Assessment of the Contribution of Power-To-Hydrogen to the Flexibility of the Future European Energy System

Eva Joskin[1], Matija Pavičević[2], Chiara Magni[2], Sylvain Quoilin[1,2]
[1] Faculty of Applied Sciences, ULiège, 4000 Liège
[2] Faculty of Engineering Technology, KU Leuven, 2440 Geel
e-mail: matija.pavicevic@kuleuven.be

ABSTRACT

The European Commission is planning to become climate-neutral by 2050. At the power sector level, this implies turning to renewable sources such as PV panels and wind turbines. However, the intermittence of variable renewable sources is making this task more complex and putting at risk the power sector security of supply. Coupling sectors is a solution to that problem. In particular, power-to-hydrogen is getting more and more attention. This is about using electricity when it is abundant to synthesize hydrogen which can then be used for various purposes. The first goal of this work was to add the power-to-hydrogen sector into the unit-commitment and power dispatch model Dispa-SET. The second objective was to soft-link Dispa-SET with the long-term investment model JRC-EU-TIMES and investigate the benefits of this sector in terms of curtailment, total costs, CO2 emissions, etc. The linking between JRC-EU-TIMES and Dispa-SET allowed to observe the importance of power-to-hydrogen in using the extra renewable production and avoiding curtailment. Indeed, 20% of the total renewable production is used to produce hydrogen. This highlights the importance of sector coupling in future energy systems. Moreover, the results showed that hydrogen storage is not seasonal. Finally, the importance of validating system feasibility provided by long-term planing models was demonstrated as TIMES overestimates renewable production by 15% compared to Dispa-SET.

KEYWORDS

Power-to-hydrogen, hydrogen, Power-to-gas, soft-linking, Dispa-SET, JRC-EU-TIMES, flexibility

1. INTRODUCTION

Global warming is becoming an increasing concern around the world. Extreme weather events such as forest fires, flash floods and typhoons have been multiplying in recent years. In 2018, temperatures above the Arctic Circle were 5°C above ordinary [1]. The vulnerable communities are the most threatened, but climate change is impacting everyone. Therefore the European commission has been building a strong plan aiming at becoming climate-neutral by 2050. The main goal is to keep global warming well below 2°C. At the power sector level, this implies turning to renewable sources such as PV panels and wind turbines. However, what is called the intermittence of variable renewable sources is making this task more complex and putting at risk the power sector security of supply. Different solutions exist, and it is likely that a mix of them will allow us to succeed in the energy transition. A first key to solve the problem is to increase power transmission capacities across countries. Secondly, more flexibility can be obtained by coupling different energy sectors. It has been widely proven that coupling the power sector with the transport and heating sectors could have a large impact on decreasing emissions ([2], [3]). Increasing storage capacities such as pumped hydro storage and developing demand side management are other key aspects. Another solution that is attracting more and more attention is the Power-to-Hydrogen sector. It is part of what is called Power-to-X (P2X) which indicates transforming electricity into another energy vector. The concept of Power-to-Hydrogen, also called Power-to-gas (P2G), is about using electricity when the production from renewable sources is high to synthesize hydrogen from water. This hydrogen can then act as a coupling commodity and be consumed in sectors such as transport, heating or industry, or it can be stored and consumed by fuel cells to produce electricity when needed. Hydrogen can also be combined with CO2 to produce methane, a process called methanation, or produce synthetic chemicals and fuels (called electro-fuels). This last process is named Power-to-Liquid (PtL). Those fuels can also be directly produced from CO2 and electricity, which is more efficient than producing hydrogen in the first place. Many variants of the system described hereabove exist. For instance, the CO2 needed for PtL could come from carbon capture but also from biomass gasification. If electrolysers are considered today as a mature technology, PtL is still in its infancy. In order for power-to-hydrogen to become competitive, its efficiency should be increased. The biggest advantage of this process is that hydrogen can be used in a wide range of applications, which is an interesting flexibility option since future energy systems will be closely interlinked. Hydrogen, methane and liquid fuels are also much easier to store than electricity. Moreover, PtL could be the solution to decarbonize the part of the transport sector that cannot be electrified, such as heavy trucks and planes. Another attracting feature is that with large capacities, electrolysers are able to reduce curtailment.

One of the first descriptions of P2G dates back to 1999 [4]. Hashimoto et al. presented a circular use of CO2 thanks to seawater electrolysis with solar energy, methanation and carbon capture in industrial plants [5]. Since then, a growing interest in P2G has led to numerous pilot plants all around the world [6]. The size of those plants ranges between lab scale test units, couple of kW, and a utility scale unit, few MW, such as the 6 MWe plant built in Werlte, Germany.
Götz et al. [4] and Schiebahn et al. [7] provide a description of P2G possibilities as well as technical data. They point out that power-to-gas provides a good interconnection with the heat sector since methanation is a very exothermic process. Schiebahn et al. also list the requirements electrolysers need in power-to-gas applications. Those include high efficiency, long lifetime, low investments, ability to deal with fluctuating renewable power, low minimal load and high output pressure. Sterner et al. [8] show that synthetic methane and energy network development are key elements for reaching 100% renewable energy supply structures. Parra et al. [9] also estimate that power-to-hydrogen and power-to-methane will play a key role for the energy transition. Bolat and Thiel [10] provide a very complete description and review of literature on techno-economic description of the hydrogen supply chain. Steward et al. [11] study the interest in hydrogen electrolysers powered by PV energy for load levelling and vehicle refuelling. Also many roadmaps have been published on the topic, studying the introduction of a hydrogen economy in large spatial scale (e.g. [12] in Europe) or in smaller regions, such as [13] for Flanders, Belgium. Different studies also found out that electrolysers and fuel cells could be key players of ancillary markets due to their fast regulation ([14], [15], [16]).

Many energy modeling tools now include P2G and PtL, and the modeling possibilities are wide. Berger et al. [17] proposed an investment model which considers only electricity and gas sectors. Storage technologies such as pumped-hydro, batteries, hydrogen and methane sinks are included. Results demonstrates that if battery content is very dynamic with short term periodic variations, H2 and CH4 storage dynamics show that the former would be used for short term to medium term storage whereas the latter is more event-driven, meaning that it discharges in short period of time but not often. PyPSA is a complete European sector-coupled investment and dispatch model [18]. It considers in a detailed way the transport, heating and electricity sectors and their interactions through for instance Battery Electric Vehicles (BEVS), Fuel Cell Electric Vehicle (FCEVs), combined cycles, heat pumps or electrolysis and methanation. The power-to-gas sector consists of hydrogen electrolysers, hydrogen fuel cells, hydrogen storage and methanation units. The CO2 that is needed for producing methane is obtained by direct air capture which decreases the efficiency of methanation from 60% to 40%. Results show that methanation allows to decrease total system costs for a certain level of CO2 emissions. However, long term district heating storage and high shares of BEVs-V2G are even more beneficial and their introduction decrease the need for power-to-methane. Concerning hydrogen, FCEVs are competitive in few cases. Balmorel is an investment model that optimizes social welfare. Their modeling of the P2G sector does not include methanation. Jensen et al. [20] observes that hydrogen has a strengthened role when less bio-energy is assumed available. METIS simulates both energy systems and energy markets for electricity, gas and heat [21]. In [22], a scenario with full carbon neutrality by 2050 is studied. Main conclusions are first that the main sources of flexibility would be cross-border capacities, storages such as pumped-hydro (where possible) and demand-side management. Moreover, Power-to-X are useful to adapt to the residual load, depending on the energy mix of each country. If large hydrogen storage capacities are available, it is found that water electrolysers would be widely used. However, methanation could only be economically relevant in countries with particularly low power prices. Finally, JRC-EU-TIMES is a widely used European long-term investment model, using linear optimisation. The description of the energy model is very detailed including many sectors. Also, hydrogen sector is very complete, including centralised and decentralised hydrogen production technologies (from fossil fuels, biomass and electrolysers) and many delivery pathways. Blending of H2 in the natural gas grid is included as well as fuel cells for power production, fuel cell vehicles, hydrogen delivery for industries, methanation and PtL possibilities ([23], [24], [25]). Simulations on the hydrogen sector showed that electrolysers can decrease greatly renewable curtailment. Hydrogen could also play a significant role in sectors such as the industrial and transport ones. However, the large-scale development of stationary fuel cells still requires considerable cost improvements. In [25], a study of the potential of hydrogen and PtL in low-carbon Europe is realised. In their simulations, uses of hydrogen increases compared to today. Demand for hydrogen also depends on development of PtL, which is supposed to grow only if carbon storage is not possible and under strict CO2 targets. In this case, PtL could meet 60 to 90% demand in aviation and up to 60% of diesel demand. According to TIMES, the preferred energy carrier for transport should be electricity, with a contribution of hydrogen in applications that cannot be electrified.

Power-to-methane is represented by methanation of hydrogen and upgraded biogas (addition of H2) [24]. The needed CO2 comes from carbon capture in industry, power plants, biogas, hydrogen or from the atmosphere directly. After simulation, it comes out that power-to-methane is present in scenarios with at least 95% CO2 reduction by 2050, no CO2 underground storage and low CAPEX. Other factors that increase its use are, among others, limited biomass potential, low PtL performance and use of power-to-methane waste heat in order to increase the efficiency of the process.

The first goal of this work is to add the power-to-hydrogen sector into the unit-commitment and power dispatch model Dispa-SET. The second objective is to soft-link Dispa-SET with the long-term investment model JRC-EU-TIMES and investigate the benefits of this sector in terms of curtailment, total costs, CO2 emissions, etc.

2. METHODS

This section starts with a description of Dispa-SET. Then JRC-EU-TIMES is presented followed by an introduction to model soft-linking and how it is applied here. The last parts consist of a detailed presentation of the modeling of the power-to-hydrogen sector in Dispa-SET and of the scenarios.

