ENSPRESO - an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials

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ABSTRACT

Data on the potential generation of energy from wind, solar and biomass is crucial for analysing their development, as it sets the limits on how much additional capacity it is feasible to install. This paper presents the methodologies used for the development of ENSPRESO, ENergy System Potentials for Renewable Energy SOurces, an EU-28 wide, open dataset for energy models on renewable energy potentials, at national and regional levels for the 2010–2050 period. In ENSPRESO, coherent GIS-based land-restriction scenarios are developed. For wind, resource evaluation also considers setback distances, as well as high resolution geo-spatial wind speed data. For solar, potentials are derived from irradiation data and available area for solar applications. Both wind and solar have separately a potential electricity production which is equivalent to three times the EU's 2016 electricity demand, with wind onshore and solar requiring 16% and 1.4% of total land, respectively. For biomass, agriculture, forestry and waste sectors are considered. Their respective sustainable potentials are equivalent to a minimum 10%, 1.5% and 1% of the total EU primary energy use. ENSPRESO can enrich the results of any energy model (e.g. JRC-EU-TIMES) by improving its analyses of the competition and complementarity of energy technologies.

1. Introduction

Triggered by the Paris Agreement on Climate Change which entered into force in November 2016, the European Parliament in the resolution of 4 October 2017 at the COP 23 UN Climate Change Conference [1], urges the European Commission "to prepare by COP24 [2018] a mid-century zero emissions strategy for the EU." In line with this request, the European Commission published the EU's vision for a prosperous, modern, competitive and climate-neutral economy by 2050 – A Clean Planet for All (COM(2018) 773 final). The Communication has triggered an EU-wide debate that should lead to the adoption of an ambitious strategy by early 2020 as requested under the Paris Agreement. Furthermore, the Regulation on the Governance of the Energy Union

and Climate Action (EU) 2018/1999 which ensures that the Climate and Energy Union goals are met, requires the EU member states to develop Integrated National Energy and Climate Plans that cover the five dimensions of the Energy Union for the period 2021 to 2030. Within this framework, the need for EU-wide transparent and coherent sets of data to meet the planning demands of future energy systems is clearly demonstrated.

Abundant literature has addressed the issue of determining how much renewable energy is potentially available in Europe. Past research in the field, initially triggered by the setting of EU-2020 targets, addressed the question as to how much RES energy could be provided at what cost, given the existing technologies. An extensive example –covering wind onshore, solar and biomass sources-is found in Ref. [2].

This effort attempted to clarify the share of the energy demand that could be supplied with RES. A suite of models, ranging from resource and land use to conversion technologies-, was set up to derivate cost and potential supply curves. Equivalent-full-load-hours is the metric used to account for the variability of wind and solar resources.

Since then, the question regarding available RES potentials has evolved. As the renewable electricity share grew in the energy system, so did the interest in understanding the variable nature of wind and solar resources in energy systems in general [3], while land use and sustainability considerations have also been gradually incorporated. An overview of the type and evolution of data and requirements for solar and wind resource characterization is given in Ref. [4]. The study highlights how earlier resource maps "were based on limited observations extrapolated across a landscape" while "recent maps have applied high-resolution weather models and satellite data coupled with radiative transfer modelling" on the terabyte scale.

When it comes to the wind resource estimation, [5] makes use of extensive EU-wide data (ERA (ECMWF Re-Analysis)). Available wind is characterized through average wind speed at 80 m and 100 m height, while CORINE Land Cover [6] provides land use. On a global scale [7], introduces the consideration of transmission losses, cost and visibility restrictions, finding that they can significantly impact the final technical potential available. A further study [8] estimates onshore and offshore wind global resource, adjusting the turbine power curves according to altitude, and classifying the resulting resource quality for a single representative wind turbine. Wind speed is derived from the Climate Four Dimensional Data Assimilation (CFDDA) mesoscale reanalysis climate dataset NCAR [9]. The resolution of the data set is approximately 40 km by 40 km. The potential electricity production is given for ranges of capacity factors. The use of capacity factors by timeslice, derived from hourly data to estimate global potentials is introduced in Ref. [10]. Starting from NASA MERRA-2 [11], 50 km by 50 km resolution data sets are used to provide potentials to energy systems and TIMES/MARKAL family models. A composite model of wind turbines is derived from the characteristics of key commercial generators. Results are given at country level. A follow-up of this approach for offshore wind can be found in Ref. [10]. Using an alternative perspective regarding Energy Return on Investment, [12] performs an analysis of existing global potentials.

Solar RES research has followed a similar evolution as wind. A condensed summary of physical resource evaluation until 2016 can be found in Ref. [13]. From the energy system point of view, first efforts tried to quantify the maximum theoretically available capacity.

A review of methodologies used up to 2013, taking into account "real present and foreseeable future efficiencies and surface occupation of technologies, land competition and other limits such as mineral reserves" is provided in Ref. [14] Approximately 65–130 EJ/yr were identified as the global accessible resource. A further study incorporates land use of both solar and wind resources in a global GIS-based analysis [15]. Roof and façade surfaces are assessed using country specific estimators, obtaining a potential between 130 EJ/y and 2800 EJ/y. Urban environment resource evaluation and building integrated PV become the focus of research and are summarised in the review [16], analysing more than 200 tools. On the technology side, [17] focuses on the evaluation of the technical conversion efficiency and proposes a distinction between *yield prediction ("an estimate of how much energy a particular PV installation will produce over a period of time")* and *energy rating, (as a way "to present the productivity of a PV module type in a certain type of climate")*. Energy rating leads to improved estimates of the real installation performance. The study obtains climatic data sets relating to the energy ratings of PV modules in Europe. The focus of [18] is on the selection of optimal sites in a given region. It proposes a simplified approach to obtain the average solar irradiation and temperature for specific areas, relying on the Photovoltaic Geographical Information System (PVGIS). Building on PVGIS [19], introduces the tool PVMAPS, enabling, to derive solar radiation and photovoltaic module

performance. A first assessment of the technical potential for Europe can be found in Ref. [20], where the criteria for EU cohesion funds allocation is assessed. This work proposes an evaluation chain that includes technical, economic, social and environmental factors. Geographical factors such as slope, land use, urban extent, population distribution or proximity to the power grid, are considered in order to generate 1 km resolution suitability maps for photovoltaic power plants. The solar resource is weighted according to yearly irradiation levels derived in Ref. [21], but it does not include the typical input data (a combination of technology, resource, performance and costs) required for an energy system model. The work presented in Ref. [22] reviews site suitability methodologies, decision criteria, and restriction factors and finds the "solar irradiation amount as the highest reported decision criteria followed". The field that has most recently experienced considerable development is research addressing the variability of solar (and wind) resources, an example of which can be found in Ref. [23]. The research in Ref. [24] reviews how energy system models approach the variability analysis, concluding that" there are still some challenges related to representation of spatiotemporal variability and openness as well as the demand side that should be addressed in future model development and application". ENSPRESO aims to contribute to the areas of spatiotemporal variability and openness. In Ref. [25], key opensource wind and photovoltaic power capacity factor datasets are compared [26] or [27] (based on MERRA reanalysis [11] data), EMHIRES [28,29] and Renewables.ninja [30]. This article concludes that "even based on the same data sources, time series were strongly dependent on methods applied subsequently", demonstrating the evolving nature of this research field.

