

## ROBUST DESIGN OF A FUTURE 100% RENEWABLE EUROPEAN ENERGY SUPPLY SYSTEM WITH HYDROGEN INFRASTRUCTURE

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### ABSTRACT

The role of variable renewable energy sources (VRES) in future energy supply system is evident when the latest trends in global installed capacities are examined. However, the intermittency of these technologies remains an obstacle to their widespread penetration. This issue can be addressed by introducing hydrogen as an alternative chemical energy carrier to enable greater flexibility. Despite a number of studies considering hydrogen, its seasonal storage and transmission are often overlooked in optimized designs for the future European energy supply system. In this analysis, a robust energy supply system is designed with consideration to hydrogen infrastructure and variations over a number of weather years to ensure security of the energy supply. Applying an iterative approach over 38 optimal system designs resulted from different weather years, a 100% renewable European energy supply system is proposed that consists of 920 GW of wind power and 654 GW of photovoltaics, in addition to 154 GW of biomass combined heat and power plants and 203 GW of hydropower. Furthermore, the system has total storage capacities of 130 TWh, 562 GWh and 587 GWh for salt caverns, vessels and lithium-ion batteries, respectively. The total annual VRES curtailment is estimated to be 441 TWh a<sup>-1</sup>.

**Keywords:** Renewable energy systems, energy supply system, hydrogen pipeline, power-to-hydrogen.

### INTRODUCTION

The goal of reducing greenhouse gas emissions by 80 to 95% against 1990 levels by 2050 has triggered the shift towards renewable energy sources in the energy supply system. Nonetheless, the intermittency of wind and solar energy (variable renewable energy sources – VRES) remains an issue that could be solved by chemical energy carriers [1]. These can be produced during peak power generation periods and utilized in grid balancing or as feedstocks [1]. Hydrogen is the most promising alternative energy carrier, with its carbon-free nature and high energy density, and can be produced by electrolysis. It can be used not only in heavy industry, but also in the transport sector as a fuel for fuel cell-electric vehicles, enabling so-called ‘sector coupling’ [2]. In the literature, many spatio-temporal energy system analyses exist with high shares of renewable energy at the European scale; nevertheless, most of these do not involve hydrogen in their system. Amongst the studies that do consider hydrogen, a potential hydrogen infrastructure is not fully evaluated, overlooking either the storage or transmission of hydrogen.

In the design of a future energy supply system with high shares of renewable energy technologies, four main aspects must be addressed. First aspect is the high spatial and temporal resolution due to the variability of VRES technologies. Secondly, the future characteristics of the selected technologies must be considered in the context of 2050, such as larger turbine blades or more highly efficient electrolyzers. Thirdly, the geological storage of hydrogen and hydrogen pipelines must be taken into account due to their lower investment costs and high storage/throughput potential. Finally, the hourly weather pattern cannot be predicted in the future context, especially in 2050, and the energy supply system design varies with respect to the generation time series of renewables (i.e., the weather year used in the modeling) [3,4]. Therefore, the variations in system design with respect to different weather years must be scrutinized in order to obtain a robust design that ensures the security of supply. To the knowledge of the authors, none of the existing studies covers all of these aspects together in a 100% renewable European energy supply system.

In this study, an iterative approach is employed in order to design a 100% renewable European energy supply system that incorporates hydrogen infrastructure in the context of 2050. For this purpose, an optimization model that minimizes the total annual cost (TAC) is built with hourly temporal resolution [5]. Furthermore, Europe is divided into 96 regions in order to afford higher spatial resolution. The optimal results involve optimal capacities for the technologies considered in the system design, as well as the optimal operation of these technologies. The potentials and simulations for wind and solar energy in these regions are estimated by using future-oriented VRES technologies. Significant variations are observed in the system designs for different weather years, ranging from 1980 to 2017. On the basis of these variations, a robust design is attained by using an iterative approach over individual system designs for different years. These results can then be used as an indicator to understand the roles of individual countries in a 100% renewable energy supply system.

## METHODOLOGY

The analysis is performed by using the open source optimization framework, the Framework for Integrated Energy System Assessment (FINE) [6]. The objective function of the problem is the minimization of the TAC of the system. From a regional perspective, Europe is separated into 96 regions. Although hourly temporal resolution is used, time series aggregation [7] is employed in some model runs to simplify the optimization problem. Model runs simplified with the time series aggregation method involve 30 typical periods, representing the entire year.

The techno-economic parameters for demand, generation, conversion, storage and transmission technologies are defined exogenously as input parameters in the optimization problem. Despite the greenfield approach for 2050 employed in this analysis, the capacities of run-of-river and hydropower (pumped-hydro storage and reservoirs) plants are assumed to have the same values as reported in 2015. Electricity demand was derived using the same approach as the E-Highway study [8]. However, electricity demand for battery-electric vehicles and plug-in hybrid vehicles are excluded, as fuel cell-electric vehicles are involved in the system with 75% market penetration. Existing driving behavior, annual driving distance and the number of passenger vehicles are used to derive annual hydrogen demand, which is then projected onto the hourly profile of fueling stations. With respect to electricity generation, onshore wind, offshore wind, open-field photovoltaics (PV), run-of-river and biomass combined heat and power (CHP) plants are included. The simulation of wind and PV technologies is performed by using historical weather data from the reanalysis dataset, Modern-Era Retrospective analysis for Research and Applications (MERRA) [9]. In order to determine the maximum capacity that can be installed in each region, land eligibility analyses are performed individually for onshore and offshore wind, as well as open-field PV. Additionally, the conversion of hydrogen and electricity is addressed by several conversion technologies such as open-cycle gas turbines (OCGT), combined-cycle gas turbines (CCGT) and electrolysis. Hydrogen transmission is enabled by defining possible pipeline connections, which are determined by finding the shortest path between regional centroids amongst the combination of roads, railways and existing natural gas infrastructure. Finally, electricity transmission is taken into account when considering high voltage alternative current (HVAC) and high voltage direct current cables (HVDC), the capacities of which are derived by using the same method as employed in the E-Highway study [8].

