Quantification of electricity storage needs for Belgium energy transition: a sensitivity analysis based on EROI

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Abstract:

The world has experienced several energy transitions. During the end of the XIX century, coal became the first energy resource before biomass. After WWII, the thermodynamic quality of hydrocarbons made them the first primary energy resource. Finally, today due to global warming threats, humanity starts a decarbonising energy transition from fossil fuels to renewable energy (RE) sources. This study focuses on the energy storage mix required for the energy transition of the electricity system to high RE shares illustrated by the case of Belgium. An hour-based model is used in order to yearly optimise the country RE energy return on investment (EROI). The storage dynamics is studied through its monthly needs. For an 80% RE Belgium, curtailment reaches 3.4%. It induces as much losses as the batteries. At high RE shares, Power to Gas (PtG) becomes unavoidable even if the amount of energy involved is less than 2% of the overall yearly consumption.

Keywords:

Energy storage, EROI, seasonal storage, energy transition, energy management, ECOS Conference.

1. Introduction

The world has experienced several energy transitions. During the XIX century, coal became the first energy resource before biomass. After WWII, the thermodynamic quality of hydrocarbons made them the first primary energy resource. Finally, today with global warming threats, humanity starts a decarbonising energy transition from fossil fuels to renewable energy (RE) sources.

Non-flexible RE sources bring new challenges to the electricity grid. To face these challenges, five tools can be used: first, gas-fired and hydro power plants flexibility, second, interconnection with neighbours (import/export), third, demand side management (DSM), fourth, storage of energy, and fifth, oversized RE installed capacities combined with curtailment. These five tools are complementary and have to be implemented together to match production and demand.

The storage required for the energy management (time scales ranging from one hour to one year) can be split into two categories: a high efficient short-term storage and a longer-term storage. Historically, short-term storage was provided by pumped hydro energy storage (PHES). Nowadays, batteries become the most competitive solution for short-term storage, thanks to their high efficiency and decreasing cost. Longer-term storage is used as a backup energy to support production for days or even weeks. Power to Gas (PtG) is a promising technology, it consists of converting excess electricity into hydrogen through electrolysis. Then, the hydrogen produced can be combined with carbon dioxide, or even other molecules, into synthetic fuels such as methane, methanol, dimethyl ether, and ammonia.

Optimal storage would be based on a mix of batteries, PHES and PtG [1-2,5,8]. Other technologies such as compressed air energy storage or flow batteries can partially substitutes PHES or batteries, respectively.

Based on this mix, several studies have been performed for regions of different sizes and resources such as 100% RE Denmark [8], Germany [1,5], Belgium [6-7], and western Europe [2-3,14].

Most of these studies optimise the future electricity system by minimising the financial cost [1-3,5-8,14]. Such an analysis based on the return on investment relies on strong economic assumptions about the inflation, growth, subsidies, policies or even lobbies. To overcome this problem, the present study uses the Energy Return on Investment (EROI). The EROI is the ratio between the energy produced during the lifetime of an energy system and the energy mobilised to produce, maintain and dismantle the same energy system. A direct and strong correlation between a society's welfare and its EROI has been highlighted [9-11]. This metric is regularly used in scientific papers when analysing RE integration in energy systems [9-11].

In a previous work [16], the Belgium energy transition has been computed while optimising the EROI. It highlighted a trade-off between the five tools. Regarding storage, the main conclusions were, first, necessary short-term storage capacities once RE share in production reaches 30%, and, second, unavoidable PtG for RE shares higher than 70%.The present study goes deeper in the analysis and understanding of the storage requirements during the energy transition. Energy fluxes are monthly analysed. Then a sensitivity analysis is performed in order to identify the most critical assumptions or assets. Moreover, a generic weather distribution is used in order to analyse the impact of a lack of production during a given period on storage needs.

The paper is organised as follows: first, the methodology introduced in a previous study [16] and summarized here is applied to the case of Belgium. Then, results are analysed and conclusions are drawn about energy fluxes and the storage behaviour. Eventually, a sensitivity analysis is performed and brings critical assumptions out.

2. Methodology and case study

The methodology used has been described in a previous work [16]. The first paragraph outlines its main features. The following paragraphs illustrate the methodology applied to the case study.

2.1. Summary of the methodology

To model a large-scale electricity system, a trade-off between system size and accuracy is required. The used methodology is country scale oriented with an hourly resolution over a typical year. The electricity system is split in different cells. A cell defines a region with specific weather conditions (for RE), policies (for a country), a high interconnection (copper plate), RE and storage potential. Cells are interconnected with transmission lines representative of the current high voltage grid. The overall system mimics an electricity system.

Each cell can contain units of production, conversion, transport, storage and consumption. The fossil assets are user defined. The potential assets for RE and storage are input and the effective amount of assets are optimised by the model. The system can import energy from the outside with limited capacity for electricity, gas, coal…

The model optimize the EROI under the constraint of hourly balanced power fluxes. Moreover, the solution must respect some physical constraints such as transmission line capacities, storage losses, weather conditions, etc. The overall optimization problem is then converted into a linear programming problem to obtain the solution.

2.2. Case of Belgium

The case of Belgium is well defined and challenging. It is well defined because the exogenous parameters needed by the model are well known. The weather conditions are quite homogeneous, simplifying the modelling approach. Yet, it is challenging due to the high population density and the consequent low RE potential per capita, especially for wind energy.