In the field of biomass, interest has also shifted from quantifying the maximum global resource available (such as in Ref. [31] or [32]) to addressing more detailed questions such as land use, regional impacts or sustainability. This evolution is extensively analysed in the review performed by B. Elbersen et al. [33]. The EU BEE project [34] from 2008 is considered a milestone in terminology definition. It establishes agriculture, forest and bio-waste as the main source sectors for biomass. The review covers 40 studies, concluding that a critical future element will be the consideration of "sustainable practices and the development of appropriate infrastructures in agriculture and forestry for both energy and bio-based product and materials applications". While this framework has delivered a remarkable increase in the understanding of the biomass sectors, the link between these sectors and the demand side within energy systems faces its own challenges. As identified by Ref. [35], the description of the biomass supply in energy systems triggers a need for "dedicated modelling of bio-based sectors, covering the full range from feedstocks to products, with more details regarding chains and technologies". I. Kluts et al. review [36] in more detail how sustainability constraints are taken into consideration, concluding that, in general, sustainability constraints other than GHG emissions are neglected, purely selecting crops on the basis of the highest yield.

From the above discussion, we conclude that for the evaluation of wind, solar and biomass potentials, four evolutionary fields can be distinguished:

- Initial global resource evaluation, triggered by the debate regarding the feasibility of renewable and CO_2 emissions reduction targets.
- Techno-economic analysis, aiming to clarify technical and economic efficiency gains that are a crucial input for foresight and investment decisions models.
- Variability and dynamics for wind and solar, or sustainability related impacts for biomass.
- Local impact and detailed potential evaluation. Sub-national and regional studies aiming to provide more localised insight.

It has been noted that existing works addressing the techno-economic analysis of potentials:

- do not always provide full open and transparent access to their output data.
- rarely provide explicit or accessible input assumptions.
- often only provide one out of two essential blocks:
  - o the potential to expand technology installation levels.
  - o how much energy such installation would produce from the raw resource.
- often implement RES potentials via energy potentials for different technology classes. This approach, from the energy system models, has the disadvantage that technology-specific assumptions (such as typical technology type) are already included in the resource potential data, not allowing for analysis of the trade-off between technologies of different technology classes (e.g. CSP vs ground-mounted PV).
- Specially earlier studies did not consider sustainability concerns such as type of land available, setback distances or agriculture/ forestry practices.

The Joint Research Centre (JRC) strategy for 2030 states that JRC should aim *"to play a central role in creating, managing and making sense of collective scientific knowledge for better EU policies"*; it updates the mission of the centre to *"support EU policies with independent evidence throughout the whole policy cycle."* To provide evidence-based support to policy makers the JRC has recently pursued two complementary approaches in the renewable potentials field: ENSPRESO and EMHIRES [28,29].

The ENSPRESO database presented in this paper provides an estimation of the technical potential available for energy system models. ENSPRESO data set:

- covers biomass, wind (onshore and offshore) and solar resources.
- is transparent in its input assumptions with regards to key parameters, such as meteorological data, land use and technical hypothesis.
- presents a coherent set of modelling arrangements for the three source sectors.
- derives the raw available area for the different renewable resources, thereby allowing analysis of the competition between technologies.
- provides GIS-based estimations for the physical availability for every location and timeslice combined with the technological options, including cost estimates:
  - o For wind energy, capacity factor distributions are provided as a result of a technology matrix combining possible technologies and resource scenarios.
  - o For solar energy, potentials derived from solar irradiation data, available area for solar applications, and the solar technologies, are implemented independently of the potentials.
  - o For biomass sources, land-use and sustainability, specific scenarios are defined, by implementing criteria by sector and biomass subtype. Coherent land use modelling assumptions are made.

Thus the existing EMHIRES data sets, providing meteorologically-derived power time series at high temporal and spatial resolution, are complemented. As these are based on the current generation fleet, the data cannot be used directly in an energy system model analysing capacity expansion and requiring data on new installations. EMHIRES could be expanded to provide scenarios for 2030 or 2050 but even in that case, the aim would be the provision of detailed input data for power system models by simulating future wind farms or solar PV at the hourly level. Nevertheless, the hourly wind [28] and solar [29] data from EMHIRES can be used indirectly in energy system models. Country specific parametrisation of variable renewables and storage, based on EMHIRES data, is used to improve, for example, the representation of variable power in the energy model JRC-EU-TIMES ([37–40]), as presented in Fig. 1.

In the following sections, the modelling setting for each renewable source (wind, solar and biomass) is outlined, together with a condensed summary of the main inputs and outputs for each evaluation exercise. The ENSPRESO database can be accessed at the Joint Research Centre Data Catalogue (JRC-DC): https://data.jrc.ec.europa.eu/.

2. Wind potential

In this section, a description of the data and the underlying methodologies for the derivation and processing of wind potentials is presented. The meteorological wind potentials are systematically derived from 30 years of meteorological data at ½° latitude by ⅝° longitude and temporal hourly resolution based on the MERRA reanalysis dataset [11], and from high resolution geo-spatial data based on the Global Wind Atlas [41]. Since the main limitation for wind installations is the availability of suitable areas, three scenarios have been created to reflect different levels of land availability. These are based on varying degrees of stringency for the minimum allowed setback distance from settlements (onshore technologies), and for the exclusion of sensitive maritime zones (offshore technologies). The spatial analysis is combined with high-resolution mapping of wind climate, yielding a series of capacity factors within the identified available areas. To allow foresight scenario analysis using this set, CF distributions are obtained, enabling an estimation of newly installed farms will produce in a given grid cell. Finally, technical parameters are provided for several classes of wind technologies, yielding a detailed representation of future wind energy technologies. Further details can be found in Ref. [42].

2.1. Methods

This section describes the wind potential assessment method main steps as depicted in Fig. 2.

2.1.1. Land and surface availability scenarios and setback distances

For onshore wind, the current regulation for setback distances for wind generators from settlements varies greatly per Member State or even at more local levels [43–49]. There are cases in which the legislation does not explicitly mention a specific setback distance, defining setback distances as a function of the rotor diameter, hub height or acceptable noise levels. In 2016, the range of setback distances was from 120 m to 1200 m for small turbines and from 400 m to 2000 m for large turbines. Assumptions regarding the height and noise levels of these turbines are summarised in Table 3 of the supplementary data. Three scenarios have been obtained by projecting setback distances data to 2050:

- Reference Scenario: Current setback distances remain the same in future years.
- High Wind Scenario: Setback distances in all countries converge in 2030 to the lowest setback currently observed: 120 m and 400 m for small and large turbines, respectively. Setbacks remain the same in subsequent years.
- Low Wind Scenario: Setback distances in all countries converge in 2030 to the highest setback currently observed: 1200 m and 2000 m for small and large turbines, respectively. Setbacks remain the same in subsequent years.

