Energy Conversion and Management 228 (2021) 113649

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables

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ARTICLE INFO

Keywords:
Green hydrogen
Renewable energy
Electrolysis
Hydrogen strategy

ABSTRACT

The increasing ambition of climate targets creates a major role for hydrogen especially in achieving carbon-neutrality in sectors presently difficult to decarbonise. This work examines to what extent the currently carbon-intensive hydrogen production in Europe could be replaced by water electrolysis using electricity from renewable energy resources (RES) such as solar photovoltaic, onshore/offshore wind and hydropower (green hydrogen). The study assesses the technical potential of RES at regional and national levels considering environmental constraints, land use limitations and various techno-economic parameters. It estimates localised clean hydrogen production and examines the capacity to replace carbon-intensive hydrogen hubs with ones that use RES-based water electrolysis. Findings reveal that -at national level- the available RES electricity potential exceeds the total electricity demand and the part for hydrogen production from electrolysis in all analysed countries. At regional level, from the 109 regions associated with hydrogen production (EU27 and UK), 88 regions (81%) show an excess of potential RES generation after covering the annual electricity demand across all sectors and hydrogen production. Notably, 84 regions have over 50% excess RES electricity potential after covering the total electricity demand and that for water electrolysis. The study provides evidence on the option to decarbonize hydrogen production at regional level. It shows that such transformation is possible and compatible with the ongoing transition towards carbon–neutral power systems in the EU. Overall, this work aims to serve as a tool for designing hydrogen strategies in harmony with renewable energy policies.

1. Introduction

In late 2019, the European Commission (EC) presented the European Green Deal [1], outlining the main policy initiatives for reaching net-zero greenhouse gas (GHG) emissions by 2050. The Green Deal identifies clean hydrogen as a priority area for achieving carbon neutrality by 2050. There are two aspects: firstly the European Union (EU) currently uses approximately 9.7 million tonnes (Mt) of hydrogen annually [2] and this needs to be decarbonised. Secondly, hydrogen is considered a key input to the future energy system as a flexible energy carrier for industry and transport, helping to reduce GHG and particle emissions. The targets for the Green Deal should be broken down in two phases: phase 1: now until 2030 and phase 2: 2030 until 2050. In the short term the EU's dependency of the European Union on fossil fuels for transport services will only marginally decrease according to the long-term scenarios (LTS). However, according to the EU's hydrogen strategy [3], at least 6 GW (of electrolysers powered by renewable energy should be installed between 2020 and 2024. Depending on its utilisation, such capacity could produce up to 0.8 Mt of clean hydrogen, annually [4]. This number should then increase to 40 GW by 2030. By that time the hydrogen demand in EU + UK according to the 2019 Hydrogen Roadmap Europe's ambitious scenario [2] will be 665 TWh or 16.9 Mt [5]. In phase 2, renewable hydrogen demand will increase further, even if the demand from refineries is gradually decreasing. Refineries currently consume approximately 30% of total European hydrogen production for the processing of intermediate oil products [6]. As the implementation of the Green Deal advances, it is expected that oil product demand will decline along with the associated hydrogen consumption. However, the deep decarbonisation of industries like the chemical industry or steel industry is expected to outbalance this decline. By 2050, the Hydrogen Roadmap Europe report [2] indicates that hydrogen could provide up to 24% of total energy demand corresponding to ~2251 TWh of energy in the EU + UK. By sector that means, 675 TWh in transportation, 579 TWh in heating and power for building,

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https://doi.org/10.1016/j.enconman.2020.113649
Received 13 July 2020; Received in revised form 13 October 2020; Accepted 8 November 2020
Available online 20 November 2020

391 TWh in existing industry feedstock, 257 TWh in new industry feedstock, 237 TWh in industry energy, and 112 TWh in power generation.

Today, around 120 Mt of hydrogen are produced globally each year, of which two-thirds is pure hydrogen and one-third is in mixture with other gases. This equals 14.4 exajoules (EJ, equivalent of 4000TWh or 102 Mt), about 4% of global final energy and non-energy use, according to International Energy Agency (IEA) statistics [7]. Around 95% of all hydrogen is generated from natural gas and coal. Around 5% is generated as a by-product from chlorine production through electrolysis. In the iron and steel industry, coke oven gas also contains a high hydrogen share, some of which is recovered. Currently there is no significant hydrogen production from renewable sources [8].

Looking to the future, the IEA [8] reports a global economic potential for 19 EJ (5277 TWh or 135 Mt) of hydrogen from renewable electricity in total final energy consumption by 2050 whereas others (for example, the Hydrogen Council) see this number increasing to around 80 EJ (22222 TWh or 568 Mt, not necessarily all from renewables).

Hydrogen can be produced from a variety of processes associated with a wide range of emissions depending on the technology and energy source used [9].Renewable hydrogen (or green hydrogen) is produced through electrolysis using renewable energy sources (RES) and it is a near-zero carbon production route [8] with its cost at \$6.00 (€5.09) per kilogram in 2020 [10]. It is projected to cost \$2.50 (€2.12) per kilogram in 2030 under average European wind energy productivity. However, the recent rapid cost reductions for RES electricity opens up new opportunities [11]. Renewable hydrogen has significant decarbonisation potential and is therefore the most compatible option with the EU's climate neutrality goal. Electrolyser CAPEX, the utilisation factor (operating hours) and electricity price are the main parameters determining the cost of producing green hydrogen. Electrolyser costs are projected to halve by 2050, from \$840 per kilowatt in 2019, while renewable electricity costs will continue to fall as well [8]. In parallel, Europe, and more specifically the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), already funds a pioneering electrolysis project of 20 MW [12], and R&D has led to notable technological and cost reduction achievements [13]. A 40 MW wind park coupled with electrolysers is planned near a chemical industry site in Germany by VNG, Uniper, Terrawatt and DBI, including 50 billion cubic metres of storage and a dedicated hydrogen pipeline, with potential expansion to 200 MW by 2030. Similar upscaling efforts are occurring in other European countries as well as in Australia, China, Japan and elsewhere.

Fossil-based hydrogen with carbon capture and storage (CCS) will be an additional option when the technology scales and reaches market maturity (blue hydrogen). Future projections of SMR production with CCS in Europe show production cost at €1.50/kg in 2030 [10]. However, such hydrogen is not necessarily CO2-free. CO2-capture efficiencies are expected to reach 85–95% at best, which means that the other 5–15% is leaked [8]. Fossil-based hydrogen is produced from conventional steam methane reforming (SMR) or coal gasification representing currently the primary sources of global hydrogen production (grey hydrogen). This practice is not sustainable and it is associated with 830 MtCO2e emissions per year, 2.3% of total global CO2 emissions, are released during the production [14]. Steam methane (natural gas) reforming (SMR)[1] has an emission factor of 8.9 kg CO_2/kg H_2, while coal gasification's emission factor is even higher, at 29.33 kg CO2/kg H_2 [15].Today around 8.2 Mt of fossil-based hydrogen are produced in the EU- the vast majority of it by SMR from natural gas [16]. The cost of such grey hydrogen is \$1.60/kg (~€1.35/kg) in 2020 [10]. Lastly, hydrogen can also be produced by using nuclear energy but this route is linked to high socio-economic risks [17].

The present study provides a first analysis and estimation of the technical potential to decarbonise hydrogen demand by producing green hydrogen with electrolysers powered by a combination of local RES resources. More specifically, this work identifies to what extent the EU (27) and the United Kingdom (UK) can cover the current and increased electricity needs (across all sectors) and substitute grey hydrogen with green by using local RES and the possible implications. The potential role of solar photovoltaic (PV) and onshore/offshore wind energy, together with existing hydropower capacity is examined. Biomass potential is not considered on the basis that the available sustainable resources would be more needed as industrial feedstock in the circular economy of the future [18].

Initially, the study estimates the current levels of hydrogen production and electricity demand. Both parameters are spatially analysed at the regional level. Subsequently, the technical potential of renewable energy technologies is estimated for all regions. The available options are onshore/offshore wind, ground-mounted and rooftop solar PV and hydropower. Eventually, the analysis clarifies to what extent EU regions can generate the required electricity from local RES to cover hydrogen and power demand. In that sense, the analysis reveals potential hubs of hydrogen production, challenges, and opportunities for regional trade. The uniqueness of the current analysis is that it builds on georeferenced spatial assessments of RES' technical potentials i.e. the maximum electricity generation utilizing the RES' under specific topographic, environmental, and land-use constraints. More importantly, it addresses two geographical levels relevant to policy design and implementation, also considering availability of data on electricity demand and existing renewable installation. The country of member state level is clear, and for the more detailed analysis the EU regions where considered most appropriate in view of the above considerations.

To the best of the authors' knowledge this is the first study to provide an estimation of the potential technical capacity to cover existing hydrogen needs with green hydrogen at national and regional level with open source georeferenced data. The results provide an opportunity for further studies to address factors such as: future increases in overall electricity demand, increased hydrogen requirements for industry, transport and heat, and analysis of demand and renewable electricity hourly time variation profiles. Although few energy system models at national level have analysed green hydrogen scenarios [19–21], the regional level has not been investigated directly from a pan-European perspective up to now.

The rest of the paper is organized as follows: Section 2 describes the data and methodology approach. Section 3 presents the results at national and regional level. Section 4 discusses the results and lastly Section 5 summarizes the conclusions.

2. Data and methods

The study assesses the feasibility of producing green hydrogen from solar, wind and hydropower resources assuming a maximum potential at both regional (NUTS2) and national (NUTS0) level following the 2016 NUTS classification[2]. Nomenclature of Territorial Units for Statistics or NUTS is a geocode standard for referencing the subdivisions of countries for statistical purposes. The standard, adopted in 2003, is developed and regulated by the European Union, and thus only covers the member states of the EU in detail.

The analysis methodology essentially compares the potential electricity demand for moving to green hydrogen industrial production in each country or region with the renewable energy potentials (solar, wind, hydro) net of that need to cover existing total electricity consumption across all sectors. To do so we collected, harmonised and aggregated a number of open source data. The following paragraphs describe the process in detail for each renewable energy sources and the

[1] Stoichiometrically the minimum emission is 5.5 kgCO2/kgH2 ($CH_4+2H_2O \rightarrow CO_2+4H_2$). Additional emissions are coming from process fuel.