The electricity system is decomposed into four actors: production, storage, transmission and consumption. Figure 1 is an illustration of the case.

The first actor is production. It is mainly based on natural gas, nuclear and RE (wind and solar). The installed capacity today is 5919 MW of nuclear, 5190 MW of flexible production (largely gas power plants simplified as combined cycles gas turbines (CCGTs)), 1700 MW of wind turbines (WT) (400 MW offshore) and 3700 MW of photovoltaic panels (PV) (Belgian TSO, 2017).

The second actor is storage. Today, it is limited to a 5 GWh PHES storage with 1.2 GW power. The PHES potential is reached in Belgium. Only batteries or PtG assets can be built. PtG is assimilated to

a technology of electrolysis and methanation with an overall efficiency (electricity to methane) of 63%. This synthetic fuel is stored and later used in CCGTs.
The third actor is the transmission grid. The mainland is connected to neighbouring countries (France and The Netherlands) by transmission lines with a total capacity of 4500 MW.
The fourth actor is the electrical consumption. It varies between 7 GW at night and 11 GW during the day in summer and between 9 GW at night and 13 GW during the day in winter. The average consumption is 9.7 GW. In the model, the hourly electricity consumption corresponds to the consumption of the year 2015 (from European TSO: ENTSOE).
The model is composed of two cells. The mainland (Cell 1 in Figure 1) is well interconnected and has homogeneous weather conditions. The offshore wind farm (Cell 2 in Figure 1) has different weather conditions and is connected to the mainland with a limited transmission line. The capacity of the line is set at 2800 MW. This value is four times larger than today offshore WT installed capacity but only 75% of the maximum potential capacity. Offshore batteries can be built at a higher price than onshore batteries to support the transmission line.

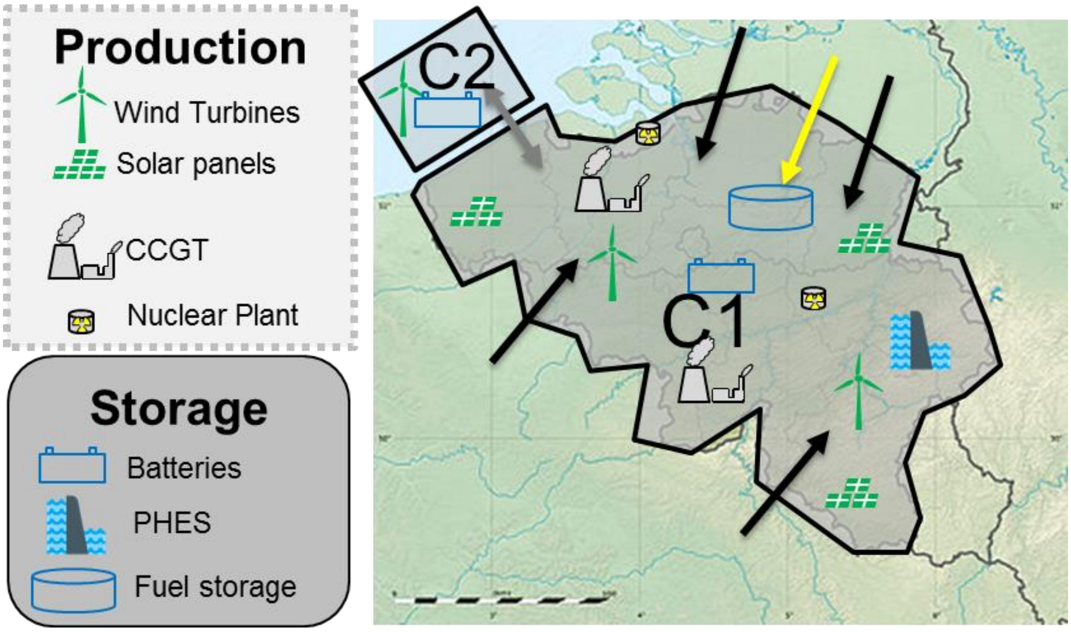

Fig. 1. Representation of the case of Belgium composed of two cells. Cell 1 (C1) is the mainland. It has production (RE, nuclear and CCGTs), consumption, interconnections (electricity and gas), storage (PHES, batteries, PtG). Second cell (C2) represents the offshore wind park composed of wind turbines and batteries. Yellow and black arrows represent gas and electricity imports, respectively.

Both cells are also represented in Figure 2, which illustrates the underlying mathematical representation with all components of each cell and the main variables.

2.3. Model

On an hourly basis, the model solves the power fluxes of the electricity system based on the variables summarised in Figure 2. To avoid speculative scenarios the lowest number of inputs are user defined. The necessary inputs are of two types. First, for each cell, several hourly distributions. They are the electricity consumption [GW], the irradiance [W/m²] and the wind [m/s]. Second, inputs representative of the scenario policies which are the overall RE production share, Nuclear and gas capacities and share, the yearly import share (the default value is 10% of the yearly consumption), the yearly fuel import and the PtG minimum capacity factor. This last input sets the minimum amount of time the PtG must be producing to avoid spurious results. The model is detailed in [16]. Based on these data, and the estimated energy inputs, the EROI is 11.6 for onshore WT, 10.9 for offshore WT, and 7 for PV. These values are coherent with other works estimating an EROI of around 14 for wind and between 3 and 8 for solar PV [10-11,17].