2.1 Dispa-SET

Dispa-SET is an open-source short-term unit-commitment and power dispatch model (UCM) mainly developed by the Joint Research Centre of the EU Commission. It minimizes the total production cost of energy during a certain period while observing different demands and constraints that will be detailed later. The model also includes different flexibility options such as hydro pumped storage, hydro dams (HDAM), batteries, BEVs, Thermal Heat Storage (TES) and Demand Side Management (DSM). Moreover, not only the power sector is modelled. The heat sector is included as well as part of the transport sector. The model is expressed as a Mixed-Integer Linear Program (MILP) but can also be simplified into a Linear Program (LP). The integer variables are the commitment status of the units. A complete description of the model is out of the scope of this paper and can be found in the official Dispa-SET documentation[1].

Dispa-SET offer many possibilities, and its main features are :

- Minimum and maximum power for each unit
- Power plant constraints: minimum power, ramping limits, minimum up/down times, start-up, no-load costs
- Outages (forced and planned) for each units
- Reserves (spinning & non-spinning) up and down
- Load Shedding
- Curtailment
- Storage technologies
- Non-dispatchable units (e.g. wind turbines, run-of-river, etc.)
- Multi-nodes with capacity constraints on the lines (congestion)
- Constraints on the targets for renewables and/or CO2 emissions
- CHP power plants and thermal storage
- Power-to-heat (heat pump, electrical heater) and thermal storage
- Demand Side Management-ready demand
- Integrated mid-term scheduling and short-term optimal dispatch
- Different model formulations and levels of clustering complexity generated from the same dataset.

2.1.1 Hydrogen sector

The modelling of the hydrogen sector is represented in Figure 1. Electrolysers, storage and fuel cells are considered as one unit and modelled similarly as other storage units. The storage inflows and outflows are always defined as null. *StorageOutput* represents the hydrogen that goes out of the storage to satisfy the demand. This demand is made up of two components: *H2Demand* that represents the hydrogen demand linked to industry and fuel cell electric vehicles and *PtLDemand* that is the hydrogen needed to produce electro-fuels. *H2Demand* is defined constant at each timestep whereas the shape of *PtLDemand* is optimised to take into consideration the storage capacity of liquid fuels. The maximum capacity to produce those electro-fuels is considered so that *PtLDemand* is limited at each time step. This capacity is the aggregated capacity to produce methanol and diesel.

The optimisation variable *StorageSlack* represents hydrogen bought from outside of the system and has two purposes. First, it is needed to avoid infeasibilities in the model in case there is not

[1] http://www.dispaset.eu/en/latest/index.html

enough energy to fulfil hydrogen demand. Secondly, since a cost is associated to this variable, it can be used to assess if hydrogen production cost of electrolysers is competitive.

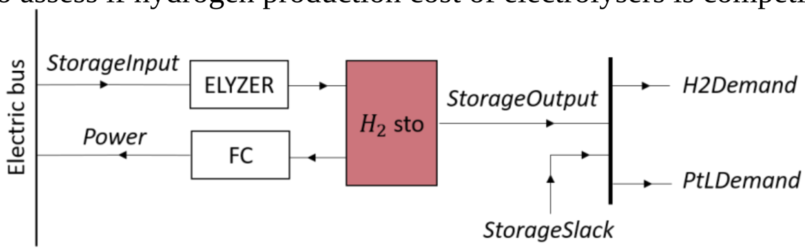

Figure 1: Model of a hydrogen unit in Dispa-SET

2.1.2. Mid Term Scheduling (MTS)

In order to limit the model complexity, simulations are run for a couple of days at a time. Then, the last day of the simulation is dropped to avoid end-of-simulation effects and the next simulation can start. However, this means that storage technologies will tend to empty at the end of each simulation which is not optimal. To solve this issue, an additional simulation has been introduced and is called Mid-Term-Scheduling. This simulation consists in a simplified linear version of the final simulation with a 24 h-time step and runs for the whole year at once. It allows to compute pre-defined storage levels that are then entered as exogenous inputs in another optimisation that will gove final results. It also allows to compute the shape of *PtLDemand* so that the total demand is respected. In this configuration, all equations concerning unit commitment are not considered and the binary variables *Committed*, *StartUp* and *ShutDown* are defined as linear. The following constraints are therefore ignored:

- The committment equations
- The minimum Up and Down times equations

The Ramp up and Ramp down limitation equations

2.2 JRC-EU-TIMES

JRC-EU-TIMES is a European long-term Energy System Optimization Model (ESOM) developed by the Joint Research Center of the European Union. As such, it forecasts capacity expansion and computes the investment and operation costs while minimizing total system cost via linear programming on a multi-year horizon. The main goal of JRC-EU-TIMES is to analyse the future potential and interactions of energy technologies in order to give recommendations on European energy policies. This includes making estimations of the best shares of flexibility options (storage technologies, power-to-X, demand side management) needed to cope with systems including a lot of Renewable Energy Sources (RES).

While both the supply and demand sides are included in the model, the following seven sectors are represented: primary energy supply, power generation, industry, residential, commercial, agriculture and transport [26]. The model calculates prices endogenously, based on supply and demand curves.

The model includes EU and neighbouring countries, each of them representing a node, and carries out simulations from 2005 to 2050. Given the complexity of the model and the large covered timespan, each year is divided in 12 representative time-slices. Those represent a mean day, night and peak demand for each season. This approximation has important consequences when energy systems with large shares of RES are modelled. Indeed, the reduced number of time slices decreases the insights on the variability of renewable production.

2.3 Uni-directional soft-linking

Despite the complexity of JRC-EU-TIMES, the time step of long term investment models does not allow to completely appreciate the real needs for flexibility ([27], [28]). Also some technical constraints such as start-up times or minimum running times cannot be included. On the other side, an operational and economic dispatch model such as Dispa-SET having a small time step, a large covered area and unit commitment constraints is too complex to also include investments and a long simulated period. This is why most of the time that kind of model only runs a few days long simulations. This does not allow long-term investment previsions.

Therefore, it is interesting to link the two kinds of model. This action is called *soft-linking* [29].It allows to take advantage of the long-term investment strategy of the ESOM as well as the short time step of the operational model. In this work, JRC-EU-TIMES and Dispa-SET are unidirectionally linked, which means that some results from TIMES simulation are included as inputs in Dispa-SET. Those variables are the following:

- The available technologies and their installed capacities. Those technologies are related to power, heat and hydrogen generation as well as storage.
- The annual demands per country related to power, heat, transport and hydrogen.
- Carbon emission and commodity prices.

Pavičević et al. [30] present some of the techniques that were implemented within the scope of linking the two models.

Figure 2 represents the block diagram of the relation between TIMES, Dispa-SET and the different data sources used. Some outputs from JRC-EU-TIMES are given as annual values and need to be processed as hourly profiles. This is done in the Soft-linking toolbox. Other inputs such as availability factors (needed for RES, BEVS, etc.), river inflows and outside temperatures are assumed similar to historical values from 2016. NTCs values are based on the e-Highway 2050 project. Those data, together with the power plant portfolio constitute the Dispa-SET Database. At that point 2 Dispa-SET simulations are performed. First, the Mid-Term Scheduling allows to computes storage levels and PtL demand profile. Then the second simulation gives the final results. Those include the economic dispatch throughout the year, curtailment, total cost, CO2 emissions, etc.

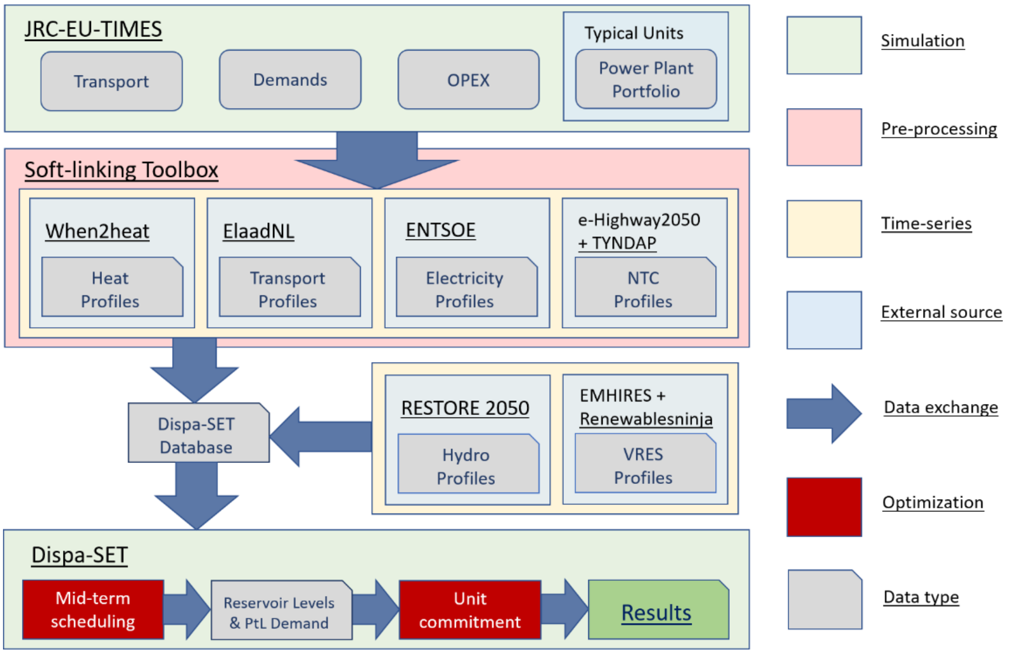

Figure 2: Explanatory block diagram of the model coupling

The coupling methodology applied here is inspired by Blanco Reaño [27]. It consists of the following steps:

- Recover the output data of the TIMES simulation and put them in the right format to enter Dispa-SET.
- Run Dispa-SET with the new database.
- Identify lost loads and excessive shed loads. Compute the maximum of those values in each zone and add the same amount of capacity in the form of combined cycle gas turbines. This step is necessary because long term planning models usually over-estimate RES production and therefore under size the thermal capacity needed to avoid lost loads.
- Run Dispa-SET again and analyse the results.