In addition to setback distances, certain land areas (such as forests, NATURA2000 areas or urban surfaces) are unavailable for onshore wind in all scenarios, as summarised in Table 5 of the supplementary data.

The area classification is taken from the LUISA database [50] and the combined Global Land Cover and CORINE databases (named GLCplus) [51]. The total available area in the various scenarios is reported at NUTS2 regional level. Figure 8 in the supplementary data presents country-level summaries for onshore wind in the Reference
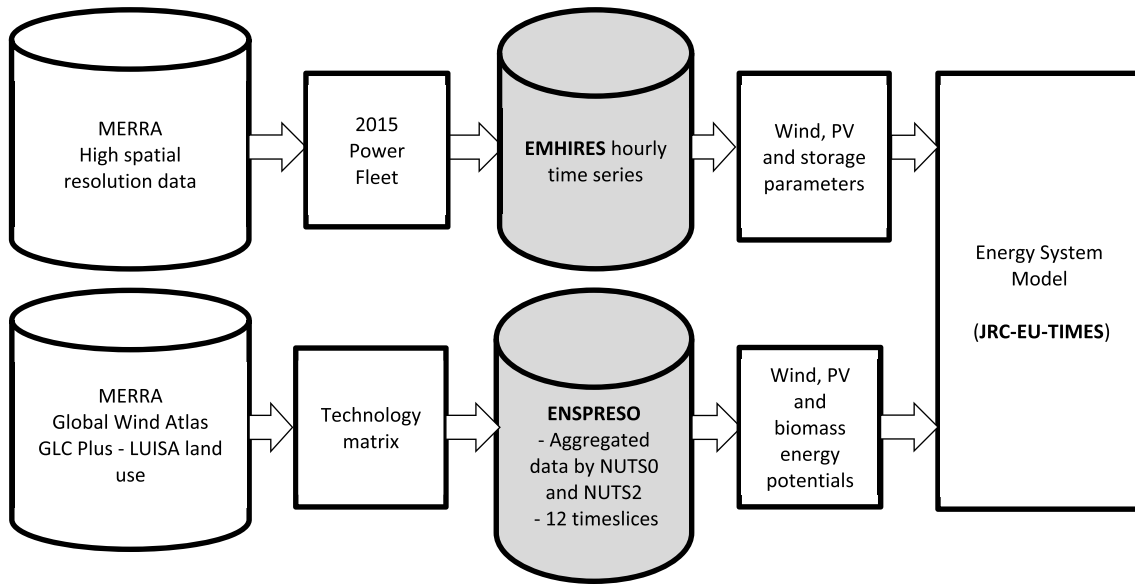
Fig. 1. Usage of EMHIRES and ENSPRESO datasets in an energy system model.

Scenario. The available land is different for small and large onshore wind turbines, due to the different setback distances applied.

For offshore wind, three scenarios have also been constructed by applying different buffers around offshore exclusion zones. These include protected areas, sea depth, shore distance and setback distances to shipping lanes, and pipelines. These scenarios (Table 4 of the supplementary data) are derived from the scenarios analysed in the WindSpeed project [52]. The total available area in the various scenarios is reported at NUTS2 regional level. Fig. 9 presents the resulting country-level summaries for offshore wind in the Reference Scenario. For offshore technologies, the turbine size does not influence the available area, hence no distinction is made (effectively only large turbines are considered for offshore installation), and therefore it is not possible to calculate the influence of wake effects.

2.1.2. Technology matrix

Area is converted into wind turbines' capacity based on an average turbine density of 5 MW/km^2. This is a representative value [5] that ensures that wake effects are kept to a minimum. The performance of a turbine in a given wind regime is characterized by its power-velocity curve. For this research we consider three different turbines, whose power-velocity curves are based on the V136–3.45, V112-3 and V90-3 Vestas turbines with a specific power of 240 W/m^2, 300 W/m^2 and

470 W/m^2, respectively. Vestas is the leading wind turbines' manufacturer in terms of capacity. The power curves of the three selected turbines cover a very wide range of the existing turbines, including more recent models. As an example, the V164–9.5 has nearly the same power-velocity curve as the V90-3. These turbine curves are combined with resource-area types and hub heights in a technology matrix to derive a discrete set of resource-generator type-installation combinations for which optimization decisions can be taken, as shown in Table 6. The relevance of technical and meteorological parameters is assessed in Ref. [53], finding that the wind speed variables (via location and hub height) have a larger impact on the power production than those related to the technology of a specific turbine.

2.1.3. Wind resource assessment

Capacity factors (CF) by timeslice (ts) and by turbine technology are evaluated as follows on a high-resolution grid:

- The capacity factors per technology, and per timeslice, are calculated on a high resolution grid, using the 6-h MERRA reanalysis data (1981/01/01 to 2009/12/31) to derive (I) the Weibull A (A_{ts}) and k (k_{ts}) parameters as a function of height, sector, season, and time of day as in Table 7 and (II) the Weibull A (A_{ren}) and k (k_{ren}) parameters as a function of height and sector. Also, the normalised wind
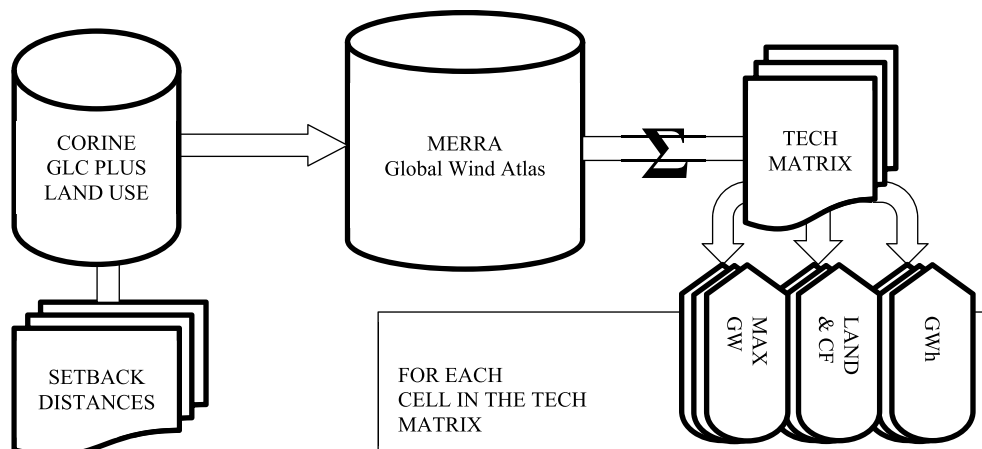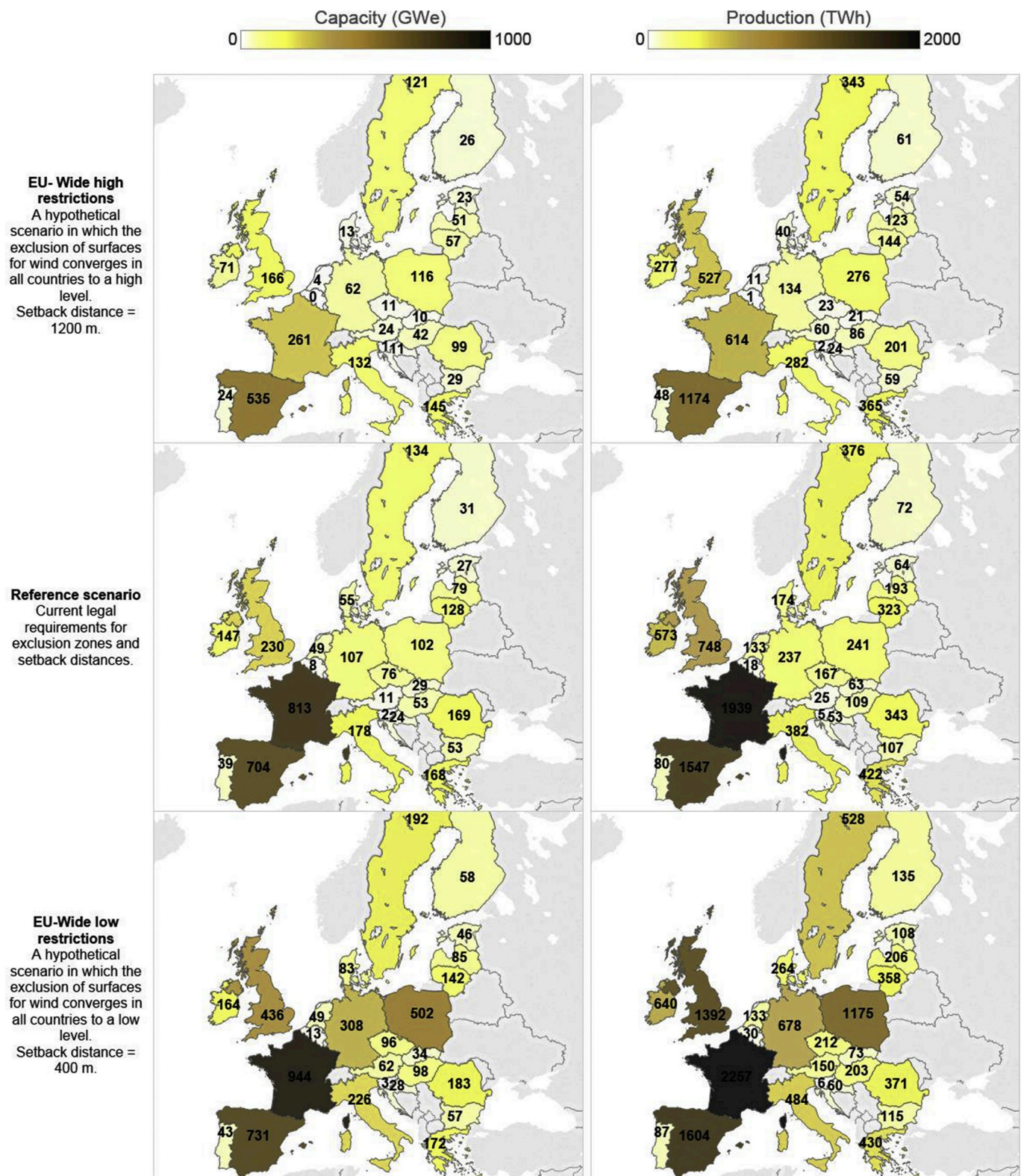

Fig. 2. Wind potentials evaluation scheme.

Fig. 3. Potential Capacity (GW) and electricity production (TWh) - Wind Onshore - High wind conditions. Only available areas with Capacity Factor > 20% for a turbine with 300 W/m² specific power at 100 m hub height. Total EU potential wind onshore capacity and production in the reference scenario amounts to 3400 GW and 8400 TWh, covering 16% of the total EU area.

direction frequencies (FWD$_{ts}$) are calculated for every height, season, and time of the day. All intermediate results are stored in netCDF files. The full details of the calculation process are given in section 7.9 of the supplementary data section. The research presented in this paper has not investigated the implicit and/or future

possible effects of climate change in the MERRA data.

- The final resulting geoTIFF files are re-projected onto the land-availability maps and aggregated at NUTS2 (regional) and NUTS0 (country) level.
- In the process of aggregation, CF on available areas have been sorted

for each NUTS area, to be able to assess distribution of the CF within each area, as wind turbines will probably be installed in the windiest areas first. This can be used to evaluate the CF of newly installed wind turbines depending to the potential already used. Fig. 10 in the supplementary data illustrates how these distributions are obtained.

2.2. Wind potentials

The results of the described potential evaluation can be accessed at the JRC-DC. Fig. 3 illustrates the resulting potential capacity and electricity production for 300 W/m^2 specific power turbines at 100 m hub height.

2.3. Discussion

The new dataset includes capacity factors for turbines with varying specific power. This allows for calculating trade-offs between levelised costs of electricity and costs of system integration (flexible demand) at low CFs. Low specific power wind turbines are able to generate electricity with increased capacity factors. In regions where low wind speeds prevail, these wind turbines can be economical due to their large rotor diameter. In more windy areas, low specific power turbines produce less electricity per turbine and it is often more economical to use high specific power turbines that have a larger generator.

Without relaxing the current legal requirements, the overall wind potential in the EU is equivalent to three times its current total yearly electricity demand. Onshore wind contributes with 8400 TWh and offshore wind with 1300 TWh. For comparison, in 2017 wind power accounted for 11% of the total net electricity production in the EU. The identified potentials are in line with results from Refs.[5,7,8,23,54–56]. A larger potential was identified by Ref. [23] (offshore results), [57–59]. The assumptions on power density (MW installed per km^2) for onshore wind and on the upper sea depth for offshore wind are key drivers behind these differences. Detailed output comparison with references given can be found at the wind data sets available at the JRC-DC.

3. Solar potential

Although the final data is provided at NUTS2 regional level, the analysis of solar irradiation is done at a higher spatial disaggregation based on satellite pixel data of roughly 1 km by 1 km resolution.

3.1. Methods

Data from the geo-spatial analysis of areas suitable for solar installations are combined with solar irradiation data to derive the potentials for different solar technologies, as shown in Fig. 4. In Table 8 in the supplementary material, a detailed overview is given of the interrelations between area, irradiation and technology clusters. Several technologies can compete for the same available areas. This allows, for example, for the modelling of the trade-offs between ground-mounted PV vs. CSP in high irradiation areas.

3.1.1. Spatial analysis

There is no spatial data available which directly provides surface area for roofs, facades and natural area available for solar deployment at the resolution required for this study. The CORINE land cover data set [60] provides a detailed classification of land cover information at a 100 m spatial resolution for EU-28 countries in the scope of this paper. Exclusion criteria per type of area and the final shares of available area for ground mounted solar are included in the supplementary data in sections 7.13 and 7.14. The resulting final areas available can be consulted at JRC-DC.