The system has to respect two physical laws. First, it balances, at any time, the power fluxes between consumption, production, import and storage. Second, for each cell, some potentials are limited such as the number of wind turbines.
The model optimizes, under the given constraints, the EROI of the energy system. The EROI does not take into account the gas and nuclear assets. It is solely based on the RE assets. Therefore, the net EROI is the ratio between the RE energy consumed by end users (taking into account losses in the storage systems) and the energy invested for the RE and storage assets.

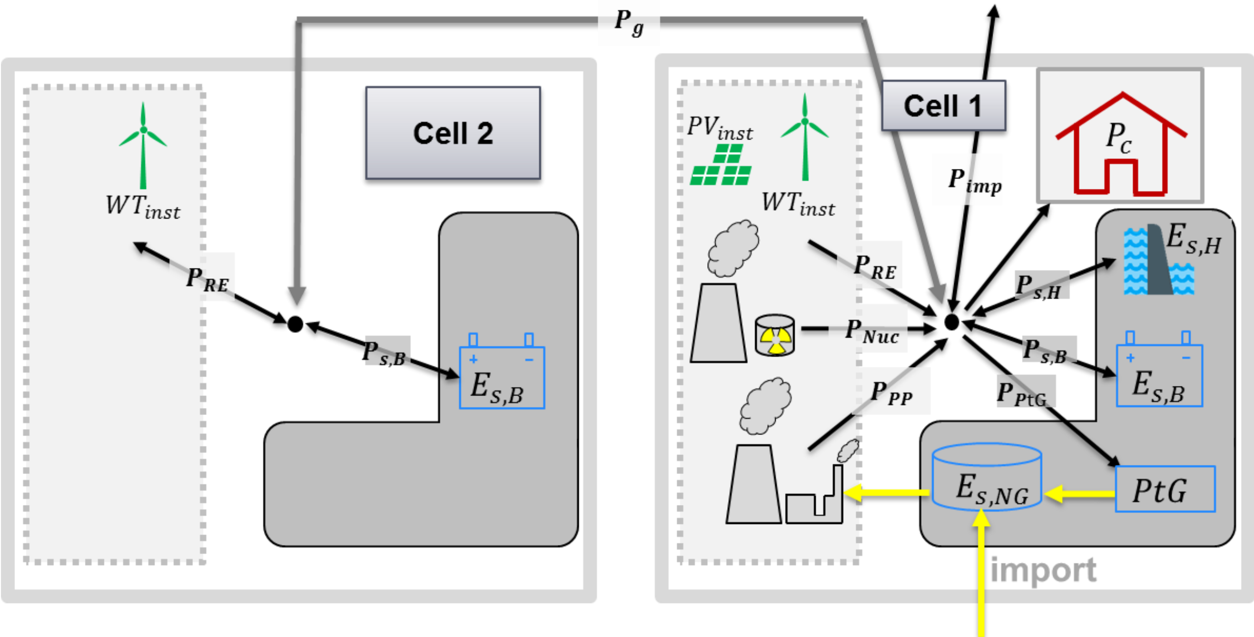

Fig. 2. Mathematical representation of power fluxes for a two-cell system representative of Belgium. Cell 1 represents the mainland and cell 2 represents offshore farms with local battery storage. The installed capacity is variable for solar PV (PV_{inst}) and wind (WT_{inst}). The electrical power fluxes can be production from RE (P_{RE}), nuclear (P_{Nuc}) and power plant (P_{PP}) or consumption (P_c) or transmission from the neighbouring cell (P_g) or imports (P_{imp}) or finally stored in PHES ($P_{s,H}$), batteries ($P_{s,B}$) or PtG (P_{PtG}). The storage sizes (energy capacities) are also variables implemented for PHES ($E_{s,H}$), batteries ($E_{s,B}$) and gas ($E_{s,NG}$).

2.4. Reference scenarios

Four reference scenarios representative of Belgium energy transition are defined similarly to a previous work [16]. Import consumption share is fixed at 10%, therefore the production mix supplies 90% of the consumption. The first scenario is a representation of tomorrow's society with a production mix of 50% nuclear, 20% RE and 30% gas. The second scenario presents a society in 15-20 years with a production mix of 10% nuclear, 50% RE and 40% gas. The third scenario presents a speculative case with a high share of renewable. The production mix is 0% nuclear, 80% RE and 20% gas. The fourth scenario presents an even more ambitious production mix of 100% renewable electricity for Belgium. For each scenario, the transmission system and flexible power plant (CCGT like) capacities remain constant (see values in Section 2.2).

3. Results

3.1. Reference scenarios

The main results for the four reference scenarios are listed in Tables 1 and 2. Table 1 shows the EROI, CO_2 emissions, and storage requirements.

Table 1. EROI, CO_2 emissions and storage requirements for the reference scenarios.

Scenarios		EROI	CO_2	Battery			PtG		
RE	Nuc'		[Mt/y]	[GWh]	[GW]	Cycles	[MW]	Charge	[GWh]
20 [%]	50[%]	9.70	12.1	2.3	2.3	27	0	0%	0
50 [%]	10[%]	9.44	16.2	8.9	4.4	111	0	0%	0
80 [%]	0 [%]	8.53	10.3	86.7	20.3	146	815	15%	815
100[%]	0 [%]	7.92	4.6	241	50.0	109	1000	49%	2 661

The RE assets are built based on the EROI merit order as illustrated in Table 2. Moreover, wind is more homogenously distributed in time than irradiance and therefore the model favours WTs over PV panels. Thus, first, onshore WT are installed. Then offshore WT are installed until their installed capacity reaches the transmission line capacity. At this point, both PV and offshore WT are installed. Once WT reaches its potential, only PV can be built. Note that the minimum PV installed capacity in the model is the currently installed capacity in Belgium (3.7 GW).