[2] Detailed information of EU statistics on regions at: https://ec.europa.eu/eurostat/web/regions-and-cities/

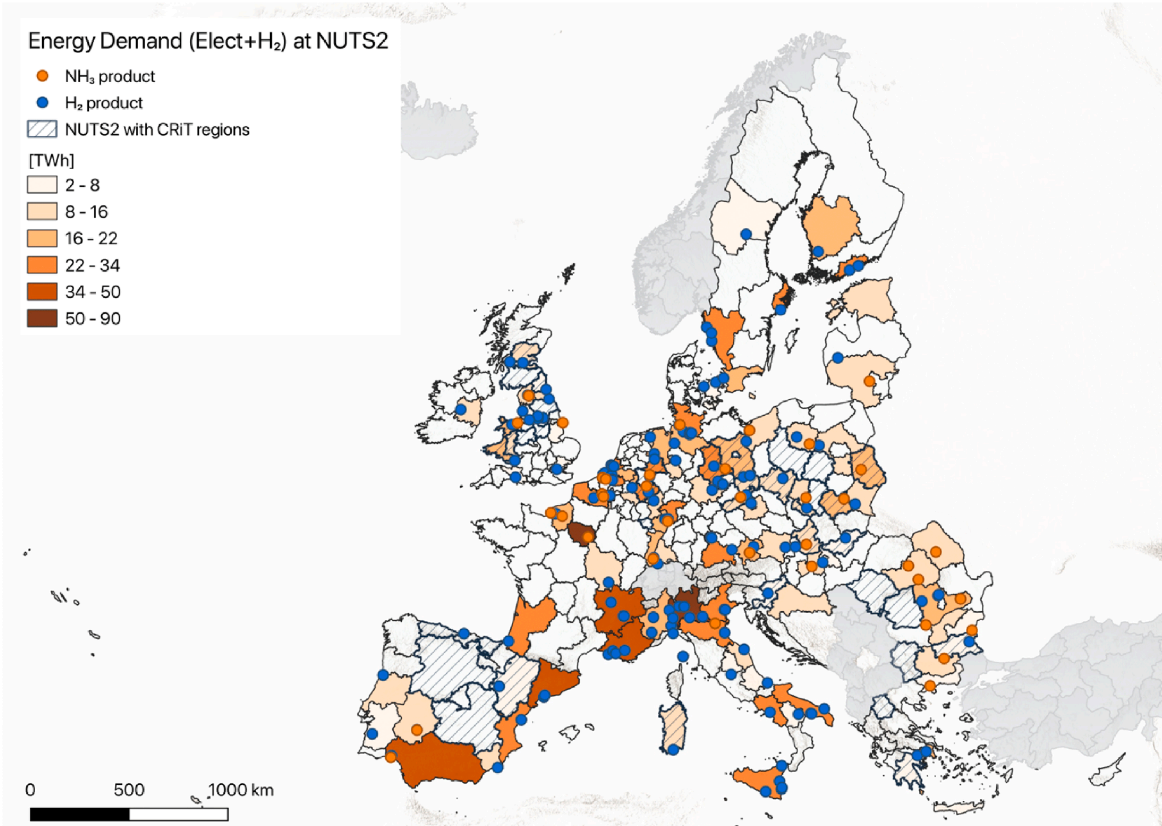

Fig. 1. Distribution of main hydrogen production hubs in EU27 + UK. Green and blue dots represent chemical industries with hydrogen and ammonia production [15]. Shaded polygons show EU coal regions in transition (CRiT) [30]. Background colours represent total demand in TWh per year i.e. the sum of electricity consumption and the potential demand for electrolysis only in hydrogen-producing regions.

methodology followed.

2.1. Hydrogen production at national and regional level in EU

The total annual production of hydrogen in Europe is in the range of 9.756 Mt (merchant hydrogen and purposely produced hydrogen, and not hydrogen produced as a by-product) [22]. The majority of hydrogen consumption is associated with two industries: oil refineries (ca. 52%) and ammonia production (ca. 43%) [14] the rest is other industrial use (ca. 2%). In Europe, oil refineries account for approximately at 30% and ammonia at 50% [6]. Together with methanol production (ca. 5%) and use in metal industries (ca. 3%), these four sectors correspond to 90% of the total hydrogen consumption in Europe.

Since this is a geospatial analysis, the first step is to locate the main hubs of hydrogen production in Europe that make up the current annual production. The Roads2HyCom report [22] presented three categories of hydrogen sources: merchant, which supplies hydrogen to other industrial customers; captive, where the hydrogen remains on site for use, and lastly the hydrogen that has no further use within the process or on site. Only hydrogen in this last category can be made available for other applications. An earlier analysis by the Joint Research Centre [15] developed a chemical industry database in Europe, in which hydrogen production is reported. This includes geographical coordinates of plants, their capacities and annual output in kilo-tonnes (kt). It is noted that this database lacks geo-references for 22% of the hydrogen production reported, although it still assigns it to a country. The database included refineries consuming hydrogen for petrochemicals but not the refineries consuming hydrogen for other purposes. Following checks with other sources [22] and harmonization, the hydrogen production hubs were geo-located in a GIS environment and the annual production volumes were aggregated at NUTS2 regional level (Fig. 1). These selected hubs are typically refineries with dedicated hydrogen production plants and ammonia plants. For the latter, pure hydrogen is also typically produced and used at a proportion of approximately 17 wt% per unit of ammonia production [23,24]. This hydrogen portion was included in the estimation of the total hydrogen production at each NUTS2. As shown in Table 1, the geo-located hydrogen production is 68% of the total estimated EU and UK annual production. At NUTS2 level (EU27 + UK), the developed dataset has georeferenced information of industries with hydrogen or ammonia production in 109 regions (out of the total 272). This corresponds to a total 290 TWh of hydrogen or 6626.2 kt (73.7 billion m^3).

The energy consumption for converting electricity to hydrogen varies between electrolyser technologies and is subject to continuous improvement. Alkaline electrolysers consume 50–51 kWh/kg, proton exchange membrane (PEM) electrolysers 55–58 kWh/kg, and solid oxide electrolysis (SOE) 40–41 kWh/kg[3], with a downward trend [25]. This study adopted an electrolyser efficiency value of 48 kWh/kg[4] in lower heating values (LHV) [26]. The multiplication of the electrolyser efficiency with the mapped hydrogen production resulted in values of

[3] The thermoneutral electrical efficiency of a SOE is usually presented for a system in which the thermal energy required for achieving a higher temperature of the electrolysis system is not accounted for in the electrical efficiency balance. This necessary thermal load is usually not included in these calculations since it depends on the actual whole process design and the process boundaries considered, which should go beyond the electrolyser itself.

[4] To be noted that 48kwh/kgH_2 is not current state of the art, but a likely development by 2030.

Table 1
EU27 + UK hydrogen production according to available data sources combined.

Source	Annual H_2 production[5]	
	kt	**bn m^3**
Hydrogen Roadmap Europe 2015 [2]	9 756	109.5
Chemical industry database [15]	8 716	97.2
of which pure H_2 (not geo-located)	2 090	23.5
of which pure H_2 (geo-located)	2 886	32.1
of which H_2 for NH_3 production (geo-located)	3 740	41.6

[5] Standard Ambient Temperature and Pressure (SATP), Standard ambient temperature is 25 °C, Standard pressure is 1 bar.

electricity demand for hydrogen electrolysis at country and regional level reported in Annexes 1 and 2 respectively. On this basis the country with the highest need for electricity for electrolysis is Germany (102.8 TWh) followed by the Netherlands (74 TWh).

2.2. Electricity demand at national and regional level

Net zero carbon and climate mitigation strategies involve the deployment of RES at large scales to cover electricity demand. Efforts to produce green hydrogen using processes powered by renewable electricity should not affect the transition towards clean electricity generation systems. Accordingly, for our analysis it is also necessary to take account of electricity demand across all sectors to examine the potential of covering all electricity consumption using green energy. Eurostat provides monthly net electricity generation data for Europe [27]. The ENTSO-E transparency platform also provides detailed information on electricity load/generation for European countries and for each renewable technology [28]. These two sources were the references for our analysis at NUTS0 level.

The regional character of the study required disaggregated data at NUTS2 level for electrical generation and load, but these are neither collected nor published by official sources. Regional electricity consumption can be estimated using different modelling approaches. The present study used values from [29], where electricity demand was disaggregated at regional and municipal level. Their simulation takes account of population distribution and the location of electricity intensive industries. Since [29] adopted the Global Administrative Areas Database (GADM) definition for administrative units, their final modelled outputs were harmonised with the NUTS definition used in this study. To do so, the demand values at municipal level were aggregated at the regional level corresponding to the NUTS2 definition.

Fig. 1 shows the calculated electricity demand across all sectors per year (2019) at regional level, covering the current consumption and demand of hydrogen by using water electrolysis. It also shows the locations of pure hydrogen and ammonia production as identified by [15] and [22]. Annexes 1 and 2 report the national and regional aggregate values, respectively.

2.3. Green electricity potential

Our analysis considered the technical potential for electricity generation from wind, solar photovoltaic and hydropower resources. Biomass electricity generation was excluded, although it is an additional low-carbon option. At a technical level this reflects biomass' lower density power than that of wind and solar. Biomass may also contribute to hydrogen production via different processes than electrolysis such as gasification. Such processes exceed the scope of our analysis that focuses exclusively on power-to-gas using electrolysis. The authors argue that sustainable use of biomass should prioritise its role as raw material in a circular economy concept. More importantly, bioenergy options are concentrated in specific Member States and their potential for expansion varies significantly among regions [31]. Concerning hydropower, our analysis assumed that capacities will not expand significantly from current levels. This is because Europe has already developed approximately 60% of it hydropower technical potential [32], the highest share among all continents. This percentage includes already the majority of advantageous locations. Other renewable energy sources such as ocean or geothermal energy were also omitted as they are not at the same level of maturity as wind and solar technologies. Also, the readily available energy potential is proportionally small compared to the resources included in this study. Annexes 1 and 2 report the national and regional aggregate values for PV, wind and hydropower technical potential at country and regional level respectively based on our analysis. The following sections provide details of the data sources and assumptions in each case.

2.3.1. Solar photovoltaic electricity technical potential

The technical potential generation of electricity from solar photovoltaic (PV) energy was estimated for each NUTS2 region for both ground-mounted and rooftop systems, using layers of location-specific PV system yield (kWh/m^2). The postulated PV system mounting configuration is free-standing racks facing south at an inclination angle of 20 degrees (40 degrees for locations north of 60 degrees N). The area required was calculated assuming 5.5 m^2 per kWp of PV modules, i.e., 18.2% efficiency. The distance between the module racks was calculated to avoid shadowing between arrays. The location-specific annual energy yield was calculated using hourly solar radiation data for from the JRC's PVGIS repository [33].

For the ground-mounted systems, the analysis followed an approach previously developed by the authors [34]. The CORINE Land Cover layer [35] was used to identify suitable land areas. Artificial areas (urban buildings, industrial, infrastructure etc.), forests, and wetlands were excluded. The agricultural areas class was considered suitable under a number of conditions. To avoid conflicts with food production, the analysis considered only 3% of eligible lands as available for solar PV deployment. This rather conservative estimation originates from the EU average for set-aside land [34]. Protected areas were excluded according to the Natura 2000 classification. Moreover, very steep land (more than 20 degrees) and steep north-facing land were also excluded as they are not appropriate for solar PV systems' deployment. Terrain characteristics (slope, orientation) were analysed using a 30 m digital elevation model provided by the SRTM consortium [23].

