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Assessing global climate change mitigation scenarios from a power system perspective using a novel multi-model framework

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ABSTRACT

There is a debate regarding the suitability of global integrated assessment models (IAMs) for long-term planning exercises of the global energy system. This study informs this debate from a power system perspective and proposes a methodological framework for soft-linking of global IAMs with detailed global power system models. With the proposed open-source framework, the scenario results from IAMs can be fed into a power system model to assess given scenarios with enhanced modelling resolution. Results from these simulations can be redirected to the IAM through iterative bi-directional soft-linking. A proof of concept application is presented by linking global IAM MESSAGEix-GLOBIOM with global power system model PLEXOS-World. Among others, the results suggest that the assumption of unconstrained electricity flows inside large regional copperplates without internal network constraints causes an overestimation of the potential of variable renewables within MESSAGEix-GLOBIOM. We propose areas for informed improvements in MESSAGEix-GLOBIOM and for IAMs in general.

1. Introduction

1.1. Background

Integrated Assessment Models (IAMs) are widely used to assess scenarios for the long-term evolution of the global energy system over multiple decades (Pietzcker et al., 2017). IAMs are intended to broadly assess the long-term impact of interlinked developments such as the impact of emission mitigation policies on climate change and the economy (Rogelj et al., 2018). IAMs therefore not only represent different energy demand and supply sectors, but also integrate the constraints and impacts associated with material and land-use requirements and emissions, as well as water consumption and fossil- and renewable resource availability (Collins et al., 2017a). In addition to the broad sectoral representation, IAMs are commonly applied for analysing policy questions that deal with large spatial coverage – often global – and long modelling horizons of up to one century. Hence, to remain computationally tractable, limits must be placed on the overall computational details of model simulations (Pfenninger et al., 2014), and as such IAMs are restricted in temporal resolution with a significant geographical aggregation of model regions (Iwanaga et al., 2020).

A significant challenge for IAMs is the modelling of the variability in electricity demand and supply as a result of the integration of large amounts of distributed variable renewable energy sources (VRES) in emission mitigation scenarios (Pietzcker et al., 2017). Traditional power systems with high levels of dispatchable technologies whose output can be controlled and requested on demand can be well represented in IAMs due to their often-predictable operation. However, due to the limited amount- or absence of sub-annual time resolution, a weakness of IAMs lies in realistically representing the operation of VRES technologies and the corresponding integration challenges (Collins et al., 2017a). To account for the above, global IAMs tend to integrate generic relationships to represent the integration of VRES technologies in a stylized manner. For example, in the global IAM MESSAGEix-GLOBIOM, the amount of solar and wind curtailment per region is accounted for using a marginal curve with increasing curtailment at higher VRES penetration levels (Johnson et al., 2017). Curtailment in power systems refers to the unplanned reduction of generation output.

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A number of model improvements have been made in recent years regarding power system representation in IAMs as well as general efforts regarding model evaluation and transparency in model inputs (IAMC, 2019) and outputs (Huppmann et al., 2018). Following the ADVANCE project (Luderer et al., 2016), the global IAMs AIM/CGE (Dai et al., 2017), IMAGE (de Boer and van Vuuren, 2017), MESSAGEix-GLOBIOM (Johnson et al., 2017), POLES (Després et al., 2017), REMIND (Ueckerdt et al., 2017) and WITCH (Carrara and Marangoni, 2017) have made model specific improvements regarding VRES integration. Ueckerdt et al. (2017) developed Residual Load Duration Curves (RLDCs) that represent the electricity demand of a specific region that must be met by non-VRES. These curves have been adopted by a number of global IAMs for enhanced parameterization of VRES integration challenges. Pietzcker et al. (2017) developed a set of qualitative and quantitative criteria which allows for critical scrutiny of power system representation in IAMS. Based on these criteria additional required improvements for future versions of global IAMs have been identified. This includes the overall modelling of electricity transmission infrastructure with a focus on the general pooling effect of shared generation resources through transmission integration as well as limitations on internal electricity flows in large model regions like Latin America due to power transmission constraints. Furthermore, mentioned as the most critical improvement in IAMs is to extend the data basis to enhance the overall spatial representation as well as refined implementation of region specific model input- and assumptions. However, as argued in the literature, there is a limit on internal IAM model improvement both regarding computational functionality as regarding available time and resources for model development (Gambhir et al., 2019). To fill this gap, additional modelling tools can be utilized to complement IAMs regarding assessments of sectoral specific detailed dynamics. For integration of new model assumptions in IAMs, it is recommended to benchmark simulation results with operational power system dispatch models (Collins et al., 2017a). Power system models can assess operational aspects of a given power system with high spatial, temporal, and technological detail. Due to the dedicated sectoral scope, a range of state of the art energy and power system models such as Artelys Crystal Super Grid (Artelys, 2020; Brinkerink and Shivakumar, 2018), LUSYM (Van Den Bergh et al., 2015; Delarue and Van den Bergh, 2016), LUT Energy System Transition model (Bogdanov et al., 2019), PLEXOS (Energy Exemplar, 2020; Brinkerink et al., 2021) and PyPSA (Brown et al., 2018, 2019) have the proven ability to simulate spatially rich continental- or global-scale models with hourly temporal resolution at minimum.

1.2. Model interlinkage

By accepting that all sets of simulation models have clear limitations, it is possible to make use of the strengths of one type of model to inform and improve the other by means of inter-model linkages that facilitate data flows (Chang et al., 2021). There are two main approaches that can be distinguished, one being a soft-link approach in which results from the IAM are being fed into the power system model to gain insights into important aspects of power system design and operation and to assess the overall feasibility of a given scenario (Deane et al., 2012). For example, Collins et al. (2017b) used power system model PLEXOS to assess scenarios from the PRIMES energy systems model as used to inform European Union energy and climate policy to provide additional insights from a power system perspective. Results highlight among others an overestimation of VRES generation within PRIMES. Optionally, by means of an iterative process between the two models through bi-directional coupling, the results from the power system model simulations can be used to adjust the model input and reparameterize the IAM. The other main approach that can be applied is a hard-link method in which the optimization occurs in a parallel fashion by means of an algorithm that communicates dynamically between both models and leads to a singular set of results (Wene, 1996). An example application of this can be found in Després et al. (2017), where the authors use a hard-coupled implementation of global IAM POLES with the European Unit Commitment and Dispatch model (EUCAD). In this study the hard-coupling is only utilized for countries within Europe, other regions solely rely on the simulation equations in POLES.

Despite successful applications, both linking methods have their disadvantages that can act as barriers for implementation. Soft-linking often requires manual data manipulation, and as time passes or the users involved in the specific soft-link change, it becomes challenging to repeat the exercise (Johnson et al., 2017; Wene, 1996). Hard-linking involves significant time and resources to develop a smooth operation of co-optimization of both models which is not always feasible (Wene, 1996), nor are all modelling tools computationally able to function in this setting. Next to the above, Collins et al. (2017a) argue that due to the small number of very sizable regions in global IAMs – each of which is assumed to be a "copperplate" without internal network constraints – as well as long modelling horizons, it can be challenging to perform power system model simulations for every IAM region for all years in the modelling horizon.

A common approach therefore is to make use of a power system model based on a limited spatial scale to benchmark given scenarios from global IAMs. The results from these spatially limited power system model simulations are often used to develop stylized relationships for power system representation in the IAM uniformly for all regions (Sullivan et al., 2013). This approach is viable given practical constraints such as availability of data to construct accurate power system models for all regions globally, yet recent open-data initiatives have made the development of detailed global power system models such as the LUT Energy System Transition model (Bogdanov et al., 2019), OSeMOSYS Global[1], PLEXOS-World (Brinkerink et al., 2021) and Supergrid[2] possible. Open access model input data from PLEXOS-World (Brinkerink and Deane, 2020) and Supergrid can easily be transferred to other modelling tools.