Table 2. Optimised RE assets for all four scenarios.

Scenarios		WT onshore		WT offshore		PV onshore		Curt
RE	Nuc'	$[GW_{inst}]$	$[5MW_{eq}]$	$[GW_{inst}]$	$[5MW_{eq}]$	$[GW_{inst}]$	[km²]	[%]
20 [%]	50[%]	5.0	999	0.8	151	3.7	24	0.2
50 [%]	10[%]	10.1	2023	3.3	660	8.8	58	2.1
80 [%]	0 [%]	10.1	2023	3.8	756	30.6	201	3.4
100[%]	0 [%]	10.1	2023	3.8	756	65.8	427	19.0

Therefore, the net EROI first increases to peak approximately at around 40% of production share of RE (maximum WT potential in Belgium). Then the optimal EROI reaches lower values because it is negatively impacted by the increase of curtailment and storage at higher RE share.

3.1.1. Energy sources distribution

In order to cope with the intermittency of RE sources, four of the five tools described in the introduction are used: power plants flexibility, imports, storage and curtailment. Figure 3 shows the distribution of the energy among the production technologies for scenarios 2 and 3.

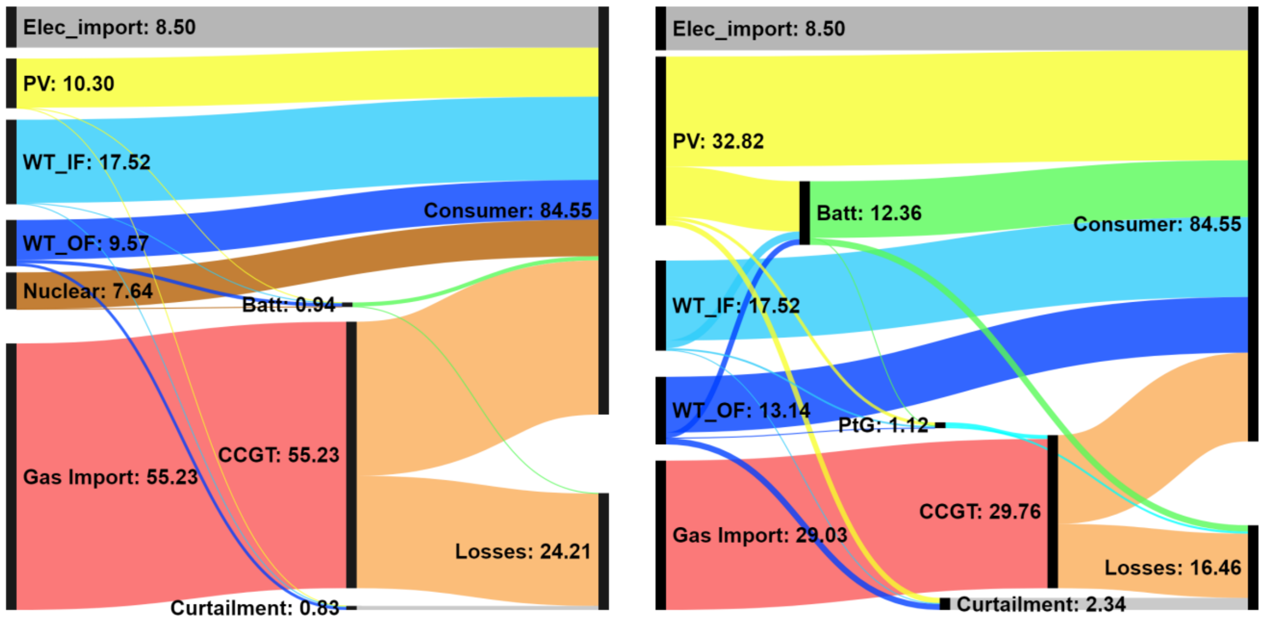

Fig. 3. Sankey diagrams of energy fluxes for scenario 2 (left, 50% RE and 10% Nuclear of production share) and scenario 3 (right, 80% RE of production share).

Scenario 2 is based on a 50% share of RE in the electricity production, mostly produced by WT. 92% of the RE intermittent production is directly consumed. The remaining is either curtailed (6%) or buffered in batteries (2%). In this scenario, the installed offshore capacity reaches 3.3 GW for a transmission line of 2.8 GW. When the offshore production reaches its maximum, the excess of 0.5 GW is stored in the 10 GWh offshore batteries. However, when these batteries are full, the excess must be curtailed. These situations correspond to 92% of the overall curtailment. Most of the batteries are installed in the offshore parks to support the transmission line.

Scenario 3 reaches 80% of RE in the electricity production. It is composed of a mix of 50% PV and 50% WT. 75.7% of the intermittent RE production is directly consumed. The rest is curtailed (3.4%) or buffered in batteries (19.2%) or used in PtG (1.7%) that appears for a share of RE higher than 70%. Half of curtailment is due to the same reason as in scenario 2. The other half is due to excess of solar energy during summer peaks to 30.6 GW of production. Batteries are predominantly used (80%) to store PV excesses. It allows to shift the surplus production during the day to the night. During shiny days, part of wind energy is also stored (10%). The 10% remaining is due to offshore transmission line support.

