy consumption and to increase **energy efficiency by 44%** – complemented with an ambitious deployment of wind power, solar power, heat pumps, and electric mobility by 2030. Such sustainability transformation has **far-reaching implications** for the management and operation of Luxembourg's (future) energy system: thousands of decentralized electricity generators, such as photovoltaic (PV) systems, will supply electricity on a highly volatile basis, depending on uncertain weather conditions.

At the same time, electricity consumption will not only grow due to the **increasing electrification** of different activities (heating, transport, etc.) in Luxembourg, but will also be increasingly characterized by **complex behavioural and technical constraints**, e.g., when it comes to the charging of electric vehicles or the use of heat pumps. In addition, **self-consumption** levels will generally rise for certain consumer groups. All of these developments underline the importance of the various **interconnections** with Luxembourg's **neighbouring countries**, which are also pursuing their own sustainability transitions, including for instance Germany's nuclear phase-out. Integrating the anticipated increased number of renewable electricity-generation facilities and the new consumers (together with their new usage patterns), the Luxembourg **electricity grid** must be developed as a backbone in such a way that it is **ready for** an energy future embracing **decarbonization, decentralization,** and **interconnection**. This includes both grid investment and flexibility-related questions.

On the consumer side, **demand response** has the potential to better integrate more consumers as well as volatile RES into such future grid. Thus, flexibility can enable the **further low-carbon transition** and avoid that this process is slowed down or even stopped due to severe constrains of the grid. In addition, flexibility can help customers to reduce their energy bill, by being active on the (wholesale) market or by adapting to grid tariff incentives. In all of these aspects, the **involvement of citizens and enterprises** plays a key role to successfully enable a flexible adaption of energy consumption, e.g., via market-based incentives or other forms of agreements.

In simple terms, demand response describes the change in the consumption pattern according to some monetary or non-monetary incentive. For instance, an industrial consumer could decrease its electricity consumption in hours where wholesale electricity prices are high, or an electric vehicle could be charged preferably in hours where the sun is shining strongly. Various consumers in **different sectors** have been identified that could potentially provide flexibility at different places, under different restrictions, and **with different flexibility characteristics**, i.e., the Luxembourgish industry, small and medium enterprises (SMEs), households (with, in turn, various heterogenous user groups), and electric mobility.

Against this background, in the short to medium term, grid operators will be compelled to find ways of how to increase the use of decentral flexibility options. The **FlexBeAn project**, which is driven by Creos, the Interdisciplinary Centre for Security, Reliability and Trust (SnT) of the University of Luxembourg, and the Luxembourg Institute of Science & Technology (LIST), **aims to investigate** the potentials of **demand-side flexibility in Luxembourg**, to assess associated potential revenues, and to identify key enablers in different areas. In this way, FlexBeAn contributes to Luxembourg's sustainable energy future with flexible consumers as "the beating heart" of the energy transition.

2. Flexibility Needs

In our future energy system, **flexibility** is a **key** for grid operators **to manage energy grids** in a more efficient and effective way, contributing to a secure grid operation in alignment with ambitious RES and CO_2 targets defined in the NECP. While, in general, there are **various flexibility needs** of the many stakeholders, in the FlexBeAn project we have a specific look at the potential use of demand-side flexibility for grid requirements.

In this context, flexibility is required to successfully integrate renewables into the grid, to enable the rapidly increasing demand for consumption capacity, and tackle increasing congestion issues. For these reasons, **grid operators are required to consider flexibility** as part of their grid development plans (Network Code Demand Response) and to assess their future flexibility needs (Electricity Market Design Reform). The methodology to assess future flexibility needs on national levels of ACER separates flexibility needs into two types:

System needs for instance relate to load and RES forecast errors, residual load variations, or RES integration. These needs are required at national level, or even regional level, as Creos has delegated its **balancing responsibility** in the common load-frequency control area to Amprion. Although Amprion is currently taking care of these needs for Creos, a look at them shows how important flexibility is becoming in the future. Already today, **Luxembourg requires up to 100 MW of balancing energy due to forecast errors** of the BRP. Also, the maximum ramp-up and ramp-down capacities (load differences in one hour) are around 100 MW in both directions (positive and negative). These values relate to the situation of today and **will grow in the future**. For the RES integration, the Creos scenario report 2024 estimated that excess generation could reach about 1.400 MW on the HV transmission grid in 2040. These numbers indicate how important demand-side flexibility will become in the future.

Network needs relate to responses to congestion and voltage issues, which can stem from generation or consumption. With respect to network needs, the **geographical location** of the flexible units is highly relevant, as well as the **voltage level** of the respective connection point. A flexible unit in the south of Luxembourg does for instance not contribute to solving grid constraints in the north of the country, and units connected to the MV do not help solving grid constraints in the LV. Until now, and taking into account ongoing reinforcements, Creos has managed **integrating** most **connection requests into the grid**, without major challenges. Nevertheless, this **will become more difficult** in the next years, as the energy transition is moving on at full speed and grid reinforcements take time or might not be economically efficient.

Given the above network and system needs, the following **concrete use cases for flexibility** have been identified as highly relevant cases for Luxembourg:

RES **generation** (wind turbines and PV installations) already **induce grid constraints** today and need to be curtailed from time to time. Also, for some parts of the grid, new installations need to wait for grid reinforcements to be realised. **Flexibility** is, thus, **required to** be able to **integrate more wind turbines and PV** installations into the existing grid.

The **electrification of bus and truck depots** can introduce some **local constraints** to the MV grid. As the buses are mainly charged during night, full capacity is required when overall grid loads are lower. Nevertheless, these customers need to be **motivated to charge** their buses **during times of low demand or high renewable** energy production.

Except for a few local issues, the low voltage grid does not face any grid constraints today. Nevertheless, the decarbonisation of households via **electromobility, PV, and heat pumps will increase the loads in the LV** and increase the flexibility needs also on this voltage level. Demand-side **flexibility** will especially be **required to integrate** the midday **generation peak of PV units** in summer, and the **evening consumption peak** in winter.

The **decarbonisation of industries** and the **development of data centres** will increase the consumption loads in the future on the HV and MV, and potentially **create** some **local flexibility needs**.

3. Technical demand-side flexibility potential

Luxembourgish **electricity consumers can supply flexibility** by adjusting their consumption patterns in response to external signals. As part of the **FlexBeAn project**, we **assessed the technical demand response potential** across the industrial, tertiary (SMEs), residential, and mobility sectors. Each sector was analyzed independently, applying specific methodologies tailored to its characteristics. Such approach was chosen due to fundamental differences in technologies, data availability, and levels of complexity, which required sector-specific analyses.

