"Flexibility options in a multi-regional whole-energy system: the role of energy carriers in the Italian energy transition"

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ABSTRACT

Integration of a high share of intermittent renewable energy sources is essential to reach a fossil free energy system. In the southern European countries, solar energy appears as an ideal candidate. Due to the spatial and temporal disparity of such an energy source, it faces two main challenges: (i) the seasonal pattern of solar irradiation induces a need for long-term storage; (ii) the locations with the biggest solar potential are not close to the major places of consumption. Many studies have shown the interest of the electro-fuels (e.g. hydrogen) as long-term storage and energy carriers. However, their integration in a whole and multi-regional energy system is rarely studied. This work addresses the following two questions: What will be the contribution of the electro-fuels as energy carriers and longterm storage? How can the different regions collaborate to reach a fossil free energy system at the lowest cost? We applied a whole and multi-regional energy model, EnergyScope Multi-Cell, to the Italian energy system of 2050. Italy is divided into 3 interconnected regions or cells: the North, the Centre, and the South. The country has a large solar potential in the South and high energy demand in the North. In the modelled scenario, Italy does not reach a self-sufficient renewable energy system. It imports 7.7% of its primary energy as electricity and 1.4% as green hydrogen. The North is responsible for 88% of those imports. The overall system relies on high electrification of the demand, sector-coupling, and exchanges between regions to integrate high shares of renewab...

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Flexibility options in a multi-regional whole-energy system: the role of energy carriers in the Italian energy transition

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Abstract:

Integration of a high share of intermittent renewable energy sources is essential to reach a fossil free energy system. In the southern European countries, solar energy appears as an ideal candidate. Due to the spatial and temporal disparity of such an energy source, it faces two main challenges: (i) the seasonal pattern of solar irradiation induces a need for long-term storage; (ii) the locations with the biggest solar potential are not close to the major places of consumption. Many studies have shown the interest of the electro-fuels (e.g. hydrogen) as long-term storage and energy carriers. However, their integration in a whole and multi-regional energy system is rarely studied. This work addresses the following two questions: What will be the contribution of the electro-fuels as energy carriers and long-term storage? How can the different regions collaborate to reach a fossil free energy system at the lowest cost? We applied a whole and multi-regional energy model, EnergyScope Multi-Cell, to the Italian energy system of 2050. Italy is divided into 3 interconnected regions or cells: the North, the Centre, and the South. The country has a large solar potential in the South and high energy demand in the North. In the modelled scenario, Italy does not reach a self-sufficient renewable energy system. It imports 7.7% of its primary energy as electricity and 1.4% as green hydrogen. The North is responsible for 88% of those imports. The overall system relies on high electrification of the demand, sector-coupling, and exchanges between regions to integrate high shares of renewable energy sources (RES). The disparity of RES potentials and end-use demand among regions drives exchanges of electricity (58 TWh), synthetic gas (20 TWh), and woody biomass (7 TWh) between them. In particular, the South produces an excess of energy and export it to the two other regions.

Keywords:

Multi-region energy system modelling; Whole-energy system; Electro-fuels; EnergyScope; Energy carriers

1. Introduction

With the Green Deal, the European Union has the ambition to reach net zero carbon emissions by 2050 [1]. The energy system is responsible for more than 75% of those greenhouse gases (GHG) emissions, the rest comes from agriculture, land-use change, forestry and industrial processes [2]. To reach this target, a complete paradigm shift is necessary in the energy system. The planning of this energy transition relies on models to evaluate the different scenarios and strategies. According to recent reviews, there exist more than 480 different energy system models [3], each having its specific approach and point of interest. This clearly reflects the growing complexity arising from the forecasting of fossil free energy systems.

In all this diversity, Prina et. al.[4] identified 6 main challenges of bottom-up energy models for strategic planning: (i) temporal resolution; (ii) techno-economic resolution; (iii) sector-coupling resolution; (iv) spatial resolution; (v) uncertainty quantification (vi) transparency. Other reviews mention similar challenges for the energy modelling community [5–7].

Among the many models existing we choose one that is well suited for those challenges, EnergyScope typical days (TD) [6]. It is an open-source whole-energy system model with high temporal resolution and suitable for uncertainty analysis [8, 9]. Contino et al.[10] define the concept of whole-energy system models as "energy optimisation models that include all forms of energy and find the optimal pathways to convert resources into end-use energy demands". They motivate the added-value of such an approach to consider the "complex interactions and synergies among different technologies, energy vectors and specific needs". This is the highest degree of sector-coupling which is seldom achieved by energy models. EnergyScope TD has a lower resolution in two domains : techno-economic, and spatial. It does not consider all the dispatching constraints in the power system (e.g. ramp-up). This aspect has been verified retrospectively through soft-linking it with a dispatch model [11]. For the spatial resolution, it considers a region or a country as a single node.