The installation of solar PV systems on buildings' rooftops offers an additional option for solar energy. The authors estimated the potential power capacity of rooftop in [37] by calculating the available rooftop area at NUTS2 level and by applying standard coefficients for useful area, rack distance, shading etc.

2.3.2. Wind energy technical potential

Wind energy potentials at national and regional levels are available as part of the JRC's ENSPRESO open dataset [19]. ENSPRESO provides regional estimates of wind power capacity (GW) and annual generation (TWh), under a number of different scenarios. For onshore wind, values are provided for the case of high land use restrictions and for that under which the allowed distances between buildings and wind turbines sites are smaller. The present analysis opted for the high constraints' scenario. It also excluded onshore sites with less advantageous wind characteristics (capacity factor (CF) between 15 and 20%). This decision reflects the assumption that future wind energy development will probably prioritise prime locations and this analysis only considered locations with a CF higher than 20%.

In ENSPRESO values for offshore wind are given only at national scale. For this study we excluded deep water location depths that require floating systems and focused on offshore areas with a CF higher than 25%. The offshore wind energy was disaggregated at NUTS2 level by using the demand of each region, assuming that an offshore installation serves the whole country in proportion to the regional consumption. For certain countries the offshore wind potential is zero. Our analysis used the Reference scenario and excluded all types of floating offshore wind.

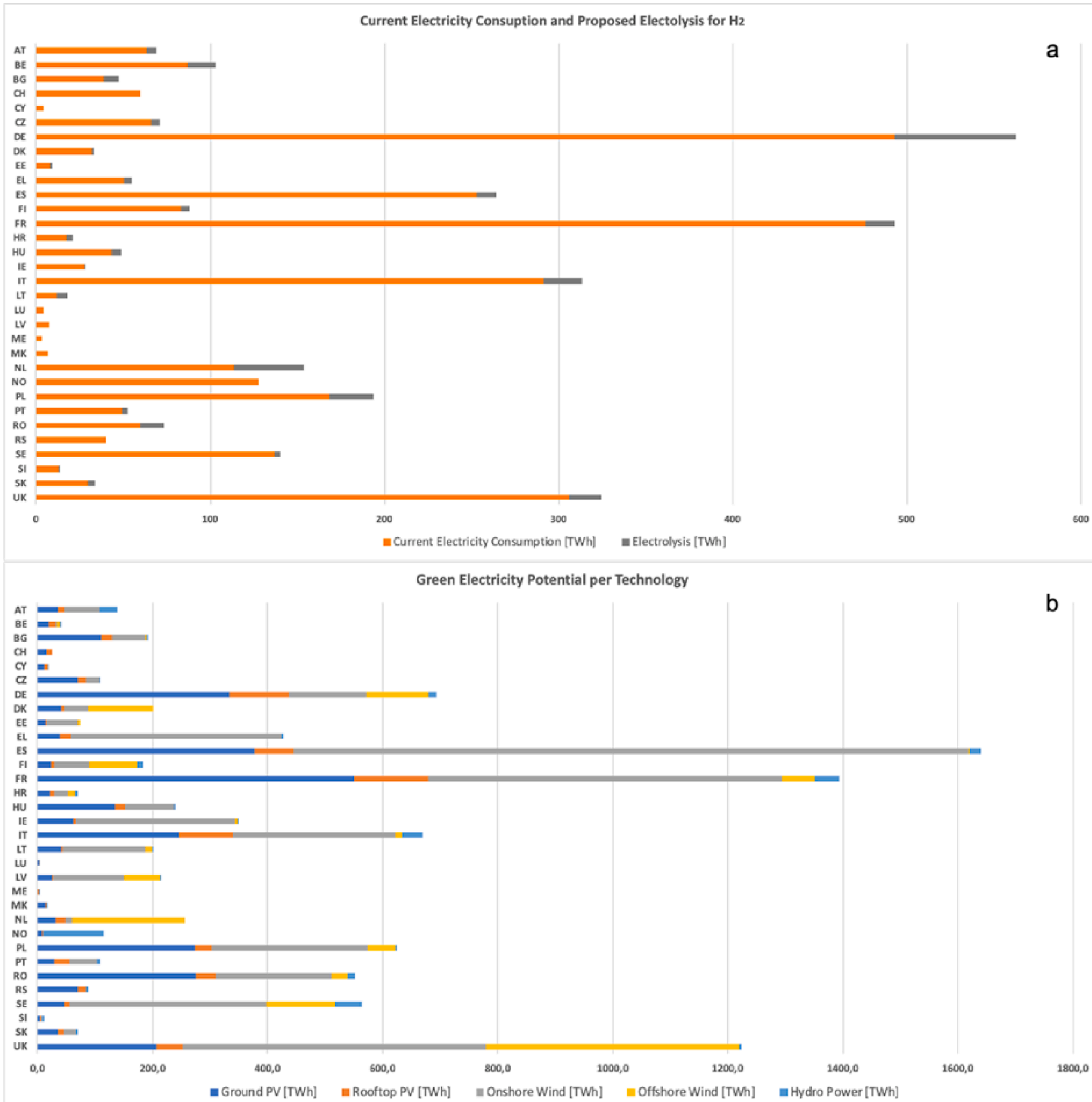

Fig. 2. a: Country breakdown of current electricity consumption and postulated electricity demand for electrolysis; b: Total green energy potential per technology at national level in terawatt hours.

Also, potential offshore wind installations with an estimated capacity factor 15–20% were also omitted as they were considered as non-viable investments.

The analysis also considered the EMHIRES dataset[5] that provides average productivity at national and regional scale for a 30-year period (1986–2015) with hourly time step and NUTS2 spatial resolution [38]. The added value of EMHIRES is the hourly capacity factors that allow the future extension of this study to analyse intraday grid balancing playing a decisive role in determining the expected excess generation, curtailment, and storage needs.

2.3.3. *Hydropower*

To estimate the existing hydro power generation available in Europe two different open source databases were used: the JRC Hydro-power database [39] and the JRC open power plants database [40]. The combination of the two resulted in a comprehensive database. Our analysis extracted information from the first database on hydro plants that have nominal installed capacity lower than 100 MW, while the second provided information for larger plants with installed capacity of 100 MW and over. Hydro plants were then geo-located and associated with the relevant NUTS 2 region; lastly an aggregation at NUTS2 level was performed.

In order to calculate regional hydropower generation, the analysis used the following approach to overcome data limitations. Country average hydropower productivity (capacity factor) was calculated using Eurostat data [41]. For every EU Member State, the annual output of the

[5] EMHIRES is available online at: https://setis.ec.europa.eu/EMHIRES-datasets

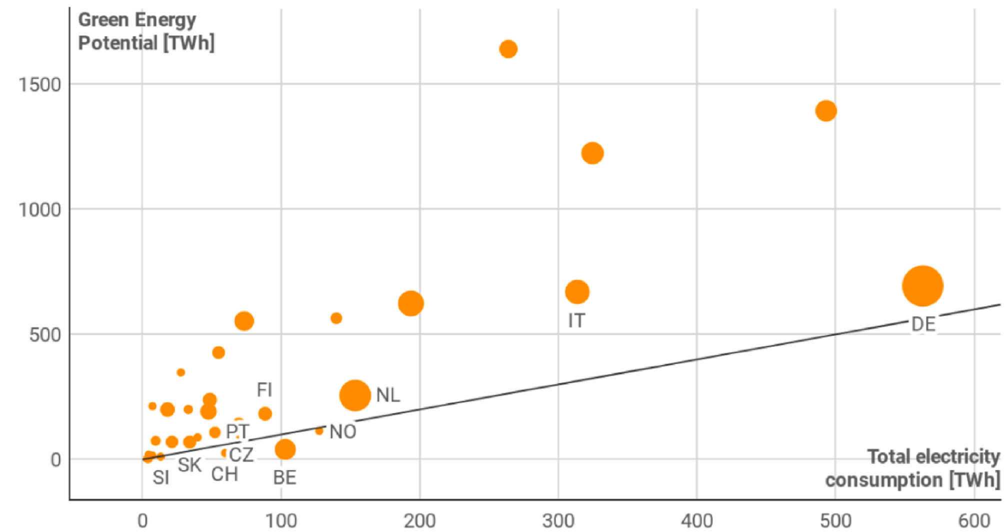

Fig. 3. Total electricity demand (current consumption + proposed electricity for hydrogen electrolysis) in EU27 and UK compared to countries' green electricity potential. The size of the markers represents the calculated electricity for hydrogen electrolysis per country. The solid black line is the 1:1 line.

hydro fleet was divided by the installed capacity, for the period 1990–2016 providing average CFs per Member State. Nominal power capacities of hydropower plants [42] were aggregated at regional level. The average CFs for 1990–2016 were then multiplied with the aggregated regional installed capacity and the total annual output (GWh) at regional level was obtained.

3. Results

3.1. EU and national level

Looking first at the continental level, in 2019 electricity consumption for EU27 + UK stood at 2939.6 TWh, the equivalent amount of electricity that would be needed for hydrogen electrolysis (including that for ammonia production) is estimated at 290 TWh, giving a total electricity demand of 3229.6 TWh. In comparison the combined technical potential for wind, solar PV and hydropower electricity considering the specific restrictions described in Sections 2.3.1–2.3.3, is over 10,000 TWh/yearly, of which 819.9 TWh was actually produced in 2019 [41]. So, there are generally ample resources for hydrogen production from renewables.

At country level, Fig. 2a shows the total electricity demand per country, split between current consumption plus the calculated demand for green hydrogen production from water electrolysis. Fig. 2b shows the breakdown of technical potential for green electricity from wind, solar PV and hydropower.