Summary and qualitative evaluation of flexibility potentials

The numbers given in Table 1 and the charts in the following paragraphs are inherently **simplifications of complex results**, since flexibility potentials for the different sectors vary for instance over time – for some sectors with the daily cycle, weekly schedule, based on seasons or weather conditions. Hence, the shown simplified numbers are mostly averages of a fluctuating availability of this flexible power, that could be provided over a limited, also fluctuating and individual duration.

Further, the **data availability for each sector is very different**, which should be considered regarding the varying uncertainty of the results. This also concerns, in particular, the rapidly growing sectors (EVs, heat pumps, and PV BESS), where the future technology penetration is modelled based on scenarios, which inherently underly large uncertainties, although the scenarios were evaluated against current developments and based on national, either political strategy or technical scenario papers.

A short outline on each flexibility asset is given further down in this section – for more information, please consult the full report. The numbers in the following table show that **a high flexibility potential will come from decentralised assets such as heat pumps, PV-batteries and EVs**. Nevertheless, also other sectors can deliver flexibility, however at reduced capacity.

» ***Technological readiness*** – using flexibility from different assets and sectors requires technical solutions and a level of standardisation that is quite different for each sector. The maturity of technical solutions (e.g., communication, automation, and standardisation of control interfaces) plays a crucial role in assessing how quickly a flexibility potential could be mobilised. This qualitative assessment has been summarized in the Table 1.

» ***Ease of implementation*** – besides the technical aspects other factors influence the complexity and challenges of mobilising the flexibility potentials, e.g., within the industry sector, a small amount of stakeholders hold a large part of the potential, which can be considered as an advantage as compared to the potentials from the residential sector, that is very scattered in large amounts of small units.

» ***Matching the characteristics of flexibility potentials to needs and main use cases*** – Some of the network needs for flexibility are characterised by specific properties regarding where and when these conditions occur. These characteristics need to be matched by the characteristics of the individual flexibility potential to effectively alleviate the stress on the network:

Distribution (LV) and MV-networks will be increasingly experiencing **congestions and voltage-issues due to high PV-production** during spring- and summer period, which specifically concerns rural areas with long distribution lines and low demand. **Downward flexibility from tertiary sector** would be suitable during this period, but is generally **situated mainly in urban areas**. **Heat pumps are seasonally not well suited, but could contribute to a limited extend** via domestic hot water production, such as electric water heaters can deliver this downward flexibility. **EV-based flexibility** is limited during mid-day (**mainly public- and workplace charging**), but suitable. **If PV BESS are purely operated for optimisation of self-supply** (as done today), the grid-relieving **effect is minimal**, but they could contribute very targeted flexibility if operated smartly, by e.g. forecast-assisted charging over noon. Hence, the indicators in brackets in the table below assess the suitability of PV BESS if charging is optimized to cover the peak production period. Since the batteries do not fully discharge by pure self-consumption during summer nights, the **potential could further increase if an active discharge towards the grid overnight would be incentivised.**

The already existing **evening peak**, specifically during winter, is **expected to be fortified** by the home-charging of EVs and intense operation of heat pumps in the cold period. To alleviate potential congestions, **upward flexibility by reducing or postponing loads could be activated**. Specifically, **home-charging EVs** have the potential to be very effective for this use case, being available at the suitable time and location, while the average durations to shift their charging is long enough. **Heat pumps** themselves, having long operation cycles during cold periods, are limited in the flexibility duration, while whitewares[1] and electric water heaters (EWH) could potentially shift loads into the night. Also **PV battery systems** are potentially available to feed energy back to the households, but their average state of charge during winter evenings is low, resulting in short durations. If the PV BESS would be charged from the grid during the day, the potential is obviously largely increased.

1 Whiteware refers to large household appliances-, in this study washing machines, tumble dryers and dishwashers were considered.

		Industry sector	Tertiary sector	Heat pumps	White ware / EWH	PV-Battery	Evs
	Technical maturity	●	◑	◔	◑	◑	◔
	Ease of implementation	◑	◑	◑	◕	◕	◑
Average flexibility potential [MW]							
2024 avg. Pot.	Upward Flexibility	-20,2	-29	-3,6	-16	-6,6	-17
	Downward Flexibility		48	7,9	74	4,8	
2030 avg. Pot.	Upward Flexibility	-41,0	-29	-60	-16	-122	-76
	Downward Flexibility	20,8	48	130	74	92	
2040 avg. Pot.	Upward Flexibility	-61,7	-29	-123	-16	-401	-212
	Downward Flexibility	41,5	48	265	74	299	
avg. flexibility duration [min.]							
	Upward Duration	*15-240*	*60**	*20-120*	*60* / 5.6*	*20-60*	*180-600*
	Downward Duration		*60**	*9-80*	*- / 3.6*	*0-40*	

* marked durations are not modelling results, but assumptions of the model
(EWH = central Electric Water Heaters (up from 50l); whiteware = washing machine, tumble dryer, dish washer)

Table 1 - Summary of flexibility potentials, average durations, and qualitative assessment indicators.

Flexibility use case: High PV peak production mid day, spring/summer locations: LV and MV, (urban &) rural	**Industry sector**	**Tertiary sector**	**Heat pumps**	**White ware / EWH**	**PV-Battery**	**EVs**
Suitability rating		◑	◔	◑	○ (◑)	◑
Seasonal suitability		+ +	-	+	- - (+)	+
Diurnal cycle		+	+	+	- - (+)	-
Location (voltage level, urban/rural)		-	+	+	+	+

Table 2 - Qualitative assessment of the suitability of flexibility to alleviate the grid during PV peak periods.

Flexibility use case: Heat pump and EV peak evenings, winter locations: LV, urban & rural	**Industry sector**	**Tertiary sector**	**Heat pumps**	**White ware / EWH**	**PV-Battery**	**EVs**
Suitability rating	○	◔	◑	◑	◔	◕
Seasonal suitability	+	-	-	+	-	+
Diurnal cycle	+	-	-	+	+	+
Location (voltage level, urban/rural)	- -	+	+ +	+	+	+ +

Table 3 - Qualitative assessment of the suitability of flexibility to alleviate the load peaks at winter evening.

SUMMARY ON INDIVIDUAL FLEXIBILITY POTENTIALS

Industry sector

Industrial demand-side flexibility varies significantly across sectors, as differences in manufacturing processes, operating schedules, and technical constraints determine the potential for adjusting electricity demand. Based on the reported flexibility potentials in the literature and the annual consumption profiles of the largest industrial companies within Luxembourg, we calculate an **average theoretical flexibility potential of 20,2 MW in 2024**. However, the duration of this flexibility varies substantially across industrial processes, **ranging from as little as 15 minutes to several hours.**

In the medium to long term, the **plastic manufacturing sector is expected to provide temporary additional flexibility between 2030 and 2050**, primarily due to the **electrification of steam production.** The actual magnitude of this contribution will depend on the rate of electric boiler adoption and the degree of simultaneity in investments across companies, **ranging from 15,2 MW to up to 54,8 MW**. This flexibility is expected to diminish once gas boilers are fully phased out, at which point additional inflexible electric loads will be introduced into the system. Although temporary, this flexibility can be particularly valuable for CREOS, as it provides a critical window of opportunity to prepare the power grid, **allowing time for necessary infrastructure upgrade**s such as capacity expansions, transformer replacements, and network reinforcements.