The design of the energy supply system differs with respect to the generation time series of VRES technologies. Thus, the aforementioned method is enhanced to attain a robust system design. An iterative method is developed to achieve this purpose and keep the system cost as low as possible. The iterative approach consists of three main steps: optimization of the overall system, adjusting the biomass CHP plant capacities to capture extreme weather periods and, finally, optimizing the operation of these technologies. Each iterative step consists of 38 model runs conducted by all weather years between 1980 and 2017. In the optimization of the overall system, 38 optimal capacities of each technology for each weather year are averaged and defined as minimum capacity; afterwards, the system is optimized with these new constraints. By doing so, the fluctuations between the regions are smoothed. This step is performed until the change in TAC of the system is below 1%. Until this stage, 30 typical days are used in each model run. Once the plateau is attained by means of optimal capacities, the capacities of all technologies are fixed to their average (from the last iteration), except biomass CHP plants. From this step on, the time series aggregation is eliminated in the model runs in order to capture the extreme weather periods and ensure the security of supply. Therefore, biomass CHP plants are assumed for back-up generation in these periods. Finally, maximum biomass CHP plant capacities are fixed in the final iterative step to attain the optimal operation of technologies.

## RESULTS AND DISCUSSION

The net annual transport of the two main commodities (electricity and hydrogen) between regions are shown in Figure 1. Electricity transport is shown for both HVAC and HVDC cables. It must be noted that except hydropower capacities, greenfield approach is assumed. The final system design, which ensures security of the supply over 38 weather years, consists of 654 GW open-field PV without tracking and 920 GW wind energy. In addition, 154 GW of biomass CHP plants and 135 GW of hydrogen re-electrification technologies are estimated. Ireland, the United Kingdom and Nordic countries are both electricity and hydrogen exporters owing to their capacity for cheap electricity generation compared to the other regions, which is also seen in the figure. In other words, continental Europe imports these commodities from the aforementioned countries. Using electricity transport, most German regions import electricity from their neighbors.

Additionally, the Europe-wide storage requirement for hydrogen is 130.5 TWh, 130 of which corresponds to salt cavern storage. Salt cavern availability therefore plays a crucial role in the design of the system. Three major streams can be seen for hydrogen transport. Norway and Sweden behave like net exporters owing to the high operational flexibility of electrolyzers coupled to hydropower plants and cheap electricity generation locations. Moreover, Ireland and the United Kingdom export hydrogen to countries such as France and Belgium. Finally, Italy imports from France, mainly because of salt cavern availability and relatively cheaper electricity generation in southeastern France.

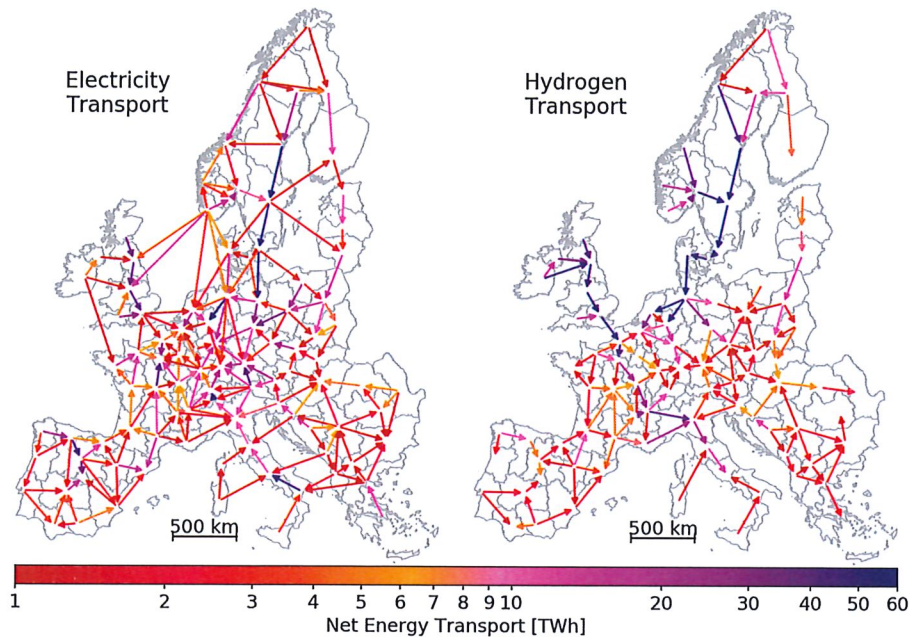


Fig. 1. Net energy flow between regions in the proposed robust design for a European energy supply system in 2050 (left) electricity (right) hydrogen.

## CONCLUSIONS

The robust energy supply system proposed in this work involves 1574 GW of VRES technologies, nearly 60% of which is comprised of wind energy. 154 GW of biomass CHP plants and 134 GW of hydrogen re-electrification technologies (OCGT and CCGT) compensate the intermittency of VRES technologies. Hydrogen storage in salt caverns plays an important role with a storage capacity of 130 TWh, in addition to 0.5 TWh of vessel storage and 0.5 TWh of batteries. Considering hydrogen as a flexibility source, the average annual curtailment is found to be 441 TWh a<sup>-1</sup>. When the distribution of technologies are analyzed, it is seen that Ireland behaves as a net exporter because of its capacity for cheap electricity generation. Large demand centers such as London, Paris and Milan can be considered net importers of both hydrogen and electricity.

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