1.3. Contribution of this study

This paper proposes a methodological framework for soft-linking of continental- or global IAMs with power system models. With the proposed framework, output from IAMs can be fed into a power system model to assess given scenarios with increased spatial, technological, and temporal resolution. The power system model output can in turn be redirected to the IAM to use assessment outcomes for internal improvements such as renewed region-specific power system input and model assumptions. The novelty of this framework and paper is multifold and developed in response to the identified limitations of IAMs and existing model linking methodologies. First, the framework is not used to assess scenarios with the often coarse spatial representation of IAMs as is, but actually uses the long-term capacity expansion module within the power system model to downscale the regional copperplates as used in the IAM to a more spatially detailed level. This allows for a more accurate assessment of local power system dynamics within the given IAM scenario. Secondly, the framework promotes using a standardized data format, making it non-discriminatory and useful for a wide range of IAMs and power system models while simultaneously allowing the exercise to be easily repeated when needed. Lastly, being a first of its kind, the framework is designed and applied in this paper to link a global IAM with a global power system model.

Considering the importance of global IAMs for key scientific reports such as Chapter 2 of the Special Report on Global Warming of 1.5 °C by the Intergovernmental Panel on Climate Change (IPCC) (Rogelj et al., 2018) and Chapter 3 of the forthcoming Sixth Assessment Report (AR6), an ongoing debate exists within the scientific community (Gambhir et al., 2019; Pindyck, 2017; Schwanitz, 2013) whether global IAMs are

[1] https://github.com/OSeMOSYS/osemosys_global.

[2] https://github.com/niclasmattsson/Supergrid.

suitable for long-term planning of the global energy system due to among others the limitations as described in this section. The proposed framework informs this debate from a power system perspective by providing the ability to scrutinize IAM scenarios in dedicated power system models while simultaneously supporting internal improvements of power system representation within the IAMs. As a proof of concept, the global IAM MESSAGEix-GLOBIOM (Krey et al., 2016; Fricko et al., 2017) is soft-linked to PLEXOS-World (Brinkerink et al., 2021; Brinkerink and Deane, 2020), a 258-regional detailed global power system model developed in PLEXOS (Energy Exemplar, 2020). In the past, Johnson et al. (2017) had concerns regarding the reproducibility of soft-linking MESSAGEix-GLOBIOM to a detailed power system model however they stated that "it would be useful to compare the results of MESSAGE with those from a detailed power system model with high temporal resolution to validate how well MESSAGE simulates the impacts of VRES deployment". The proposed standardized framework for soft-linking IAMs and power system models makes the soft-link easier to reproduce and hence the envisioned exercise can be applied as shown in this study. By means of a snapshot analysis for the year 2050, a 1.5 °C and high VRES scenario from MESSAGEix-GLOBIOM is assessed regarding its technical feasibility. Furthermore, results from PLEXOS-World are used to improve parts of the power system representation of MESSAGEix-GLOBIOM to show the frameworks potential for bi-directional soft-linking. Section 2 describes the proposed methodological framework and Section 3 includes the results of the proof of concept application of the framework. Section 4 includes a discussion regarding the results of this paper and regarding the power system representation of MESSAGEix-GLOBIOM including suggested improvements. Section 5 concludes with the main findings including a commentary on the theoretical discussion regarding the suitability of IAMs for planning exercises of the global energy system.

2. Methods

The proposed methodological framework for soft-linking IAMs with dedicated power system models allows for assessments of the technical feasibility of specific IAM scenarios with higher spatial, technological, and temporal resolution. This model soft-linking enables enhanced insights regarding VRES integration and provides the ability to assess the suitability of uniformly applied stylized relationships and model inputs for the power system representation in IAMs. Even though the framework is designed to be generally applicable to most global IAMs and power system models, this paper includes a proof of concept soft-linking the global IAM MESSAGEix-GLOBIOM with global power system model PLEXOS-World. This allows for a general understanding of the framework steps and also provides an example of a practical application. Before diving into the details of the framework, a general introduction of the modelling tools and how they represent power system dynamics is merited. Aspects specific to the integration of scenario data from MESSAGEix-GLOBIOM in PLEXOS-World and vice versa as well as modelling assumptions relevant to a specific step in the framework will be covered in Section 2.3.

2.1. MESSAGEix-GLOBIOM

MESSAGEix-GLOBIOM is a global IAM with a detailed representation of technological, socioeconomic and biophysical processes in energy and land-use systems (IIASA Energy Program, 2020). The model has different spatial resolutions, typically ranging between 11 and 15 world regions, with the spatial resolution of the 11-region model as assessed in this study visualized in Fig. 1. MESSAGEix-GLOBIOM is built using the open-source MESSAGEix modelling framework (Huppmann et al., 2019). Although the MESSAGEix framework is capable of model simulations with sub-annual timeslices, the global model MESSAGEix-GLOBIOM generally runs with yearly resolution. The main characteristics of MESSAGEix-GLOBIOM with respect to the representation of the power system is summarized and compared with other global IAMs in Pietzcker et al. (2017). To account for challenges associated with VRES integration and power system reliability Sullivan et al. (2013) introduced four constraints in MESSAGEix-GLOBIOM, including (I) capacity reserves to meet peak electricity demand at all times with a desirable reserve margin, (II) operating reserves to provide short-term system flexibility based on the amount of load and electricity from VRES in the system, (III) expected curtailment values relative to different penetrations levels of VRES and (IV) grid integration costs also relative to VRES penetration levels.

Johnson et al. (2017) argues that the approach in Sullivan et al. (2013) has a range of limitations for example the fact that the parametrization of the introduced constraints were uniformly applied for all MESSAGEix-GLOBIOM regions solely based on simulations from a single-region power system model (Sullivan et al., 2013; Sioshansi, 2010). Johnson et al. (2017) therefore applied a hybrid approach using region specific RLDCs from (Ueckerdt et al., 2017) to create regionally stylized parameterization for the impact of VRES deployment on for example curtailment and non-VRES flexibility requirements. Minimum firm capacity requirements following (Johnson et al., 2017) have been defined per region and decade as a multiplier of average annual electricity demand. Firm capacity represents capacity that is available at any given time. The multiplier is based on the region-specific relative ratio between average demand and peak demand combined with a 20% reserve margin where the margin is intended to ensure sufficient available capacity at all times. Capacity Factors (CFs)[3] for VRES technologies are based on regional resource potentials identified per range of CFs and assumed CFs for thermal powerplants are year and region specific with globally uniform technological parameters per technology. There are a number of short-term and long-term flexibility options in MESSAGEix-GLOBIOM, including a generic storage object, hydrogen electrolysis, direct air capture, electric vehicles, and electricity export to neighbouring regions. As part of the modelling effort in parallel to this study, the representation of inter-regional electricity trade in MESSAGEix-GLOBIOM has been adapted to only allow for trade bilaterally by means of investments in transmission grid infrastructure. Intra-regional trade of electricity is accounted for by means of costs as a function of final electricity demand, relative VRES penetration and the size of a specific region. However, regions are assumed to be copperplates without restrictions on internal transmission flows.

2.2. PLEXOS-World

PLEXOS (Energy Exemplar, 2020) is a transparent energy- and power system modelling tool among others used for electricity market modelling and planning freely available for academic use. All data input is customizable and the linear equations can be queried and modified by the user. PLEXOS has an integrated user interface enabling data management and model simulation to occur within the tool, yet also supports automation of data flows and model simulation by means of COM or. NET. The tool facilitates use of open source (GLPK, SCIP) and commercial (CPLEX, Gurobi, MOSEK, Xpress-MP) solvers depending on availability of licenses, with Xpress-MP being used for the simulations in this study.

The model used for this paper is based on the PLEXOS-World model, a detailed global power system model with 2015 as baseline year capable of simulating the generation of over 30,000 individual powerplants (Brinkerink et al., 2021; Brinkerink and Deane, 2020). The spatial representation of the model specified for this study is visualized in Fig. 1, with a total of 258 PLEXOS-World regions grouped per larger IAM region following the spatial representation of MESSAGEix-GLOBIOM.