3. SCENARIOS

3.1 Definition of the scenarios

Four scenarios are studied in this work. The first step is to compare two scenarios (CHEAPSLACK and H2FLEX) whose only difference is the hydrogen slack cost. As a reminder, it is the cost of the hydrogen that can be bought from outside of the system. In a second step, three scenarios with the same hydrogen slack cost are compared (H2FLEX, No_PtL and NOH2STO).

3.1.1 CHEAPSLACK

CHEAPSLACK scenario has a H2 slack cost of 88 EUR/MWh. This is a reasonable cost for hydrogen produced by methane steam reforming with carbon capture [10].

3.1.2 H2FLEX

In H2FLEX scenario, the hydrogen slack has an associated cost of 160 EUR/MWh. This cost prevents that electrolysers consume electricity produced by gas turbines. Therefore, the hydrogen production from electrolysers is from renewable electricity.

3.1.3 No_PtL

In this scenario, *PtLDemand* is constant during the year and not optimised by the mid-term-scheduling. This scenario allows to assess if the PtL planification is usefull.

3.1.4 NOH2STO

Finally, NOH2STO scenario has a null hydrogen storage capacity.

3.1.5 Summary

Table 1 summarises the characteristics of the 4 scenarios.

Table 1: Definition of the scenarios

Scenario	Cost H2 Slack		Variable PtLDemand	H2 storage
	88 EUR/MWh	160 EUR/MWh		
CHEAPSLACK	●		●	●
H2FLEX		●	●	●
No_PtL		●		●
NOH2STO		●	●	

3.2 Database

3.2.1 Countries

In this study, each zone correspond to one European country. The United Kingdom, Norway and Switzerland have been added to the list of the simulated countries whereas Malta and Cyprus have been removed. The ISO 3166-1 standard has been adopted to describe each country at the NUTS1 level (except for Greece and the United Kingdom, for which the abbreviations EL and UK are used according to EU Interinstitutional style guide).

3.2.2 Scenario from TIMES

The scenario from TIMES that was used in this work is called *NearZeroCarbon*. It has a very ambitious CO2 emission target of -95% by 2050 compared to 1990 levels. This scenario also heavily relies on P2G with a total capacity of 3,800 GW of electrolysers in the considered countries. A storage capacity of around 3,800 GWh is also considered.

3.2.3 Commodities price

The cost of commodities can be found in Table 2. They are used to compute the variable costs of the power plants. For such a scenario with high CO2 reduction target in TIMES, a high CO2 emission cost around 350 EUR/t can be expected. Considering the entirety of this cost into the marginal price of generators could excessively skew the optimisation results. Therefore, it has been decided not to take those costs into account. The reality will probably lie between including the whole CO2 cost into marginal price of generators and taking a null cost for CO2.

Table 2: Commodities price

Name	Price EUR/MWh
Nuclear	4
Black coal	20

Gas	20
Fuel oil	78
Biomass	30
Lignite	15

3.2.4 Storage units

The storage efficiencies of the different storage units can be found in Table 3. All efficiencies except those related to heat storage come from JRC-EU-TIMES database [31]. For P2GS units, the discharging efficiency is the one related to power production. The efficiency associated to hydrogen discharged to satisfy the demand is assumed equal to 1.

Table 3: Characteristics of storage technologies

Technology	Self-discharge	Charging efficiency	Discharging efficiency
-	%/d	-	-
P2H2	3	1	1
CHP	3	1	1
SCSP	3	1	1
P2GS	1	0.72	0.46
HDAM	1	0.89	0.89
HPHS	1	0.89	0.89
BEVS	1	0.94	0.94
BATS	1	0.89	0.89

3. RESULTS

The results from the 4 scenarios (CHEAPSLACK, H2FLEX, No_PtL and NOH2STO) are presented in this section. Each simulation took between 13 and 20 h to run on a 64 GB 8-CPU cluster node [2].

3.3 CHEAPSLACK vs. H2FLEX

In this first part of the results, the 2 scenarios CHEAPSLACK and H2FLEX are compared.

3.3.1 Hydrogen demand satisfaction

Figure 3 shows the part of the hydrogen demand that is supplied by the electrolysers and the one that needs to be covered by the slack for both scenarios. The slack produces hydrogen whenever cheap renewable energy is already used for other purposes or there is too few of it; or when the slack price is too competitive.

It can be observed that the slack is still producing the biggest part of the demand, even when its price is 160 EUR/MWh. This high price forces the system to produce 1000 TWh, which is less than one third of the demand. CHEAPSLACK has half less hydrogen produced by the electrolysers.

The next comparisons will investigate the reason behind this difference of production.

[2] http://www.ceci-hpc.be/clusters.html

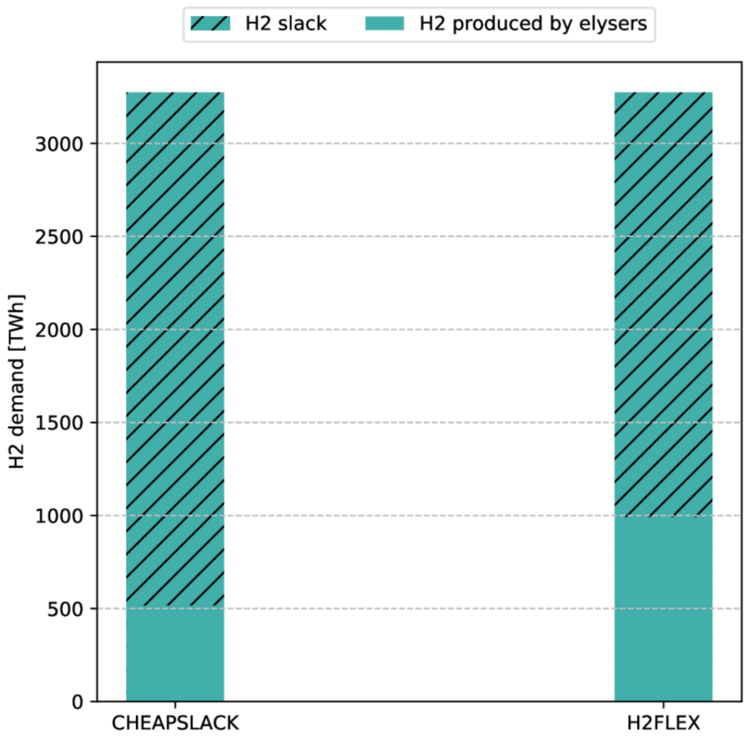

Figure 3: Repartition of the hydrogen production from the slack and from the system

3.3.2 Curtailment

The total curtailment compared to the total and peak renewable production is represented in Figure 4. Curtailment is very small. It seems that the difference between the scenarios may only be explained by solver precision. This had to be relaxed so that objective function falls within 5% to take into account the complexity of the model. Since curtailment is very small, there is no real opportunity of producing more hydrogen from renewable sources, whatever the slack cost.

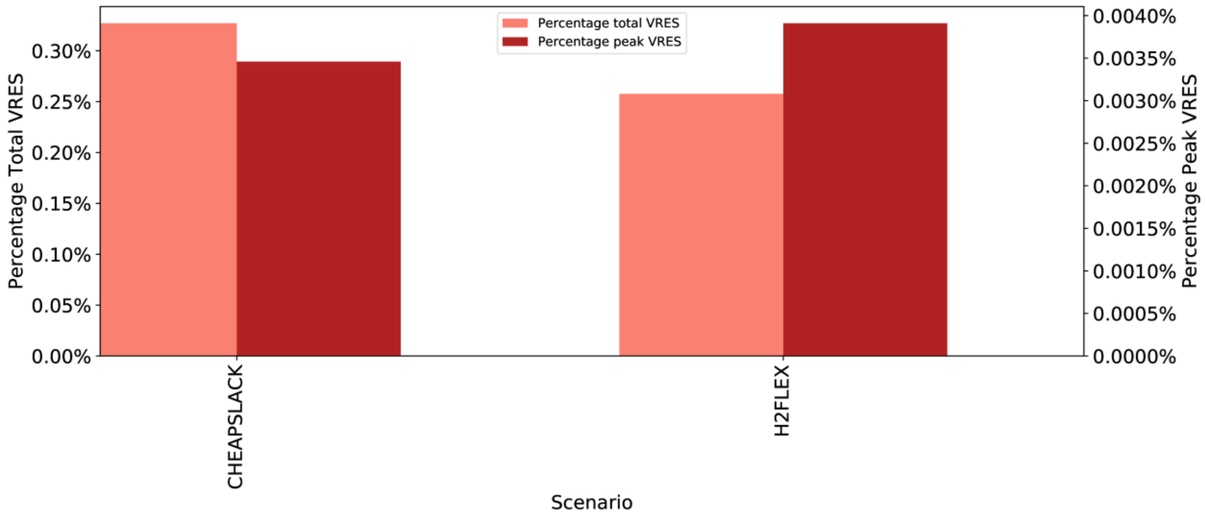

Figure 4: Total curtailment in both scenarios

3.3.3 Power dispatch

Power dispatch plots of a selected week in June are represented in Figure 5 and Figure 6. In the reservoirs level plots, the hydrogen storage is discharging without producing power since it satisfies the demand.
A first observation is that, despite a very sunny week, no curtailment is to be observed. Comparing both scenarios, it can be seen that CHEAPSLACK is producing less hydrogen, storing more energy in batteries and BEVS. This energy allows then to reduce gas turbines production when the load exceeds the renewable production.
In other words, increasing the cost of the slack results in more hydrogen produced by the electrolysers. However, it also increases the gas consumption since less renewable energy is stored to later satisfy the demand when there is a lack of renewable production.