Fig. 3 compares the supply and demand values per country. The total green electricity potential exceeds the total electricity demand including

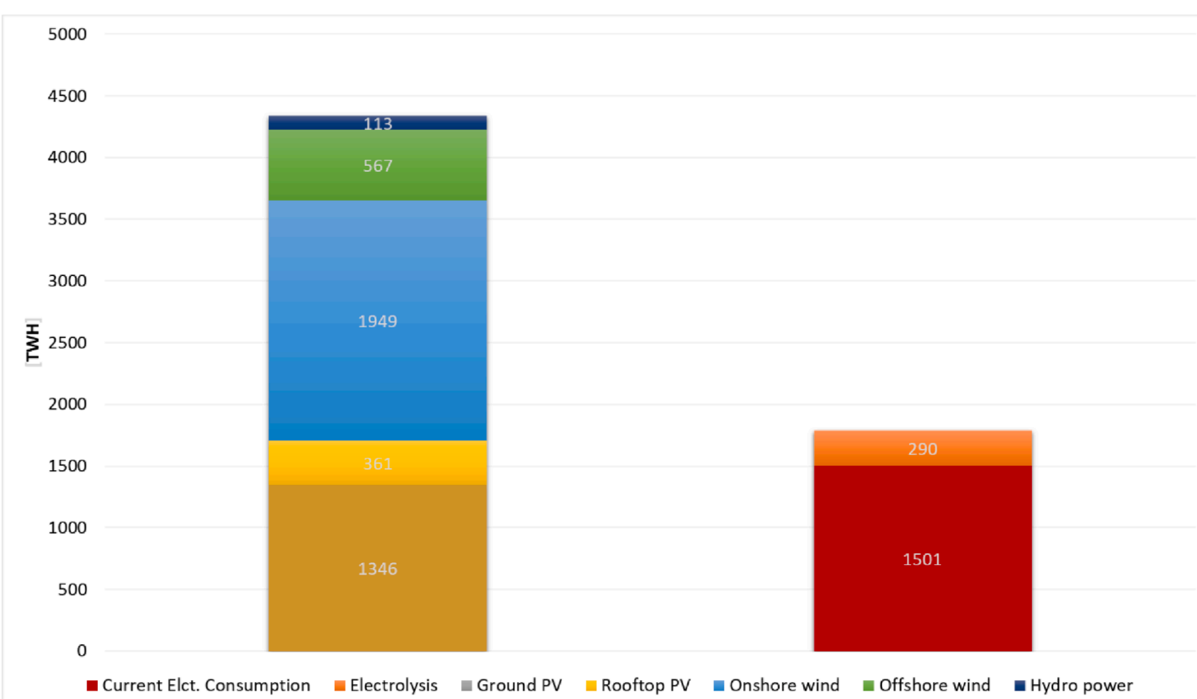

Fig. 4. Comparison of the RES technical potential for all hydrogen-producing regions and electricity demand (current consumption + proposed electrolysis for hydrogen).

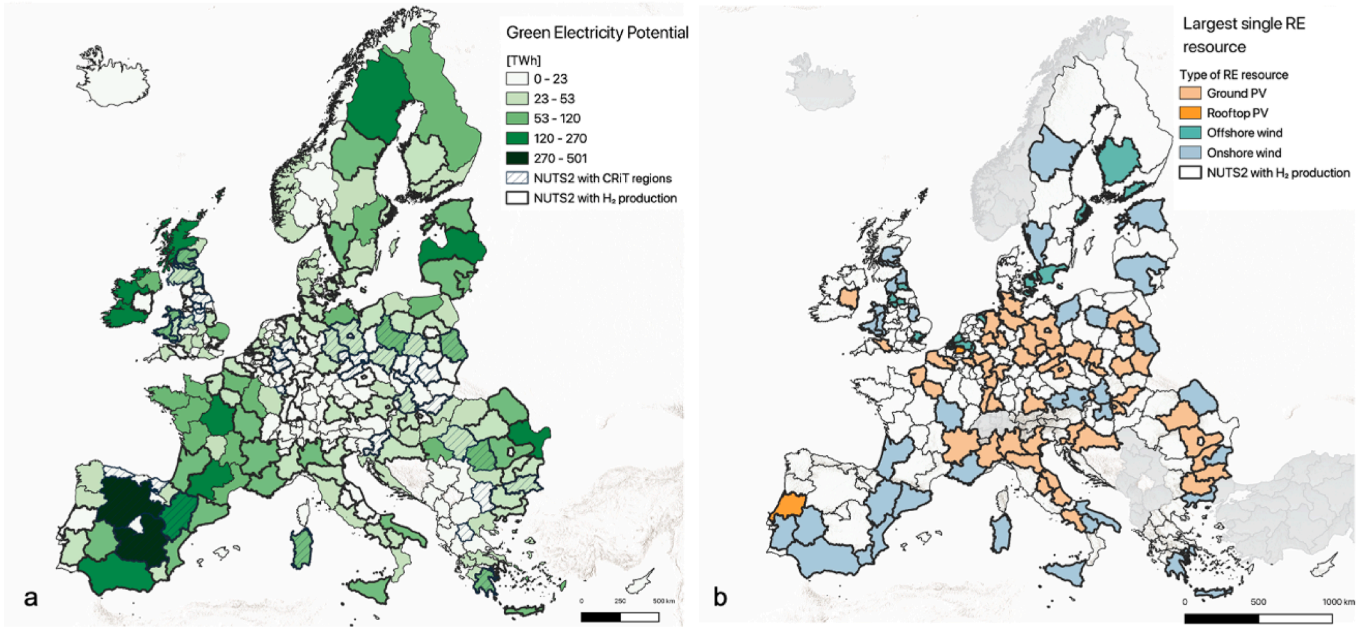

Fig. 5. For the 109 NUTS2 regions with hydrogen production, panel a shows the total technical potential for green electricity per region, while panel b shows the largest single resource in that region from the categories considered in this study: ground solar PV, rooftop solar PV, onshore and offshore wind, and hydropower.

that for hydrogen production in the majority of countries with the exceptions of Belgium (−62.7 TWh) and Luxemburg (−2.2 TWh). The countries with the highest amount of surplus green energy potential are Spain, France followed by Romania and Poland. For neighbouring non-EU countries with significant hydrogen production, the UK has a large surplus renewable green electricity potential (+900 TWh), while Switzerland would have a net deficit of −34 TWh.

3.2. Regional level

For the 109 NUTS2 (EU27 + UK) regions associated with hydrogen production, the table in Annex 2 lists estimates for current total electricity consumption, estimated electricity requirement for hydrogen electrolysis and the calculated technical potential for wind, solar PV and hydropower electricity generation. Overall, for this set of regions (Fig. 4), the total technical potential for green electricity is 4334 TWh, showing that these resources can cover the demand for electricity (1791 TWh) as well as that needed to produce all hydrogen by electrolysis (290 TWh).

At the individual regional level, Fig. 5a presents the technical potential for green electricity and Fig. 5b the renewable technology with the largest estimated technical potential in regions associated with hydrogen production.

From the 309 studied regions (EU27 + UK), 109 regions are associated with hydrogen production that was geo-located. A total of 246 regions have excess of RES electricity potential after subtracting the current electricity demand. From the 109 regions with hydrogen production, 13 have deficit of RES potential for covering the current electricity consumption. The remaining 96 regions (88%) have excess green potential and 90 of those still have an excess even after subtracting the postulated electrolysis demand (indeed for 84 the remaining excess is over 50%). It is noted that 20 regions out of the 90 regions belong to the coal regions in transition group (CRiT) [34].

Of these six regions with a deficit of green energy after adding the demand for electrolysis, Ile de France (FR10) has a deficit of 46.3 TWh followed by Zeeland (NL34) with 12 TWh deficit. The other 4 rest of regions show deficit values below 6 TWh. Zeeland (NL34) faces the highest percentage of deficit (-12%) compared to demand. It is noticeable that the regions with lack of green potential electricity often include large metropolitan areas or lack wind power potential.

Overall, the three regions with the highest hydrogen production and therefore electrolysis demand, are Sachsen-Anhalt (DEE0) with 20.3 TWh electrolysis demand (or 4236.89 kt) with the capacity to have its total demand fully covered and with an excess of 46%, Zeeland (NL34) with a 18.2 TWh demand and no renewable energy excess, and Prov. Antwerp (BE21) with a 9.9 TWh demand with marginal deficit of 0.3%.

Moreover, in Fig. 5b the largest single resource potential for each NUTS2 region associated is presented. Ground-mounted PV and wind sources are dominant, with the former mainly for in land regions and the latter for regions closer to the coast. Rooftop PV technology was of secondary importance in the latter.

Fig. 6 highlights the regions with excess and deficit of RES electricity potential to cover the total demand. It also shows that neighbouring regions could cover for the RES generation deficit by transmitting power from regions with surplus potential (marked in green) to those in deficit (flagged red/orange).

4. Discussion

A major finding in our study is that most of the examined European regions have sufficiently high technical potentials to be self-reliant using renewable energy. The regional focus of our work serves two additional purposes. First, it shows up to which extent each European NUTS2 region can take advantage of the decreasing costs of modern renewables in order to become energy self-sufficient. Furthermore, clean hydrogen offers new opportunities for re-designing Europe's energy partnerships

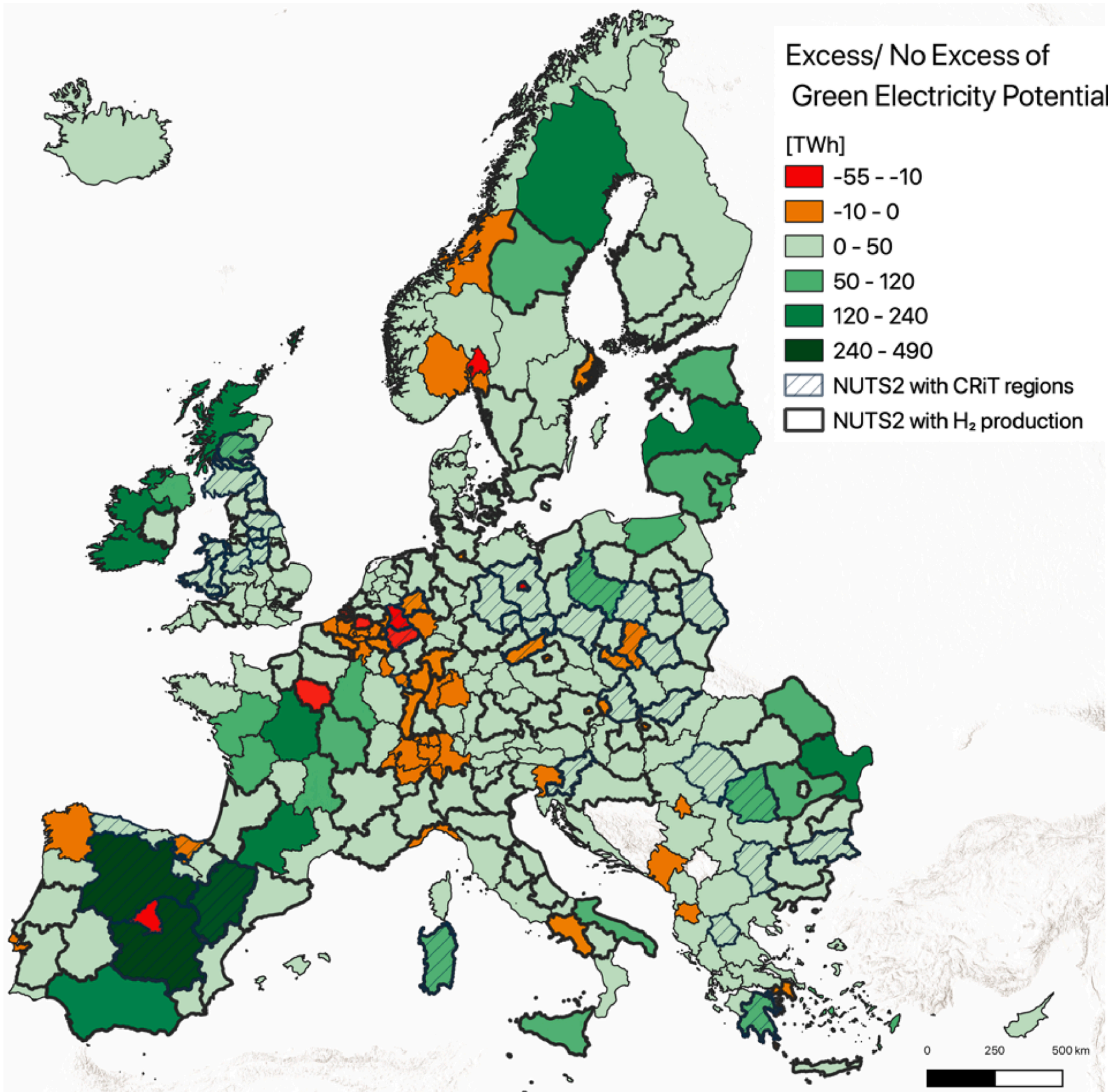

Fig. 6. Regions with an excess or deficit of technical potential for green electricity after subtracting the current consumption for all sectors and that needed for moving from existing hydrogen production from grey to green. The shaded regions represent the CRiTs and the bold black outlined polygons the NUTS2 with current hydrogen production.