[3] CFs refer to the ratio of actual electricity output compared to the theoretical maximum generation of a powerplant. In case of renewables this is affected by the availability of wind, solar irradiation or water inflow.

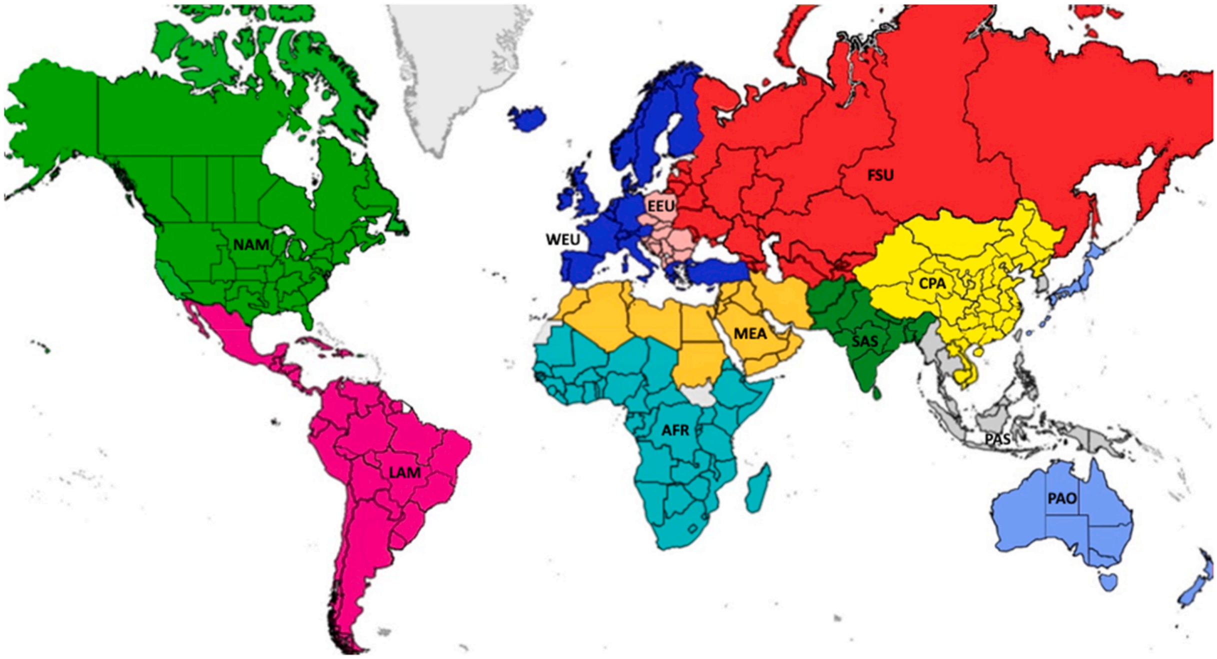

Fig. 1. Spatial representation of the 11-region MESSAGEix-GLOBIOM global IAM based on (IIASA Energy Program, 2020) as well as the spatial representation for MESSAGEix-GLOBIOM scenarios in PLEXOS-World. Every individual colour represents a copperplated region following MESSAGEix-GLOBIOM, whereas every area separated by borders as shown on the map represents a single (sub-)country region in PLEXOS-World with a total of 258 individual regions (Brinkerink et al., 2021; Brinkerink and Deane, 2020). The region abbreviations following MESSAGEix-GLOBIOM from left to right as used in this study are NAM (North America), LAM (Latin America & the Caribbean), WEU (Western Europe), EEU (Central & Eastern Europe), AFR (Sub-Saharan Africa), MEA (Middle East & North Africa), SAS (South Asia), FSU (Former Soviet Union), CPA (Centrally Planned Asia & China), PAS (Other Pacific Asia), PAO (Pacific OECD).

Powerplants in the PLEXOS-World model are modelled per turbine unit with standard unit sizes to be able to incorporate technological generator characteristics relevant for hourly Unit Commitment & Economic Dispatch (UCED) modelling. UCED modelling within power system models refers to the optimal utilization of available generator capacity to match system demand within a given simulation period while abiding to technical- and operational constraints. The model version used includes perfect foresight- and market assumptions. Refer to Section 1 of the Supplementary Material for detailed equations of the UCED modelling in PLEXOS-World. The PLEXOS-World model as applied for this study including all input data and timeseries can be found in Brinkerink (2020).

2.3. Soft-link framework

Fig. 2 provides an overview of the different steps of the framework. The framework is setup in a non-discriminatory way allowing it to be applied to most IAMs and power system models. However, the scope of this framework from a spatial perspective is to downscale the regional copperplates in IAMs to a detailed spatial resolution in the power system model. The benefits of this framework are therefore more applicable to assessments of global IAM scenarios with a coarse spatial representation versus scenarios from already more spatially defined IAMs. The openly available python script[4] accompanying this paper that can be used to coordinate the soft-link between IAMs and power system models is based on IAMC data template format.[5] The IAMC data template format is the main data format used for many global IAM intercomparison projects as well as for influential reports such as the forthcoming Chapter 3 of IPCC AR6. Note that the script is a helpful tool to automate the data processing workflow within the soft-link yet other languages or manual data conversion (e.g. in Excel) can also be applied. Although the methodological framework is developed to address the limitations of global IAMs, the framework is also suitable for soft-linking to other long-term planning models like energy system optimization models. The following sections describe the different steps of the framework in more detail.

2.3.1. IAM model simulation

In general, data inputs for IAMs are model and scenario specific depending on the IAM used, but most IAMs include basic parameters for socioeconomic developments (e.g. GDP, urbanisation and population projections), technology characteristics and inputs for non-energy impacts such as land- or water use requirements following energy system developments. Within this framework, generally any type of IAM can be used with the bare minimum requirement that the IAM is able to report technology specific regional powerplant capacities and regional electricity demand. However, to assess the technical feasibility of a given IAM scenario in the power system model, it is recommended to use all available IAM scenario output data relevant to power systems. If not available, additional required data for power system models such as carbon- and fuel prices, technology parameters and capacities of balancing assets that can assist with matching electricity demand and supply such as storage, power to gas and electric vehicles can either be standardized (pricing) or optimized (balancing assets) in the power system model. Using additional input data for the power system model not coming from the IAM affects the harmonization of both models and the overall representativeness of scenario assessment, yet due to the limited power system representation in IAMs it is often necessary. The python script as designed for this paper uses pyam,[6] an open source python package for analysis and visualization of IAM scenario data (Huppmann et al., 2021). The pyam package is used to extract MESSAGEix-GLOBIOM scenario data for integration in PLEXOS-World

[4] https://github.com/iiasa/IAM-powersystemmodel-linkage.
[5] https://data.ene.iiasa.ac.at/database/.
[6] https://github.com/IAMconsortium/pyam.