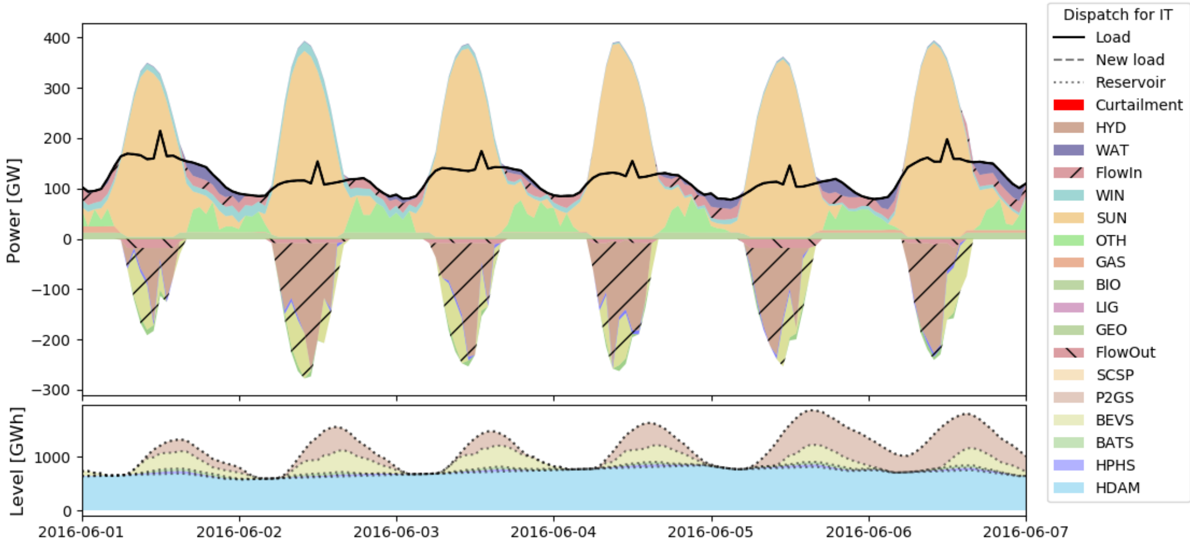

Figure 5: CHEAPSLACK scenario - Power dispatch and reservoir levels of a selected week in Italy in June. Negative values in the dispatch plot indicate exported power or power going into storage.

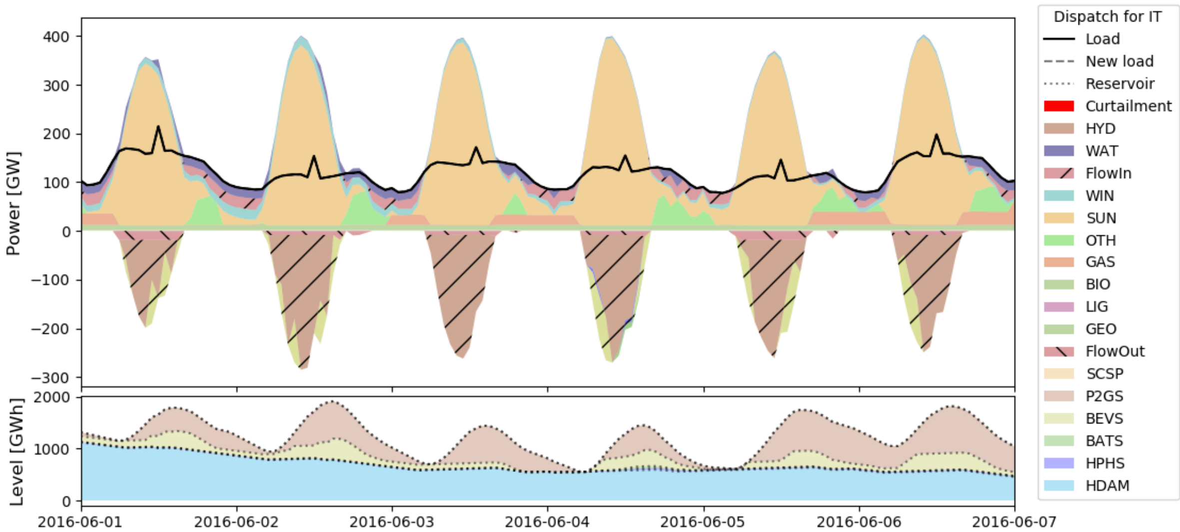

Figure 6: H2FLEX scenario - Power dispatch and reservoir levels of a selected week in Italy in June. Negative values in the dispatch plot indicate exported power or power going into storage.

3.3.4 Generation breakdown

The power generation of each fuel is represented in Figure 7. As expected, gas is producing more in the H2FLEX scenario to offset hydrogen production. On the other hand, batteries and BEVS are producing more in the CHEAPSLACK scenario. H2FLEX has a greater total power generation than CHEAPSLACK due to the additional hydrogen production. This also means better sector coupling because more electricity is used to produce hydrogen in H2SLACK than in CHEAPSLACK. A last remark is that despite a certain capacity of fuel cells, very little hydrogen is used to produce electricity. This makes sense since electrolysers are not producing enough hydrogen to satisfy the demand, and efficiency of fuel cells is only 46%.

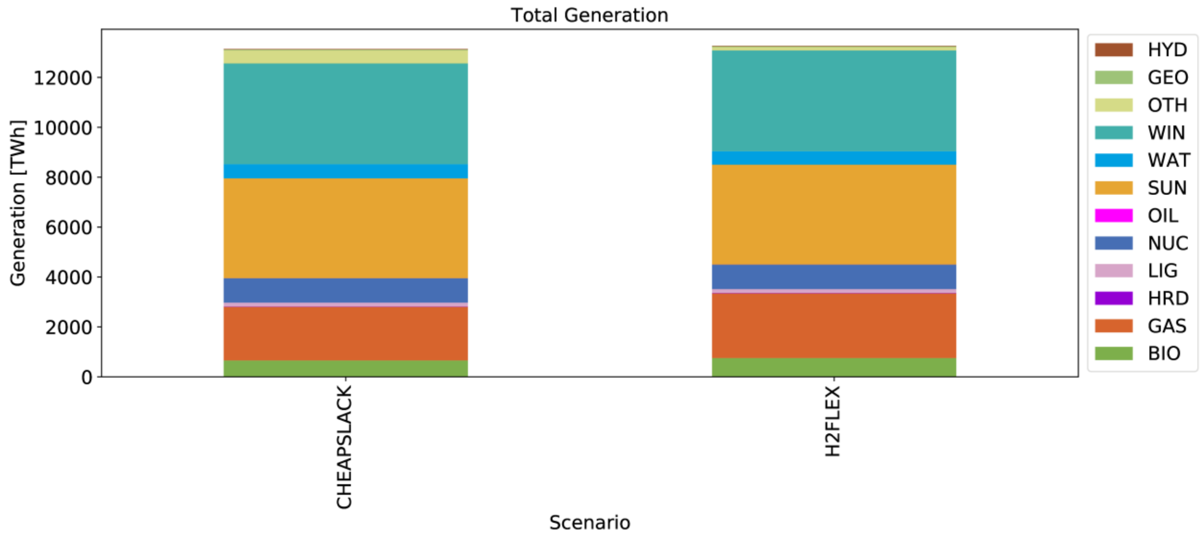

Figure 7: Generation breakdown by fuel type for both scenarios.

3.3.5 Electrolysers operation

As a reminder, there is around 3,800 GW capacity of electrolysers in this scenario. Compared to the 1000 TWh of hydrogen production in H2FLEX scenario, this gives a global capacity factor of around 3%, or an Equivalent Full Operating Hours (EFOH) of 263 h. This variable with marginal price of electricity is very important to determine if electrolysers can be profitable. The EFOH per country are represented in Figure 8.

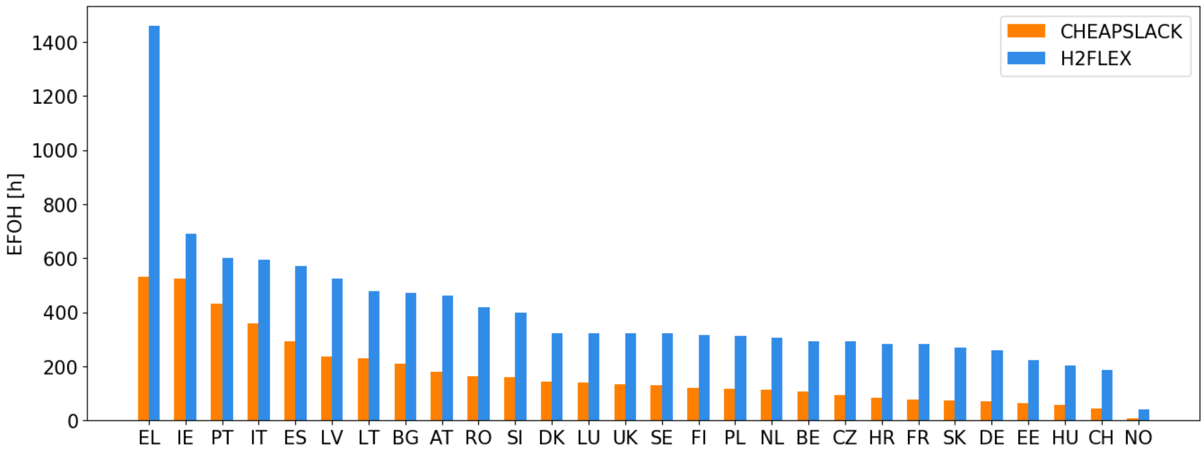

Figure 8: EFOH per country and per scenario.

As is represented in the figure, the EFOH are highly dependant of the simulation parameters, namely the price of H2 Slack. If the slack was not included in the simulation or had a very high price, the EFOH would be higher. However, they would produce hydrogen from electricity

produced by thermal plants, whereas for now, electrolysers only produce with RES electricity and a very small amount from biomass CHP plants because their marginal cost is smaller than the slack cost in both scenarios.
A possibility to have green hydrogen and satisfy the whole demand of this TIMES scenario is to increase the RES capacity. Installing more gas turbines with CCS or methane reforming units with CCS would also allow to produce hydrogen without emitting CO2. The advantage of producing hydrogen via electrolysers is that it allows Europe to be less dependant on fuels importation.