with both neighbouring countries and regions and its international [3], regional and bilateral partners, advancing supply diversification and helping design stable and secure supply chains. As for example several major hydrogen-producing regions and especially densely populated regions (large cities, metropolitan areas) would not have sufficient green electricity to cover both current electricity consumption as well electrolytic production of hydrogen. However, given the overall technical potential for surplus of green electricity at EU and Member State level, these needs could be covered by inter-regional electricity transmission.

This paves the way for further analyses of time complementarity between the various sources using production profiles and grid integration assessments. Second, the regional scope allows the identification of high/low production areas and reveals opportunities for energy trade in the forms of electricity and/or hydrogen. This is of particular policy importance for specific areas such as the Coal Regions in Transition (CRiT) as it allows the mobilisation of specific implementation instruments e.g. the Just Transition Fund [43] to ensure a smooth transition and generate the necessary investments for supporting the affected local societies.

The impact on employment should be also considered when assessing the possible deployment of high shares of RES in industrial and energy sectors. A conversion to a hydrogen economy offers new economic prospects to countries and regions that rely today on fossil fuel exports for a significant part of their national revenues. It may also help to create new export opportunities for countries with rich renewable energy resources. Moreover, a recent study on the Coal Regions in Transition [34] found that a large proportion of the current mining jobs (approximately 230,000 across 31 regions and 11 EU countries) could be substituted with jobs related to renewables.

Furthermore, this research can be used as basis for a future complete techno-economic analysis which would involve many other factors. For instance, here we assume that hydrogen production is co-located with the point of industrial use. However, possible options for future consideration include the transmission and storage of green hydrogen across regions and countries using dedicated pipelines or adapted gas infrastructure. Secondly, efficient and economic operation of electrolysers requires a sufficient high load factor (over 30–40% for reaping a significant economic advantage) and cheap electrical power [44]. In an electricity system based on a high share of variable renewables, flexible operation of electrolysers may be able to take advantage of periods of high renewables supply and low demand (e.g. sunny weekends or windy nights). Electrolyzers' costs are expected to halve in 2030 compared to today with economies of scale. In regions where renewable electricity is cheap, electrolysers are expected to be able to compete with fossil-based hydrogen in 2030.

Several major hydrogen-producing regions and especially densely populated regions (large cities, metropolitan areas) would not have sufficient green electricity to cover both current electricity consumption as well electrolytic production of hydrogen. However, given the overall technical potential for surplus of green electricity at EU and Member State level, these needs could be covered by inter-regional electricity transmission.

It may appear that the targets of the European Green Deal are contradictory to the EU hydrogen strategy. The implementation of the latter depends on the production of clean hydrogen for refineries. However, the reduced dependence on the refineries' oil products is on the core of the Green Deal vision. Future projections for energy use in the EU show that fossil fuel demand will not decrease significantly in the short-term (until 2030), especially in difficult-to-decarbonise sectors (e.g. transport). The authors' view is that the EU policy sees the refineries as the opportunity to scale clean hydrogen production, advance technological and market maturity and achieve economies of scale. In the long-term (2030–2050), hydrogen demand in sectors other than refineries (e.g. industrial processes, transport) is expected to have increased substantially and absorb any reductions of hydrogen demand in the refineries.

Energy models and simulations reveal that the future hydrogen needs (i.e. transport, industry and heating) increase significantly under decarbonisation scenarios. Such scenarios also cover more sectors (for example heavy industry and buildings, where the role of hydrogen may be crucial. From this perspective, decarbonising current hydrogen production is a no regret option and can pave the way to make sure that the future hydrogen will be produced in a carbon–neutral way.

5. Conclusions

The current work assesses the replacement of grey hydrogen with green hydrogen production through electrolysis power by renewable energy resources for the EU27 and UK at regional level (NUTS2), considering existing electricity consumption and hydrogen demand.

- Switching the current annual EU hydrogen production of 9.75 Mt to electrolysis would require 290 TWh of electricity (about 10% of current production). The available technical potential for producing green electricity from wind, solar and hydro is easily sufficient to cover all current electricity consumption as well as this additional demand for green hydrogen, showing that a partial utilisation of prime locations could suffice.
- It was possible to geo-locate approximately 75% of current hydrogen production to 109 out of the 309 NUTS2 regions in the EU and UK. Of these, 96 have sufficient wind, solar and hydro resources to cover all current electricity consumption as well as to substitute shift all grey hydrogen to green hydrogen. These regions account for 88% of overall hydrogen production. For the EU27, hydrogen production currently takes place in 82 regions and 76 of these have sufficient solar photovoltaic, wind and hydropower resources to fully decarbonise both electricity consumption and hydrogen production. The remainder could also do so with green electricity imported from neighbouring regions.
- The results are relevant to the design of policies to implement the EU energy transition, in particular in relation to the role for green hydrogen and implications at regional level for deployment of renewable electricity generation capacity.

Further studies are recommended to address factors such as: detailed techno-economic analysis of regional energy systems with integrated green hydrogen production; possibilities for transmission and storage of green hydrogen across regions and of the impact of growth of hydrogen demand for new applications in industry, transport and for heat (even as petrochemical use declines with increasing decarbonisation).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully acknowledge the valuable comments and suggestions of Christian Thiel, Tim Tröndle for providing electricity demand data, Nicola Zaccarelli sharing input and data on hydrogen transport and distribution options and Julian Somers for valuable comments on the document. This study was performed under the European Commission Joint Research Centre Annual Work Programme 2020.

Disclaimer

The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

Appendix A

Annex 1

Data for renewable energy supply potential, corresponding consumption from current demand and postulated hydrogen electrolysis for the EU member states and neighbouring countries. The data for technical potential of the ground and rooftop photovoltaic technologies are estimated based on [34,37]. The technical potential of the offshore and onshore wind derived from data available JRC's ENSPRESO open dataset [19] and EMHIRES available online at: https://setis.ec.europa.eu/EMHIRES-datasets. The technical potential of the hydropower technology was estimated using data from JRC Hydro-power database [39] and the JRC open power plants database [40].

Country ID	Technical potential (green electricity)					Hydrogen Electrolysis Require-ment [TWh]	Current electricity Consumption [TWh]	Electricity Balance Supply-Demand
	Ground PV [TWh]	Rooftop PV [TWh]	Onshore Wind [TWh]	Offshore Wind [TWh]	Hydro Power [TWh]			
AT	34.9	12.9	59.5	0.0	31.8	5.8	63.6	69.7
BE	19.0	12.5	0.9	7.6	0.2	15.9	87.2	−62.8
BG	111.3	17.5	58.5	1.3	3.5	8.9	38.8	144.4
CH	15.5	10.2	0.0	0.0	0.0	0.0	59.6	−33.9
CY	11.0	5.7	2.4	0.0	0.0	0.0	4.5	14.7
CZ	70.1	13.7	23.4	0.0	1.1	4.7	66.1	37.5
DE	333.0	104.6	134.5	106.5	14.9	69.7	493.2	130.5
DK	41.2	6.2	40.1	112.6	0.0	0.8	32.3	167.0
EE	14.1	1.3	54.3	5.1	0.0	1.4	8.1	65.3
EL	38.6	19.2	365.4	0.1	4.2	4.0	50.9	372.5
ES	376.2	69.3	1172.4	2.1	20.7	11.2	252.7	1376.7
FI	23.7	5.2	61.1	84.6	8.2	5.3	83.2	94.4
FR	550.5	129.5	613.4	57.2	42.9	16.9	476.4	900.3
HR	20.8	9.0	23.6	11.7	5.5	3.8	17.4	49.3
HU	133.9	18.0	86.4	0.0	0.2	5.6	43.0	189.9
IE	62.5	3.0	277.3	4.6	0.7	0.0	27.7	320.4
IT	246.8	93.7	282.2	12.6	34.3	22.6	291.1	356.0
LT	40.3	3.0	144.2	11.8	0.4	6.4	11.7	181.6
LU	1.3	0.7	0.1	0.0	0.0	0.0	4.3	−2.2
LV	26.1	1.5	123.5	60.9	1.2	0.0	7.2	206.0
ME	0.7	1.2	0.0	0.0	0.9	0.0	3.4	−0.6
MK	13.1	2.3	0.0	0.0	0.7	0.0	7.0	9.0
MT	0.03	0.9	0	0	0	0	2	−1.1
NL	31.4	17.9	10.6	196.0	0.0	39.8	113.7	102.4
NO	7.8	2.6	0.0	0.0	104.0	0.0	127.6	−13.1
PL	272.4	31.0	270.5	48.7	1.3	25.4	168.3	430.2
PT	29.3	25.7	48.2	0.0	5.4	2.8	49.5	56.3
RO	274.5	35.9	201.1	27.4	14.5	13.3	60.0	480.0
RS	70.7	12.5	0.0	0.0	5.4	0.0	39.8	48.7
SE	46.5	7.9	343.2	119.7	47.4	3.0	136.9	424.8
SI	3.8	2.7	1.9	0.0	3.1	0.0	13.2	−1.6
SK	35.5	9.1	21.3	0.0	4.1	4.5	29.7	35.7
UK	207.1	45.3	526.8	441.2	4.2	18.4	306.3	899.9

Annex 2

Data for renewable energy supply potential and corresponding consumption from current demand and postulated hydrogen electrolysis for the NUTS2 regions. With grey shaded colour regions that are European Coal Regions in Transition (CRiT).