It thus seemed relevant to increase the spatial resolution of the EnergyScope TD model. It resulted in an improved version called EnergyScope multi-cell (MC). To keep a whole-energy system approach, electricity is not the only considered vector for energy exchanges. Other energy carriers are also included, such as synthetic natural gas (SNG), woody biomass and synthetic liquid fuel (SLF). The latest is a category aggregating methanol, ammonia and other liquid fuels that are produced either from biomass or as electro-fuels.

This new version of the model is applied to a fossil free Italian energy system in 2050 divided into 3 macro-regions. Italy has been chosen as case study for 5 reasons: (i) representativity of other European countries; (ii) availability of data and of comparative studies; (iii) no loop in the interconnection pattern among regions; (iv) difference of demands and potentials between the regions (v) possibility to study the spatial resolution at different scales: data can be found to model Italy as 1, 3 or 6 cells. This modelling approach provides new insights on the future energy system of Italy in terms of sector-coupling and integration of renewable energy carriers.
This paper is structured as follows: Section 2 presents EnergyScope TD and the methodology to extend it to a multi-cell (MC) model. Section 3 defines the case study with the main hypotheses and presents a preliminary study of the input data. Section 4 analyses the main results: from the general overview of the overall energy system to a more detailed view looking at each region's energy system and their interactions. It also discusses the advantages and limitations of the model used.

2. Methodology

This section presents briefly the model EnergyScope TD. Then, the main challenges to increase the spatial resolution are depicted. Finally, the methods used in the new model, EnergyScope MC, to face those challenges are explained. The full code and data are available on Github [12].

2.1 Presentation of EnergyScope Typical Days (TD)

EnergyScope TD is a linear programming model that minimizes the total annualised cost of regional whole-energy systems. The investment cost of infrastructures and conversion technologies is annualised considering their lifetime and assuming an interest rate of 3.125%. The optimization is subject to a series of constraints to ensure physical sense of the solution (e.g. energy balance, and availability of energy resources) [6]. One of those constraints is the limit on GHG emissions. The model optimizes both the design and the hourly operation of the conversion technologies of the energy system to supply the demand using the available energy resources (Figure 1).

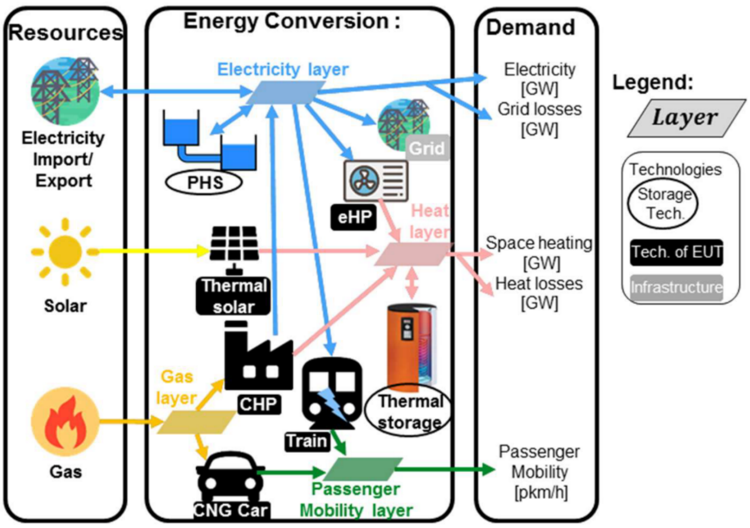

Figure 1: Conceptual example based on the EnergyScope Typical Days (TD) modelling approach. A region uses an energy conversion system to supply its energy end-use demand (EUD) using the available resources. The energy conversion system is composed of different layers representing the different types of energy carriers. The technologies allow to convert energy from one layer to another. Abbreviations: combined heat and power (CHP), compressed natural gas (CNG), electrical heat pump (eHP), end-use type (EUT), pumped hydro storage (PHS). This figure is adapted from [13].

As a whole-energy model, EnergyScope TD considers 6 types of end-use demand (EUD): (i) electricity; (ii) low temperature (LT) heat for space heating and for hot water; (iii) passenger mobility; (iv) freight; (v) high temperature (HT) heat for the industry; (vi) non-energy demand, that is energy as a feedstock for material. It considers 24 different energy resources (e.g.: electricity, gas (fossil, biogas or electro-gas), hydrogen, etc.). Each resource and each EUD is linked to a layer. On each layer, the energy must be balanced at each time step. The 107 technologies convert the energy from one layer to another with a certain efficiency (e.g. a combined cycle gas turbine (CCGT) converts gas into electricity with an efficiency of 63%).
The model uses typical days (TD) to reach a low computational time while keeping a hourly resolution. Furthermore, a reconstruction method by Gabrielli et al.[14] allows to consider seasonal phenomena. In the regional case, 12 TD is the best trade-off between accuracy and computational time [6]. We assume this is also true for a multi-regional case study.