Region	Average	Pessimistic	Optimistic
Centre	2.6	1.4	4.5
North	2.7	1.5	3.8
West	3.8	1.9	9.0
East	4.2	2.0	8.9
South-East	4.0	2.8	7.0
South-West	3.0	1.7	5.8
Total	**20.2**	**11.3**	**38.8**

Table 4 - Upward industrial flexibility potential (in MW).

Tertiary sector

Electricity demand in the **tertiary sector is very diverse and heterogeneously distributed** over versatile processes and demands. The **assessment focused on** building related demands linked to three processes: **air-conditioning, cooling processes,** and **ventilation**. Since individual data on the sector and these processes is scarce, the model has been mainly building on three data sources: the yearly electricity demand and standard load profile of the sector, literature data on the share of those processes on the total demand, temperature data of past years to model the demand and flexibility potential over time. The demand and availability of **flexibility from cooling and air-conditioning is dependent on the ambient temperature**. Hence, it is unevenly distributed over the season and shows large peaks during the summer period. That is why a reliable and plannable utilisation of flexibility from the tertiary sector should either be oriented along the average available flexibility or needs to be well aligned with the fluctuating demand of the relevant processes.

Monthly averages	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg.
Downward flex. [MW]	16	16	17	25	83	88	109	112	57	17	16	17	48
Upward flex. [MW]	-25	-25	-24	-23	-34	-37	-47	-36	-25	-24	-25	-24	-29

Table 5 - Monthly averages of tertiary sector demand response from air-conditioning, cooling processes & ventilation.

Residential sector (Heat pumps)

Heat pumps are an essential component of the national decarbonisation strategy in the residential sector. Our technology **penetration scenarios** for heat pumps in 2040 are based on national strategy papers (NECP & CREOS Scenario report). This considers that **by 2040, 56% of all residential buildings** (existing and new) would be heated by heat pump systems. Our model includes different activation signals for flexibility from blocking the operation (e.g. for up to 2 hours) or using smart grid ready functions .

<u>Downward flexibility</u> (increasing or preponing the consumption) could only be reasonably used during the heating period (Sept/ Oct – April/May) and reaches from **about 225 – 345 MW**, with the higher values during warmer periods. **If the back-up heater is activated** in addition, this could even be **further increased by 50-60 %**, but would drastically reduce the efficiency. The average **duration** of this flexibility provision strongly depends on the activation signal and **is very short** (e.g., 10 minutes on average) if the temperature set points for the buffer storage are not increased, which could prolong this duration to about 1 – 1,5 hours.

<u>Upward flexibility</u> (reducing or postponing consumption) is conventionally done by a blocking signal and could be held for **up to 2 hours**, if the heat pump systems are designed for this (as common in some EU countries). During the heating period, a **potential of -91 MW to -256 MW** has been estimated, growing with falling temperatures.

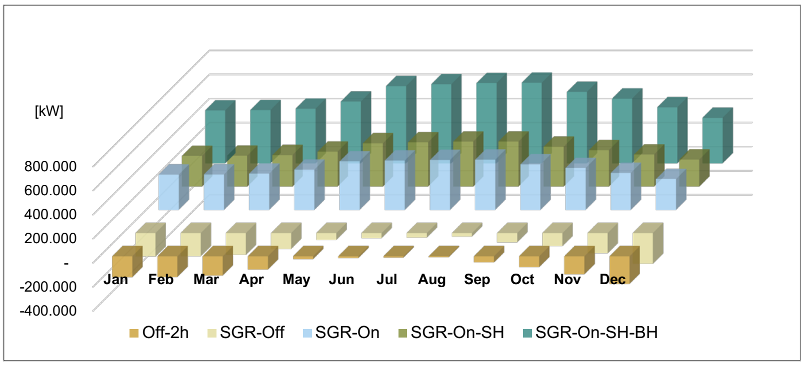


Figure 1: Flexibility potential, heat pumps by activation signal (scen. 2040).

Residential sector (Whiteware and Electric Water Heater)

In this context, residential whiteware refers to **washing machines, tumble dryers and dishwashers**, which are shiftable devices with inherent flexibility potential. These appliances can be **scheduled to operate at alternative times** of the day or could be controlled by an energy management system. The estimation of their flexibility potential is based on statistical device ownership rates, specific to Luxembourg and **simulate the shift of the operation by 1 hour** with typical load profiles. The aggregated flexibility from those three device types reaches up to 11 MW, on average and **could ramp up to 22 MW in the evening hours.**

	Avg. Flexibility Potential (MW)	Max. Flexibility Potential (MW)
Weekday	11	22
Weekend	11.5	23

Table 6 - Monthly demand response potential - residential whitewares.

Electric water heaters (EWH), such with larger storage tanks, can be **rescheduled without immediately affecting user comfort**, which allows for meaningful flexibility and are already used for flexibility purposes in EU countries where these are more common (e.g. France). The flexibility has been estimated for national ownership rates and three different control mechanisms. Overall, EWHs represent a **highly reliable source of downward flexibility, at short durations**, requiring adequate activation strategies.

Activation method Downward Flexibility	Avg. flex. (MW)	Avg. Duration (min.)	Activation method Upward Flexibility	Avg. flex. (MW)	Avg. Dura. (minutes)
On/Off Control	74.3	3.6	On/Off Control	4.9	5.6
5°C Setpoint Increase	90.0	6.2	5°C Setpoint Decrease	5.5	8.4
10°C Setpoint Increase	92.4	7.7	10°C Setpoint Decrease	5.6	9.3

Table 7 - Downward (left) and upward (right) flexibility potential from residential electric water heaters.

Residential sector (PV BESS)

Battery energy storage systems for PV installations (PV BESS) are becoming increasingly popular and are meanwhile also being financially supported in Luxembourg. Besides the optimisation of self-consumption for the battery owner, the battery capacity could technically be used to provide flexibility. Although meant to improve the grid integration of PV, their grid-relieving effect today is minimal. The flexibility potential has been simulated based on historic weather data and load profiles, estimating a huge future potential. Although the absolute results largely **depend on the future scenarios** for PV and storage systems, it is clear that the daily availability of storage flexibility, under the current operation modes, is very limited with regards to grid-integration of the PV mid-day peak.

