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highRES-Europe: The **high** spatial and temporal **R**esolution **E**lectricity **S**ystem model for Europe

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ABSTRACT

The high spatial and temporal resolution electricity system model, highRES, is used to design cost-effective, flexible and weather resilient electricity systems for Great Britain and Europe. The model is specifically designed to analyse the effects of high shares of variable renewables and explore integration/flexibility options. As the proportion of renewables in electricity generation increases, there will be increasing imbalances between electricity demand and supply. highRES is a high-resolution electricity system model that simultaneously considers infrastructure planning (investment) and operational (dispatch) decisions to identify the most cost-effective strategies to cope with growing shares of intermittent renewables. It does this by comparing and trading off potential options to integrate renewables into the system including the extension of the transmission grid, interconnection with other countries, building flexible generation (e.g. gas power stations), renewable curtailment and energy storage.

highRES is written in GAMS and its objective is to minimise power system investment and operational costs to meet hourly demand, subject to a number of unit and system constraints. It can model a variety of technical characteristics of thermal generators (e.g. ramping restrictions, minimum stable generation, startup costs, minimum up and down times) depending on the requirements of the research question, their CO2 emissions, and the technical characteristics of a variety of energy storage options. The transmission grid is represented using a linear transport model.

Code metadata

Current code version	V1
Permanent link to code/repository used of this code version	https://github.com/ElsevierSoftwareX/SOFTX-D-20-00101
Code Ocean compute capsule	
Legal Code License	MIT
Code versioning system used	git
Software code languages, tools, and services used	GAMS
Compilation requirements, operating environments & dependencies	Tested with GAMS 27.2
If available Link to developer documentation/manual	
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1. Motivation and significance

Here we present the high-spatial-resolution and high-temporal resolution electricity system model "highRES" which helps to answer questions around how to transition to a power system based on variable renewable energy technologies (VREs), i.e. wind and solar energy.

Wind and solar energy have come down dramatically in cost and their large-scale deployment now represents a technically and economically feasible solution to decarbonise the electricity sector. In light of the maturity of these VREs, electrifying other sectors such as transport and heating makes sense. Further, with

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rising temperature we can expect an increasing deployment of cooling technologies. In such systems, weather and climate have a crucial influence on energy supply (wind and solar generation) and demand (e.g. heating and cooling are weather-dependent). Such increases in the sensitivity of the power system to weather mandate the need for weather-resilient system planning.

Long-term whole energy system models (e.g. JRC-EU-TIMES [1], POLES [2]) usually trade off spatial and temporal resolution to provide long-term pathways for the entire system. However, it has been shown that such tradeoffs in terms of spatial [3], temporal [4,5] and technical [4] detail significantly affect the system design with high shares of VRE [6].

To address these issues more recently, different modelling teams have

(i) developed spatio-temporally disaggregated models that attempt to better capture VRE intermittency and their integration (e.g. highRES described here, REMIX [7], PyPSA [8], Calliope [9], Balmorel [10]) usually focusing on the power sector including the electrification of other sectors such as transport and heating;

(ii) used longer periods of historic weather from Reanalyses [11] or satellite data to consider the impact of inter-annual weather variability (e.g. as done in a study using highRES [12] and Ref. [13]) in determining "optimal" future power system design.

There are several open-source energy/power system models/frameworks such as OSeMOSYS [14] (http://www.osemosys.org), PyPSA [8] (https://pypsa.org), Calliope [9] (https://www.callio.pe) and Balmorel [10] (https://www.energyplan.eu/othertools/global/balmorel/). OSeMOSYS is a long-run energy system model whereas Balmorel, PyPSA, Calliope and highRES are power system models and are run for one snapshot year in the future (8760 h). Balmorel can be run for 250 time segments per year over a 20 year time-horizon, or 8760 time segments per year over one year.