2.2 Extension to the Multi-Cell version

There are two main challenges to extend EnergyScope TD to a multi-cell model. The first one is to link the resource layers of the different regions and take into account the impact on the energy balance in each region. The second one consists in considering the cost and limitation of exchanging the resources.

In this version, each region is modelled as one cell (also called node in other papers) with specific energy demand, resources and energy conversion system (Figure 2). Each region has the same structure as the regional modelling of EnergyScope TD [6]. The energy resource layers of the cells are interconnected, allowing exchanges of multiple energy carriers between them, such as electricity, gas, SLF, and woody biomass. Hence, the resources can impact the energy balance in 3 distinct ways: (i) the quantity produced locally; (ii) the quantity exchanged with neighbouring cells; (iii) the quantity imported from outside of the overall system.

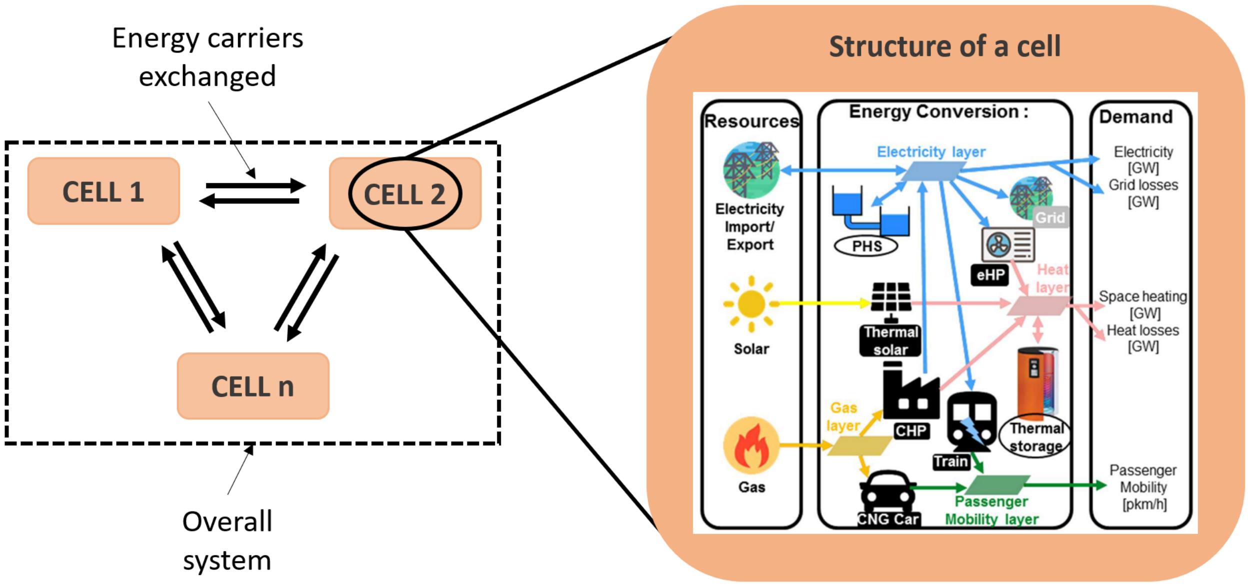

Figure 2: Conceptual example based on the EnergyScope Multi-Cell (MC) modelling approach. Each region is represented by a cell with its own energy conversion system. The different cells are interconnected through exchanges of energy carriers. Abbreviations: combined heat and power (CHP), compressed natural gas (CNG), electrical heat pump (eHP), end-use type (EUT), pumped hydro storage (PHS). This figure is adapted from [13].

The cost and limits of exchanges of energy carriers depend on the facilities used to transport them. In the model the resources that can be exchanged are divided into 2 categories: (i) exchanges through a network (i.e. : electricity, and gas); (ii) exchanges through freight (i.e. : SLF, and wood). Each category has different factors of cost and limits (Table 1).

Table 1: Implementation of exchanges through the different types of facilities with related costs and limits

	Network	Freight
Energetic cost	Losses	Additional freight demand
Fixed cost	Infrastructure	More freight vehicles
Limitation	Transfer capacity	None

Exchanges through a network are limited in power by a fixed transfer capacity. The network has an investment and maintenance cost. They are the only resources with non-null exchange losses ($exch_{losses}$). Those losses are expressed as a percentage of the energy carried.

Exchanges through freight directly increase the freight EUD of the two regions at stake. The additional freight is computed considering the density of the resource exchanged and the typical distance travelled by the energy carrier in each region. This results in an additional need for trucks, trains or boats to transport those resources. Thus, it induces both the investment into more freight technologies and the use of more energy resources to fuel the transportation.