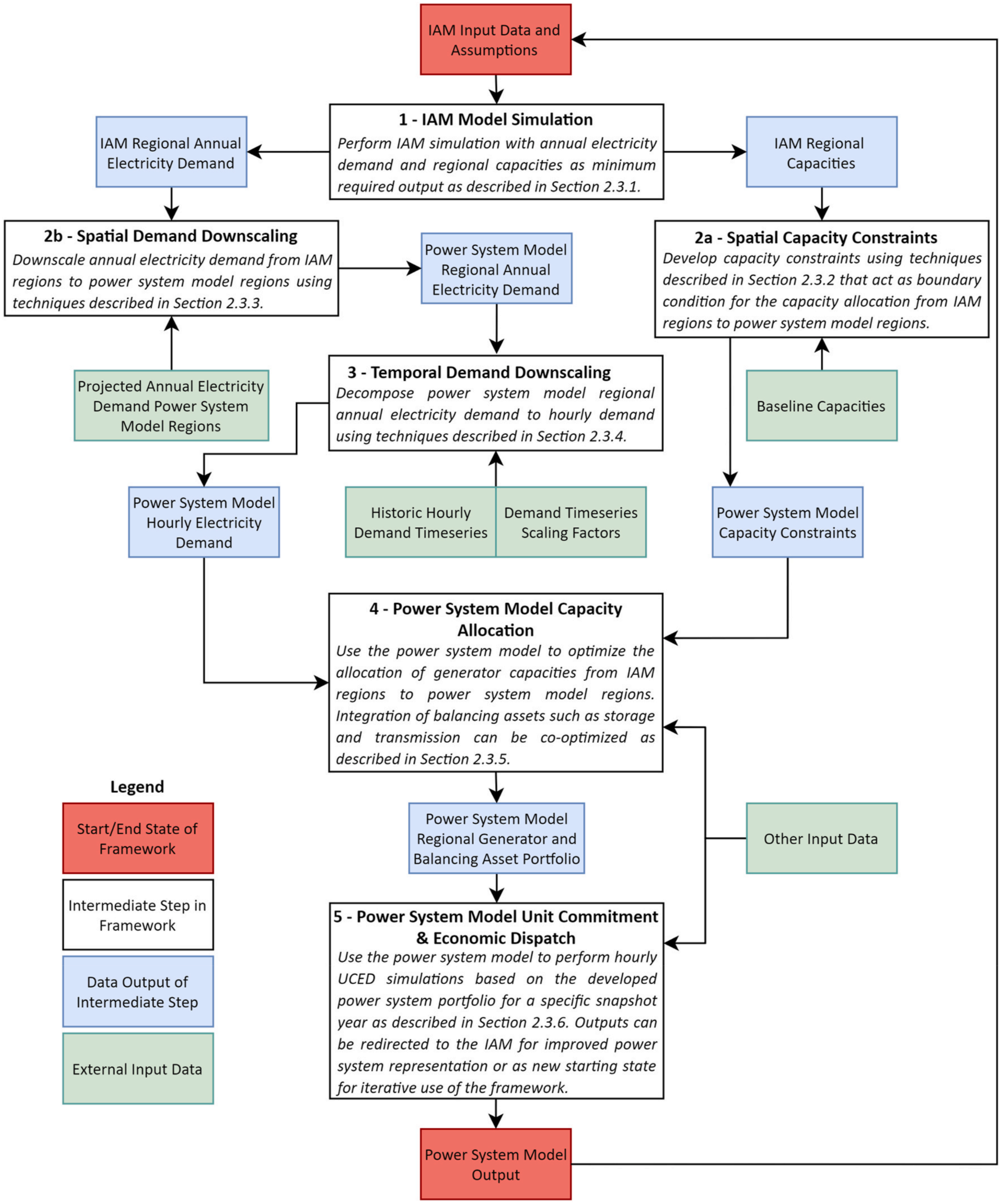

Fig. 2. Overview of the proposed framework for soft-linking of global IAMs and power system models. 'Other input data' relates to input data for the power system model that is not directly supplied by the IAM, for example detailed technological parameters. Explanations of the different steps and its required data inputs and outputs are covered in separate paragraphs within this section.

from databases such as the IAMC 1.5 °C scenario explorer (Huppmann et al., 2018) that among others includes scenario data underpinning Chapter 2 of the Special Report on Global Warming of 1.5 °C by the IPCC (Rogelj et al., 2018).

2.3.2. *Spatial capacity constraints*

One of the core aspects of the framework is the ability to assess IAM scenarios with higher spatial resolution in the power system model. Especially relevant from a power system perspective, this allows for any IAM scenario to be assessed in the context of local characteristics with the ability to provide detailed insights that cannot be provided with a coarser representation. For this to occur IAM scenario data must be downscaled to a newly defined spatial resolution to be used as input for the power system model. An exemplary visualization of indicative spatial resolutions of both sets of models is shown in Fig. 3.

The first set of IAM scenario output that requires spatial downscaling are regional powerplant and optionally balancing asset capacities. Within this framework, regional capacity expansion- and retirement constraints need to be developed that can be calculated by comparing the IAM scenario output with existing baseline capacities. These constraints determine per scenario region and technology how much capacity needs to be expanded or retired compared to the baseline to match the values provided by the specific IAM scenario for a given year. The constraints are used as boundary condition for the capacity

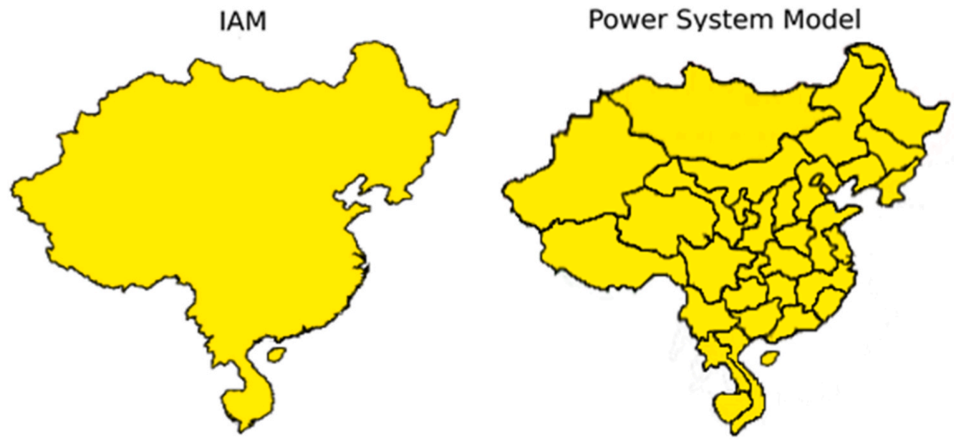

Fig. 3. Example of indicative spatial resolutions for global IAMs and global power system models. The left side shows the CPA region of global IAM MESSAGEix-GLOBIOM consisting of the combined area of Cambodia, China, Laos, Mongolia, North Korea, Taiwan, and Vietnam. The right side shows the spatial resolution of global power system model PLEXOS-World which represents every country in the CPA region individually and China as 34 separate regions.

allocation exercise within the power system model as described in Section 2.3.5. They can be setup in multiple ways. First, a ‘greenfield’ approach can be used in which existing powerplant capacity portfolios in individual (sub-)country regions are not considered. Albeit easier to apply, existing portfolios are in the near to medium term of significant relevance considering the often-long lifetimes of powerplants. It is therefore advisable to start with a baseline portfolio, which can be based on any preferable source.

For the MESSAGEix-GLOBIOM and PLEXOS-World proof of concept this paper and the accompanying python script uses the PLEXOS-World 2015 dataset (Brinkerink and Deane, 2020) for baseline capacities. The dataset includes global powerplant-, storage- and transmission capacities as of 2015 divided by 258 regions. Given the high temporal resolution of power system models, modelling exercises are often restricted to time horizons of a single year thus providing a snapshot analysis of that given year. Taking 2050 as an example as intended simulation year, scenario specific expansion and retirement constraints *Ex* per region *r* and technology *t* for the period up to 2050 can be calculated with eq (1) by subtracting the reported scenario specific capacities from the IAM *Cs* from the baseline powerplant capacities *Cb*.

$$Ex_{r^t} = C_b - C_s \qquad \text{(eq1)}$$

If the difference is negative it means that expansion of capacity is required for that specific technology and region and vice versa retirement. For accurate modelling of powerplant expansion and retirements, constraints can be calculated per interval (e.g. constraints for the period 2015–2020 … 2045–2050) or constraints can be determined for the full period to make the capacity expansion exercise computationally less intensive. The latter approach is used for this proof of concept study as automated in the python script. Fig. 4 shows an example of calculated expansion and retirement constraints for the period 2015–2050 for the LAM region for MESSAGEix-GLOBIOM.