3.1.2. Solar irradiance and irradiation

Among the several computational methods that have been used in the past decades for estimating the downward solar irradiance from satellite observations [61], the HELIOSAT method [62] has proven to be reliable in several European research projects. The general idea of the HELIOSAT method for the estimation of surface solar irradiance from satellite images is to deal with atmospheric and cloud extinction separately. In a first step, the clear sky irradiance for a given location and time is calculated. In a second step, a cloud index is derived from Meteosat imagery. This step uses the fact that the reflectivity measured by the satellite is approximately proportional to the amount of cloudiness characterized by the cloud index. This value then is correlated to the cloud transmission. Finally, the clear sky irradiance is diminished by the cloud transmission to infer the surface irradiance. Section 7.15 gives a detailed summary of the HELIOSAT method.

The irradiation map data derived from the resulting irradiance is computed on a regular lat-lon grid of 5 arcmin (0.083°). This means the solar radiation is calculated on each grid point with a regular distance of 5 arcmin. The map covers an area from 30°North to 72°North and from 12°West to 40°East, which extends throughout Europe and some parts of Northern Africa.

The calculation of the irradiance on the tilted planes (for rooftops and facades) was performed according to the Muneer Model [63], which provides global and direct normal irradiation conversion onto an arbitrarily oriented surface. It considers the geometry of the plane in question and a non-isotropic distribution of the diffuse radiation from the sky and cloud conditions in the sky. The maps are aggregated to the
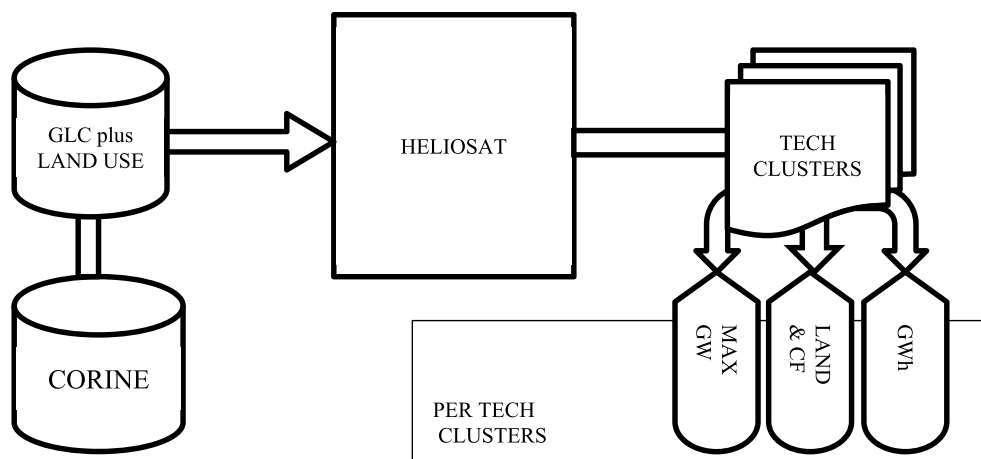

Fig. 4. Solar potential derivation process scheme.

Table 1
Difference in kWh/m^2 of the spatial average in a year to the average of all years, for GHI and DNI.

	2005	2006	2007	2008	2009	2010	2011	2012	2013
GHI	24	61	51	28	−160	−202	29	85	84
DNI	−55	−48	−31	−39	−177	−51	−8	198	212

NUTS2 regions by overlaying a NUTS2 vector layer and computing the average solar radiation in each NUTS region.

For the production of the timeslice data, an hourly time series is extracted for each centre of every NUTS 2 region. As the data for the centre of a NUTS2 region does not necessarily need to be of the same value as the geographical average of the region, a scaling table is produced that shows the scaling factors which are needed to achieve the same values that come from the analysis of the maps. The peak hour in summer is chosen from an analysis of the radiation in the summer season throughout all regions covered by the METEOSAT data. The irradiation data is merged with the data from the spatial analysis in order to receive the correct irradiation for the different area classes.

We assess irradiation data as an average of the period 2005 to 2013. The data is calculated on an hourly basis and then aggregated to annual average values, as well as to the sub-annual time division (timeslice level) of the JRC-EU-TIMES model. Therefore, a time series of hourly irradiation data for the period 2005–2013 has been analysed by calculating the variation of each year to the long-term average. Table 1 shows the difference of the spatial average in a year to the average of all years, for global horizontal irradiation (GHI) and direct normal irradiation (DNI).

An example output figure of the resulting timeslice irradiation for roof-top solar, is available in Fig. 13 of the supplementary data.

For some countries, the irradiation across the NUTS2 regions varies substantially (see, for example, Fig. 14). In order to include this kind of difference in the system models where the regional resolution is on a country level, we introduce four irradiation classes for areas not suitable for CSP technology, hence with low irradiation areas. Due to the heterogeneity of irradiation between the European countries, the bandwidth of the irradiation classes has to be individually determined for each country.

3.2. Solar potentials

By characterising solar energy potentials through solar irradiation and available area, the choice of solar technology can be left to the models. This requires the introduction of technology parameters which reflect:

(a) the efficiency of transformation of solar irradiation and
(b) the area a technology needs to convert a certain amount of solar energy.

To fully exploit such decisions of the model, the JRC-EU-TIMES model introduces the following to the revised model set-up for solar technologies:

- Trade-offs between ground-mounted PV vs. CSP, by technologies using the same land available, explicitly considered in the modelling.
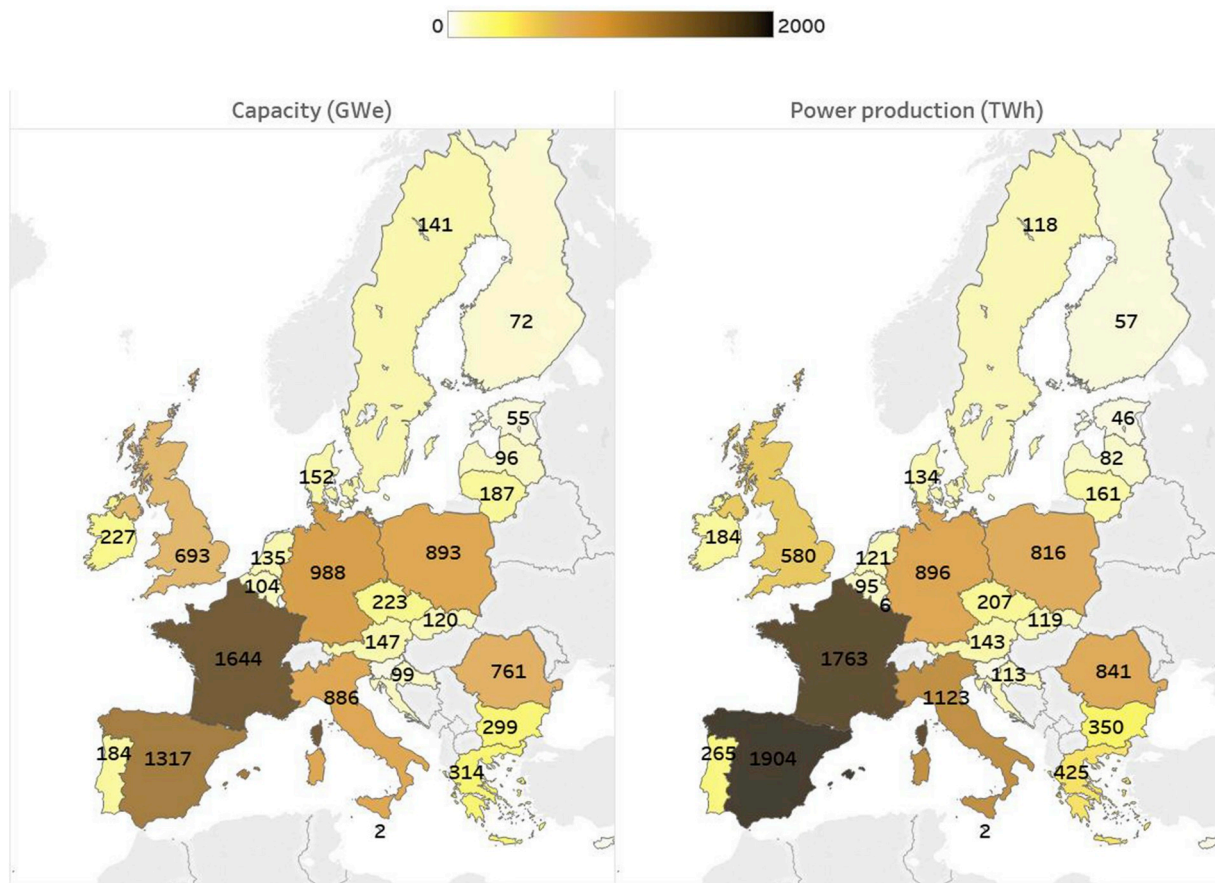

Fig. 5. Solar potential capacities and power production, assuming 170 MW/km^2, a 100% use of the available artificial areas and a 3% use of the available non-artificial areas. A performance ratio of 0.75 is assumed for the estimation of the potential power production. Total EU potential solar power capacity and production in such a scenario amounts to 10,000 GW and 11,000 TWh, covering 1,4% of the total EU area.

- Irradiation is modelled via process efficiency coefficients of solar technologies. These coefficients are multiplied (in the TIMES model) with the solar area (which is a process input) which results in energy production.
- Differentiation of roof type and orientations with corresponding irradiation and area potential.

In this way, technology evolution pathways will influence the electrical potential derived from the estimated solar irradiation. Section 7.17 covers the formulation of such pathways.

Resulting potentials attributed by NUTS2 region can be consulted at the JRC-DC, while a summary for the EU28 is provided in the supplementary data in Section 7.19 and Fig. 5.

The EU's total potential for solar electricity production (PV + CSP) ranges from 11,000 TWh to 550,000 TWh. For the low estimate, we assume 170 MW/km^2 and a 3% use of the available non-artificial areas. For the high estimate, we assume 300 MW/km^2 and 100%, respectively. Only a small share of this potential consists of roof-top and façade mounted PV, ranging from 1200 TWh to 2100 TWh.

3.3. Discussion

By far the largest share of the solar potential consists of open field solar systems. The potential electricity production, 11,000 TWh, is large as it is equivalent to three times the EU's 2016 total electricity demand. However, this would only require 3% of the available non-artificial areas or 1,4% of total EU land. Estimates from Ref. [64] on the technical potential for rural utility-scale PV in the US are in the middle of our range: 280,000 TWh. The surface area of the US is approximately double that of the EU28, however the authors used a conservative power density of 48 MW/km^2. These findings can be considered in line with [21], where it was estimated that the theoretical surface area needed to satisfy the 2004 total electricity demand varied between 0.1% and 3.6% of the total country area.

4. Biomass potential

This section outlines the evaluation scheme for biomass potentials, as described in detail in Ref. [65]. Agriculture, forestry and waste are the main sectors providing biogenic resources for energy production.

Agriculture sector energy sources considered are *energy crops* and *residues* (*primary, secondary* and *solid*). "Energy crops" refers to those crops whose primary target is the production of end-use energy carriers: sugar, starchy and oily crops, energy maize silage for biogas, and lignocellulosic biomass. "Primary residues" includes the dry and wet manure coming from cattle than can be gasified. "Secondary residues" refers to olive pits while "solid agricultural" gathers the waste obtained from pruning of permanent crops (namely orchards, vineyards, olives, citrus, nuts) and the straw and stubbles residues.

Biomass from the forestry sector is classified into *roundwood* production and *primary and secondary residues*. The roundwood used for energy purposes is considered. "Primary residues" are logging residues and other pre-commercial thinnings, while the "secondary residues" covers woodchips and pellets, sawdust and black liquor.

Finally, the waste sector produces energy biomass in the primary and tertiary residues categories. The primary residues consist of residues from landscape care management, roadside verges and abandoned lands. The tertiary residues cover biomass residues from different industries and municipal solid waste.

The general modelling scheme for each biomass sector is shown in Fig. 6 and further explained in the next section.

4.1. Methods

Sustainability criteria are key drivers when assessing the final amount of biomass available for energy, although there is no agreed definition of what constitutes "sustainable biomass". In this exercise, the maximum biomass potentials for energy are estimated under three scenarios. The High, Medium and Low bioenergy availability scenarios differ in assumptions related to land use, agricultural practices, and protected areas. The definition of the sustainability scenarios, and their assumptions regarding available land, harvesting and the limitations of biofeedstocks for each biomass type, is described in detail in Ref. [65]. A summary of the assumptions applied to the key variables is included in Table 13 to Table 15 in the supplementary data. In general, sustainable scenarios are generating lower yields, more limited bio-feedstocks and available land.

In addition to the resource potentials, the related supply costs are key to determining the systemic impact of biomass, together with other system-related variables, such as carbon price. In order to estimate the harvesting costs, we consider the cost of biomass production and of harvesting for biomass at the place of origin, transport, pre-treatment cost up-to the conversion gate (including the cost made after harvesting for pre-processing), and forwarding and transport to the place of collection. A distinction is made between the types of cost and price estimates specific to the biomass type and, based on data availability, different assumptions and methodologies are applied. For biomass types that are already traded in the market, the market price is considered as a good proxy for cost levels. For the other biomass categories, cost estimates are made taking account of national specific labour and machinery cost for production (in case of crops), harvesting and collecting of the biomass up to the roadside. Country-specific cost levels have been assessed considering labour costs, diesel and machinery price levels. Future evolution pathways follow the market price evolution as in their respective reference model runs depicted in Fig. 6.