3. Case study: the Italian energy system in 2050

This section presents the main data and assumptions for the Italian case study. First, the main data sources and the GHG emission target are set. Then, the division of Italy into macro-regions and the choices made for the modelling of interconnections are described. Afterwards, the hypotheses made for imports from the exterior of the overall system are presented. Finally, the renewable energy sources (RES) potentials and EUD of the regions are summarized.

3.1 Data and main assumptions

The data comes from Borasio et al.[7] for the Italian specific data (time series, EUD, etc.) and from Limpens[15] for the costs of the technologies. In this case study, the non-energy demand is neglected (less than 8% of the total demand)[16]. The system is constrained to be fossil free. Thus, only the net emissions from waste valorisation are allowed (6.7 $Mt_{CO_2,eq}$). In this case study, Italy is divided into 3 macro-regions defined by possible bottlenecks for the electricity network [7]: North, Centre and South (Figure 3).

Figure 3: Italy is divided into 3 interconnected macro-regions: the North, the Centre and the South.

The resources allowed for exchanges are: electricity, gas, synthetic liquid fuel (SLF), woody biomass, waste and CO_2. The first two are exchanged through network exclusively. Their interconnections have a annualized cost of 237 M€/(y·GW) for electricity [17] and 0.541 M€/(y·GW) for gas [18]. The transfer capacities of the gas network are considered as non-limiting as the cost of the network is negligible compared to the ones of the electrical network. This assumption will be verified a posteriori. Table 2 gives the electrical transfer capacity forecasted for 2030 [19]. As no forecast has been found for 2050, we will take those values for our case study.

Table 2: Electrical net transfer capacity in [GW] between the North, the Centre, the South [19]. To be read as: from column to line.

	North	Centre	South
North	0	3.1	0
Centre	4.30	0	8.25
South	0	4.44	0

The four other resources are exchanged through freight. To compute the additional freight induced by those exchanges, the density of each resource and the average distance travelled in each region are evaluated as in [18].
As we are targeting a fossil free energy system, the only imports from the exterior that are considered are renewable fuels and electricity. The renewable fuels contain hydrogen, SNG and SLF. There is no limit to their importation but they are expensive: 160, 180 and 190 €/MWh, respectively. On the contrary, electricity imports are cheaper (105 €/MWh) but are limited both in terms of maximum power at each hour and in terms of total quantity over the year (Table 3). As no forecast for those two values has been found for 2050, we take the ones for 2030.

3.2 Potentials and end-use demands of each region

The analysis of the RES potentials in each region compared to their total end-use demand (EUD) (Figure 4) provides an overview of the input data and a first intuition on the role of each region. The RES potentials are computed as the quantity of energy that could be produced if each region deployed those resources and technologies to their full potential. The total EUD is a sum of the 6 types of EUD. As all types of energy do not have the same value, the following assumptions have been made to convert all of them into electrical or mechanical energy: (i) heat LT is assumed to be converted thanks to heat

Table 3: Electrical import capacity from the exterior for each region in terms of maximum power [GW] and total yearly electricity imported [TWh/y].

	Power [19]	**Yearly energy** [19, 20]
North	11.34	69.2
Centre	3.57	6.8
South	0	0

pump (HP) cith a coefficient of performance (COP) of 3.2; (ii) Space and process cooling are converted into electricity with a COP of 6.2 and 6.9 respectively; (iii) Mobility is converted into TWh/y thanks to the average mobility energy intensity ratio forecast for Italy in 2050, 0.23 GWh/Mpkm for passenger mobility and 0.34 GWh/Mtkm for freight [16]; (iv) for the other types of EUD a ratio of 1 is used.

There are noticeable disparities between the different regions of Italy in terms of RES potential and EUD. All the regions have a high photovoltaic panel (PV) potential. The Northern region has the most significant hydro power potential. The Southern region has the highest wind potential. As they will rely on different sources with different hourly profiles of production, the different regions will most likely be inclined to exchange energy.

The EUD is not uniformly distributed among the regions. The EUD in the North is 2.6 times the one in the South. From this disparity in term of demand and potentials, we can expect that the Southern region will be able to produce energy in excess and will send it to the other regions that are most likely to be in deficit.