2.3.3. Spatial demand downscaling

IAM scenario- and region specific yearly electricity demand values need to be downscaled to the power system model regional level. In principle any preferred energy downscaling method can be applied, however within the python script we apply a forecasting methodology to project country-level yearly electricity demand based on multivariate linear regression with GDP at purchasing power parity X_{GDPppp} per capita and urbanisation share X_{urb} as independent variables and electricity consumption per capita Y_{pc} as the dependent variable. Historical country level values *h* for the above variables have been retrieved by means of the World Banks World Development Indicators and the World Bank Data python package.[7] Country level values are grouped per IAM region according to the spatial representation of the specific IAM, followed by the derivation of the regional regression equations (eq (2)) for the period 1980–2014 with *a* being the intercept, b_{GDPppp} and b_{urb} the respective slopes and *e* the residual. More recent data years for electricity consumption per capita are not available within the World Bank World Development Indicators.

$$Y_{pc^h} = a + b_{GDPppp}X_{GDPppp^h} + b_{urb}X_{urb^h} + e \qquad \text{(eq2)}$$

For country-level projections of the independent variables as well as population projections we used the Shared Socioeconomic Pathways (SSP) (Riahi et al., 2017) and the accompanying quantifications (KC and Lutz, 2017; Dellink et al., 2017; Crespo Cuaresma, 2017; Leimbach et al., 2017; Jiang and O’Neill, 2017), all retrievable through the SSP Public Database.[8] The SSPs describe five different narratives based on alternative global socio-economic development pathways. The choice for a specific SSP to follow is in certain cases straightforward, but when in doubt it is advisable to use SSP2 as the ‘middle-of-the-road’ pathway. Given the regional regressions and the country-level SSP projections *p* for GDP at purchasing power parity X_{GDPppp^p} and urbanisation share X_{urb^p}, per capita electricity demand at country-level Y_{pc^p} can be projected specific per SSP (eq (3)). An example regression is visualized in Fig. 5 for the LAM region.

$$Y_{pc^p} = a + b_{GDPppp}X_{GDPppp^p} + b_{urb}X_{urb^p} \qquad \text{(eq3)}$$

By multiplying Y_{pc^p} with country-level population projections for the corresponding SSP X_{pop^p}, aggregate projected country-level electricity demand Y_p can be calculated (eq (4)). The regression can be applied manually as shown in this section, yet in the python script we use the linear regression module of the sklearn python package.[9]

$$Y_p = Y_{pc^p}X_{pop^p} \qquad \text{(eq4)}$$

Per IAM region, the Y_p values can be used as a proxy to downscale the IAM scenario regional demand values Y_r to country-level final demand values Y_f (eq (5)). Within the python script this occurs by making use of downscaling functionalities within pyam. Fig. 6 showcases an example comparison of Y_p, Y_f and 2015 country-level historical demand Y_h based

[7] https://github.com/mwouts/world_bank_data.

[8] https://tntcat.iiasa.ac.at/SspDb.

[9] https://scikit-learn.org/stable/modules/generated/sklearn.linear_model.LinearRegression.html.

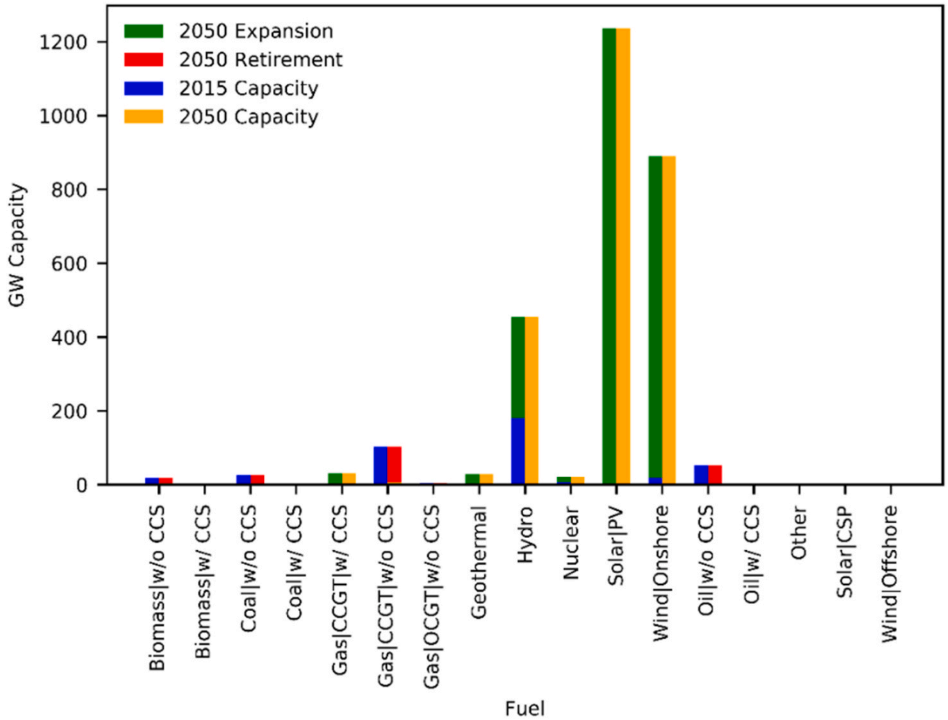

Fig. 4. Example powerplant expansion and retirement constraints for the LAM region of global IAM MESSAGEix-GLOBIOM for the period 2015–2050. Per technology in gigawatt (GW), the left bar indicates the existing baseline capacity in 2015 (blue) and the to be expanded capacity (green). The right bar indicates the required capacity in 2050 (yellow) and the to be retired capacity (red).

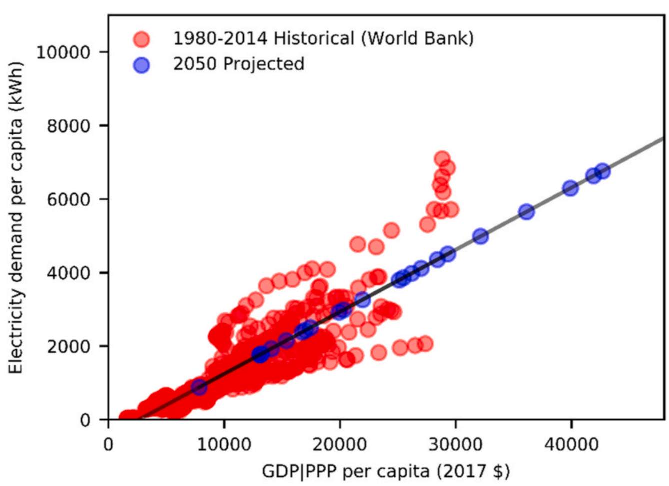

Fig. 5. Regression example with GDPppp per capita as independent variable (2017 $) and electricity demand per capita in kilowatt-hour (kWh) as dependent variable. Every red dot in the graph represents a single year value for one of the countries in the LAM region of global IAM MESSAGEix-GLOBIOM for the period 1980–2014. The blue dots represent the country-level projected electricity demand values based on SSP specific projections for the independent variables.

on the PLEXOS-World 2015 dataset (Brinkerink et al., 2021; Brinkerink and Deane, 2020) for contextual purposes. Compared to the historical demand, the graph indicates different demand growth rates as a result of different SSP projections for the independent variables per country. It can also be seen that in the given example the projected demand is lower compared to the downscaled scenario demand. There are multiple aspects that can affect the relative growth of electricity demand compared to the historical linear regression. For example, it could be expected that due to efficiency improvements and behavioural change a partial decoupling of economic growth and increase in energy demand could occur in the more developed parts of the world, yet on the global scale this trend is less obvious (Schandl et al., 2016). More importantly, electricity as end-use is expected to gain a more predominant role in a variety of sectors (e.g. transport), leading to significant expected growth of the share of electricity in global final energy demand (McCollum et al., 2018).

$$Y_f = \frac{Yp}{\sum Yp} Y_r \tag{eq5}$$

2.3.4. Temporal demand downscaling

Global IAMs and power system models have different modelling horizons and temporal resolution. An example of this is visualized in Fig. 7. IAMs focus on the long-term development of the energy system with planning horizons of up to a century and modelling periods of between 1 and 10 years with a specified baseline year as starting point. Timesteps in global IAMs are generally applied on an annual basis with investment decisions reported at the end of every modelling period. Within the framework, the power system model is used to assess IAM model output for a specific year with detailed temporal resolution, for example on an hourly basis for the full year depending on the aim of the study (Holttinen et al., 2013). Results can be reported per timestep or on a yearly basis for direct comparison with the IAM.