4.1.1. Agriculture

The main quantitative model used to derive biomass potentials for agriculture is CAPRI [66]. CAPRI is an agricultural partial equilibrium model that covers the global, regional and farm-type scale. CAPRI ensures consistency in the scenarios and assumptions adopted across modelling exercises when estimating future land use and livestock production changes in the EU28, including land demand for domestic biofuels. The LUISA [67] model was used to estimate the evolution of built up areas as input for the yields input to CAPRI.

Yields and changes in yield levels, per region and country for conventional crops in CAPRI are implemented in the baseline scenario. They are derived from the AgLINK modelling system of the OECD [68], which takes information from questionnaires submitted by all OECD Member States as a basis. The Member States fill in time series on future developments relating to several variables including yield developments of their main crops. The national input is then recovered in AgLINK by adapting the behavioural equations in the model while at the same time adapting these to joint worldwide future development expectations regarding import/and export relations, worldwide price and technological developments. CAPRI takes the AgLINK results as input but adapts these where necessary to keep them consistent with other constraints set on yields for vegetable and animal products in CAPRI. These internal CAPRI constraints are needed to maintain stable relationships between very influential factors such as yield increase parameters, technology developments, seed use and losses and land use ratio factors. Further details on this aspect and also other technical details of the CAPRI model, the CAPRI Coco database and the incorporation of bioenergy crops can be found in Ref. [69].

4.1.2. Forestry

For the forestry biomass resources, the EFISCEN model [70] is used to evaluate the potentially harvestable stemwood in the three sustainability scenarios, mainly based on the European Forest Sector Outlook Study II scenarios. For stemwood and primary residues, EFISCEN provides the level of roundwood extraction that can be sustained for a prolonged period, resulting in the data for potentially harvestable
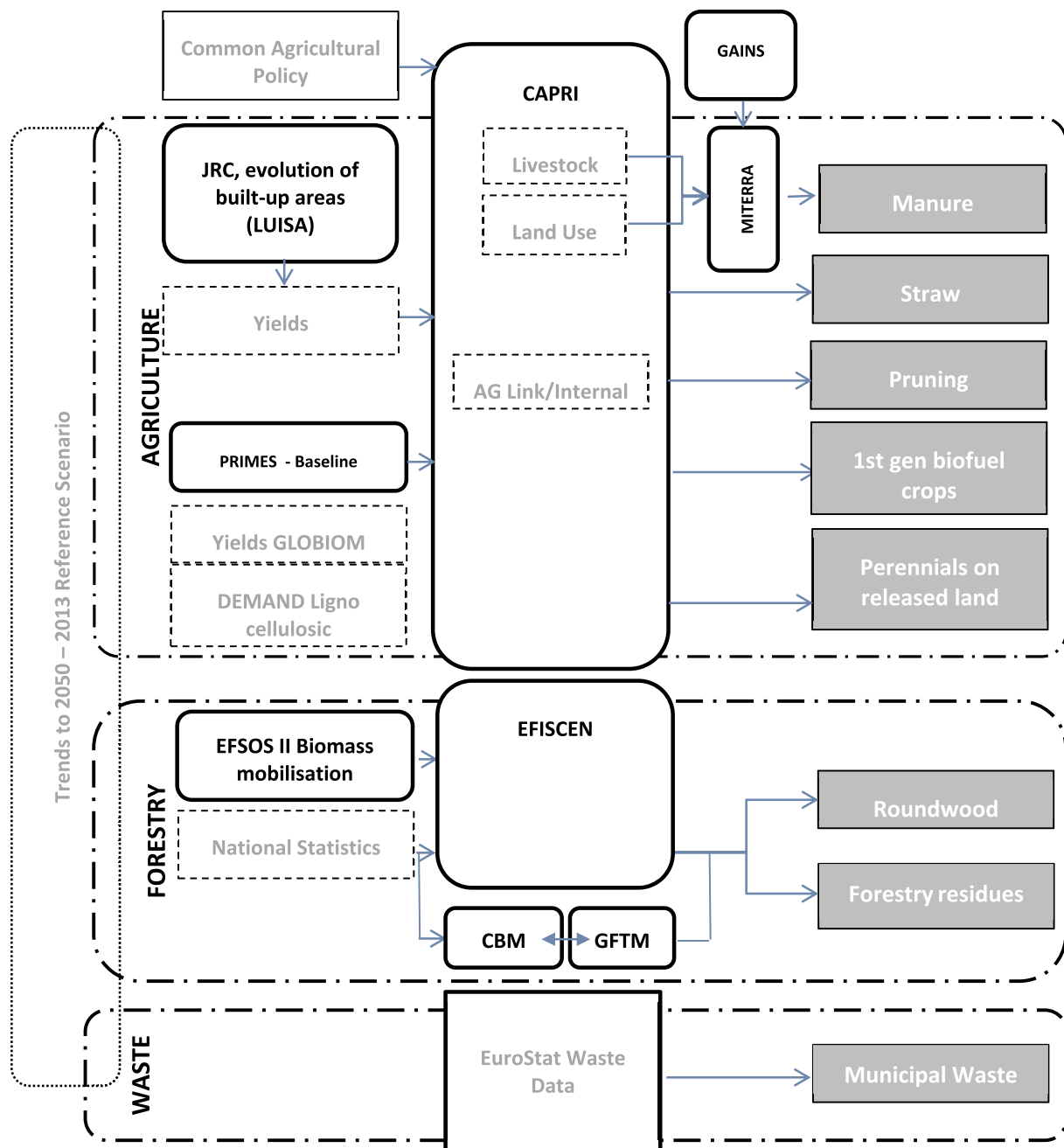
Fig. 6. Biomass modelling scheme.

stemwood and primary residues. The input data for running the EFISCEN model is the national forest inventory data providing as detailed information as possible on 'forest available for wood supply' specifying data on area (ha); growing stock volume (m^3/ha overbark); (if available) net annual increment (m^3/ha/yr overbark); if available gross annual increment (m^3/ha/yr overbark) and annual mortality (m^3/ha/yr overbark). For the associated extraction of primary forestry residues three to 895 million (m^3/yr overbark in 2030) from EFSOS are applied through a spatial method [71].

As for the biomass potential from the wood processing industry, secondary forestry residues include sawmilling residues (wood chips and sawdust, the latter often converted in pellets before being traded) and black liquor from the pulp & paper industry. For the assessment of the secondary residues that come from wood processing industries, we build on former assessments in the EU-wood and Biomass Futures project [72], that account for secondary residues in the current

roundwood production. Estimates for this potential were made at national level taking account of the size of wood processing industry activities.

In addition to the previously described sustainability scenarios, further work was conducted in the context of the Biomass study, carried out by the Joint Research Centre [73]. A business-*as*-usual scenario (BaU) has been produced with an alternative model setting (see Fig. 16 in the supplementary data). In this BaU forestry scenario, no major deviations from current market developments and utilisation of forest resources are foreseen, therefore providing a projection where current management practices are maintained. It is worth noting that Member States will soon have to propose forest reference levels of average annual net atmospheric emissions following the accounting rules of the LULUCF Regulation (Reg. 2018/841), but, in the short term, this may not directly affect BaU projections (Grassi et al., 2018). The modelling framework developed in the study (see Fig. 16 in the supplementary

data) integrates a forest resource model (the Carbon Budget Model, CBM, as described in Ref. [74]), and a global economic forest sector model (the Global Forest Trade Model, GFTM), as described in Ref. [75] to assess the European forest-based biomass harvest potential.