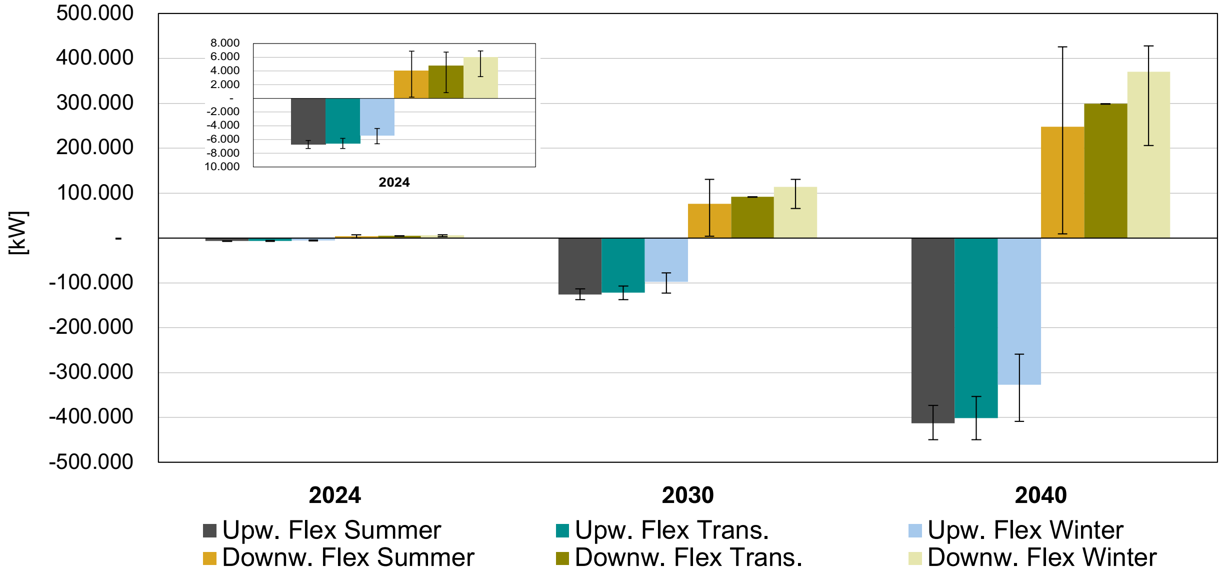


Figure 2: Average flex. potential of PV BESS today & scenarios 2030, 2040.

Electro mobility

The shift to full electric mobility is the main pillar of Luxemburg's strategy for climate change mitigation in the mobility sector and brings **opportunities for flexibility via "smart charging"**. Our study simulates very **conservatively** the flexibility potential, assuming unchanged mobility habits and purely demand driven charging behaviour (**no incentivised charging, no V2G**). Based on data from public charging stations and artificial mobility profiles, the study distinguishes public-, home- and workplace-charging. The potentially available flexibility varies throughout the day and is highest during evenings/nights (from home-charging) when demand is the highest and parking durations are long. During the days, the consumption level is generally lower, so does flexibility as well (mainly from work- and public charging).

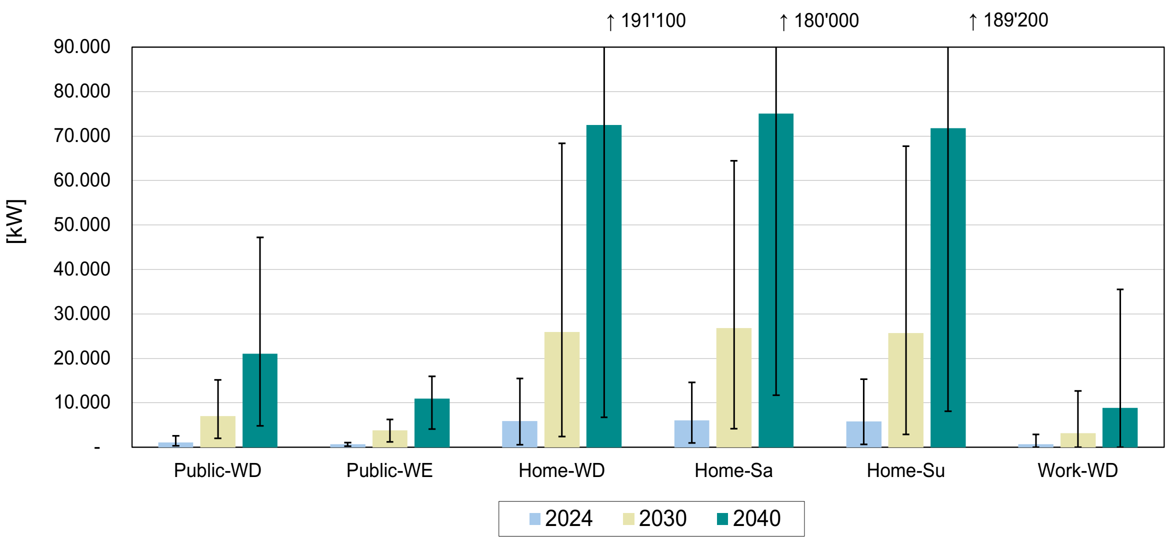


Figure 3: Daily average, instant flexibility for different charging options & scenario years. Interval bars indicating the daily fluctuation (min/max).

4. Flexibility activation

From Theoretical Flexibility Potentials to Successfully Used Flexibility

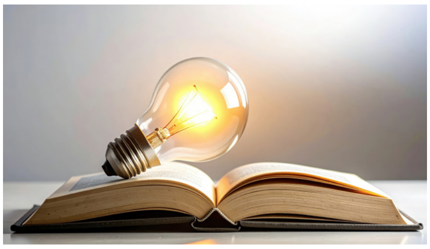
The previous sections have demonstrated that, on the one hand, there is a high demand for flexibility, while on the other hand, various consumers possess significant flexibility potentials. However, **substantial barriers currently hinder the effective utilization of this demand-side flexibility** as will be described in this section. Therefore, a targeted approach is required to, first, gain a detailed understanding of these obstacles and, second, derive appropriate and actionable recommendations to overcome them. To successfully harness the demand response potential and enable electricity consumers to play their transformative role, system operators, suppliers, the Luxembourgish Ministry of the Economy, the regulator, and other decision-makers will have to initiate a targeted flexibility transition to be able to efficiently access and activate demand response in Luxembourg, where and when needed. To that end, in this section, **we identify main barriers of today and give recommendations** as concrete suggestions **for a successful flexibility activation.**

4.1. MAIN BARRIERS TOWARDS FLEXIBILITY ACTIVATION

Investigating current barriers to a provision of demand response of certain consumer groups is a first key step towards developing targeted solutions to those barriers and enabling demand response as described above. Below, we highlight some of the key barriers that currently prevent an efficient use of demand response in Luxembourg.