The spatially downscaled yearly electricity demand values from Section 2.3.3 require additional downscaling in terms of temporal resolution. Once again multiple approaches are possible, yet for the results in this study we use historical timeseries based on the PLEXOS-World 2015 dataset (Brinkerink et al., 2021; Brinkerink and Deane, 2020) which includes hourly demand data for all countries globally as well as for a wide range of sub-country regions for the 2015 calendar year. Approximately 50% of profiles in the dataset are based on actual historical operational power system data with the remainder being country specific synthetic demand timeseries adapted from Toktarova et al. (2019). The country-level final electricity demand Y_f per hourly interval

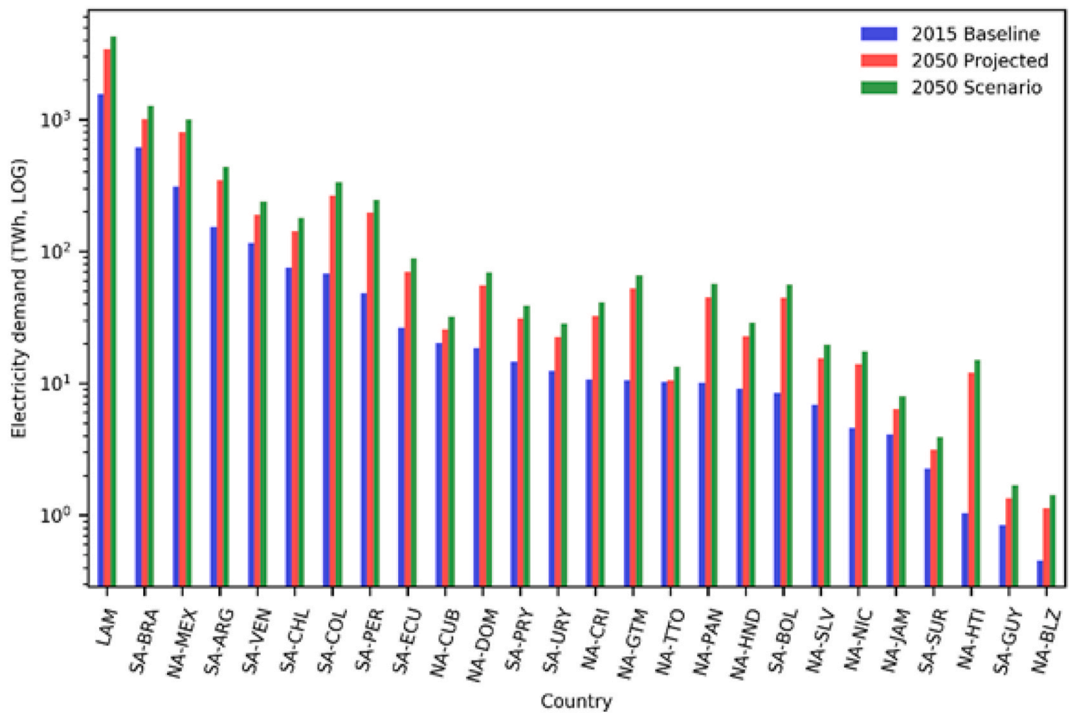

Fig. 6. Comparison of regional- and country-level projected electricity demand Y_p (red), the downscaled final demand Y_f (green) and the 2015 historical demand Y_h (blue) in terawatt-hour (TWh) for the LAM region of the global IAM MESSAGEix-GLOBIOM and the PLEXOS-World regions within LAM.

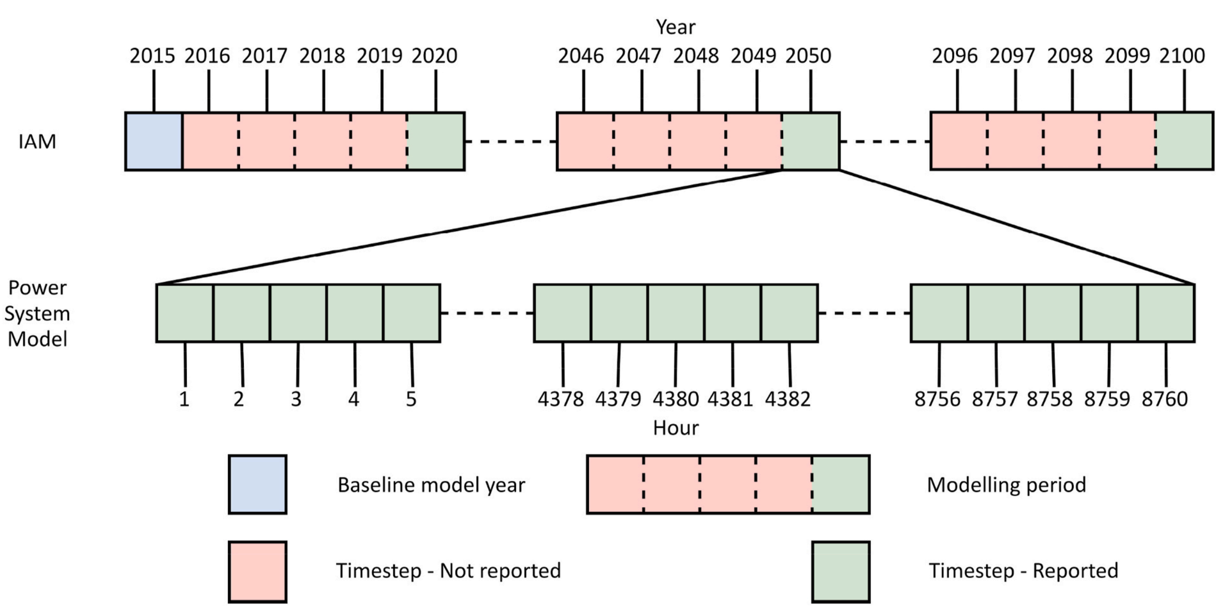

Fig. 7. Comparison of indicative modelling horizons and temporal resolutions for global IAMs and global power system models within the framework.

i can be calculated with eq (6) by using the historical hourly values Y_{h^i} as proxy for linear downscaling.

$$Y_{f^i} = \frac{Y_{h^i}}{\sum Y_{h^i}} Y_f \quad \text{(eq6)}$$

For this study the country level final electricity demand profiles are further downscaled to sub-country level Y_{fsc^i} with eq (7) by using historical relative demand shares for sub-country regions per interval Y_{hsc^i} as proxy. Peak demand for all demand timeseries relative to the total demand is kept equal compared to 2015 values. The limitation of this and other applied downscaling steps are discussed in Section 4.3. The development of the demand timeseries based on the linear downscaling for all countries globally occurs within the python script.

$$Y_{fsc^i} = \frac{Y_{hsc^i}}{Y_{h^i}} Y_{f^i} \quad \text{(eq7)}$$

Next to the expansion- and retirement constraints and the downscaled demand timeseries, used input data for PLEXOS-World based on MESSAGEix-GLOBIOM outputs for this exercise consist of regional specific carbon- and fuel prices, generator heat rates, storage capacities- and available technical parameters.