PyPSA and Caliope are written in Python (Pyomo), whereas Balmorel and highRES are written in GAMS. People have different preferences and backgrounds that make it easier to use either Pyomo or GAMS. One advantage with Pyomo is that it is open-source and distributed under a BSD license, while GAMS requires a license to be purchased for use beyond small demonstration models. Previously, GAMS enabled highRES modelling that would have been very computationally expensive in Pyomo due to long model compile times before being passed to the solver, such as optimising over 10-weather years at once (e.g. [4]); it is possible that today Pyomo allows the same. Many modelling teams use the TIMES modelling framework, whose core code is written in GAMS, for energy systems analyses (e.g. UCL for UK with UKTM [15]; Institute for Energy Technology with the Norwegian TIMES model [16]), thus this legacy language, i.e. GAMS, makes it easier for modellers to switch between frameworks. In the past we have run the European TIMES and the UK TIMES models to give us electricity demand and carbon budgets for the power sector.

A specificity of the highRES model is that we can run the variable renewables at a grid cell resolution (based on Reanalysis; e.g. 30 km for ERA5) and demand supply balancing at a zonal level (as demonstrated in Ref. [17]). Calliope-Italy is following a similar approach adopting a double spatial scale: renewables being modelled across 20 regions based on region-specific weather conditions while dispatchable generation and transmission is modelled across 6 bidding zones.

It is of benefit having different energy/power system models and to compare/discuss their setup and results in model comparison projects such as SENTINEL (https://sentinel.energy), the Energy Modelling Platform for Europe (https://www.energymodellingplatform.eu) or OpenENTRANCE (https://openentrance.eu) all funded by the European Union Horizon 2020.

The highRES software is currently used by researchers and students at the UCL Energy Institute and the Department of Technology Systems at the University of Oslo. We have a version for Europe, GB and are currently developing highRES-Norway. The intended user groups are researchers and policy makers within the energy/climate policy space, with a particular focus on power sectors with a high penetration of variable renewables.

2. Model description, software design/architecture

highRES is a cost-minimising power system model run for one snapshot year (8760 h). Currently, there are two highRES versions: 1. Great Britain: split into 20 zones, which are based on those used in the National Grid's Seven Year Statements [18] and 2. Europe: split into 31 zones (27 EU member states plus Iceland, Norway, Switzerland and the United Kingdom).

The model minimises power system costs (operating costs and annualised investment costs) to meet hourly demand subject to a number of technical constraints; thereby optimising the dispatch and locational investment into power plants, storage and transmission grid extension. The transmission network is represented using a computationally efficient linear transshipment formulation (see [19] for more discussion). The balancing equation ensures that supply each in zone, from a combination of local power plants, storage and imports, is greater or equal to demand in every hour, with the excess either exported, stored or curtailed depending on what is most cost effective at the time. Other constraints describe the operation of power plants and energy storage operation, the flow of electricity via the transmission grid (with transmission losses accounted for), safety margins and emissions intensity. In addition to spatial explicit investment decisions, other outputs from highRES are for example total annuitized power system costs, generation per source and emissions.

Fig. 1 gives an overview on the highRES modelling framework showing input data and results.

Input are technical constraints on power plant operation, the current transmission grid and future technology costs including annualised investment and operating costs. In terms of thermal power we model nuclear, natural gas CCGT with carbon capture and storage and natural gas OCGT. The annual electricity demand and emissions constraint can be sourced from the output of a cost-optimising long time horizon (2010–2050) whole energy systems model (e.g. UKTM [15] for GB or ETM-UCL [20] and JRC EU-TIMES [1] for Europe). Such energy system models assess the mitigation trade-offs between sectors to meet a specific GHG target and capture the resulting electrification of different sectors. In addition, these inputs can be obtained from any relevant third party scenario of the country or region being modelled.