In this scenario, PtG becomes profitable in terms of EROI. The electricity consumed in the PtG units comes from the excess of production of PV during summer days (70%), from onshore wind in summer (7%), from offshore wind (7%) and even from PV energy stored in batteries and delivered during nights (14%).

3.1.2. Monthly energy distribution

RE production and electricity consumption are unequally distributed across the year. Figures 4 and 5 give the energy fluxes in the energy system for scenarios 2 and 3, respectively.

WT production is 3 times larger during winter than during summer. Conversely, the PV production is 10 times larger in summer than in winter. Hence, due to its RE asset mix, Scenario 2 displays limited variations in the RE distribution over the year. To fit the demand, the needs for imports and CCGTs are thus also relatively constant over the year. Curtailment occurs in December and January due to the excess production in offshore wind farms. The amount of energy stored in batteries is negligible compared to the other energy fluxes (Figure 4).

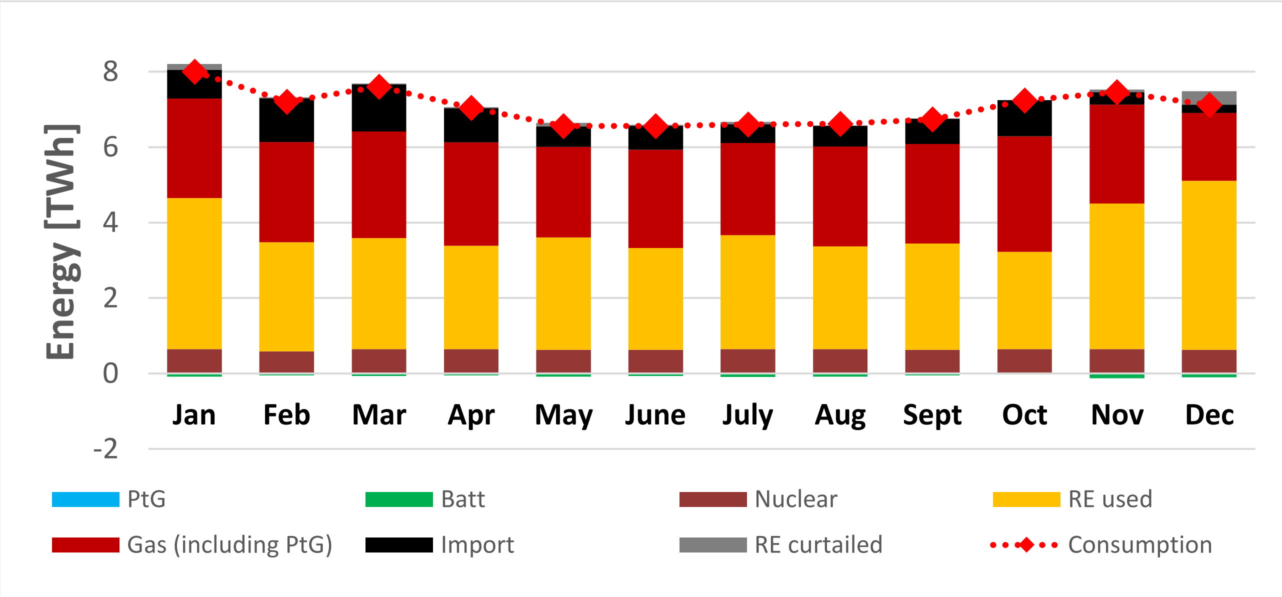

Fig. 4. Monthly energy distributions for Scenario 2. Positive values represent the energy produced. Negative values represent energy stored

Figure 5 illustrates scenario 3. The RE production is 30% higher in summer than in winter. This effect is compensated by shifting the electricity import to winter. Battery storage is mostly used between March and September to shift solar daily excesses from day to night. During the sunniest months (from April to August), PtG is used to convert PV excesses into synthetic gas. The use of PtG is more profitable than just curtailing excesses. Nevertheless, the RE production cannot be fully absorbed and the rest is curtailed. During fall and winter, batteries are used to buffer the rarer RE excesses.