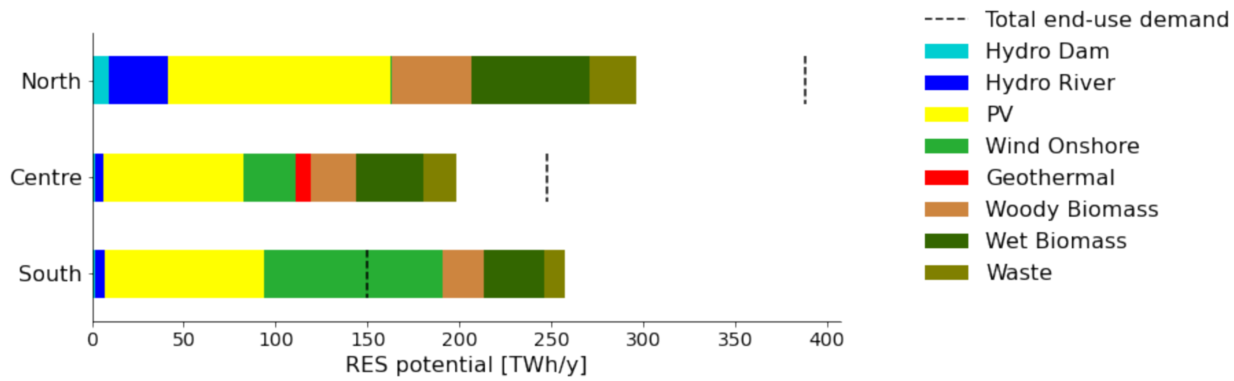

Figure 4: Renewable energy sources (RES) potential and total end-use demand in each region. Abbreviations: photovoltaic panel (PV).

4. Results

This section presents the results obtained for the case study of the fossil free Italian energy system for 2050 divided into 3 macro-regions. In a first part, a general overview of the overall system is presented. Then, the difference between the 3 regions is investigated, focusing on the electricity sector. Finally, the balance of exchanges between regions and the imports from the exterior are analysed.

4.1 Overview of the energy system

The optimal fossil free Italian energy system for 2050 has a total annualised cost of 180 billion €/y. Figure 5 presents the yearly energy fluxes of this system. It allows to have an overview of the strategic choices made to reach a fossil free system at lowest cost.

All the RES technologies are installed to their maximum capacity and the local resources are used to their full availability. The Italian energy system still needs to import 7.7% of its primary energy under the form of electricity and 1.4% under the form of hydrogen.

This system presents a high electrification of the demand. The total electricity produced is 2.90 times the electrical EUD. The LT heat is directly electrified through heat pump (HP) except for some production of geothermal heat for the district heating network (DHN) (9% of heat LT produced). The private mobility is fully supplied by electric vehicles. The public mobility relies on synthetic gas, electricity, and synthetic diesel. The freight is indirectly electrified through the production of hydrogen used in fuel-cell vehicles. The industrial HT heat is provided by woody biomass (41%), waste (31%) and electricity (28%).

4.2 Focus on flexibility in the electricity sector

Most of the system is electrified with the electricity production heavily relying on wind, PV and hydro river which are intermittent renewable energy sources (IRES). Thus, the main challenge of the system is the integration of those