Second, we use historical meteorological data from climate reanalysis in physical power production models to model hourly wind, solar and hydro capacity factors from 1983–2017 30 km resolution (when using ERA-5 reanalysis produced by ECMWF). Climate reanalyses combine past observations with models to generate consistent (each grid point around the globe and regular output over time) time series of multiple climate variables (e.g. air temperature, pressure, wind speeds). The variable renewable energy (VRE, i.e. onshore/offshore wind and solar PV) component of highRES can be run in two modes: either at the grid cell level or with the cells aggregated to zones or countries. In both cases supply–demand balancing occurs at the zonal level via the transmission grid but in the former case the model is able to deploy VRE capacity in whichever cells within a zone are optimal. In the latter case, an hourly zonal average capacity factor for each technology is computed from all cells in that zone before running the model. Only cells with annual capacity factors above a certain threshold are included in this average.
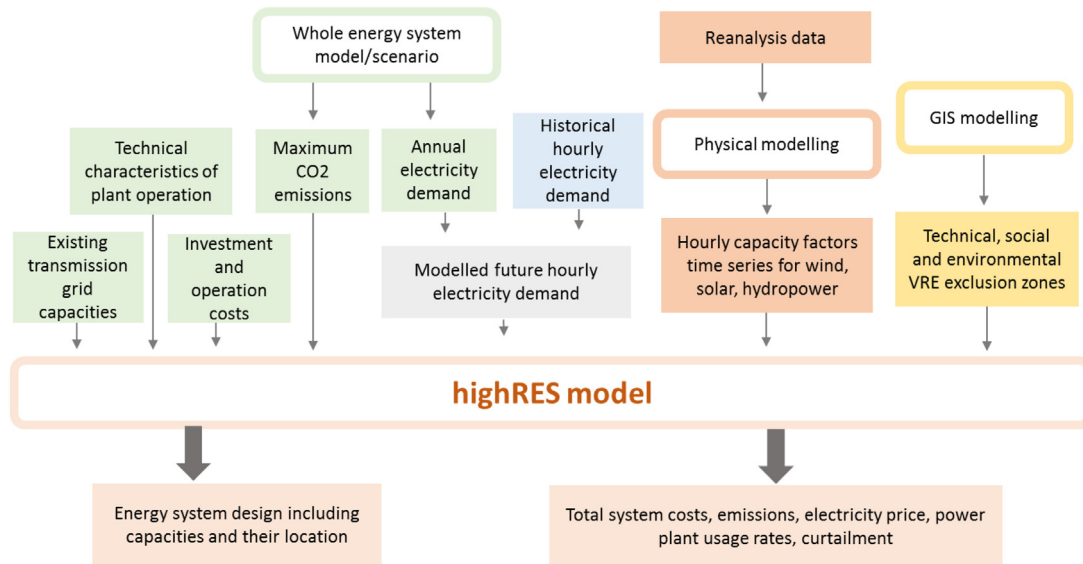
Fig. 1. The highRES modelling framework.

Third, we model spatially where renewable generation can be built. To do so we first perform a review helping us to define technical, social and environmental exclusion zones.

The highRES model is implemented in the General Algebraic Modelling System (GAMS) and solved using the solver CPLEX. Data is imported as text files (.dd files) and we convert output GDX to sqlite database as it is more convenient to read into Python and R.

This submission consists of the European version with weather data from 2013 based on ERA-5 reanalysis hosted on github: https://github.com/highRES-model/highRES-Europe. We model a 2050 power system in which annual electricity demand amounts to 5870 TWh and an emissions constraint of max 14.9gCO2/kWh (from whole energy system model run with a −80% GHG cut target). We also run a GB version which is practically the same GAMS code but with different input data.

The framework consists of the highRES model, as well as a number of external scripts in Python which are used to generate input data for the model but are currently not part of the model repository. Users can run the model with the here provided data or generate/input their own data.

The model setup consists of various files (further explanation can be found in the files and in Refs. [4,5]):

highres.gms: the main model

highres_data_input.gms: manages data input

highres_results.gms: contains the equations for results that are reported from the model run

The following modules can be turned on or off:

highres_storage_setup.gms contains the storage equations

highres_hydro.gms contains the reservoir hydro equations

highres_uc_setup.gms: unit commitment module for highRES to better represent the technical details of thermal plant operation and security of supply (so far this module has not been used in the European version)

*.dd and *.gdx files contain the input data

3. Evidence of actual and prospective application

The highRES model has been used in various studies to model future power systems with high shares of variable renewable energy sources. We have focused on two main areas: to demonstrate that 1. inter-annual and spatial weather variability and 2. social and environmental constraints are important when designing future highly renewable power systems.

3.1. Weather variability

In many of our studies we combine highRES with a whole energy system model (WESM). We use the WESM to develop internally consistent, whole energy system scenarios that meet a future emissions reduction target: e.g. the UK's Climate Change Act or an EU wide 2050 target. The WESM decides which sectors get electrified; it sets the boundaries on the electricity system (that is, total electricity demand and CO_2 grid intensity constraint). However, as mentioned previously, these boundaries could be taken from other third party scenarios.