3.3.6 CO2 emissions

CO2 emissions are given in Figure 9. H2FLEX is producing more CO2 because of the additional gas production and because the hydrogen slack was assumed to be equipped with CCS. If those back-up units are not equipped with CCS, then H2FLEX would be the scenario emitting less CO2.

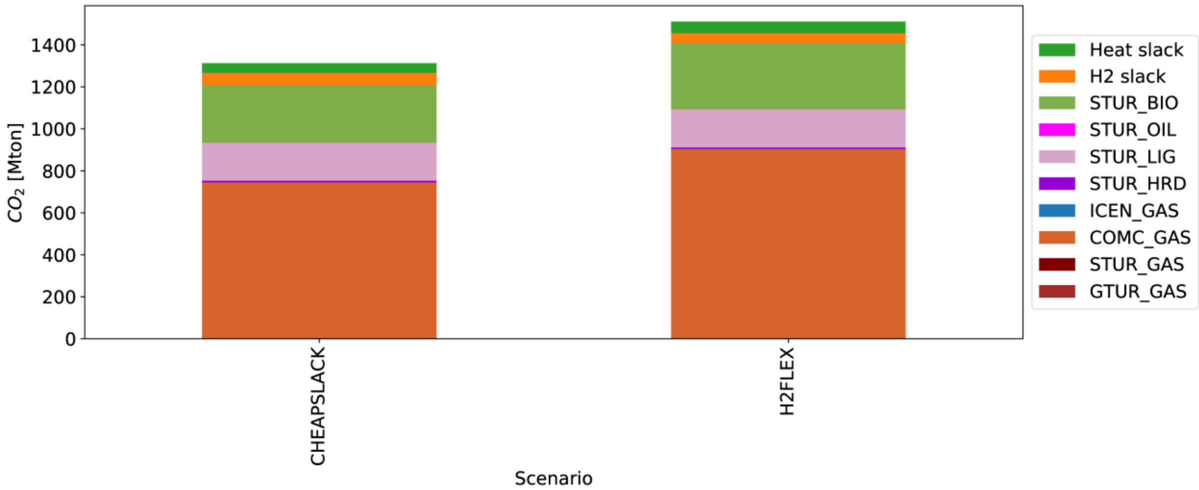

Figure 9: Total CO2 emission per scenario.

3.3.7 Shadow prices

The last part of this section is the comparison of the shadow prices of both scenarios in Figure 10 and Figure 11. In CHEAPSLACK scenario, electrolysers are producing only when marginal price is under the price of hydrogen slack times the efficiency of electrolysers, which gives:

$$88 \times 0.72 = 63.4 \text{ EUR/MWh}$$

In H2SLACK, electrolysers are producing when marginal cost is under :

$$160 \times 0.72 = 115 \text{ EUR/MWh}$$

Therefore, whenever prices in CHEAPSLACK scenario are between those 2 values, they increase to 115 in H2SLACK. This illustrates how much influence electrolysers can have on the demand and on the market prices. It is also worth noticing that introducing electrolysers in power system implies less volatile prices and a higher average price of electricity, which could act as an incentive for investors to invest in renewable generation. Countries like Portugal that have prices often under 63.4 EUR/MWh keep their low prices in both scenarios because it indicates that at those time intervals the hydrogen demand is satisfied.

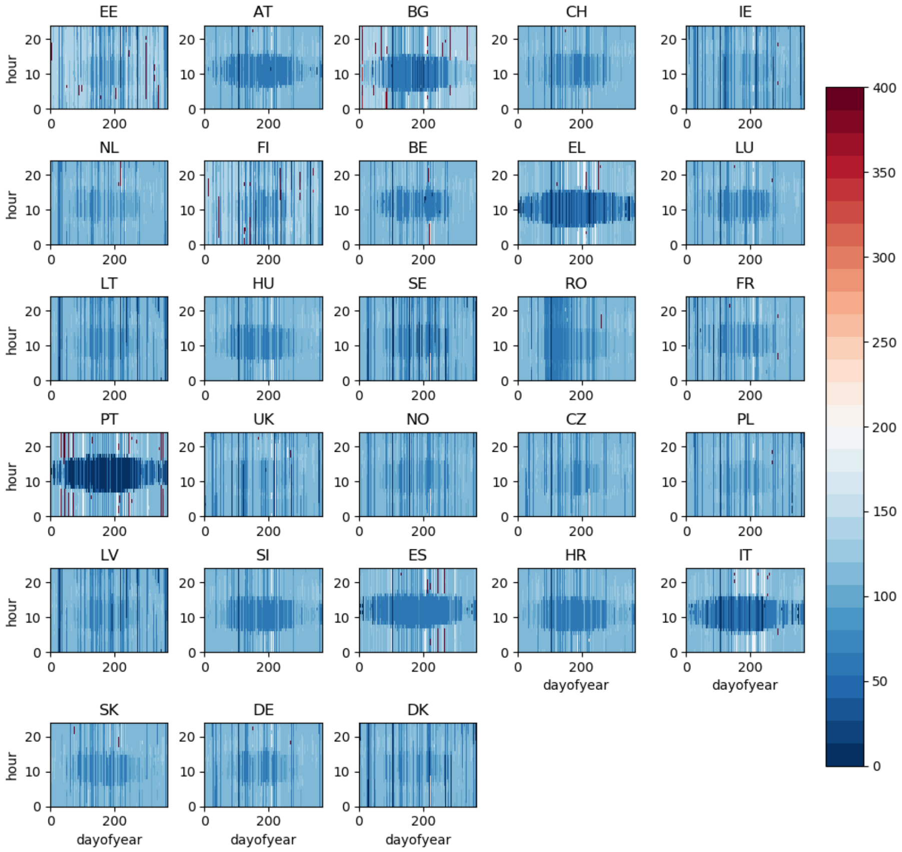

Figure 10: Marginal price of electricity at each hour of the year for CHEAPSLACK scenario.

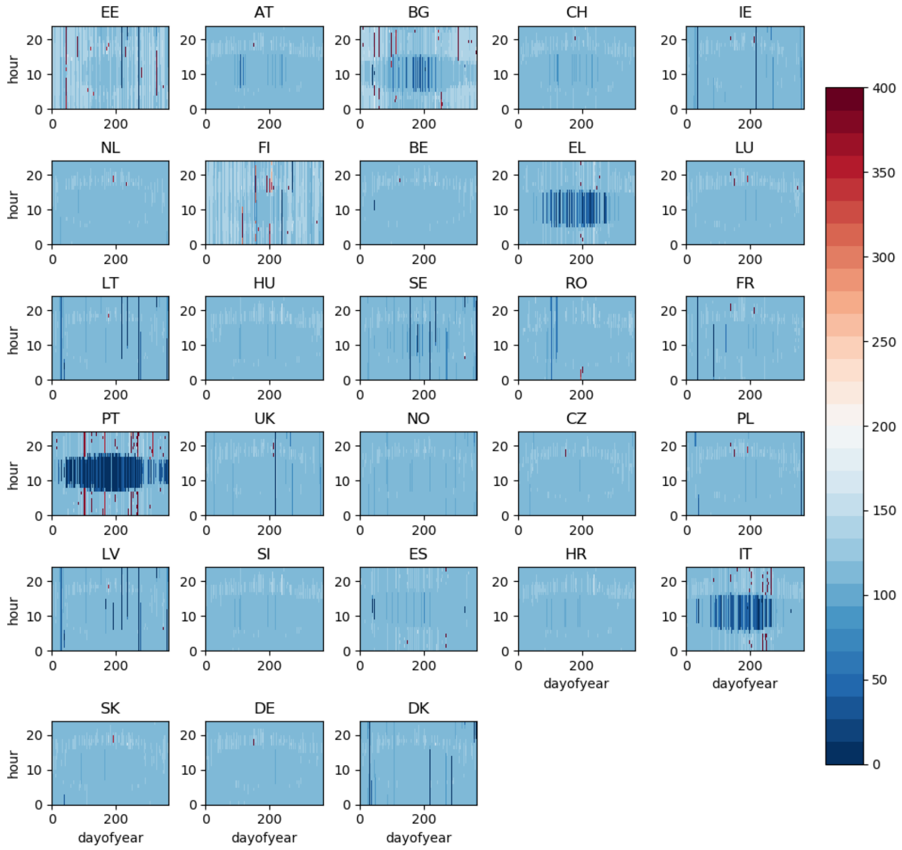

Figure 11: Marginal price of electricity at each hour of the year for H2FLEX scenario.

3.4 H2FLEX, No_PtL and NOH2STO

This section seeks to first understand the interest of the PtL part of the simulation. The only difference between H2FLEX and No_PtL can be found at the modelling level: in H2FLEX, the profile of hydrogen demand linked to PtL is shaped during MTS whereas it is fixed flat in advance in No_PtL. The second goal is to evaluate the role of hydrogen storage.

3.4.1 Hydrogen satisfaction

First of all, the part of the hydrogen demand that is satisfied by the system and by the slack is represented in Figure 12. H2FLEX produces slightly more hydrogen than No_PtL but the difference only amounts to 4 TWh. This figure indicates that hydrogen storage has a certain impact since H2FLEX produces 300 extra hydrogen TWh compared to NOH2STO. However, no storage capacity still allows to produce 60% of H2FLEX hydrogen production which is not negligible.

3.4.2 Curtailment

Curtailment is represented in Figure 13. Even though No_PtL does not produce significantly less H2 than H2FLEX, it has almost double curtailment. This implies that PtL planification has a real modelling interest. However, this modelling could be improved. Indeed, MTS has a 24-hour time step. The PtL demand is therefore given per day and is then applied at the same level all day. This is not efficient in countries with a lot of solar energy, as the sun is not shining all day. Since hydrogen storage capacities are not very high, it might be more beneficial to shape the PtL demand given by the MTS to follow solar production profile in countries depending on solar energy.