NUTS2	Name	Electricity Cons. 2019	Technical Potential						Electricity for H_2 Electrolysis
			Ground PV	Rooftop PV	On-shore Wind	Offshore Wind	Hydro	Total Green	
		[TWh]	[TWh]	[TWh]	[TWh]	[TWh]	[TWh]	{TWh]	[TWh]
AL01	Veri	2.03	1.35	0.91		0.00	4.53	6.79	
AL02	Qender	2.84	1.41	1.04		0.00	0.37	2.82	
AL03	Jug	2.18	6.40	1.32		0.00	0.23	7.96	
AT11	Burgenland	1.73	3.61	0.84	3.63	0.00	0.00	8.09	
DEE0	Sachsen-Anhalt	12.96	24.18	4.11	19.73	2.80	0.06	50.88	20.34
AT13	Wien	10.51	0.10	1.16	0.00	0.00	0.81	2.06	
AT21	Kärnten	3.46	2.02	0.89	5.27	0.00	4.37	12.54	
AT22	Steiermark	10.41	4.21	2.10	4.18	0.00	4.39	14.88	
NL34	Zeeland	2.31	2.64	0.62	1.25	3.98	0.00	8.49	18.18
AT32	Salzburg	3.22	1.28	0.76	4.95	0.00	4.16	11.16	
AT33	Tirol	4.35	0.94	1.10	10.09	0.00	6.79	18.92	
AT34	Vorarlberg	2.29	0.35	0.43	2.63	0.00	0.54	3.95	
BE10	Région de Bruxelles-Capitale/ Brussels Hoofdstedelijk Gewest	8.87	0.00	0.56	0.00	0.77	0.00	1.34	
BE21	Prov. Antwerpen	14.73	1.14	2.34	0.06	1.28	0.00	4.83	9.87
BE22	Prov. Limburg (BE)	7.75	0.92	1.32	0.08	0.68	0.00	2.99	
BE23	Prov. Oost-Vlaanderen	11.16	1.80	1.73	0.10	0.97	0.00	4.60	
BE24	Prov. Vlaams-Brabant	8.27	1.26	1.20	0.00	0.72	0.00	3.18	
BE25	Prov. West-Vlaanderen	8.77	2.88	1.52	0.24	0.76	0.00	5.41	
BE31	Prov. Brabant Wallon	3.03	1.21	0.33	0.00	0.26	0.00	1.81	
PL81	Lubelskie	9.37	27.82	2.11	32.30	2.71	0.00	64.94	9.69
NL42	Limburg (NL)	7.09	1.07	1.70	0.08	12.22	0.00	15.06	9.63
BE34	Prov. Luxembourg (BE)	2.12	1.62	0.47	0.14	0.18	0.01	2.41	
BE35	Prov. Namur	4.09	2.06	0.52	0.09	0.36	0.03	3.05	
BG31	Северозападен	4.20	24.81	2.77	9.63	0.14	0.03	37.39	
ITG1	Sicilia	23.00	27.84	9.42	62.94	0.99	0.21	101.40	8.62
DEA3	Münster	15.40	9.21	2.91	3.43	3.33	0.00	18.87	8.42
DEA2	Köln	25.42	6.54	4.28	0.38	5.49	0.16	16.84	7.93
BG41	Югозападен	11.69	7.34	3.19	3.18	0.40	0.38	14.50	
DEB3	Rheinhessen-Pfalz	12.10	4.77	3.11	0.41	2.61	0.16	11.07	7.48
CH01	Région lémanique	11.51	2.89	1.74		0.00	0.00	4.62	
CH02	Espace Mittelland	13.13	5.69	2.70		0.00	0.00	8.40	
CH03	Nordwestschweiz	7.99	1.32	1.49		0.00	0.00	2.81	
CH04	Zürich	10.63	1.43	1.52		0.00	0.00	2.95	

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CH05	Ostschweiz	8.23	2.81	1.43		0.00	0.00	4.24	
CH06	Zentralschwei z	5.58	1.29	0.84		0.00	0.00	2.13	
CH07	Ticino	2.54	0.10	0.46		0.00	0.00	0.56	
CY00	Κύπρος	4.50	11.01	5.75	2.44	0.00	0.00	19.20	
CZ01	Praha	7.76	0.29	0.82	0.00	0.00	0.00	1.11	
DEF0	Schleswig-Holstein	15.61	18.38	2.73	9.21	3.37	0.00	33.68	6.70
CZ03	Jihozápad	7.19	14.67	2.11	4.44	0.00	0.19	21.41	
UKD1	Cumbria	2.23	4.17	0.35	8.94	3.21	0.00	16.67	6.47
CZ05	Severovýchod	8.89	11.00	2.22	3.06	0.00	0.00	16.27	
CZ06	Jihovýchod	9.99	15.41	2.44	8.68	0.00	0.04	26.58	
CZ07	Střední Morava	7.11	7.50	1.46	2.55	0.00	0.00	11.50	
LT02	Vidurio ir vakarų Lietuvos regionas	8.40	36.37	2.45	72.10	8.47	0.38	119.76	6.36
DE11	Stuttgart	21.67	9.78	4.84	0.40	4.68	0.05	19.75	
DE12	Karlsruhe	14.87	4.47	3.52	0.00	3.21	1.11	12.31	
DE94	Weser-Ems	13.44	18.81	3.46	10.06	2.90	0.00	35.24	6.24
DE14	Tübingen	10.06	9.96	2.84	0.69	2.17	0.44	16.11	
FRD2	Haute-Normandie	13.16	18.10	2.73	8.80	1.58	0.00	31.21	5.95
DE22	Niederbayern	6.46	12.80	2.15	0.57	1.40	1.89	18.80	
DE23	Oberpfalz	6.11	9.13	1.81	0.51	1.32	0.29	13.06	
DE24	Oberfranken	5.73	6.50	1.62	0.12	1.24	0.03	9.50	
DE25	Mittelfranken	9.25	7.95	2.54	0.20	2.00	0.15	12.83	
DE26	Unterfranken	7.36	7.09	2.13	0.47	1.59	0.30	11.59	
DE27	Schwaben	10.09	12.28	3.29	1.40	2.18	1.00	20.16	
DE30	Berlin	18.10	0.07	1.97	0.00	3.91	0.00	5.95	
RO31	Sud - Muntenia	12.04	61.05	6.49	39.21	5.50	1.61	113.86	5.45
DE21	Oberbayern	25.33	18.82	5.94	0.90	5.47	4.50	35.63	5.41
NL33	Zuid-Holland	23.41	3.17	3.01	0.72	40.35	0.00	47.25	5.37
NL11	Groningen	5.21	3.31	0.59	1.39	8.98	0.00	14.26	5.36
DE72	Gießen	5.54	3.65	1.62	0.00	1.20	0.01	6.48	
DE73	Kassel	6.49	5.66	1.85	0.51	1.40	0.20	9.62	
DE80	Mecklenburg-Vorpommern	8.47	20.83	2.37	31.62	1.83	0.00	56.66	
DE91	Braunschweig	12.70	7.36	2.03	2.92	2.74	0.14	15.19	
DE92	Hannover	11.67	10.08	2.29	4.03	2.52	0.00	18.91	
ITH5	Emilia-Romagna	21.03	28.20	8.29	0.00	0.91	0.32	37.71	5.25
FI1B	Helsinki-Uusimaa	22.86	2.37	0.89	6.47	23.26	0.08	33.08	5.25
DEA1	Düsseldorf	50.35	4.90	4.74	0.20	10.87	0.01	20.72	
RO12	Centru	6.12	19.84	4.31	11.56	2.79	1.04	39.55	5.10
ES61	Andalucía	43.32	44.78	15.86	#####	0.36	0.42	170.91	4.78
PL42	Zachodniopo morskie	7.22	13.57	0.92	28.34	2.09	0.00	44.91	4.76
DEA5	Arnsberg	19.61	3.85	3.97	1.16	4.23	0.47	13.68	
AT31	Oberösterreic h	17.56	8.13	2.33	8.46	0.00	5.73	24.64	4.39
DEB2	Trier	2.86	3.63	0.80	0.22	0.62	0.50	5.78	
PL61	Kujawsko-pomorskie	9.34	19.18	1.21	23.41	2.70	0.78	47.29	4.31
DEC0	Saarland	10.08	1.76	1.51	0.15	2.18	0.00	5.59	
ES43	Extremadura	5.48	23.54	2.48	27.58	0.05	4.05	57.69	4.23

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DED4	Chemnitz	7.82	5.92	2.25	3.81	1.69	0.27	13.93	
BE32	Prov. Hainaut	10.06	3.78	1.48	0.16	0.88	0.00	6.29	4.20
CZ04	Severozápad	6.76	5.75	1.25	1.87	0.00	0.04	8.91	4.11
HU21	Közép-Dunántúl	5.01	16.01	2.45	21.07	0.00	0.00	39.52	3.99
BG32	Северен централен	4.35	19.69	2.31	7.94	0.15	0.02	30.11	3.82
HR04	Kontinentalna Hrvatska	12.01	19.20	4.57	7.26	8.06	1.22	40.31	3.82
PL52	Opolskie	4.62	11.75	1.28	6.13	1.34	0.00	20.50	3.70
DK03	Syddanmark	6.82	12.49	1.41	14.88	23.74	0.00	52.52	
DK04	Midtjylland	7.32	11.79	1.69	9.67	25.50	0.00	48.64	
DK05	Nordjylland	3.74	7.41	0.83	10.94	13.03	0.00	32.22	
FR10	Ile-de-France	85.66	14.25	9.17	2.21	10.29	0.00	35.92	3.44
UKL2	East Wales	5.16	6.05	1.08	23.79	7.43	0.00	38.34	3.34
EL41	Βόρειο Αιγαίο	0.48	0.65	0.40	33.19	0.00	0.00	34.25	
EL42	Νότιο Αιγαίο	1.10	1.03	1.03	53.04	0.00	0.00	55.10	
FRL0	Provence-Alpes-Côte d'Azur	46.07	4.38	13.75	28.30	5.53	9.20	61.17	3.08
SK02	Západné Slovensko	9.22	18.38	3.74	19.28	0.00	2.70	44.10	3.02
EL52	Κεντρική Μακεδονία	8.98	11.97	3.58	9.43	0.01	0.32	25.31	
EL53	Δυτική Μακεδονία	1.32	6.32	0.50	10.55	0.00	0.89	18.26	
EL54	Ήπειρος	1.56	0.59	0.75	14.33	0.00	0.87	16.54	
EL61	Θεσσαλία	3.71	4.83	1.61	16.30	0.00	0.22	22.96	
EL62	Ιόνια Νησιά	0.90	0.26	0.54	12.15	0.00	0.00	12.96	
EL63	Δυτική Ελλάδα	3.32	1.89	1.11	30.66	0.00	1.54	35.21	
EL64	Στερεά Ελλάδα	3.04	2.87	1.01	36.44	0.00	0.01	40.34	
FRF1	Alsace	13.56	6.39	3.31	0.50	1.63	4.02	15.85	2.95
ES11	Galicia	27.92	1.93	4.34	18.05	0.23	2.61	27.16	
ES12	Principado de Asturias	11.81	2.35	0.98	13.22	0.10	1.39	18.04	
ES13	Cantabria	3.05	1.64	0.57	3.43	0.03	0.16	5.81	
ES21	País Vasco	10.87	2.79	1.64	3.08	0.09	0.19	7.78	
ES22	Comunidad Foral de Navarra	3.30	8.21	1.04	17.63	0.03	0.00	26.91	
ES23	La Rioja	1.66	2.53	0.63	6.08	0.01	0.00	9.25	
BG42	Южен централен	7.78	13.68	3.67	5.95	0.26	2.97	26.53	2.80
ES30	Comunidad de Madrid	33.53	5.93	6.40	0.96	0.28	0.12	13.69	
ES41	Castilla y León	12.92	116.97	5.31	#####	0.11	6.82	501.47	
ES42	Castilla-La Mancha	11.25	103.56	4.65	#####	0.09	0.69	377.20	
RO21	Nord-Est	8.52	37.75	5.59	40.33	3.89	0.91	88.47	2.80
ITC4	Lombardia	47.81	24.98	14.85	1.56	2.06	10.58	54.03	2.63
PL21	Małopolskie	15.12	10.70	2.60	2.90	4.38	0.21	20.78	2.57
ES53	Illes Balears	5.69	3.19	2.02	3.01	0.05	0.00	8.27	
PT18	Alentejo	3.62	20.91	3.29	25.44	0.00	0.22	49.87	2.44
SE23	Västsverige	26.35	9.64	1.35	28.20	23.04	1.37	63.59	2.40
ES63	Ciudad Autónoma de Ceuta	0.40	0.00	0.05		0.00	0.00	0.06	
ES64	Ciudad Autónoma de Melilla	0.48	0.01	0.00		0.00	0.00	0.02	