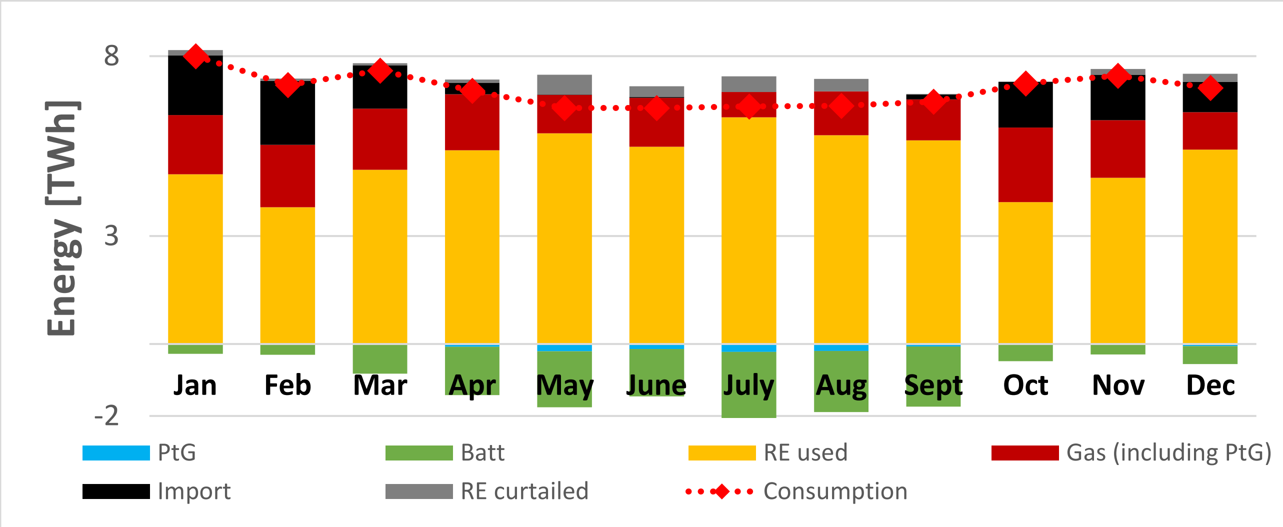

Fig. 5. Monthly energy distributions for Scenario 3. Positive values represent the energy produced. Negative values represent energy stored. Energy stored in batteries (green) mostly performs daily cycles contrary to PtG (blue) storage that discharges in the Gas (red).

In summer, production is slightly higher than consumption. The difference comes from the extra production required to produce synthetic gas or to compensate batteries losses.

3.1.3. CO_2 emissions

Based on LCA studies for each electricity production technology [15], the CO_2 emissions of Scenario 3 are represented in Figure 6. Even if fossil fuels represent 20% of the production share, they are responsible for 78% of the CO_2 emissions. The rest comes from PV (15%), WT (4%) and batteries (3%). Most of the CO_2 emissions for RE assets and batteries comes from construction (79%).
The LCA studies are based on today electricity production mix. With a greener production mix, the production of PV and WT shall emit less CO_2 [15].

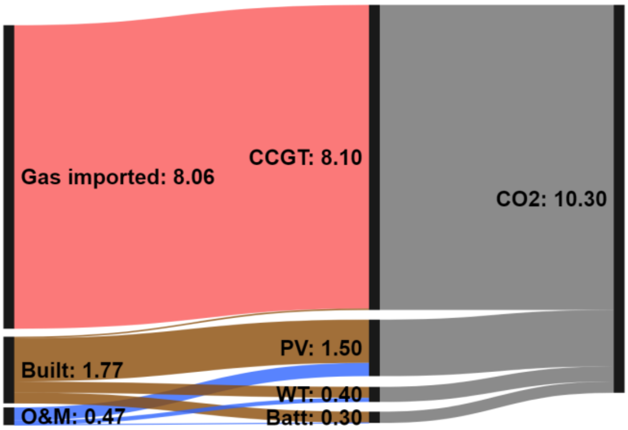

Fig. 6. Sankey diagram of CO_2 emissions for a 80% RE production share.

3.1.4. Correlation solar-batteries

Once WT potential is reached (40% of RE share), PV panels are massively built. Belgium PV load factor is around 10%. Therefore, a PV share higher than 10% implies power peaks higher than the average Belgian consumption. To face this problem, batteries are installed to store solar excess and deliver it at nights. Figure 7 shows the correlation between batteries and PV for a 10% nuclear production share (results are similar with other nuclear shares). There is a direct correlation of 3 GWh of battery required per 1 GW of PV installed.

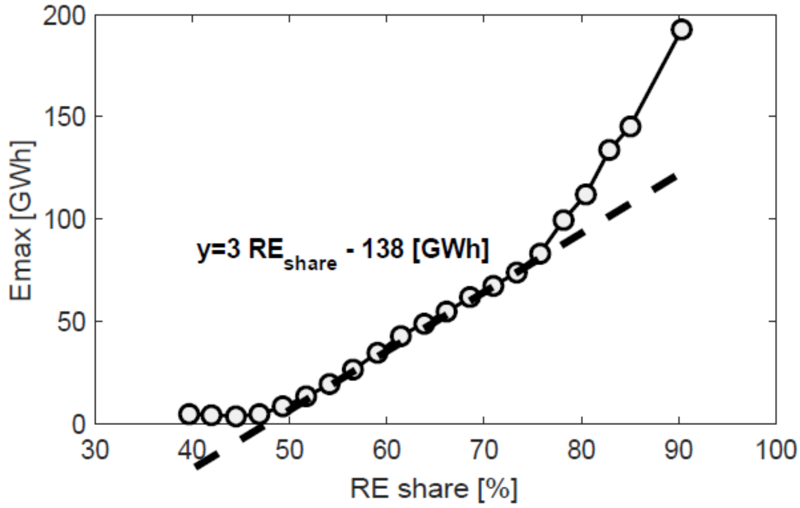

Fig. 7. Correlation between the PV installed power and the battery capacity in the case of a constant 10% nuclear share.

Once PV share reaches 35% (equivalent to an install capacity of ≈35 GW), the daily production becomes higher than the total daily consumption. Extra batteries are built to store PV electricity for several days. Thus, the correlation does not hold anymore.

3.1.5. 100% RE Belgium analysis

Belgium is a very densely populated country. The evolution from 80% to 100% RE is quite hypothetical. The hypothesis of an isolated country is not realistic anymore and imports and exports should increase. Nevertheless, the monthly energy distribution obtained with the model is proposed in Figure 8.