2.3.5. Power system model capacity allocation

Traditionally, capacity expansion exercises in power system models are used to optimize the long-term development of the power system. In contrast to the traditional application, the framework we propose in this article does not allow powerplant capacities to be expanded and retired in an unconstrained fashion. Instead, we use the expansion and retirement decisions from the IAM by means of the developed expansion- and retirement constraints in Section 2.3.2 as boundary condition for the power system model. The capacity expansion module in the power system model is used to optimize the allocation of powerplant resources to the different power system model regions with the IAM regional capacities as boundary. An example application of this exercise for MESSAGEix-GLOBIOM and PLEXOS-World can be seen in Fig. 8.

Together with the allocation of powerplant capacities, the capacity expansion module of the used power system model can optimize the expansion and integration of balancing assets such as transmission infrastructure, different storage technologies, flexible utilization of electric vehicles and demand side management. Although these assets can be accounted for in IAMs, their operational benefits and technical limitations are only visible in model simulations with detailed spatial and temporal resolution. Similar to powerplant capacities, if the IAM reports capacities of a specific technology it can be used as boundary condition for the allocation exercise rather than unconstrained optimization.

Within this framework, UCED modelling can either be performed in an integrated singular run with the capacity allocation or as two separate modelling phases with different temporal modelling resolution. Depending on the defined spatial and technological resolution of the power system model, performing long-term planning exercises with temporal resolution equal to (sub-)hourly UCED modelling can be too computationally complex. For the MESSAGEix-GLOBIOM and PLEXOS-World proof of concept the decision has been made to separate both modelling phases with different applied temporal resolutions. For the capacity allocation exercise a sampling approach is used to select representative timeslices of 3-weeks per year at 4-hourly temporal resolution (total of 126 4-hourly timeslices). Linear optimization is applied for the capacity allocation with generator units rounded to the nearest integer. Refer to Section 2.1 and 2.2 of the Supplementary Material for more details on the sampling approach used and for applied generator unit sizes and other generator characteristics in PLEXOS-World.

Firm capacity requirements in PLEXOS-World per (sub-)country region follow the same assumptions as MESSAGEix-GLOBIOM applies per IAM region. These requirements are determined by taking the relative ratio between average demand and peak demand in addition to a standardized 20% reserve margin. Whereas in MESSAGEix-GLOBIOM these ratios are approximated, in PLEXOS-World they are determined by using historic 2015 demand values for all PLEXOS-World regions following (Brinkerink et al., 2021; Brinkerink and Deane, 2020). Table 1 compares the firm capacity requirements as multiplier of average demand for 2050 following MESSAGEix-GLOBIOM values (Johnson et al., 2017) and the regionally aggregated demand-weighted values in PLEXOS-World. Compared to MESSAGEix-GLOBIOM, firm capacity requirements per region in PLEXOS-World have a much wider range. It's also worth noting that the values represent an IAM regional average, but that values per (sub-)country region in PLEXOS-World can range significantly. For example, values in CPA range from 1.40 to 2.21. Refer to Section 2.3 of

Table 1
Firm capacity requirements per region in MESSAGEix-GLOBIOM following (Johnson et al., 2017) and in PLEXOS-World for 2050. The values are relative to average annual electricity demand. Values for PLEXOS-World are regional aggregates based on (sub-)country demand weighted values.

Region	MESSAGEix-GLOBIOM	PLEXOS-World
AFR	1.66	1.78
CPA	1.61	1.52
EEU	1.76	1.68
FSU	1.72	1.64
LAM	1.73	1.67
MEA	1.75	1.88
NAM	1.78	2.01
PAO	1.7	1.92
PAS	1.68	1.6
SAS	1.68	1.6
WEU	1.71	1.82

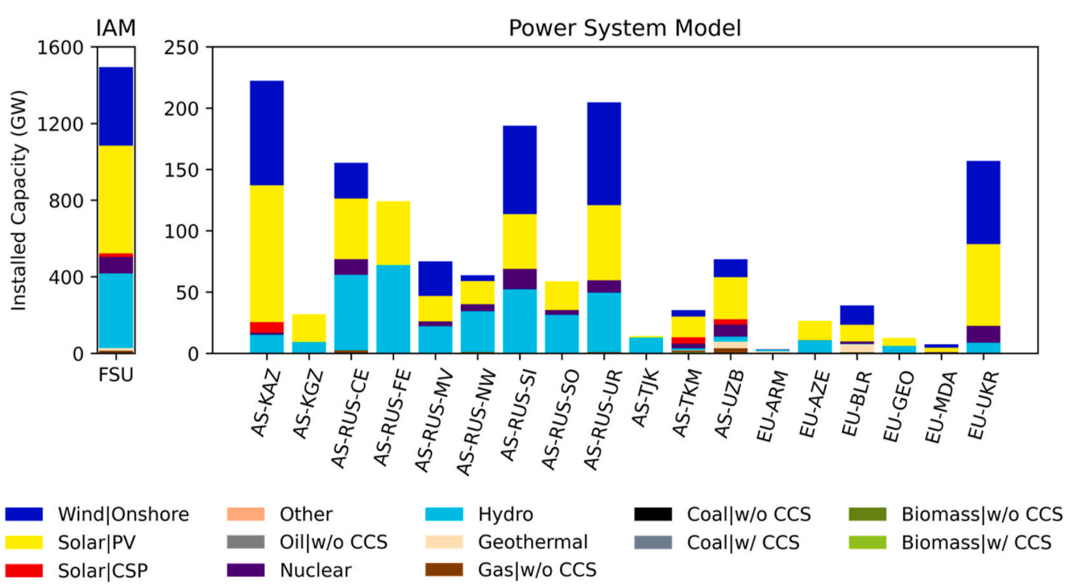

Fig. 8. Example of the capacity allocation exercise within the framework based on the FSU region of the global IAM MESSAGEix-GLOBIOM. The left bar indicates the region and technology specific powerplant capacities for 2050 based on the regional IAM output. These capacities are used as input for the power system model acting as boundary condition for the capacity allocation exercise. The right side shows powerplant capacities as output of the capacity allocation exercise within the power system model. Naming conventions for regions as used in the PLEXOS-World model follow the format of a two-letter continent abbreviation, three-letter ISO 3 country code and optionally a two-letter abbreviation for a specific sub-country region. E.g. AS-RUS stands for Asia-Russia with the sub-country abbreviations being CE (Central), FE (Far East), MV (Middle Volga), NW (North West), SI (Siberia), SO (South) and UR (Ural).

the Supplementary Material for all used firm capacity requirement values in PLEXOS-World.

Modelling of electricity storage in PLEXOS-World is in line with MESSAGEix-GLOBIOM where storage is modelled as a single generic technology with a cycle efficiency of 80%, storage capacity of 24 h and a capital cost of $800/kilowatt (Johnson et al., 2017). Hydrogen electrolysis in PLEXOS-World is constrained at the IAM regional level following capacities indicated by the MESSAGEix-GLOBIOM scenario without possibilities for conversion back to electricity. Conversion efficiency is set at 80% in line with MESSAGEix-GLOBIOM. The modelling of electricity transmission in PLEXOS-World is based on physical transmission grids with customised associated investment costs, operational costs, and operational losses as a function of transmission distance and specific transmission technology for every unique potential high voltage transmission pathway in the model – totalling 582. Different to storage technologies, the expansion of transmission lines in PLEXOS-World is not constrained by output from MESSAGEix-GLOBIOM due to the vastly different spatial resolutions and the fact that intra-regional trade is not modelled in MESSAGEix-GLOBIOM. Section 2.1 of the Supplementary Material provides more details on transmission modelling in PLEXOS-World.

For the allocation of renewable powerplant capacities, limits have been set on the resource potential per PLEXOS-World region with the same sources used as MESSAGEix-GLOBIOM to retain uniformity. Country-level resource potentials for solar technologies are based on a study by Pietzcker et al. (2014) and country-level potentials for onshore- and offshore wind-based on a global assessment by Eurek et al. (2017). Potential for new hydro-based capacity is based on a study by Gernaat et al. (2017) that identifies 60,000 potential locations for new economically viable projects. For geothermal and biomass no additional local restrictions are placed on resource potential due to the limited influence of geothermal based electricity generation in the to be assessed MESSAGEix-GLOBIOM scenario and the assumed transportability of biomass between (sub-)country regions within PLEXOS-World.