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ES70	Canarias	0.00	0.00	0.00		0.00	0.00	0.00	
UKF3	Lincolnshire	3.32	9.49	0.66	13.83	4.78	0.00	28.75	2.29
UKM7	Eastern Scotland	8.62	5.74	0.69	85.80	12.41	0.88	105.52	2.19
FI1C	Etelä-Suomi	16.60	7.68	1.19	19.33	16.89	1.70	46.79	
FI1D	Pohjois- ja Itä-Suomi	23.43	5.32	1.15	20.48	23.84	5.90	56.69	
FI20	Åland	0.38	0.14	0.08	0.05	0.39	0.00	0.66	
UKK2	Dorset and Somerset	5.81	8.90	1.34	3.54	8.37	0.00	22.15	2.14
FRB0	Centre - Val de Loire	18.25	58.68	6.05	92.70	2.19	0.23	159.86	
DE71	Darmstadt	21.16	5.13	4.25	0.00	4.57	0.00	13.96	2.05
FRC2	Franche-Comté	9.17	11.75	2.62	5.00	1.10	1.08	21.55	
FRD1	Basse-Normandie	10.49	27.40	3.04	27.80	1.26	0.00	59.49	
DE40	Brandenburg	15.14	20.78	4.61	15.97	3.27	0.18	44.81	1.98
ITG2	Sardegna	7.50	19.59	4.68	72.41	0.32	0.40	97.40	1.94
FRE2	Picardie	13.68	30.13	3.18	24.70	1.64	0.00	59.65	
BE33	Prov. Liège	8.30	2.32	1.04	0.05	0.72	0.18	4.31	1.78
FRF2	Champagne-Ardenne	9.62	34.58	2.41	48.20	1.16	0.00	86.34	
FRF3	Lorraine	17.84	24.05	4.44	9.90	2.14	0.03	40.56	
FRG0	Pays de la Loire	26.45	50.63	10.16	22.70	3.18	0.00	86.67	
FRH0	Bretagne	23.02	30.72	7.99	13.90	2.77	0.00	55.38	
BG33	Североизточен	5.10	22.48	2.70	24.12	0.17	0.00	49.48	1.78
FRI2	Limousin	5.33	16.71	1.84	21.80	0.64	2.53	43.52	
FRI3	Poitou-Charentes	13.30	37.33	6.01	32.60	1.60	0.00	77.54	
FRJ1	Languedoc-Roussillon	19.53	4.91	8.61	49.70	2.35	1.67	67.23	
FRJ2	Midi-Pyrénées	21.60	45.23	6.83	84.90	2.60	5.80	145.36	
FRK1	Auvergne	9.59	26.61	3.89	33.70	1.15	1.65	66.99	
UKE4	West Yorkshire	10.18	1.29	1.30	0.10	14.66	0.00	17.35	1.73
EL43	Κρήτη	2.94	0.16	1.24	52.78	0.00	0.00	54.18	1.70
FRM0	Corse	2.19	0.66	1.06	2.70	0.26	0.44	5.12	
FRY1	Guadeloupe	0.00	0.00	0.00		0.00	0.00	0.00	
FRY2	Martinique	0.00	0.00	0.00		0.00	0.00	0.00	
FRY3	Guyane	0.00	0.00	0.00		0.00	0.00	0.00	
FRY4	La Réunion	0.00	0.00	0.00		0.00	0.00	0.00	
FRY5	Mayotte	0.00	0.00	0.00		0.00	0.00	0.00	
HR03	Jadranska Hrvatska	5.41	1.62	4.45	16.32	3.63	4.25	30.27	
ITF4	Puglia	26.44	21.76	6.30	61.98	1.14	0.00	91.18	1.66
HU11	Budapest	7.57	0.17	1.33	1.50	0.00	0.00	3.01	
HU12	Pest	5.07	7.39	2.07	1.50	0.00	0.00	10.96	1.51
SK01	Bratislavský kraj	3.17	1.61	0.99	0.96	0.00	0.06	3.61	1.44
HU22	Nyugat-Dunántúl	4.10	15.37	2.32	16.48	0.00	0.01	34.18	
HU23	Dél-Dunántúl	3.80	22.04	1.99	28.24	0.00	0.00	52.26	
AT12	Niederösterreich	10.03	14.25	3.25	20.28	0.00	5.06	42.84	1.42
HU32	Észak-Alföld	6.45	28.50	2.79	0.00	0.00	0.05	31.35	
HU33	Dél-Alföld	5.27	32.35	2.94	17.62	0.00	0.00	52.91	
IE04	Northern and Western	5.07	15.78	0.73	#####	0.84	0.20	154.96	
IE05	Southern	9.01	30.92	1.14	#####	1.49	0.36	173.81	

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EE00	Eesti	8.12	14.10	1.27	54.30	5.13	0.00	74.81	1.40
IS00	Ísland	0.00	3.35	0.32		0.00	0.00	3.67	
DE60	Hamburg	11.77	0.26	1.12	0.05	2.54	0.00	3.98	1.36
ITC2	Valle d'Aosta/Vallée d'Aoste	0.61	0.08	0.13	2.67	0.03	2.33	5.24	
ITC3	Liguria	6.78	0.14	1.54	0.44	0.29	0.11	2.53	
EL51	Ανατολική Μακεδονία, Θράκη	2.82	6.22	1.55	29.39	0.00	0.19	37.36	1.27
ITH3	Veneto	23.29	21.09	8.72	0.00	1.00	1.88	32.70	1.23
ITF2	Molise	1.50	3.98	0.53	4.88	0.06	0.12	9.57	
NL41	Noord-Brabant	15.52	1.90	3.26	0.57	26.75	0.00	32.48	1.21
FRK2	Rhône-Alpes	48.77	22.64	14.07	18.60	5.86	15.76	76.93	1.14
ITI3	Marche	7.37	9.28	2.40	2.97	0.32	1.66	16.64	0.96
ITF6	Calabria	8.97	5.51	2.91	15.91	0.39	1.97	26.68	
ES52	Comunidad Valenciana	26.35	2.43	8.42	43.10	0.22	2.85	57.03	0.95
DE93	Lüneburg	16.38	15.11	2.07	10.37	3.54	0.00	31.09	0.85
ITH1	Provincia Autonoma di Bolzano/Bozen	2.44	0.51	0.61	2.99	0.11	3.02	7.24	
ITH2	Provincia Autonoma di Trento	2.56	0.22	0.75	1.33	0.11	2.59	5.00	
EL30	Αττική	18.13	0.42	4.87	7.79	0.02	0.00	13.10	0.79
ITH4	Friuli-Venezia Giulia	6.06	5.36	2.50	1.27	0.26	1.16	10.55	
DK02	Sjælland	4.58	8.00	0.93	4.03	15.95	0.00	28.91	0.75
ITI1	Toscana	18.00	17.14	5.43	5.37	0.78	0.61	29.32	
DED2	Dresden	8.51	6.68	2.38	4.02	1.84	0.01	14.93	0.73
ES62	Región de Murcia	7.66	6.07	2.37	16.91	0.06	0.00	25.42	0.61
ITI4	Lazio	26.47	16.59	7.62	3.08	1.14	0.64	29.07	
LI00	Liechtenstein	0.00	0.06	0.04		0.00	0.00	0.10	
LT01	Sostinės regionas	3.27	3.96	0.52	72.10	3.30	0.00	79.87	
ES51	Cataluña	40.02	11.76	10.53	40.42	0.34	0.48	63.53	0.53
LU00	Luxembourg	4.32	1.27	0.69	0.13	0.00	0.00	2.10	
LV00	Latvija	7.22	26.11	1.50	#####	60.89	1.23	213.21	
ME00	Црна Гора	3.38	0.71	1.17		0.00	0.91	2.79	
MK00	Поранешна југословенска Република Македонија	7.01	13.10	2.26		0.00	0.66	16.02	
MT00	Malta	0.00	0.03	0.92	0.00	0.00	0.00	0.96	
BG34	Югоизточен	5.65	23.26	2.84	7.71	0.19	0.05	34.06	0.46
NL12	Friesland (NL)	4.02	4.78	0.83	1.27	6.92	0.00	13.80	
NL13	Drenthe	3.08	2.37	0.64	1.24	5.31	0.00	9.56	
NL21	Overijssel	7.09	3.19	1.37	1.26	12.21	0.00	18.04	
NL22	Gelderland	12.54	3.19	2.30	1.25	21.60	0.00	28.35	
NL23	Flevoland	2.59	1.69	0.41	0.96	4.47	0.00	7.53	
NL31	Utrecht	7.86	1.41	1.05	0.20	13.54	0.00	16.19	
NL32	Noord-Holland	23.00	2.63	2.12	0.41	39.63	0.00	44.80	
CZ02	Střední Čechy	8.61	11.64	2.08	1.59	0.00	0.83	16.13	0.38
PT16	Centro (PT)	11.55	4.51	7.34	4.62	0.00	0.64	17.11	0.32
CZ08	Moravskoslezsko	9.82	3.90	1.35	1.23	0.00	0.00	6.49	0.23