01 LOW ENERGY LITERACY

Low levels of energy literacy present a significant barrier to demand response participation. When **customers lack a clear understanding** of how energy-related actions affect costs and system performance, they may develop **misconceptions or distrust**. As a result, they are for instance **less likely to engage** in direct load control and are less likely to adopt flexible energy technologies such as EVs or HEMS, even when these changes could reduce their bills and support grid stability.



02 INDUSTRIAL FLEXIBILITY ACTIVATION

Insights from the **FEDIL**[1] **workshop with Luxembourgish industry representatives** revealed that many companies either believe they have no meaningful flexibility or consider that activating it would be **too complex and economically unprofitable**. Some stakeholders also perceived that the only way to provide flexibility would be to reduce production output, which they are unwilling to do due to its direct impact on revenue and competitiveness. Additional barriers include **technical concerns**, as sensitive manufacturing processes risk damage or quality issues (e.g., due to interruptions, temperature or pressure alterations, etc); **organizational constraints**, since activating flexibility would require significant changes in manpower schedules, reducing operational spontaneity and potentially increasing night shifts; and **contractual limitations**, with many industries bound by special agreements that provide cheaper electricity in exchange for predefined consumption profiles, where deviations incur penalties.

1 Luxembourgish Business federation giving a voice to industrials and entrepreneurs

03 INSUFFICIENT KNOWLEDGE OF GRID OPERATORS WITH RESPECT TO CONSUMERS

Grid operators rely on meter data from the connection point, which provides total electricity usage, but **no disaggregated view of individual appliances** or flexibility potential. Therefore, grid operators lack a clear picture of how individual consumers (households, SMEs, and industries) use electricity behind the meter and how willing they are to adjust their consumption. This makes it **difficult to assess consumer flexibility and design effective incentives** for a grid-friendly flexibility use. A better understanding of how customers can provide flexibility is essential for developing targeted flexibility incentives, to evaluate how flexibility impacts the grid, and how the grid operator can use it to better plan and operate the grid.

04 LIMITED TECHNICAL FLEXIBILITY ACTIVATION POSSIBILITY

The technical activation of demand response remains a significant challenge for both consumers and aggregators, primarily due to the **limited availability of smart energy management systems**, steerable assets, and insufficient standardization. Although controllable assets such as wallboxes, heat pumps, batteries, and PV systems are developing and have a large flexibility potential, they are **not technically integrated** in a way **to provide flexibility to the system**. Their flexibility is currently mostly limited to increase self-consumption.

In parallel, the **lack of standardized communication** protocols leads to inconsistent implementations across manufacturers and even across software updates of the same device. This hinders the development of interoperable solutions and places a high compatibility and maintenance burden on aggregators, who must integrate a wide variety of assets and systems.

05 LOW MONETARY INCENTIVES

Lack of or low monetary incentives[1] together with insufficient market/grid signals refer to a situation where actors or market needs are not effectively communicated to consumers. **Without adequate financial incentives**, consumers have **little motivation to adjust their energy usage patterns**. Monetary incentives are crucial for encouraging participation in demand response programs and other flexibility services. However, incentives must be perceived as especially “fair” and “significant” to positively influence behaviour, and customers must understand what they have to do to benefit from it.

1 At the beginning of the project, there were no monetary incentives from the grid or the supplier to change customer behaviour. New tariffs from grid operators and suppliers have only been integrated lately, and their effect is probably still reduced and will need time to develop.

06 CAPACITY GRID TARIFF DESIGN

Our **simulations** of industrial electric boilers **show that current MV/HV capacity grid tariff designs significantly challenge flexibility provision** by creating financial constraints for consumers. Although electricity spot prices may incentivize flexible behaviour (e.g., negative electricity prices during high renewable generation encourage increased consumption) exceeding standard consumption levels can trigger higher network capacity charges.

Since these charges are based on **peak power usage** and represent a significant share of total energy costs, the **financial risk can outweigh potential savings** from spot market participation, discouraging consumers from engaging in flexibility.

07 MINIMUM MARKET REQUIREMENTS

A key barrier to the broader participation of consumers in flexibility markets is the existence of minimum capacity thresholds, which effectively **excludes smaller players**. For example, participation in integrated European balancing markets requires a minimum bid size of 1 MW. While this threshold is designed to **ensure operational efficiency and system reliability**, it blocks small electricity consumers (such as households and small businesses) from participating, even when they possess flexible loads capable of ramping up or down within the technical limits necessary to support grid frequency stabilization. Even when aggregation is permitted, such a high limit makes participation harder, as **aggregators must recruit far more customers to reach the threshold**. As a result, these consumers remain excluded due to their limited individual capacity, leaving a considerable share of demand response potential untapped.

4.2. KEY RECOMMENDATIONS FOR A SUCCESSFUL FLEXIBILITY ACTIVATION

We now offer key recommendations to overcome the identified barriers towards flexibility activation, addressing different fields of action. These recommendations are primarily **based on insights gained through the FlexBeAn project**, complemented by knowledge gained from other related initiatives conducted by the project partners. Before we present our recommendations, we outline **our vision of the future Luxembourgish electricity system**. In such future energy system, **market-based flexibility used by grid operators** is at the heart - in full alignment with EU regulation: grid operators ask for private flexibility and end consumers, suppliers, or aggregators "freely" make their corresponding flexibility-supply decisions. A successful future energy system relies on (i) the removal of barriers for the latter market participants to offer flexibility on different electricity markets as well as (ii) properly designed complementary grid tariffs.

Against this background, in a future energy system, **prices and grid-tariffs have to be aligned on the grid and market level** wherever possible. Direct and forced load control of grid operators is limited to emergency situations, i.e., situations in which market-based approaches cannot prevent a critical grid situation. In other words, **direct and forced load controls** are measures of **last resort** that help the grid operator to manage the risks that market-based flexibility is not always available. To complement this vision, we see a future energy system characterized by **digitally empowered customers**, assisted by new key actors, and **robust bi-directional communication** infrastructure.

To promote a grid-friendly customer behaviour, **(Home) Energy Management Systems[1] (HEMS)** will play a key role in **collecting** different types of **external signals** and **supporting customers making optimal decisions, while respecting their individual preferences and operational requirements**. Once these individual decisions are taken, HEMS communicate directly with steerable assets[2], **enabling both remote and scheduled flexibility activations** in alignment with the above signals.