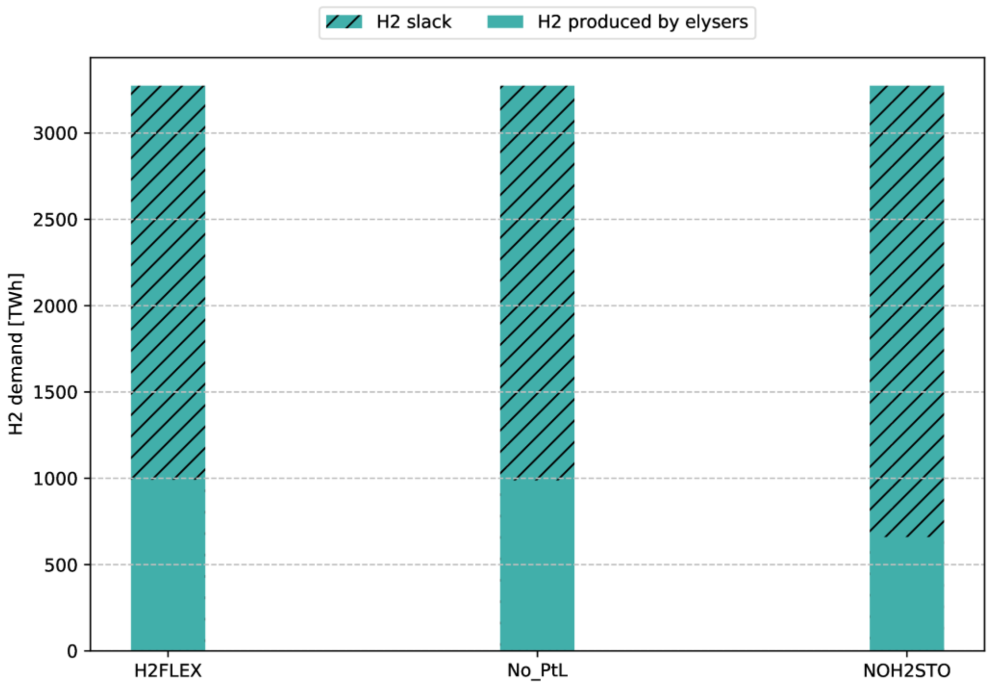

Figure 12: Repartition of the production of hydrogen from the system and from the slack

As expected, there is much more curtailment in NOH2STO scenario. This curtailment is limited by a higher use of BEVS and BATS in this last scenario than in the 2 others even though the storage capacities of electrical storage technologies are quite limited. As for CHEAPSLACK, this energy allows later to use less gas when RES production is small or equal to 0.

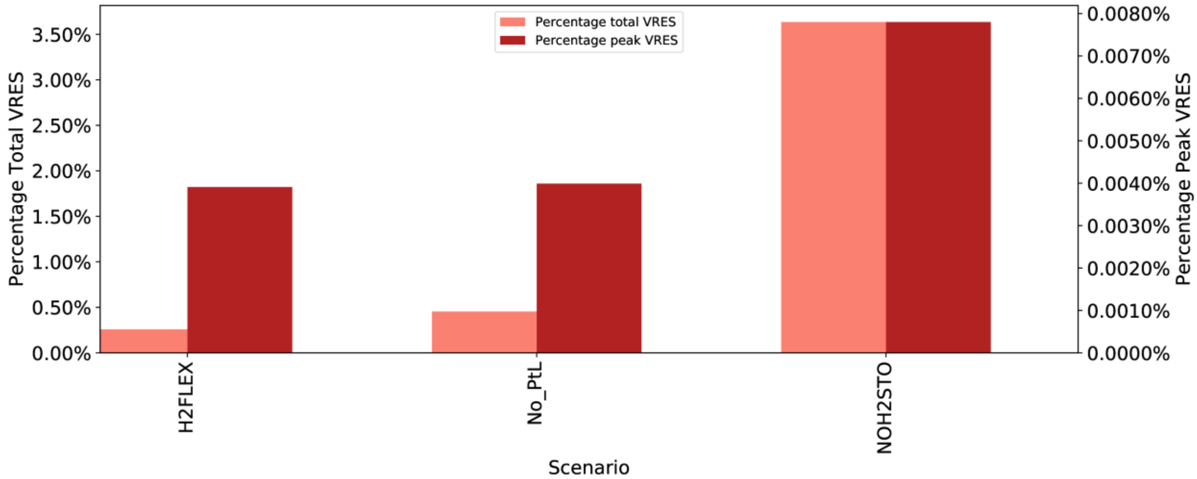

Figure 13: Total curtailment for the three scenarios

3.4.3 Electrolysers operation

The EFOH per country is represented for the three scenarios in Figure 14. It can be observed that H2FLEX does not always have higher EFOH than No_PtL. This can be particularly observed in countries whose main RES in sun such as Greece (EL), Slovenia (SI), Spain (ES) or Austria (AT).

EFOH in NOH2STO is generally smaller, especially in countries with high storage capacities. There is almost no difference between H2FLEX and NOH2STO in Ireland (IE) because this country has only 480 MWh of H2 storage.

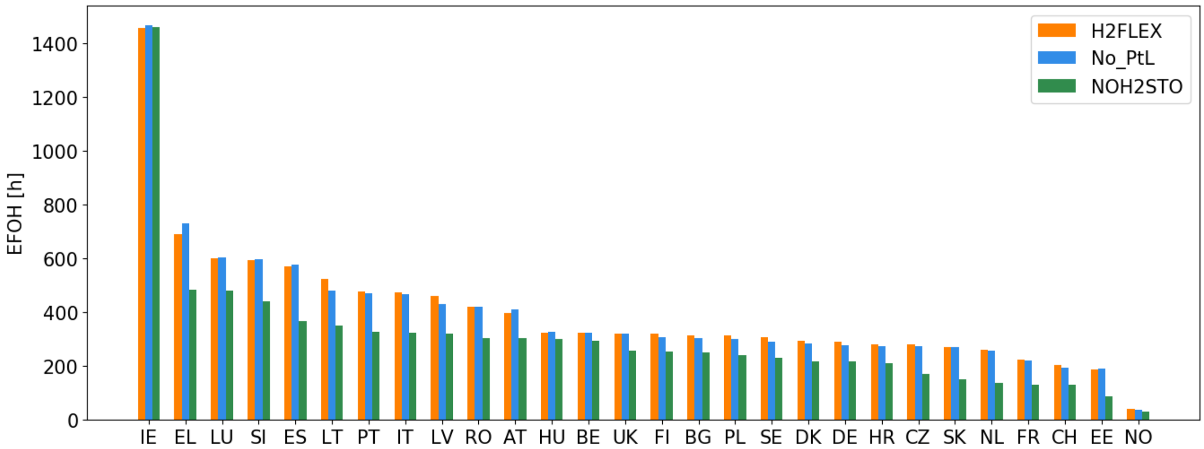

Figure 14: EFOH per country for each scenario.

3.4.4 Storage technologies dynamics

This section is not comparing the different scenarios but observes the storage dynamics. For that purpose, H2FLEX results are described. The State Of Charge (SOC) of 3 storage technologies is compared for Italy and the United Kingdom. Those countries have been chosen because Italy mainly relies on sun production whereas more energy is produced from wind in the UK. Therefore, Italy must cope with a RES production that peaks around midday but is null at night and the UK deal with a VRES production that can be very high at night. Also the sun produces more during the summer which is not the case of wind.

3.4.4.1 Italy

The SOC of batteries, H2 storage and HDAM in Italy is represented in Figure 15. The batteries have a dynamic behaviour all year, even though their activity is limited since the scenario is using a lot of hydrogen. H2 storage is fuller during the summer, which makes sense since Italy mainly relies on solar energy. Its behaviour is also very dynamic as it charges and discharges very often. Finally, the hydro dams act as the seasonal storage technology. It is also interesting to notice that none of those storage has been oversized. They are probably not undersized either since the curtailment is very small.

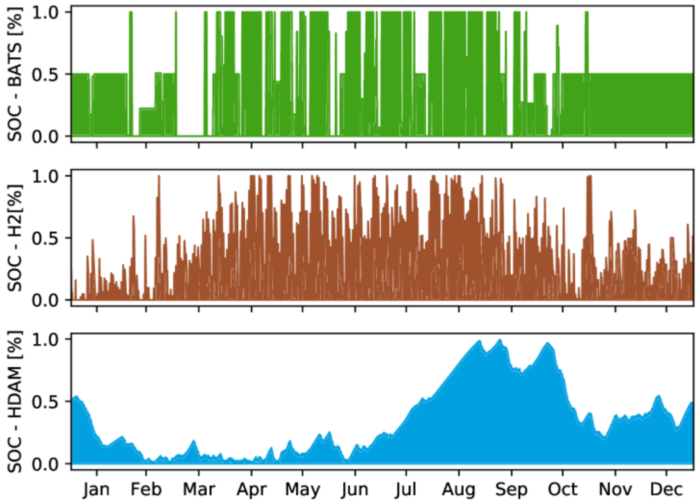

Figure 15: Evolution of the state of charge of batteries, H2 storage and hydro dams in Italy during the year.

3.4.4.2 The United Kingdom

The same study is applied to the UK. Figure 16 shows that batteries have the same behaviour as in Italy. However, the hydrogen storage content acts differently since wind is blowing all year and especially more in the winter. Since the capacity of hydro dams in the UK is very restricted, it does not have a seasonal profile and acts more as what is expected for short term storage.