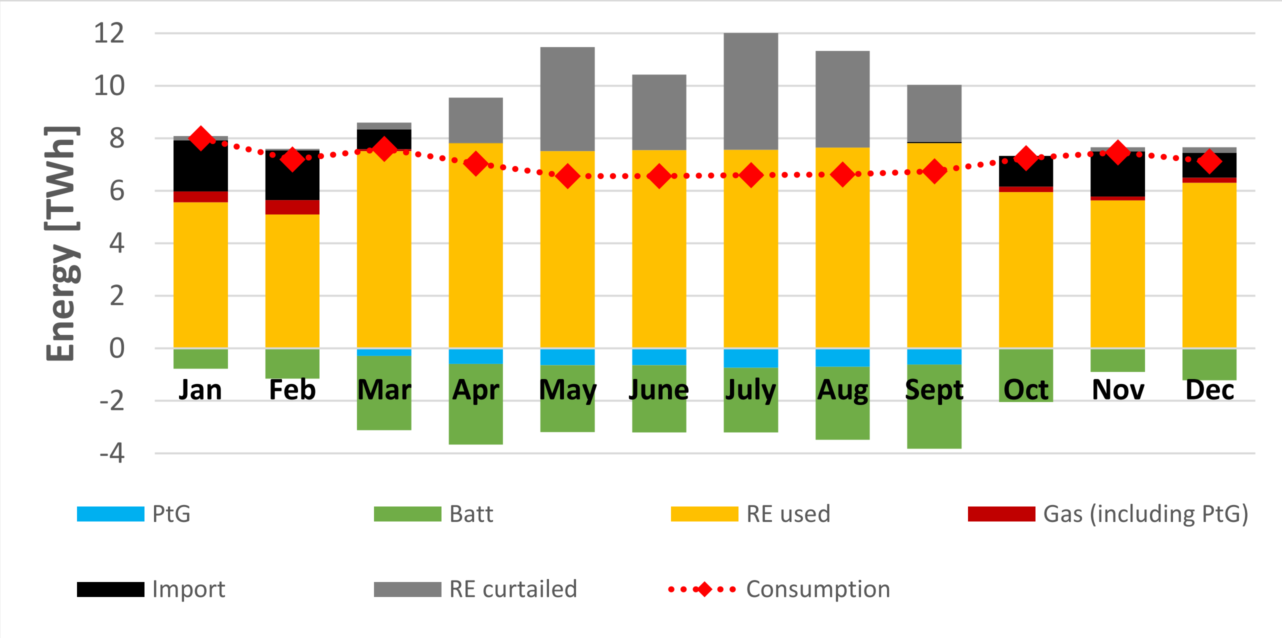

Fig. 8. Monthly energy distributions for Scenario 4. Positive values represent the energy produced. Negative values represent energy stored. PtG produces synthetic fuels during summer (blue) to winter supply (red).

In a similar way to Scenario 3, the PV installed capacity is very high and RE production is unevenly distributed among the year. Summer has an excess of PV production with power peaks reaching 70

GW and winter has a lack of PV production. To face this problem, PtG units is at full load and produce synthetic gas between March and September (blue).
Figure 9 is the Sankey diagram of scenario 4. Only 55% of the electricity produced is directly used. Storage differs the supply with batteries (22%) and PtG (4%). The rest (19%) is curtailed and the EROI collapses. In practice, this energy would be used for other purposes, like more PtG to produce gas used in other applications (e.g. long distance transportation).

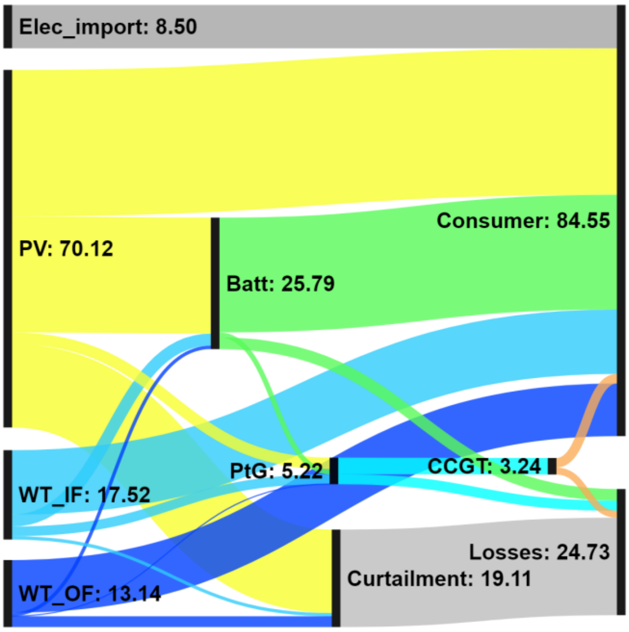

Fig 9. Sankey diagram for scenario 4: 100% RE Belgium. PV summer peaks are too expensive to be absorbed by the electricity system and are curtailed