Importantly, a new market actor, **aggregators**, play an important role to **enable the coordination** between individual users, system operators, balancing markets and (local) flexibility markets. By coordinating different flexibility needs and aggregating small-scale flexibility resources, aggregators help to efficiently manage distributed flexibilities. While in the long-term digital technologies such as self-sovereign identities have the potential to market decentral flexibility even without an aggregator acting as an intermediary, at least in the short- to mid-term aggregators will be essential for a flexible Luxembourgish energy system. Via this new market actor in Luxembourg, it is not required that the grid operator knows in every detail which customers have the flexibility, but he can request flexibility services which can be provided by the customers and/or aggregators.

The specific responsibilities and information flows are represented in Figure 4.

1 A **Home Energy Management System (HEMS)** is defined as a system that monitors, controls, and optimizes the energy consumption, production, and storage of a household by coordinating appliances, distributed energy resources and flexible assets, in response to different signals.

2 A **steerable asset** is defined as an electrical device whose power consumption, production, or storage behavior can be actively controlled or adjusted either automatically, or remotely.

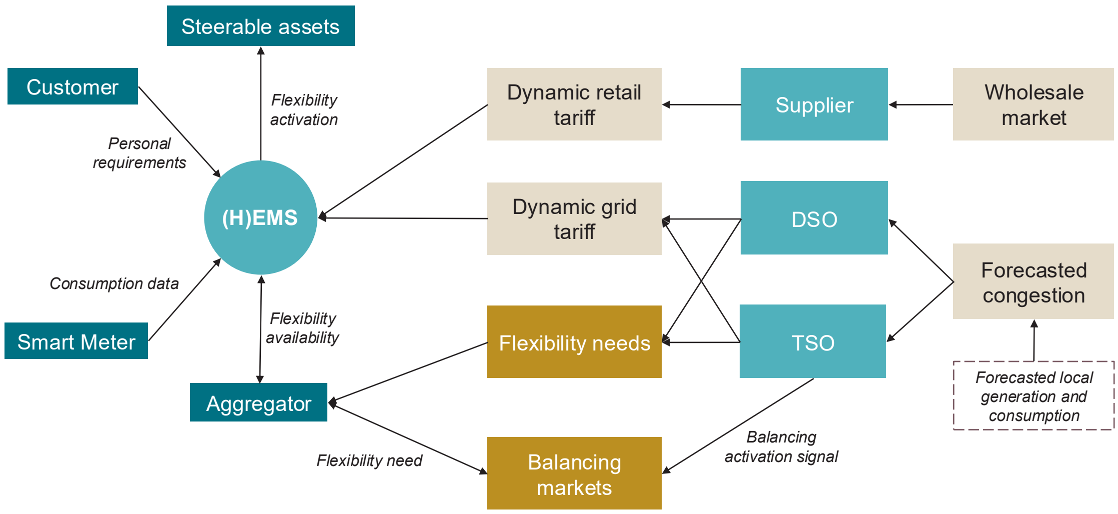


Figure 4: Representation of our future vision of the electricity system.

Given such future vision, currently several needed system and **incentive elements are still missing** within the current Luxembourgish energy landscape, which hinder the realization of this vision and prevent the successful activation and efficient management of flexibility resources as described above. Consequently, **we propose the following recommendations**, aimed at guiding Luxembourg towards establishing the necessary conditions to unlock its full flexibility potential.

Firstly, **digitalization of households must be fostered** within Luxembourg to enable a secure, reliable, and efficient activation of demand response by **integrating real-time monitoring, forecasting, control, and verification into a seamless and automated process**. The flexibility potential analysis from Section 3 demonstrates that a significant potential of demand response stems from LV household assets. To achieve the required level of digitalisation to harvest this flexibility, we give the following recommendations:

01 Standards for home energy management systems (HEMS)

The activation of residential demand response relies on the support of HEMS. Integrated algorithms within a HEMS can generate needed **forecasts** (e.g., flexibility potential of the different appliances), receive monetary and non-monetary **signals**, and integrate **customer preferences** to make **complex decisions** to optimize flexible appliances. Additionally, HEMS could potentially enable **bi-directional communication** between grid operators and/or aggregators and asset owners, ensuring secure **activation, monitoring, and verification of flexibility**. In light of the Luxembourgish government's decision to subsidize HEMS, **we recommend to define a set of clear HEMS functionalities as minimum requirements to receive the subsidies**, in order to make sure that the HEMS are future ready and well-integrated into the ecosystem (i.e., being able to receive market and grid signals), and become a major pillar of the Luxembourgish energy transition.

02 Ensure the installation of steerable and smart assets

Efficient demand response activation requires **assets whose operation can be actively controlled or adjusted in real time**. As shown in Section 3, key examples of such assets are EVs, heat pumps, and batteries. Manual activation is not only inconvenient, but also not feasible in a future dynamic electricity system. For both, system-wide and local grid needs, a **fast and timely activation** of demand response is necessary following market's or grid operator's signals. While HEMS help navigate the complexities of market dynamics and decision making, steerable assets allow "convenient" and automated load adjustment. **Automation enhances user comfort by enabling remote or scheduled activations, minimizing inconvenience and potentially optimizing the compensation needed to encourage participation**. With the cooperation of HEMS and steerable assets, an efficient, reliable and convenient activation of demand response can be achieved.

Regardless of whether control is exercised directly or via a HEMS, bi-directional communication with the asset (or HEMS) is essential for reliable, predictable, and traceable activation of the demand flexibility. Bi-directional communication should assure that the asset can provide flexibility, to what extent and finally, that the activation was successful. Hence, the used **communication protocols need to be reliable and (if possible) independent of consumer side IT infrastructure.** All the relevant stakeholders (Ministry, Fédération du Génie Technique (FGT), and grid operators) should evaluate together how it can be ensured that steerable and smart assets are installed wherever possible.

Asset specific recommendations derived from the project´s potential analysis, which could be further investigated based on a pilot, relate to:

» **PV home batteries** have potential to alleviate future PV induces grid congestions, but not in the way they are currently operated. Current support schemes could be evaluated for incentivising grid-relieving operation modes.

» **Electric vehicles** charging at home via smart wall boxes could effectively help reducing the evening peak - subsidising wall boxes should assure future-proof standards regarding communication protocols and control options.

» **Flexible heat pump** operation is possible but requires suitable design of the systems and compatible communication. Current support schemes and connection requirements should avoid creating a lock-in effect and consider more advanced control options.

03 Introduce ICT Training for Electricians

As energy systems become increasingly digital, **electricians must be able to master Information and Communication Technologies (ICT)** and manage smart technologies like HEMS and steerable assets. Based on insights from the Creos Living Lab project, we recommend the Luxembourgish government **supports targeted ICT training programs** to ensure the workforce can meet the demands of digital energy infrastructure.