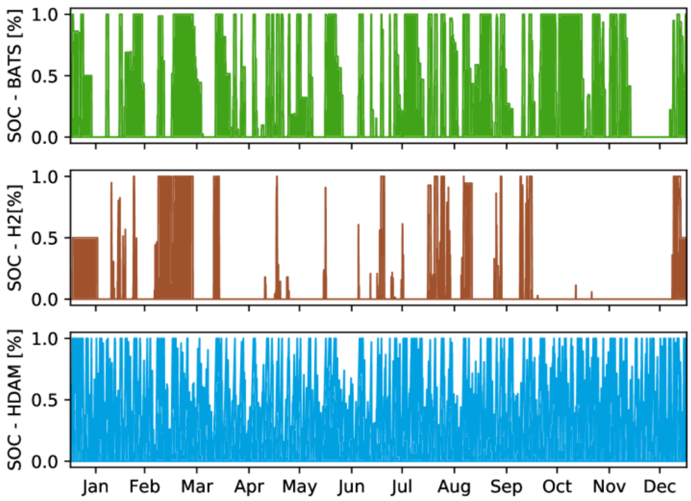

Figure 16: Evolution of the state of charge of batteries, H2 storage and hydro dams in the United Kingdom during the year.

3.5 TIMES vs. Dispa-SET

In this section, a brief comparison of Dispa-SET and TIMES results is performed.

3.5.1 RES production

It was concluded hereabove that TIMES was overestimating RES production compared to Dispa-SET simulations which led to a lack of renewable energy for hydrogen production in Dispa-SET results. In order to validate this assumption, renewable production in TIMES scenario and in Dispa-SET are compared in Figure 17. As expected, Dispa-SET has a smaller VRES generation than TIMES. The difference is small regarding solar production but is significant when looking at wind production or even water production. The higher production from fuel cells in TIMES was expected since there is less renewable production available for hydrogen in Dispa-SET simulation.

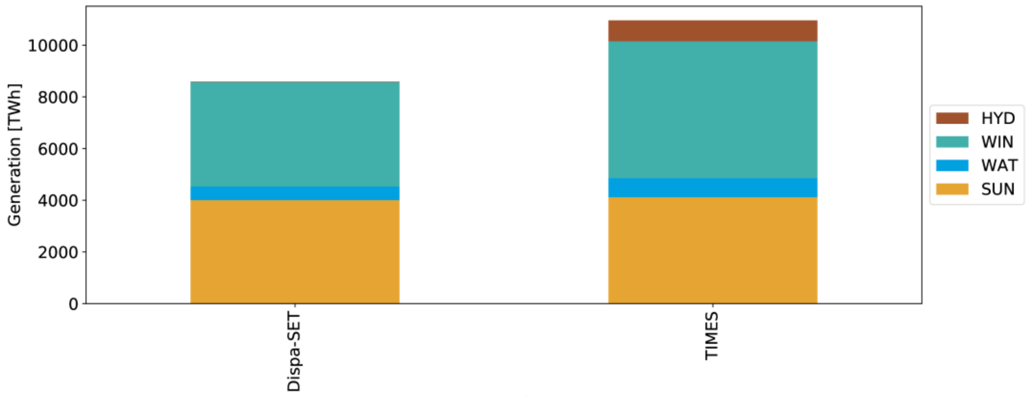

Figure 17: Comparison between renewable generation in Dispa-SET (with the H2FLEX scenario) and JRC-EU-TIMES.

Since the biggest difference can be observed for wind, this production had been differentiated by country to look from where the difference can come from. The capacity factors for both scenarios are represented in Figure 18**Error! Reference source not found.**. Capacity factors in Dispa-SET are almost always smaller than the ones in TIMES. The difference can be easily explained due to the fact that Dispa-SET uses historical capacity factors for renewable production and inflows in run-off-rivers and HDAM and TIMES uses standard capacity factors and only simulates 12 time-slices per year.

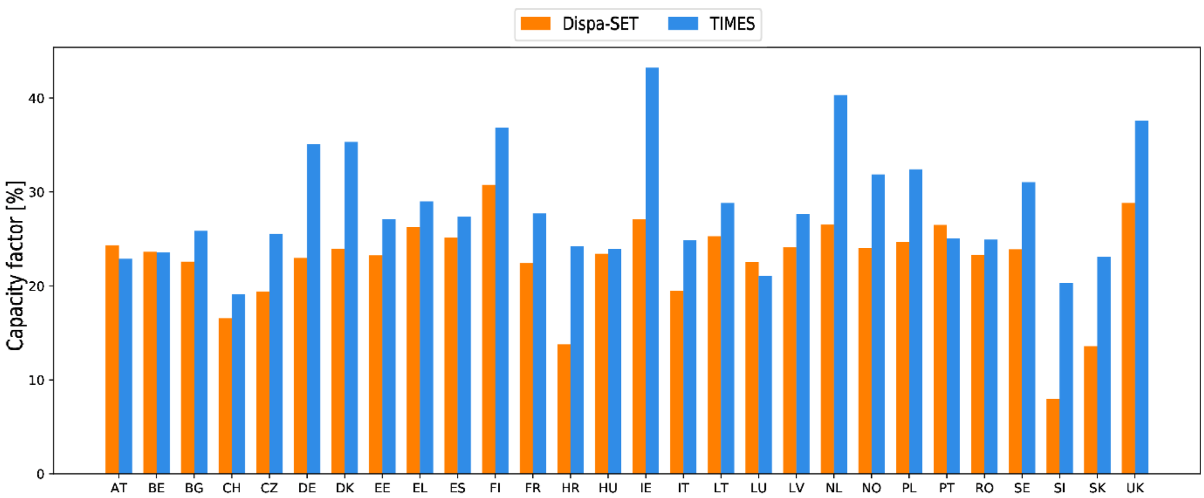

Figure 18: Comparison between renewable wind generation in Dispa-SET (H2FLEX scenario) and JRC-EU-TIMES.

3.5.2 Electrolysers capacity

Figure 19 compares the installed capacity of electrolysers in each country and their maximum utilisation. It seems that the electrolysers are over-sized. However, the hydrogen demand has been assumed partly flat, partly shaped in MTS which can be improved and could bring a large error margin. Moreover, the VRES production is different in the 2 scenarios and this also has a big influence on this graph.

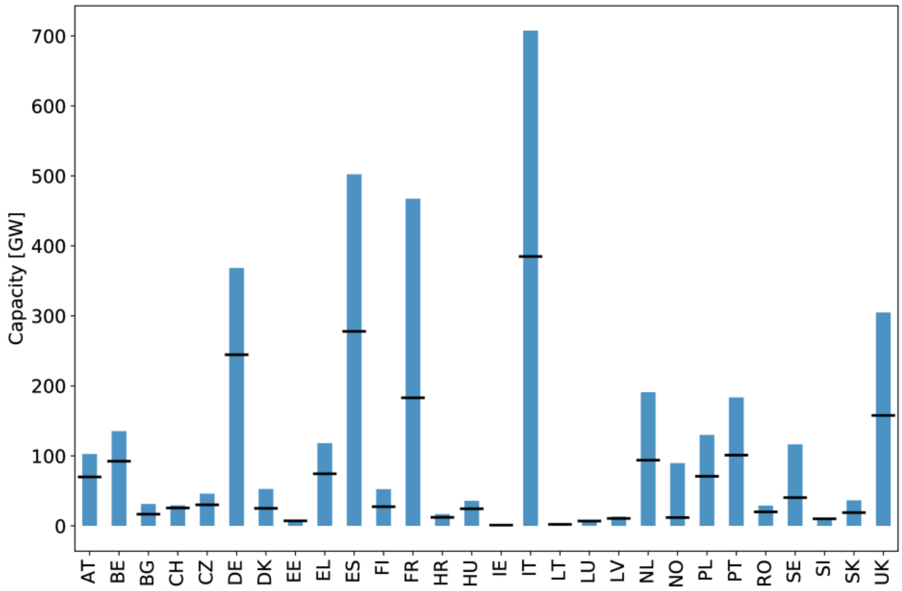

Figure 19: Electrolyser capacities in each country. The horizontal line indicates the peak hydrogen production in Dispa-SET simulations, in GWh.

4. CONCLUSION

The goal of this work was to assess the contribution of the power-to-hydrogen sector in increasing the flexibility of highly coupled energy systems. To do so, Dispa-SET, a highly detailed unit commitment and power dispatch model, was soft-linked with JRC-EU-TIMES, a European long-term investment model. A scenario from TIMES with large shares of VRES was selected. Dispa-SET was extended by adding the equations related to power-to-gas. Also the hydrogen demand for power-to-liquid was taken into account, which gave more flexibility related to liquid fuels storage. An alternative to electrolysers was included, representing methane steam reforming, to determine if electrolysers were able to produce hydrogen at a competitive price and in order to avoid infeasibilities. Four scenarios, CHEAPSLACK, H2FLEX, No_PtL and NOH2STO were studied by varying the price of the hydrogen slack, the power-to-liquid implementation and the hydrogen storage size.

The simulations directly indicate a lack of renewable generation, because renewable generation in TIMES was, due to simplified input assumptions, overestimated by 15% compared to Dispa-SET results. Therefore, the system was not able to produce the right amount of hydrogen to satisfy the demand. On the other hand, TIMES was under estimating the capacity of thermal generation needed to guarantee the security of supply at each hour of the year. Another interesting conclusion is that the RES curtailment in the system was very small, equal to 0.26% of total RES production for H2FLEX scenario, and that was due to the hydrogen sector and to the large electrolysers capacity. Indeed, in this scenario almost 20% of the total renewable production is consumed by electrolysers. Moreover, they have a large influence on the market price by flattening its volatility and increasing it when there are large shares of renewable production. For instance, the average market price in the UK increased by 11% in H2FLEX scenario compared to CHEAPSLACK scenario, due to the additional hydrogen production. On the other hand, the standard deviation of marginal prices during the year decreased by 41% in H2FLEX due to electrolysers consumption.