In Ref. [12] we are using highRES to demonstrate for GB that designing power systems with high shares of variable renewable energy technologies is highly sensitive to the inter-annual variability of weather and that planning a power system using a single year of weather data can lead to operational inadequacy and not meeting a long-term decarbonisation target. However, we also show that there are some results that do not change significantly depending on the weather year used: first expanding the transmission systems consistently leads to lower energy system costs and second electricity storage and flexible generation (so called VRE integration options) are placed close to where electricity demand is located. In a similar study using the European version of the model [21] we are examining how inter-annual weather variability affects system planning and operation of the power system in Europe. We use 28 years (1988–2015) of hourly wind/solar/hydro production from ERA-5 and optimise for each weather year individually. We demonstrate that weather variability matters, especially for spatial deployment patterns. Depending on the weather year the share of renewables in total generation is between 87% and 90% and the VRE share between 79% and 83%. Solar capacities vary between +12% and -18% and wind energy between ± 5%. The capacities of flexible generation required for VRE integration are sensitive to weather year (−23%, +40%). Transmission grid extension is less sensitive (∼±10%) but there are very large increases compared to today's cross boarder transmission capacity (5 times current capacity). Fig. 2 shows the spatial distribution of VRE capacities in this study. One can see consistent patterns: Solar is located in the South and wind energy around Europe to take advantage of areas with good potential as well as those which are spatially diversified but there are some outliers and strong variability (up to +80%, -150%) depending on the weather year.
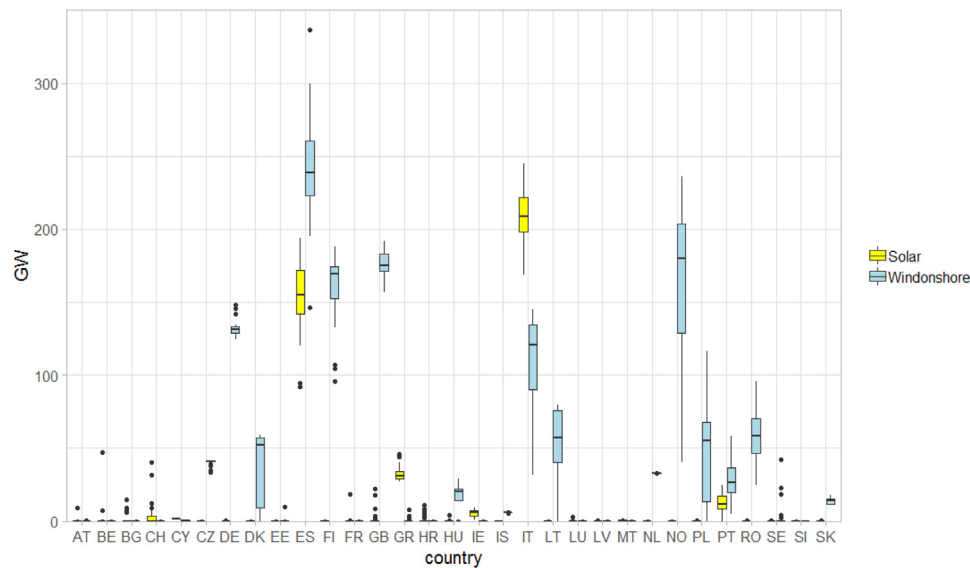
Fig. 2. Boxplots showing the spread in capacity investments per country over 28 weather-years.

In Ref. [17] we are demonstrating that floating offshore wind can be used to provide access to greater spatial diversification in future low carbon electricity systems.

3.2. Socio-environmental constraints to renewable energy deployment

The spatially explicit nature of our modelling approach also allows us to capture location dependent social and environmental constraints to renewable energy deployment:

The visual landscape impact of VREs (especially wind) can lead to low public acceptance. In Ref. [22] we use crowd-sourced scenicness data and define three scenicness scenarios (describing different public sensitivity to this visual impact) which decrease the land area available for wind energy deployment. Using these scenarios as an input into the highRES model we can assess their impact on the cost and design of the GB electricity system in 2050. Our results show that total system costs can increase by up to 14.2% when public sensitivity to visual impact is high compared to low. It is thus essential for policy makers to consider these cost implications and to find mechanisms to ameliorate the visual impact of onshore wind in local communities.