All stakeholders involved in vocational training, starting with the Ministry of Education, the professional chambers, and the FGT, must **ensure that future graduates in the sector develop strong ICT skills** via targeted measures. The same applies to continuing vocational training.

04 Promote Standardisation of Household Energy Assets at EU Level

The lack of standardisation in communication protocols across EVs, wall chargers, heat pumps, and batteries (highlighted in the Creos Living Lab project) seriously limits their seamless integration into HEMS. To enable plug-and-play functionality and ensure interoperability, the Luxembourgish government should **actively promote and push for EU-level standardisation of household energy technologies**.

Second, simulations conducted as part of the FlexBeAn project (for both low- and high-voltage customers) have shown that customers can gain significant value by being active on the wholesale market, and that current grid tariffs create financial disincentives for demand response activation. Concerning flexibility, **grid tariffs should primarily incentivise a grid friendly behaviour** and ensure a cost-efficient development of the grid. In addition, it should also **allow customers to profit from** the potential values which can be gained on **wholesale markets**. The Luxembourgish grid operators together with ILR are actively working to revise the tariff structure, as reflected in the introduction of new low-voltage grid tariffs earlier this year. However, we still observe that the following key improvements are lacking:

05 Introduction of Time-of-Use (static) and dynamic hourly grid tariffs

Current grid tariff structures are predominantly fixed and fail to incentivize consumers to adjust their behavior based on real grid conditions. Results from the FlexBeAn project, based on two large industrial companies, underlined this barrier, showing that **existing capacity-based tariffs strongly discourage flexibility**, even when electricity prices are favorable. Our analysis demonstrated that both **Time-of-Use (static) and dynamic hourly tariffs can help unlock flexibility**, while ensuring that industries do not face higher total energy costs, and the grid operators maintain the same network revenues required for grid reinforcements. Time-of-Use tariffs, which assign hourly prices based on historical averages and remain fixed for a given period, are simpler to understand and easier for consumers to prepare for. However, dynamic hourly tariffs, which adjust to hourly grid conditions, proved significantly more effective in unlocking flexibility. **We recommend that the grid operators, together with ILR and the Ministry of the Economy, evaluate the introduction of static time of use on the short term**. In parallel, **research should further investigate** the potential benefits, drawbacks and complexities of **dynamic hourly grid tariffs**, and that these tariffs are introduced as digitalisation progresses.

06 Incentives for grid-friendly injection

Our simulations have shown that highly flexible household customers can stress the grid with too much injection from batteries and V2G during peak price times. The current grid tariff structure does not provide any incentives for customers to behave grid friendly when injecting into the grid. Our simulations have also demonstrated that an exceedance fee on the grid injection above the reference capacity can help to manage these injection congestions. A symmetric exceedance fee may help managing the issues, but other models could be envisaged (could be dynamic in future). We recommend that the grid operators, together with ILR and the ministry, investigates this topic in the following years.

07 Introduction of dynamic retail tariffs with risk-mitigation features

Most consumers currently operate under fixed retail tariffs, which creates an incentive barrier towards flexibility activation. Customer uptake of dynamic retail tariffs remains low – even if they are already offered – due to concerns over potential price spikes and the risks of being confronted to a changing price. To promote the usage of these tariffs by customers, they could for instance include a protective "security cap", where the supplier absorbs excessive price peaks, or fixed prices for an ex-ante agreed consumption profile combined with price reductions in case of a flexibility activation. It should be the supplier's responsibility to assess market risks and design dynamic pricing schemes that balance customer protection with a sustainable business model.

In addition, we also believe that European electricity market rules should be refined, as certain requirements immediately block the participation of demand response. Consequently, we propose the following recommendation:

08 Lower the minimum bid size requirements of balancing markets

The current minimum bid size of 1 MW in the integrated European balancing markets poses a significant barrier to the participation of smaller, yet valuable, flexibility resources. While we recognize that this threshold cannot be reduced indefinitely due to the computational burden it would place on the market's clearing algorithm, even a modest reduction could enable direct participation from industrial sites or SMEs, it could also accelerate aggregated flexibility participation. It is, therefore, essential to investigate how much the minimum bid size can be lowered without compromising operational efficiency.

Importantly, unlocking the flexibility potential of small-scale flexibility sources requires a new market actor as described in our vision of the future Luxembourg energy system – at least in the short- to mid-term and as long as we don't have a fully digitalized energy system. Aggregators are essential to assemble individual flexibility assets into market-compliant flexibility blocks, navigate market complexities on behalf of users, facilitate prequalification processes, and communicate aggregated offers to system operators. Yet, Luxembourg currently lacks active aggregators.

Finally, even when all necessary tools and resources are made available, customers may still choose not to participate if they do not understand how to use flexibility or recognize its benefit. **A lack of awareness or comprehension can be a major barrier to engagement.** To engage with flexibility, customers need to understand how this fits with their needs, preferences or values. Therefore, we recommend the following actions:

09 Assess and improve consumer energy literacy through existing energy applications and platforms

Raising awareness and understanding is essential to enable active consumer participation. Based on the insights gained via the one2day application, we recommend (1) making a **targeted assessment of the energy literacy level** and other characteristics (e.g., environmental awareness) of households and representative citizens; and (2) **integrating energy literacy tailored content into existing applications and platforms**, to educate consumers on how to benefit from demand response activation.

Within the FlexBeAn project, we observed an increase in consumers' energy literacy when they interacted with content tailored to their level. The content was also selected based on other elements of their profile, such as personality and environmental values. This suggests the value of accessible, user-friendly educational tools and personalised nudging strategies in strengthening participation and trust.

10 Launch a pilot project to assist industrial participation in flexibility provision

Our analysis revealed that industries possess flexibility potential that could support grid stability while reducing their electrification costs. However, a clear knowledge gap on potential economic gains and how to implement the flexibility potential without negative effects can prevent them from moving forward. Therefore, **we recommend the launch of an industrial flexibility pilot project** supported by national or EU funding, **to provide guidance**, build capacity and highlight economic benefits of flexibility to industries.

11 Develop Flexible Connection Agreements

Our analysis of industrial E-Boilers showed that it can be economically interesting to gradually switch from gas to electricity. This hybrid approach means that **industrial customer**s do not need the full electrical connection capacity all the time, and that they **can start decarbonizing with a flexible connection agreement**. We recommend that grid operators develop such Flexible Connection Agreements, and promote these with MV/HV customers who have some flexibility in their consumption in order to be able to connect customers faster.

5. Conclusions

The results of the FlexBeAn project demonstrate that **Luxembourg holds a significant technical demand response potential** in terms of the potential power flexibility, although the durations that flexibility could be sustained are, for some assets, rather limited on average. **If harnessed effectively** by an adequate activation strategy, the available **flexibility could**, nevertheless, **play a crucial role** in addressing the challenges posed by the Luxembourgish power system decarbonization, i.e., alleviating grid congestion, better integrating RES, etc. As shown in Section 3, especially household assets such as heat pumps, batteries and EV hold a significant flexibility potential in the future.