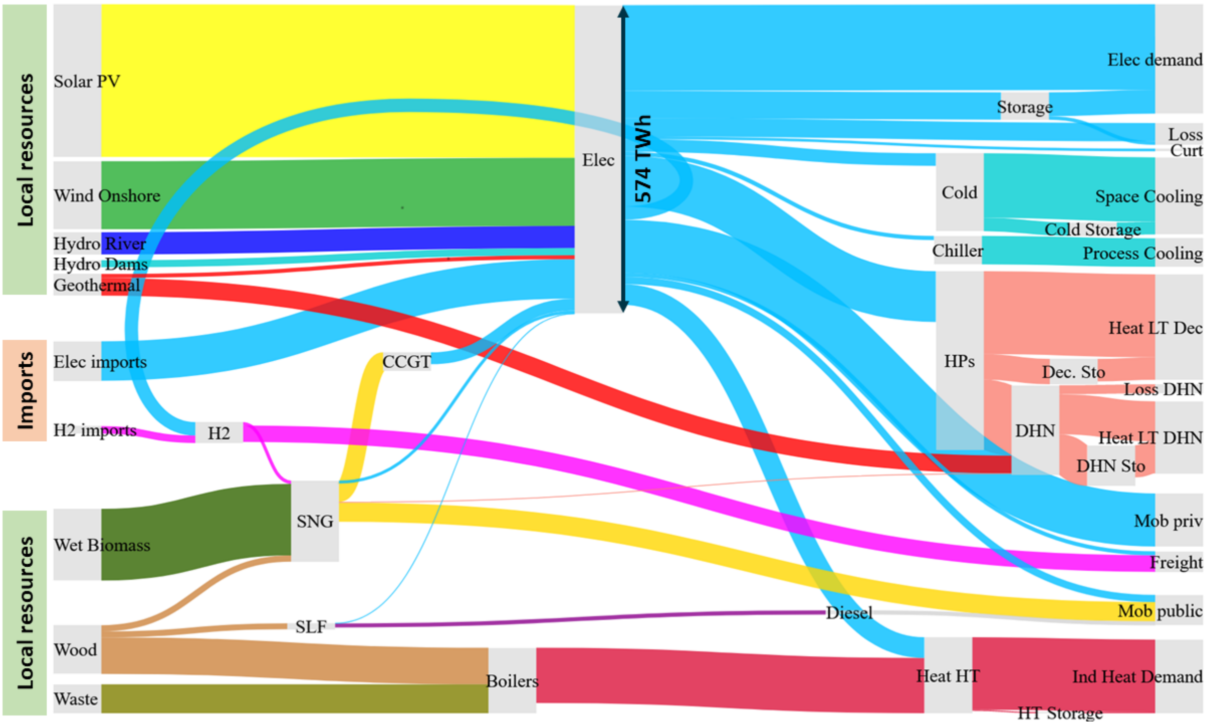

Figure 5: Yearly energy flows in the fossil free Italian energy system [TWh]. The contribution of the 3 macro-regions are aggregated. Italy uses all its local resources and still needs to import 7.7% of its primary energies under the form of electricity and 1.4% as green hydrogen. The energy system is highly electrified. Abbreviations: combined cycle gas turbine (CCGT), curtailment (Curt), decentralized (Dec.), district heating network (DHN), electricity (Elec), hydrogen (H2), heat pumps (HPs), high temperature (HT), industrial (Ind), low temperature (LT), mobility (mob), photovoltaic panel (PV), synthetic liquid fuels (SLF), synthetic natural gas (SNG), storage (Sto).

intermittent sources. Therefore, the role of each region is analysed through the study of power mismatch that is the difference between IRES production and non-flexible electrical demand.
To study this mismatch, the different loads, production units and storage units are classified into 4 categories according to whether they are dispatchable or not:

1. Non-dispatchable production units: intermittent renewable energy sources (IRES). It includes PV, wind, hydro run of river and geothermal.

2. Dispatchable production units: either output power of storage units or dispatchable power production units (e.g. CCGT, hydro dams, pumped hydro storage (PHS), electricity import).

3. Non-flexible electrical demand: electrical demand that cannot be shifted and that doesn't have any storage unit linked to it. It includes EUD, tramways, trains and chiller for process cooling.

4. Dispatchable demand: either input power of storage units, loads that are linked with a storage unit (e.g. HP and thermal storage) or loads for which the need can be covered in another flexible way (e.g. hydrogen electrolysis replaced by hydrogen imports, industrial electrical heaters replaced by woody biomass furnaces).

The situation in each region is evaluated through the analysis of the duration curve of the power mismatch (Figure 6). The system's response to the extreme cases is presented to provide insights on the flexibility mechanisms.

In the North, the IRES production is higher than the non-flexible electrical demand during 35% of the year. *The biggest lack of electricity* is 11.6 GW. It happens during a typical winter day. The lack of electricity is lower than the capacity of import of the region: 11.34 GW from the exterior and 3.10 GW from the Centre. However, the other regions are not able to export electricity to the North at that time of the year and there is an additional demand for heat as it is a winter day. Hence, it also relies on other mechanisms to produce enough electricity. This is mainly done thanks to its CCGT and hydro dam. There is no import of SNG from other region during that day. Hence the SNG used into the CCGT comes from the gas storage tanks. Furthermore, it stops feeding dispatchable loads such as electrolysers and imports 1.6 GW of hydrogen from the exterior to compensate. *The biggest excess of electricity* in that region is 57.8 GW and it happens during a typical spring day. At this moment, the production peak reaches 4.1 times the non-flexible electrical demand. The system activates all the dispatchable loads to consume the overproduction, that is industrial electrical boilers and HP.

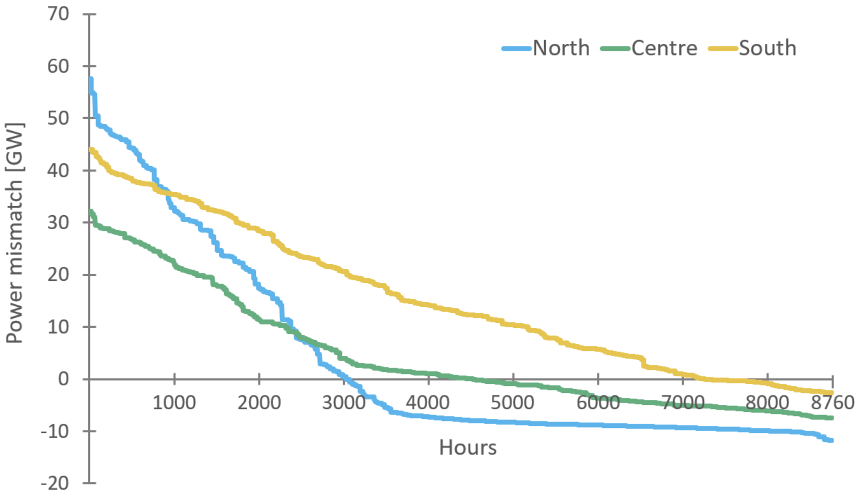

Figure 6: Duration curve of the mismatch power in each region. The mismatch is the difference between non-flexible electrical demand and intermittent renewable energy sources (IRES) production. The time series obtained are sorted separately in each region in descending order.