In Ref. [23] we study a power system that is sustainable in a wider sense including besides social and technical limitations also environmental ones: First, we develop plausible scenarios for limits on installed nuclear capacity, siting restrictions that shape VRE deployment and water use for thermal power station cooling. We then use those to perform a scenario analysis which allows us to understand the planning and operational implications of these constraints on the GB power system in 2050. We find that these factors combined can lead to up to a 25% increase in the levelised cost of electricity of the power system. We also show that such real-world limitations can cause substantial changes in system design both in terms of the spatial pattern of where generators are located and the capacity mix of the system.

4. Broader impact

There is a wide-spread consensus on the need to achieve the headline goal of the Paris Agreement [24] of keeping global warming to well below 2 °C and in so doing avoid dangerous climate change. This requires a rapid decarbonisation of the energy system; which, as has been shown by modelling based research, can be achieved by electrified and interconnected systems with a high share of variable renewable energy sources (i.e. wind and solar) (e.g., Ref. [10]) providing up to 100% of the total electricity output [25]. In such highly electrified systems with high shares of VREs, weather and climate have an important and growing influence on the supply and demand of energy, from solar and wind generation to heating and cooling demands.

With its new Green Deal [26], the EU has broadcast its ambition for global leadership in terms of achieving climate-neutrality and it offers a roadmap for socially beneficial stimulus investments [13]. The expected massive public spending as response to the COVID-19 crisis could lead to huge investments into VREs offering a unique opportunity for transitioning to a net-zero energy society.

Power and energy system models are a key policy tool to analyse the integration of high shares of renewables into energy systems that meet the Paris Agreement. Important methods to manage renewable intermittency are to integrate different renewable technologies into the system and to take advantage of the fact that different countries have different overall resource potentials but also the timing of production varies geographically, thus renewable intermittency can be balanced over larger areas (e.g., Ref. [27]). However, it is still common practice to (i) use spatio-temporally aggregated models; (ii) average multiple years or use a single weather-year thereby neglecting inter-annual weather variability (see, e.g., Refs. [28,29] for discussion). To address these issues the use of (i) spatially and temporally disaggregated models such as the highRES [12] in combination with (ii) longer periods of historic weather to consider the impact of inter-annual weather variability [12,29,30] in determining "optimal" future power system design is necessary. Using models that do not account for the inter-annual variability of weather as well as changes to weather due to climate change may lead to the design of a system that does not reach the carbon emission reductions required and intended, with possible frequent blackouts requiring costly investments. We were able to show with highRES the benefits of spatial diversification and the need to include many years of weather data when planning future renewable focused energy systems. In the future we aim to extend this method by using high resolution climate data to design climate change resilient net-zero carbon power systems.

Further, despite high levels of overall public support for renewables, their scale, visibility, and infrastructure requirements

(e.g. transmission lines) mean that specific projects often face significant opposition from local communities [31]. Some examples are the following: In 2015, the UK government responded to local opposition to onshore wind by decentralising decision-making in order to ensure the 'planning impacts identified by affected local communities [were] fully addressed, and […] the proposal [had] their backing' [32] and since then planning applications for onshore wind have decreased by 96% in the period 2016–2020 compared to 2011–2015 [33]. In Germany onshore wind installations also fell by nearly 80% in 2019 [34]. In 2019, faced with large-scale resistance from civil society and NGOs, Norway's government withdrew the national framework plan for wind energy [35]. The Norwegian Parliament (Storting) has now determined that future decisions on windpower siting are to be made or approved by the local municipalities [36,37]. While energy and power system models include high levels of techno-economic detail, they often exclude the geographically dependent social factors that will actually shape the process of energy transition. This may lead to designing solutions which are neither publicly nor politically feasible. This could, at best, make it significantly costlier, at worst, impossible, to reach long term decarbonisation targets. Modelling approaches which permit the inclusion of spatially dependent social factors such as highRES are thus important when designing future energy systems that meet the Paris Agreement.

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.

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