3.2. Sensitivity analysis (EROI based)

A sensitivity analysis has been performed for the four reference scenarios. Table 3 gives the impact of the variables as a relative difference on the EROI. Most of the variables have an impact lower than 0.1% for a variation of the input of 5% such as the CCGT installed capacity, import transmission line, PtG cost…
All the four scenarios have three similar trends. First, the net EROI is directly correlated to the RE energy cost with a small difference coming from storage and curtailment. Second, a change in the yearly consumption affects the EROI between 0.7% to 1.8% for the 3 first scenarios and up to 4.2% for the fourth scenario. As previously explained, the RE technologies have different EROI. Nowadays installed capacity is a mix of PV panels and WT. The optimal solution for an increasing share of RE in terms of EROI is to increase the amount onshore WT, hence, overall EROI increases as well. Once the maximum WT capacity is reached (around 40% of production share), only PV capacity is built and the EROI decreases. Therefore, below 40% of RE, increasing consumption will increase EROI and vice versa. Above 40%, it is the opposite. Third, a decrease in the battery energy cost has a very limited impact on the net EROI.
With more than 50% RE, onshore WT potential is saturated. An increase of the potential will increase the EROI and vice versa. Offshore WT installed capacity becomes higher than the transmission line. Increasing the transmission line capacity reduces offshore curtailment and hence increases the EROI.
With more than 80% of RE in the production share, storage is used more often. An increase of the battery efficiency decreases the energy losses and therefore increase the EROI (≈1%). The influence of PtG charge factor or efficiency has a moderated impact on the EROI, these results are coherent with conclusions from the previous study [16].

Table 3. Sensitivity analysis for the four scenarios. Influence of variables on net EROI. Most variables have a negligible impact (<0.1%) and are represented by a slash (/). Influence higher than 0.5% are bolded. The scenario 4 has two cases with no mathematical solution (NaN).

Variable	**Ref value**	**Scenario 1**		**Scenario 2**		**Scenario 3**		**Scenario 4**	
		-5%	+5%	-5%	+5%	-5%	+5%	-5%	+5%
Consumption	85 [TWh]	**-0,7**	**0,7**	**1,8**	**-1,8**	**1,8**	**-1,6**	**4,2**	*NaN*
CCGT installed capacity	5.19 [GW]	/	/	/	/	/	/	/	/
Intercell power line	2.8 [GW]	/	/	**-0,7**	**0,7**	**-0,5**	**0,5**	**-1,0**	**0,9**
Import power line	4.5 [GW]	/	/	/	/	/	/	/	/
RE cost		**5,2**	**-4,7**	**5,1**	**-4,7**	**4,9**	**-4,5**	**4,7**	**-4,3**
Onshore WT potential	10 [GW]	/	/	**-1,1**	**1,1**	**-1,1**	**1,1**	**-2,5**	**2,4**
Onshore WT potential	3.8 [GW]	/	/	/	/	-0,1	0,1	-0,4	0,3
PtG cost	100 [Wh/W]	/	/	/	/	/	/	/	/
PtG maximum capacity	1 [GW]	/	/	/	/	/	/	-0,4	0,4
PtG efficiency	62[%]	/	/	/	/	/	0,1	-0,4	0,4
PtG minimum charge	15[%]	/	/	/	/	0,1	-0,1	/	/
Battery cost		0,1	-0,1	0,1	-0,1	0,3	-0,3	**0,5**	**-0,5**
Battery efficiency	90 [%]	/	/	/	/	**-0,8**	**0,8**	*NaN*	**1,6**
PHES energy capacity	5 [GWh]	/	/	/	/	/	/	/	/

4. Conclusion

Driving electricity system through sustainability is a challenging task due to the inherent unpredictable RE production fluctuations. To manage energy fluxes and match the demand, storage, imports, fossil power plant flexibility and curtailment can be used. A model including these flexibility means and based on the optimisation of the EROI has been developed and applied to the case of Belgium through four scenarios with different renewable energy shares.

The four scenarios covering the whole Belgium energy transition are proposed and analysed. They sweep from 20% to 100% RE electricity production. For the specific case of Belgium, wind turbines produce three times more in winter than in summer. In contrast, PV production is ten times higher in summer than in winter. Therefore, a 50% RE Belgium has an optimal RE assets of 40% wind and 10% PV. In this case, RE production distribution is homogenous through the year. CCGTs production and electricity imports are also relatively constant throughout the year. A small amount of short-term storage is profitable in the offshore farm to prevent the saturation of the transmission line and to decrease the need for curtailment.

Solar capacity factor in Belgium is around 10%, hence, with a PV share higher than 10%, solar production peaks exceed Belgian consumption. An 80% RE Belgium is composed of 40% wind and 40% PV. A larger amount of batteries is necessary to shift the PV excesses for the night demand. There is a direct correlation between the storage required and the PV installed capacity. For an extra 1 GW of PV capacity, 3 GWh of battery storage is optimal. At 80% RE share, PtG becomes profitable to absorb summer electricity excesses.

The limited wind potential (40%) of Belgium combined with its low solar capacity factor makes a 100% RE Belgium expensive to reach. Production is composed of 40% of wind and 60% of solar. Hence, PV production peaks above 7 times the consumption at 64 GW, making it quite difficult to absorb. To cope with this problem, curtailment soars. PtG remains unavoidable to face RE lacks. It makes synthetic fuels necessary to back up RE production for long periods.

The imported gas dominates CO_2 emissions. Even in a 80% RE Belgium, 78% of the CO_2 emissions comes from imported gas, the rest is due to PV panels, then WT and finally batteries.

A sensitivity analysis was performed. It highlights direct correlation between the RE energy cost and the society EROI with a limited impact of storage and curtailment. Yearly consumption, battery energy cost and wind potential have a smaller influence on the overall EROI.

Nomenclature

CCGT Combined Cycles Gas Turbine
CO_2 Carbon dioxide
DSM Demand Side Management
EROI Energy Return On Investment
LCA Life Cycle Assessment
PHES Pumped Hydro Energy Storage
PtG Power to Gas
PV Photovoltaic
RE Renewable Energy
WT Wind Turbine

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