It stops importing electricity and production with dispatchable power units, that is CCGT and hydro dam.

In the Centre, the IRES production is higher than the non-flexible electrical demand during 52% of the year. *The biggest lack of electricity* is 7.44 GW. It happens at the same time as in the North. As this region cannot import as much electricity from the exterior and has less hydro dam and PHS, it uses a bigger CCGT to reinforce those dispatchable producers. The SNG needed t run the CCGT comes exclusively from the gas storage of the region. Furthermore, it stops its electrolysers and imports 1.14 GW of hydrogen from the exterior. *The biggest excess of electricity* is 32.28 GW. It does not happen at the same time as in the North but during another typical spring day. At that moment, the IRES production is 3.9 times the non-flexible electrical demand. The system stops its CCGT and hydro dam production and activates all its dispatchable loads to consume the excess electricity.

In the South, the IRES production is higher than the fixed electrical demand during 86% of the year. *The biggest lack of electricity* happens at the same time as in the two other regions and is of 2.48 GW. To compensate for that, the region uses a small CCGT unit, its dam storage and load shifting of the LT heat by storing it. It stops its electrolysers and imports hydrogen. It also stops exporting electricity to the two other regions at that moment. *The biggest excess of electricity* is 45.21 GW. It happens during a typical summer day. At that moment, the IRES production is 6.7 times the non-flexible electrical demand. The region stops its CCGT and hydro da production. It exports as much electricity as it can to the two other regions. Furthermore, it uses all its dispatchable loads to their maximum power to absorb the excess electricity.

In all the regions and during the entire year, the batteries of electric vehicles and the PHS play a key role to absorb the daily variations of IRES production. The batteries of electric vehicles are used for smart charging, that is they mainly charge when there is a peak of PV production during the day. In the Centre and the South, they are also used sometimes to feed back electricity into the grid.
To summarize, all the regions rely on CCGT using synthetic gas as back-up generator. The South has a much higher IRES production compared to its demand. It needs the smallest CCGT (2.9 GW) and is able to export both electricity and natural gas to help the other regions to face their lack of production. The North has important hydro dams (8.8 GW) and PHS (762 GWh) and can import 11.34 GW from the exterior. Hence, it can face the intermittency of renewables with a middle size CCGT (4.4 GW). The Centre installs the biggest CCGT (8.9 GW) as it doesn't have any of the advantages of the other regions.

4.3 Exchanges and imports

Figure 7 presents the yearly exchanges between regions and yearly imports for each region. They are both mainly driven by the mismatch between IRES production and non-flexible electrical demand.

The North imports 27% of its electricity from the exterior and 6% from the South. It imports 17% of the SNG used in its system from the South through the Centre and produces the rest locally from wet biomass. It also imports 52% of the hydrogen used in its system from the exterior while the rest is produced locally through electrolysis. It imports some woody biomass from the Centre.

The Centre cannot rely as much on the exterior as the North, especially for electricity imports. Therefore, 74% of the electricity exported by the South goes to the Centre and the rest transits to the North. The Centre imports 40% of the hydrogen used in its system from the exterior and the rest is produced locally. It also imports some SNG from the South to use it in its CCGT during the most critical hours of the year.

The South only imports 20% of the hydrogen it uses. It supplies all the rest of its needs with its local resources and exports a significant amount of energy to the other regions: 81% of its SNG production is sent to the Centre and the North; 30% of its electricity production is exported to the two other regions.