The output encompasses an estimate of the maximum wood supply (by CBM) which is defined as the amount of wood available under applicable silvicultural practices, without decreasing the biomass stock level in the forest area available for wood supply (FAWS). Future harvest demand is broken down into industrial roundwood (IRW) and fuelwood (FW, i.e. wood used primarily for energy purposes). IRW harvests, as well as the supply and demand of all processed wood-based products, are determined exclusively by market forces, constrained within the bounds of the maximum wood supply, as modelled by GFTM. FW harvesting is estimated based on current trends, namely according to the historical shares of IRW and FW [75]. The fraction of the maximum wood supply left in the forest is the additional potential under the assumption of constant growing stock.

4.1.3. Waste

The waste statistics provide a theoretical potential that is already 100% "used", as it is managed according to disposal laws. However, the current utilisation can be optimized by multiple cascades and a smart combination of material and energetic use. Hence, waste generation scenarios are also built by assuming an evolution pathway for future productivity and usage and recycling patterns, as described in Table 15 of the supplementary data. The waste potential evaluation is based on Eurostat statistics on national waste generation. The evolution of the waste categories over time is built considering GDP and population growth in the baseline. The current utilisation of waste is not considered. Agriculture and forestry potentials are built on models.

4.2. Biomass potentials

Fig. 7 provides an overview of the resulting potentials per feedstock at NUTS0 level. The JRC-DC provides further levels of disaggregation, regionally and per feedstock.

4.3. Discussion

A set of models has been used to tackle the features of each biomass sector, from coherent assumptions on land use and sustainability. Results are presented as total amount of primary energy available by scenario. When compared with the findings of a comparable study such

as the S2Biom project [76], similar ranges can be found for the reference scenario. For 2030 S2Biom foresees 14,674 PJ for 2030 for all the biomass source sectors, our calculations result in 11,076 PJ for the same year. The verification of future evolution through a biomass monitoring system should be the next research step, in order to circumvent the static nature of modelling projections. Contrasting the validity of the model's output with newly gathered field data should be part of coming assessments to increase the transparency of the provided data set.

5. Conclusions

The methodologies used for the derivation of a EU28-wide dataset on wind, solar and biomass resources have been presented. The dataset consists of an estimation of:

(1) suitable areas.
(2) raw resource potentials (wind speeds, irradiation, biomass yields) accounting for high-resolution effects, land use and restrictions.
(3) specific energy production (capacity factors, conversion efficiencies)
(4) energy production accounting for a wide range of technologies.

A consistent methodology was used for each of these elements and for each NUTS2 (regional) and NUTS0 (country) level, ensuring increased transparency in the input data.

In summary, resulting potentials for the base year of the reference scenario are 8400 TWh for onshore wind, 1300 TWh for offshore wind, 11,000 TWh for Solar PV and 8344 PJ (or 2,300 TWh) for the combined biomass sectors. These figures can be compared with the registered 64,758 PJ of primary energy consumption stated by Eurostat in 2016.

Presented wind potential data is one of the first examples of the EUDP Global Wind Atlas data to be used for energy models. High resolution terrain is required because low resolution wind datasets can have very serious shortcomings, in that the wind energy resource is underestimated. The MERRA 6-h reanalysis dataset allowed the time-dependency of the wind potential to be determined. The new dataset allows an analysis of the role of all types of wind turbines, including the ones with low specific power.

Scenarios for the suitable areas have been created. They can be used to better understand the impact of land restrictions. A comprehensive database of current setback distances has been compiled through literature review and expert elicitation.
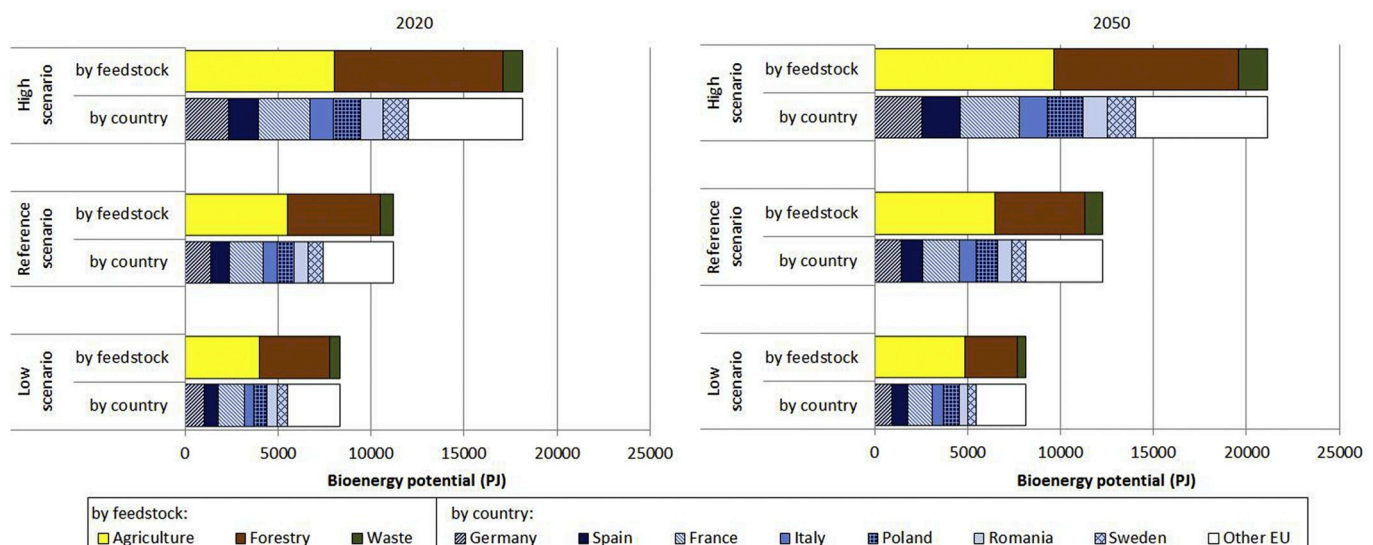

Fig. 7. Summary of EU28 Biomass potentials per feedstock, country and Scenario (excluding BaU Forestry).

Discussed solar potentials provide a comprehensive data set for characterising solar energy potentials through solar irradiation and available area. This is the first EU-28-wide data set that allows modelling of the competition for resources -and therefore land-use of the different converting technologies. The identified potentials are large, as they represent unconstrained use of a certain share of the areas identified as available. By design, we do not include public opposition or land costs.

Biomass potentials calculations establish a cross-sectorial coherent suite of models connected by sustainability and land-use assumptions. In the final data set, NUTS0 data is grouped by type of energy end-use, while specific land-related initial outputs are obtained at the NUTS2 level, per type of crop and forestry commodity.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2019.100379.

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