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EL65	Πελοπόννησος	2.61	1.43	0.99	59.33	0.00	0.12	61.88	0.23
NO01	Oslo og Akershus	26.87	1.27	0.67		0.00	0.34	2.28	
NO02	Hedmark og Oppland	8.59	1.95	0.28		0.00	7.75	9.98	
NO03	Sør-Østlandet	21.71	2.12	0.67		0.00	15.59	18.39	
NO04	Agder og Rogaland	20.87	0.76	0.35		0.00	22.92	24.03	
NO05	Vestlandet	28.42	0.35	0.26		0.00	36.36	36.96	
NO06	Trøndelag	9.83	1.22	0.21		0.00	5.42	6.85	
NO07	Nord-Norge	11.30	0.15	0.15		0.00	15.66	15.97	
ITC1	Piemonte	20.91	13.40	6.07	6.55	0.90	4.20	31.12	0.23
PL22	Śląskie	21.59	9.14	3.36	0.80	6.25	0.13	19.67	
PL41	Wielkopolskie	14.72	31.77	2.79	27.34	4.26	0.00	66.16	
SE32	Mellersta Norrland	7.48	1.68	0.41	85.54	6.54	14.06	108.24	0.23
PL43	Lubuskie	4.28	8.00	1.24	7.66	1.24	0.00	18.13	
FRE1	Nord-Pas de Calais	33.65	18.65	5.24	7.80	4.04	0.00	35.74	0.19
SE11	Stockholm	28.92	1.53	1.11	0.09	25.28	0.47	28.48	0.19
PL92	Mazowiecki regionalny	10.05	29.06	2.00	12.15	2.91	0.00	46.11	0.17
PL62	Warmińsko-mazurskie	6.17	17.56	1.14	39.28	1.78	0.00	59.76	
PL63	Pomorskie	9.74	12.23	1.32	22.71	2.82	0.03	39.11	
PL71	Łódzkie	10.97	20.48	1.85	14.40	3.17	0.00	39.90	
PL72	Świętokrzyskie	5.61	10.44	1.19	1.80	1.62	0.00	15.05	
SE22	Sydsverige	20.01	9.31	1.33	11.66	17.50	0.11	39.91	0.15
HU31	Észak-Magyarország	5.71	12.08	2.14	0.00	0.00	0.12	14.34	0.14
PL84	Podlaskie	5.06	15.37	1.17	21.40	1.46	0.00	39.40	
PL91	Warszawski stołeczny	12.49	4.45	2.06	12.15	3.61	0.08	22.35	
ES24	Aragón	7.00	38.51	2.04	#####	0.06	0.90	270.46	0.13
PT11	Norte	17.60	3.05	7.47	15.20	0.01	4.58	30.30	
PT15	Algarve	2.27	0.26	1.73	2.30	0.00	0.00	4.29	
PL51	Dolnośląskie	12.93	18.79	2.61	13.42	3.74	0.05	38.61	0.13
PT17	Área Metropolitana de Lisboa	14.51	0.54	5.83	0.68	0.00	0.00	7.06	
DE13	Freiburg	11.96	5.59	3.59	0.47	2.58	2.41	14.65	0.12
PT20	Região Autónoma dos Açores	0.00	0.00	0.00		0.00	0.00	0.00	
PT30	Região Autónoma da Madeira	0.00	0.00	0.00		0.00	0.00	0.00	
RO11	Nord-Vest	6.78	27.56	4.23	9.10	3.10	0.94	44.93	
FI19	Länsi-Suomi	19.89	8.18	1.92	14.81	20.24	0.55	45.71	0.09
UKD3	Greater Manchester	12.33	0.57	1.48	0.06	17.76	0.00	19.86	0.09
RO22	Sud-Est	6.46	54.17	5.07	77.36	2.95	0.80	140.35	
FRI1	Aquitaine	23.77	27.27	7.97	30.70	2.86	0.45	69.25	0.07
RO32	Bucureşti - Ilfov	5.94	2.89	2.43	0.00	2.71	0.00	8.02	
RO41	Sud-Vest Oltenia	9.46	37.60	4.30	12.88	4.32	7.19	66.29	
RO42	Vest	4.72	33.64	3.47	10.63	2.16	2.05	51.95	
RS11	Београдски регион	9.19	2.97	1.89		0.00	0.00	4.86	
RS12	Регион Војводине	11.09	50.56	4.48		0.00	0.00	55.05	

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RS21	Регион Шумадије и Западне Србије	11.01	7.50	3.18		0.00	1.79	12.48	
RS22	Регион Јужне и Источне Србије	8.53	9.65	2.96		0.00	3.57	16.18	
DED5	Leipzig	5.32	4.53	1.44	2.15	1.15	0.02	9.29	0.05
SE12	Östra Mellansverige	23.70	12.76	1.40	20.57	20.72	1.53	56.98	
SE21	Småland med öarna	11.17	5.21	0.71	23.96	9.76	0.06	39.71	
UKC2	Northumberland and Tyne and Wear	6.36	3.67	0.86	11.71	9.17	0.00	25.42	0.04
UKL1	West Wales and The Valleys	17.16	10.15	1.93	29.71	24.72	0.23	66.75	0.04
SE31	Norra Mellansverige	11.20	4.48	1.01	14.93	9.79	3.20	33.41	
ITF5	Basilicata	2.66	10.68	0.65	23.27	0.11	0.35	35.06	0.04
SE33	Övre Norrland	8.07	1.88	0.57	#####	7.06	26.58	194.35	
ITI2	Umbria	4.58	7.10	1.37	4.08	0.20	0.88	13.63	0.04
SI04	Zahodna Slovenija	6.24	0.66	1.19	0.38	0.00	0.97	3.20	
PL82	Podkarpackie	9.03	12.09	2.14	4.30	2.61	0.03	21.17	0.04
FRC1	Bourgogne	11.67	39.48	5.13	46.20	1.40	0.00	92.21	0.03
SK03	Stredné Slovensko	9.36	6.85	2.05	1.02	0.00	1.31	11.23	
SK04	Východné Slovensko	7.92	8.63	2.29	0.00	0.00	0.00	10.92	
DEG0	Thüringen	11.73	14.41	3.31	5.49	2.53	0.03	25.77	0.03
UKC1	Tees Valley and Durham	11.39	2.16	0.80	1.95	16.41	0.00	21.32	0.02
DE50	Bremen	6.61	0.10	0.56	0.05	1.43	0.14	2.28	0.02
UKD4	Lancashire	6.64	2.71	1.02	0.61	9.56	0.00	13.90	0.02
UKH3	Essex	7.81	5.65	1.27	0.53	11.25	0.00	18.70	0.02
UKD6	Cheshire	4.24	2.80	0.74	0.42	6.11	0.00	10.07	
UKD7	Merseyside	8.30	0.39	1.15	0.00	11.96	0.00	13.50	
UKE1	East Yorkshire and Northern Lincolnshire	4.15	4.85	0.45	7.08	5.98	0.00	18.37	
UKE2	North Yorkshire	3.63	7.55	0.58	7.81	5.22	0.00	21.16	
UKE3	South Yorkshire	6.25	1.28	0.92	0.21	9.00	0.00	11.42	
UKM8	West Central Scotland	6.67	0.64	0.70	23.05	9.61	0.00	34.00	0.02
UKF1	Derbyshire and Nottinghamshire	9.64	5.21	1.47	1.22	13.89	0.00	21.79	
UKF2	Leicestershire, Rutland and Northamptonshire	7.91	7.03	1.46	3.77	11.39	0.00	23.65	
SI03	Vzhodna Slovenija	6.93	3.15	1.54	1.48	0.00	2.17	8.34	0.01
UKG1	Herefordshire, Worcestershire and Warwickshire	5.93	8.47	1.18	3.34	8.54	0.00	21.54	
UKG2	Shropshire and Staffordshire	7.21	8.08	1.35	3.95	10.39	0.00	23.78	
UKG3	West Midlands	12.90	0.32	2.29	0.00	18.58	0.00	21.20	

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UKH1	East Anglia	11.04	19.28	1.82	21.40	15.91	0.00	58.41	
UKH2	Bedfordshire and Hertfordshire	7.95	3.83	1.16	0.74	11.45	0.00	17.18	
DEA4	Detmold	11.06	6.97	2.35	2.60	2.39	0.00	14.32	0.01
UKI3	Inner London - West	5.07	0.00	0.43	0.00	7.31	0.00	7.74	
UKI4	Inner London - East	10.08	0.00	0.78	0.00	14.51	0.00	15.30	
UKI5	Outer London - East and North East	8.17	0.14	1.03	0.00	11.77	0.00	12.95	
UKI6	Outer London - South	5.71	0.11	0.75	0.00	8.23	0.00	9.08	
UKI7	Outer London - West and North West	9.13	0.10	1.22	0.00	13.16	0.00	14.47	
UKJ1	Berkshire, Buckinghamshire and Oxfordshire	10.43	7.95	1.80	1.98	15.03	0.00	26.75	
UKJ2	Surrey, East and West Sussex	12.40	6.69	2.27	0.33	17.87	0.00	27.16	
UKJ3	Hampshire and Isle of Wight	8.55	5.22	1.74	1.70	12.31	0.00	20.97	
UKJ4	Kent	7.92	5.07	1.23	0.90	11.41	0.00	18.61	
UKK1	Gloucestershire, Wiltshire and Bristol/Bath area	10.78	10.05	2.01	1.84	15.53	0.00	29.44	
DEB1	Koblenz	8.05	5.03	2.23	0.20	1.74	0.34	9.54	0.01
UKK3	Cornwall and Isles of Scilly	2.39	4.95	0.59	1.92	3.44	0.00	10.90	
UKK4	Devon	5.11	8.44	1.08	10.05	7.36	0.00	26.92	
DK01	Hovedstaden	9.88	1.55	1.30	0.60	34.39	0.00	37.83	0.01
ITF3	Campania	26.88	8.95	6.65	6.08	1.16	0.47	23.30	0.01
UKM5	North Eastern Scotland	2.17	4.12	0.20	27.14	3.13	0.00	34.60	
UKM6	Highlands and Islands	3.03	4.49	0.29	#####	4.37	2.95	182.11	
ITF1	Abruzzo	6.24	4.43	2.30	2.47	0.27	0.85	10.32	0.01
IE06	Eastern and Midland	13.61	15.84	1.13		2.25	0.12	19.34	0.00
UKM9	Southern Scotland	4.19	7.59	0.52	23.05	6.04	0.12	37.32	
UKN0	Northern Ireland	8.29	11.90	1.30	34.30	11.93	0.00	59.44	

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2020.113649.

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