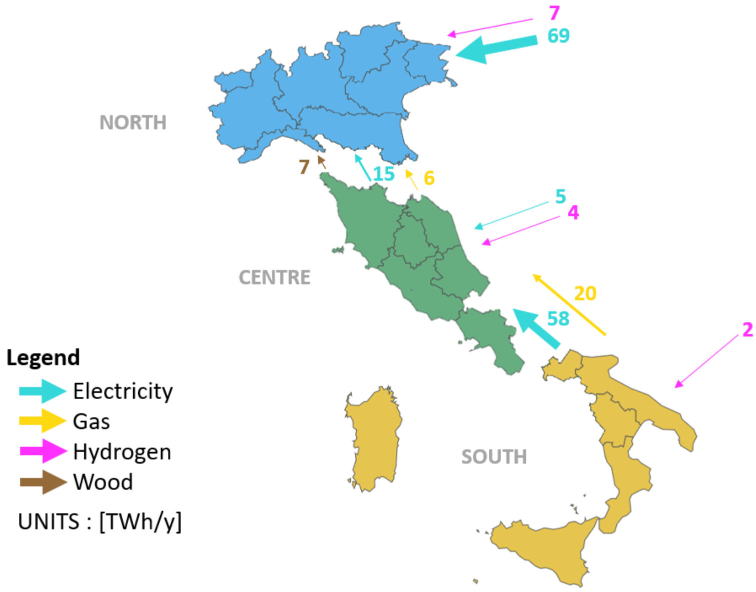

Figure 7: Yearly energy carriers exchanges among regions and imports from the exterior.

The exchanges observed should somehow be questioned by taking into account different limitations of the model: (i) The importation of electricity from the exterior acts as a perfect flexibility provider. It does not take into account the fact that it has to be produced somewhere. The neighbouring countries are expected to also strongly rely on IRES for their power production by 2050. Hence, they might lack electricity at the same time as in Italy. Therefore, the cost of electricity imports from the exterior will be much greater during the scarcity periods. Moreover, the availability of electricity imports is not guaranteed. (ii) The imports of hydrogen are questionable as it is not easy to store and ship[21]. It could be replaced by imports of gas or synthetic liquid fuel (SLF) such as ammonia or methanol and converted back into hydrogen in Italy if needed. (iii) In this analysis, the exchanges of electricity between cells are limited by the fixed transfer capacity of 2030. This might bias the results as those capacities might not be the best ones for this fossil free system. Therefore, an alternative version where those transfer capacities are considered as variables is going to be developed. (iv) Exchanges of hydrogen between regions were not considered in this study as there is no network for hydrogen yet. However, the gas network could be converted to hydrogen network or transport a blend of hydrogen and methane [22]. This possibility should be investigated in a further study.

To conclude, each region adopts a different strategy according to its situation (i.e. its EUD and its energy potential). Their strategies are interlinked to reach a fossil free energy system at the lowest cost for Italy. The South will tend to overproduce. This way, it can export a lot of energy to the two other regions. The North can rely on important electricity imports from northern neighbouring countries and has a lot of flexible hydro units. Therefore, the main part of the electricity exported by the South (58 TWh) goes to the Centre (43 TWh) and the rest transits to the North (15 TWh). The same occurs with SNG. Furthermore, the regions rely on green hydrogen imports to complement their local hydrogen production.

5. Conclusion

The whole-energy system model EnergyScope typical days (TD) has been extended to increase its spatial resolution. The new version of the model, EnergyScope multi-cell (MC), allows to model multi-region whole-energy systems interconnected through the exchange of multiple energy carriers. Depending on the considered energy carrier, it can be exchanged through a network or through freight. This induces different limits and costs.

The model has been applied to a fossil free Italian energy system divided into 3 macro-regions: the North, the Centre and the South. Those regions have disparities in renewable energy sources (RES) potentials and end-use demands (EUDs). The North and the Centre are in deficit whereas the South can produce excess energy. The application of the model to this case study provides a new insight on how the different regions can collaborate to reach a fossil free energy system at lowest cost.

The results show that Italy cannot have a self-sufficient renewable energy system. It will rely on imports of electricity and electro-fuels (in this case, hydrogen). This occurs especially in the North which has the highest demand. Overall electrification and sector-coupling allow to reach a high energy efficiency in the system and to bring flexibility to the electricity sector. Through the exchanges, the different regions take advantage of the spatial disparity. In particular, the South produces excess of electricity and synthetic natural gas (SNG) and exports it to the two other regions. In this case study, the main energy carrier used for exchanges is electricity (58 TWh) followed by SNG (20 TWh) and woody biomass (7 TWh).

The presented model and the case study are part of an ongoing work. They still present several limitations that will be addressed in future works. Many choices were made to forecast the Italian energy system in 2050, bringing questionable assumptions and results (e.g. unlimited hydrogen imports, fixed cost of electricity imports). Two methods can be used to study those issues: (i) "what if" analysis to explore alternative scenarios; (ii) global uncertainty analysis to reach a robust optimum.
For instance, the optimal system for 2050 relies on high imports of electricity and hydrogen. However, the limit of availability at each time step are not considered into the modelling framework. It biases the results by bringing artificial flexibility to the system. Therefore, the model could be improved by considering the temporal variation of the cost and the availability of resources imported from the exterior.

Acknowledgments
The authors acknowledge the support of the Energy Transition Fund of Belgium.

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