The proposed modelling framework also allowed validation of the PtL sector modeling since it allows to almost reduce curtailment by 50% and produce more hydrogen with that energy. Hydrogen storage is not seasonal due to its relatively small capacity. In most countries it can provide around 1 hour of storage capacity. In all scenarios, similar H2 storage behaviour was observed. It often fills completely when there is too much renewable production and empties shortly afterwards to satisfy hydrogen demand.

The uni-directional soft-linking between JRC-EU-TIMES and Dispa-SET provided useful insights regarding the importance of the power-to-gas sector in using the extra renewable production and reducing the curtailment. This shows the importance of sector coupling in future energy systems. The results also show the importance of validating system feasibility provided by long-term planning models.

The future step of this study would be the introduction of feedback loops which would result in bidirectional soft linking between Dispa-SET and TIMES reducing the error and increasing the accuracy of the outputs. The second step would be to refine the carbon cycle implementation in Dispa-SET in order to have a more precise estimation of carbon emission and check that the carbon goal is well achieved. That would for instance require taking into account the carbon needed to synthesize the e-fuels

NOMENCLATURE

Abbreviations	Description	Units
CCS	Carbon capture and storage	[-]
DAC	Combined heat and power	[-]
DSM	Demand Side Management	[-]
EFOH	Equivalent Full Operating Hours	[-]
Elyser	Electrolyser	[-]
ESOM	Energy System Optimisation model	[-]
FC	Fuel cell	[-]
FCEV	Fuel cell electric vehicle	[-]
NTC	Net Transfer Capacity	[-]
P2G	Power-to-gas	[-]
PtL	Power-to-Liquid	[-]
RES	Renewable energy sources	[-]
SOC	State of charge	[-]
TES	Thermal Heat Storage	[-]
UCM	Unit commitment and power dispatch model	[-]
VRES	Variable Renewable Energy Sources	[-]
Fuel	Description	Units
BIO	Biogas	[-]
GAS	Natural gas	[-]
GEO	Geothermal heat	[-]
HYD	Hydrogen	[-]

LIG	Lignite	[-]
OTH	Other (electricity produced from BATS or BEVS)	[-]
WAT	Water	[-]
WIN	Wind	[-]
Technologies	Description	Unit
BATS	Batteries	[-]
BEVS	Battery electric vehicles	[-]
HDAM	Hydro dams	[-]
HPHS	Hydro pumped storage	[-]
P2GS	Power-to-gas	[-]
SCSP	Concentrated Solar Power	[-]

Integer variables	Description	Unit
Commited	Committed status of unit {1 0} or integer	[-]
StartUp	Start-up status of unit {1 0} or integer	[-]
ShutDown	Shut-down status of unit {1 0} or integer	[-]

REFERENCES

[1] European Commission. A clean planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. COM (2018) 773 Final 2018.

[2] Mancarella P. MES (multi-energy systems): An overview of concepts and evaluation models. Energy 2014;65:1–17. https://doi.org/10.1016/j.energy.2013.10.041.

[3] Gielen D, Boshell F, Saygin D, Bazilian MD, Wagner N, Gorini R. The role of renewable energy in the global energy transformation. Energy Strategy Reviews 2019;24:38–50. https://doi.org/10.1016/j.esr.2019.01.006.

[4] Götz M, Lefebvre J, Mörs F, McDaniel Koch A, Graf F, Bajohr S, et al. Renewable Power-to-Gas: A technological and economic review. Renewable Energy 2016;85:1371–90. https://doi.org/10.1016/j.renene.2015.07.066.

[5] Hashimoto K, Yamasaki M, Fujimura K, Matsui T, Izumiya K, Komori M, et al. Global CO2 recycling—novel materials and prospect for prevention of global warming and abundant energy supply. Materials Science and Engineering: A 1999;267:200–6. https://doi.org/10.1016/S0921-5093(99)00092-1.

[6] Bailera M, Lisbona P, Romeo LM, Espatolero S. Power to Gas projects review: Lab, pilot and demo plants for storing renewable energy and CO2. Renewable and Sustainable Energy Reviews 2017;69:292–312. https://doi.org/10.1016/j.rser.2016.11.130.

[7] Schiebahn S, Grube T, Robinius M, Tietze V, Kumar B, Stolten D. Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany. International Journal of Hydrogen Energy 2015;40:4285–94. https://doi.org/10.1016/j.ijhydene.2015.01.123.

[8] Sterner M. Bioenergy and renewable power methane in integrated 100% renewable energy systems: Limiting global warming by transforming energy systems. kassel university press GmbH; 2009.

[9] Parra D, Valverde L, Pino FJ, Patel MK. A review on the role, cost and value of hydrogen energy systems for deep decarbonisation. Renewable and Sustainable Energy Reviews 2019;101:279–94. https://doi.org/10.1016/j.rser.2018.11.010.

[10] Bolat P, Thiel C. Hydrogen supply chain architecture for bottom-up energy systems models. Part 2: Techno-economic inputs for hydrogen production pathways. International Journal of Hydrogen Energy 2014;39:8898–925. https://doi.org/10.1016/j.ijhydene.2014.03.170.

[11] Steward D, Zuboy J. Community Energy: Analysis of hydrogen distributed energy systems with photovoltaics for load leveling and vehicle refueling. National Renewable Energy Lab.(NREL), Golden, CO (United States); 2014.

[12] Cells F, Undertaking HJ. Hydrogen Roadmap Europe-A Sustainable Pathway for the European Energy Transition 2019.

[13] Thomas D. (Hydrogenics), Mertens D. (Colruyt), Meeus M. (Sustesco), Van der Laak W., Francois I. (WaterstofNet). Power-to-Gas Roadmap for Flanders 2016.

[14] Grueger F, Möhrke F, Robinius M, Stolten D. Early power to gas applications: Reducing wind farm forecast errors and providing secondary control reserve. Applied Energy 2017;192:551–62. https://doi.org/10.1016/j.apenergy.2016.06.131.

[15] Mathiesen BV, Ridjan I, Connolly D, Nielsen MP, Hendriksen PV, Mogensen MB, et al. Technology data for high temperature solid oxide electrolyser cells, alkaly and PEM electrolysers. Department of Development and Planning Aalborg University; n.d.

[16] Eichman J, Harrison K, Peters M. Novel electrolyzer applications: providing more than just hydrogen. National Renewable Energy Lab.(NREL), Golden, CO (United States); 2014.

[17] Berger M, Radu D, Fonteneau R, Detienne G, Deschuyteneer T, Ernst D. Centralised Planning of National Integrated Energy System with Power-to-Gas and Gas Storages. Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MEDPOWER 2018), Dubrovnik, Croatia: Institution of Engineering and Technology; 2018, p. 80 (6 pp.)-80 (6 pp.). https://doi.org/10.1049/cp.2018.1912.

[18] Brown T, Schlachtberger D, Kies A, Schramm S, Greiner M. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. Energy 2018;160:720–39. https://doi.org/10.1016/j.energy.2018.06.222.

[19] Connolly D, Lund H, Mathiesen BV. Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renewable and Sustainable Energy Reviews 2016;60:1634–53. https://doi.org/10.1016/j.rser.2016.02.025.

[20] Jensen IG, Wiese F, Bramstoft R, Münster M. Potential role of renewable gas in the transition of electricity and district heating systems. Energy Strategy Reviews 2020;27:100446. https://doi.org/10.1016/j.esr.2019.100446.

[21] Sakellaris K, Canton J, Zafeiratou E, Fournié L. METIS – An energy modelling tool to support transparent policy making. Energy Strategy Reviews 2018;22:127–35. https://doi.org/10.1016/j.esr.2018.08.013.

[22] Bossavy A, Bossmann T, Fournié L, Humberset L, Khallouf P. METIS Studies - Study S1 - Optimal flexibility portfolios for a high-RES 2050 scenario. 2018.

[23] Sgobbi A, Nijs W, De Miglio R, Chiodi A, Gargiulo M, Thiel C. How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system. International Journal of Hydrogen Energy 2016;41:19–35. https://doi.org/10.1016/j.ijhydene.2015.09.004.

[24] Blanco H, Nijs W, Ruf J, Faaij A. Potential of Power-to-Methane in the EU energy transition to a low carbon system using cost optimization. Applied Energy 2018;232:323–40. https://doi.org/10.1016/j.apenergy.2018.08.027.

[25] Blanco H, Nijs W, Ruf J, Faaij A. Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization. Applied Energy 2018;232:617–39. https://doi.org/10.1016/j.apenergy.2018.09.216.

[26] Simoes S, Nijs W, Ruiz P, Sgobbi A, Radu D, Bolat P, et al. The jrc-eu-times model. Assessing the Long-Term Role of the SET Plan, EUR 2013;26292.

[27] Blanco Reaño H. Hydrogen potential in the future EU energy system: a multi-sectoral, multi-model approach. University of Groningen, 2019. https://doi.org/10.33612/diss.107577829.

[28] Welsch M, Deane P, Howells M, Ó Gallachóir B, Rogan F, Bazilian M, et al. Incorporating flexibility requirements into long-term energy system models – A case study on high levels of renewable electricity penetration in Ireland. Applied Energy 2014;135:600–15. https://doi.org/10.1016/j.apenergy.2014.08.072.

[29] Helistö N, Kiviluoma J, Holttinen H, Lara JD, Hodge B. Including operational aspects in the planning of power systems with large amounts of variable generation: A review of modeling approaches. Wiley Interdisciplinary Reviews: Energy and Environment 2019;8:e341.

[30] Pavičević M, Mangipinto A, Lombardi F, Kavvadias K, Navarro JPJ, Colombo E, et al. The potential of sector coupling in future European energy systems soft linking between the Dispa-SET and JRC-EU-TIMES models - Dataset 2020. https://doi.org/10.5281/ZENODO.3627258.

[31] Wouter Nijs. JRC-EU-TIMES - JRC TIMES energy system model for the EU (Version 1.1.1) [Data set]. 2019.