However, the **practical activation** of those potentials **can be a demanding task** and requires concerted actions of all involved stakeholders to set the right framework conditions and incentivise grid relieving usage of the available flexibility potential. Today, these flexibility potentials remain largely untapped due to several existing barriers. Targeted and coordinated action is required and should be taken with priority to unlock it. To that end, we propose the action plan displayed in Figure 5.

The proposed **action plan** is structured into three different time scales —short-term (within 1 year), medium-term (within 2-3 years), and long-term (> 3 years)—based on sector readiness, technological requirements, and regulatory dependencies, amongst others.

In the short term, we recommend initial measures to be taken to prepare different Luxembourgish sectors, e.g., households or SMEs for a future flexibility supply. This includes setting **standards** for home energy management systems, the facilitation of **steerable assets**, launching initiatives to raise **energy literacy**, or foster **ICT trainings** for electricians. These steps are crucial to be able to harvest the flexibility potential in the future. They shall enable the integration of digital technologies in homes to activate and use household demand flexibility of, e.g. EVs, small batteries or heat pumps.

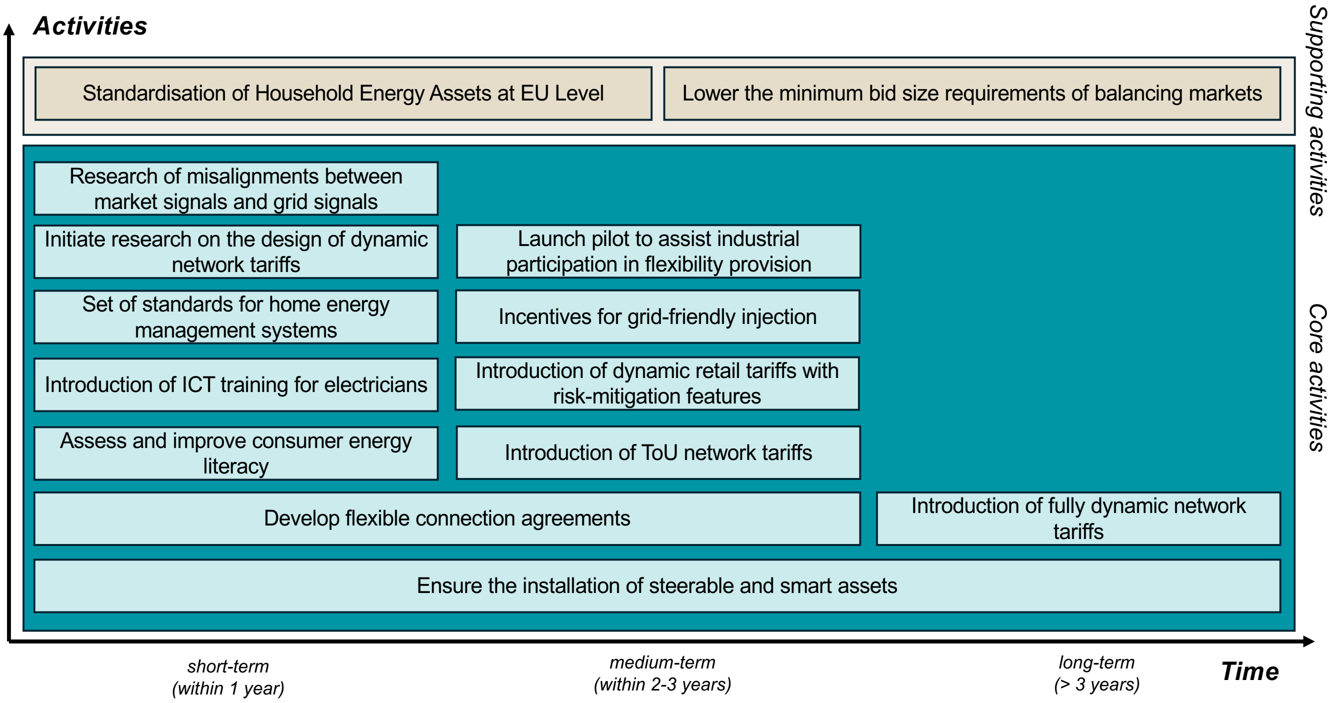


Figure 5: Action plan time frame.

To that aim, the minimal technical requirements for the smart integration of heat pumps, EV wall chargers and PV home batteries should be further investigated and existing public support schemes evaluated to assure the incentivisation of future-proof solutions and avoid lock-in effects.

Moreover, we recommend that grid operators explore and facilitate Flexible Connection Agreements for those MV/HV customers who plan to electrify their loads. This would accelerate customer connections, while mitigating grid congestion by leveraging flexibility.

In addition, we recommend supporting needed research activities to gain necessary in-depth understanding of the topics of dynamic grid tariffs and incentive misalignments between market signals and grid signals. It must be ensured, particularly in the mid-term, that market-based incentives for flexibility do not inadvertently create grid-related issues.

Conversely, grid-driven incentives, such as those embedded in grid tariff structures, should not impede overall welfare maximization or the effective integration of renewable energy sources into the overall system. A well-coordinated design of market and regulatory signals is therefore essential to align individual behaviour with both system efficiency and grid stability.

In the medium term, Luxembourg should implement ToU grid tariffs to reward grid-friendly flexibility on the basis of the successful implementation of the short-run recommendations, which enable well-informed and "smart" consumers. At the same time, suppliers should introduce dynamic retail tariffs with risk-mitigation features to incentivise market-driven flexibility in a complementary way.

In addition, the research and design of grid tariff incentives for injection should be initiated early on to incentivise flexibility on the supply side as well. With respect to the Luxembourgish industry, we recommend launching a pilot on industrial flexibility. Such a pilot should focus on new flexibility technologies to be developed for energy-flexible production processes or necessary ICT and serve as a show case for other industries in Luxembourg.

Finally, in the long term, the Luxembourgish grid operators and ILR should replace ToU grid tariffs with fully dynamic ones, completing the transition to a fully responsive and modern electricity demand landscape.

In parallel to the above activities, the Luxembourgish government, the responsible ministries, and the regulator should actively participate in European discussions to promote the EU-wide standardisation of household energy assets or lower minimum bid sizes of European balancing markets. In this way, Luxembourg can pave the way to a low-carbon society and economy with consumers at its "beating heart".

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Flexibility Potentials and User **Be**haviour **An**alysis

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FLEXIBILITY POTENTIALS AND USER BEHAVIOUR ANALYSIS

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