Two sets of input CF timeseries for hydro, solar and wind are used in the PLEXOS-World model for this study. A conservative set of timeseries is used based on the PLEXOS-World 2015 dataset which includes profiles based on benchmarked values at year- and country level for 2015 (Brinkerink et al., 2021; Brinkerink and Deane, 2020). A second set of timeseries has harmonized values equal to MESSAGEix-GLOBIOM by linearly scaling the original PLEXOS-World 2015 timeseries by comparing the regional average to the MESSAGEix-GLOBIOM output. Due to the large regional copperplates, renewable resource potentials for a specific region within MESSAGEix-GLOBIOM consist of the combined potential of a wide range of countries with often very different characteristics. In PLEXOS-World, if domestic resource potentials are to be used for export purposes the electricity must be physically transferred by means of transmission infrastructure including associated costs and losses whereas in MESSAGEix-GLOBIOM no intra-regional barriers for trade exist. This can lead to different investment dynamics, and hence as a sensitivity analysis it is merited to assess the specific MESSAGEix-GLOBIOM scenario in the context of conservative CFs.

2.3.6. Power system model Unit Commitment & Economic Dispatch

If the decision has been made to separate the capacity allocation exercise from the UCED modelling in two distinct modelling phases, the main output from the capacity allocation exercise – being the generator and balancing asset portfolios of the power system model regions – should be used as input for the UCED modelling. Temporally detailed model simulations of the downscaled generator portfolio and balancing assets can provide detailed insights in the technical feasibility of a given IAM scenario. It furthermore allows for benchmarking of simulation results with generic model assumptions within the IAM. Examples can be assumed generator CFs as well as stylized relationships regarding curtailment and occurrence of possible unserved energy.[10] Unserved energy represents the share of final electricity demand that cannot be met with the available generator resources. The UCED modelling in PLEXOS-World based on the output of the allocation exercise is done with hourly modelling resolution based on Mixed-Integer Programming (MIP). Data flows between both modelling phases in PLEXOS-World occurs in an automated fashion.

2.3.7. Feedback loop

The results from the model soft-link exercise within this framework consists of quantified simulation output that can assist with optimizing the power system representation in IAMs while considering the computational requirements of model simulations. Relevant outputs of the power system model to be used in IAMs for improved power system representation are for example technology CFs, curtailment values and costs of generation. Before the power system model output data can be used as input for an IAM the data needs to be post- and pre-processed. Outputs from the power system model need to be converted into a format that is readable for the specific IAM. In the case of PLEXOS-World results can be written to individual flat files per variable and easily be converted to the IAMC data template format that MESSAGEix-GLOBIOM and a number of other global IAMs use. As a result of the open-ENTRANCE[11] project, the IAMC data template format has the extended ability to support sub-annual data which is critical for temporally detailed power system modelling results. Next to format conversion, the data also need to be aggregated from the power system model regional level to the IAM regions. For some output variables this can easily be done by simple aggregation whereas others require more thought. For example, when it comes to technology CFs a normal average can be taken based on reported values in the different power system model regions or a capacity weighted average can be used as well. The potential for a scripted feedback loop within the framework allows for an iterative process between the IAM and power system model until the power system representation in the IAM is deemed satisfactory in terms of power system adequacy – the ability of a power system to meet demand under normal operational conditions – or other criteria.

2.4. Scenarios

The ENGAGE SSP2 NPI2020 500 scenario as simulated by MESSAGEix-GLOBIOM is consistent with end-of-century warming of 1.5 °C without temperature overshoot (Riahi et al., 2021). In 2050 as assessed snapshot year for this study, it exhibits high penetration of VRES, with approximately 64% of electricity in the grid coming from wind (33%) and Solar-PV (31%) globally. Furthermore, the share of electricity in final energy demand is slightly over 50% in 2050 (cf. 20% in 2020 (IEA, 2021)) and the share of electric mobility in the transportation sector is 33% in 2050 (cf. 1% in 2020 (IEA, 2021)) both at the global level. By assessing this scenario, the soft-link framework can be used to evaluate MESSAGEix-GLOBIOM in a setting where IAMs may struggle in terms of adequately incorporating the detailed implications of variability in electricity supply and demand. We perform a 'Baseline' simulation and a set of sensitivity simulations in PLEXOS-World

[10] Different to MESSAGEix-GLOBIOM where occurrence of unserved energy is not possible, PLEXOS-World allows for unserved energy at a cost of 10,000 €/megawatt-hour. The model can determine that often it is more efficient for unserved energy to occur than to invest in additional flexibility assets such as storage or in further transmission expansion to mitigate this unserved energy.

[11] https://github.com/openENTRANCE/nomenclature.

summarized in Table 2. As a proof of concept for the potential of the framework to streamline informed model improvements in global IAMs, the results of the model simulations in PLEXOS-World related to inter-regional electricity trade between the larger IAM regions are fed back to MESSAGEix-GLOBIOM and used as model input for a second iteration. The simulations in MESSAGEix-GLOBIOM as performed for this study can be found in Table 3. It is important to recall that in line with the framework, key model input in PLEXOS-World such as powerplant capacities and electricity demand are at an aggregate level equal to the MESSAGEix-GLOBIOM model output at all times.

The 'Baseline' simulation represents the reference for the soft-link framework in that it attempts to replicate the original MESSAGEix-GLOBIOM scenario with harmonized inputs between both models such as input CF timeseries for hydro, solar and wind technologies. The 'Conservative CFs' model simulation on the other hand uses the original PLEXOS-World 2015 dataset timeseries as a sensitivity analysis. Whereas in the 'Baseline' and 'Conservative CFs' simulations the expansion of storage capacity is bound at a regional level following the MESSAGEix-GLOBIOM scenario output, the 'No Storage Constraints' simulation allows for full optimization of storage capacity. This allows for an assessment of how accurately storage expansion is integrated in MESSAGEix-GLOBIOM and moreover how it impacts other variables such as generator CFs, generator reserve requirements and transmission utilization.

Because the 'No Storage Constraints' simulation allows for unconstrained competition between transmission and storage in the optimization it provides the best indication for the potential of inter-regional electricity trade. The results from this simulation regarding inter-regional trade are therefore used as model input for a second iteration in MESSAGEix-GLOBIOM to optimize its representation of inter-regional electricity trade as a proof of concept for the framework in terms of bi-directional model soft-linking. Section 2.4 of the Supplementary Material provides more information regarding the renewed representation of inter-regional trade in MESSAGEix-GLOBIOM including a full overview of the adjusted input parameters based on PLEXOS-World.

3. Results

This section includes the modelling results for the proof of concept application of the proposed soft-link framework where PLEXOS-World is used to assess a high VRES scenario from MESSAGEix-GLOBIOM with a 64% share of VRES in the electricity grid at the global level. The results from PLEXOS-World will be compared to the model outputs from MESSAGEix-GLOBIOM based on which suggestions are being made for additional internal model improvements regarding power system representation.

Table 2
Overview of PLEXOS-World model simulations to assess the MESSAGEix-GLOBIOM 1.5 °C and high VRES scenario from a power system perspective.

PLEXOS-World simulation	Soft-linked to	Renewable CFs in 2050	Storage assumptions
Baseline	First iteration MESSAGEix-GLOBIOM	Renewable CFs scaled to MESSAGEix-GLOBIOM values in 2050.	Storage capacity allocation constrained by MESSAGEix-GLOBIOM scenario output.
Conservative CFs	First iteration MESSAGEix-GLOBIOM	Renewable CFs based on PLEXOS-World 2015.	Storage capacity allocation constrained by MESSAGEix-GLOBIOM scenario output.
No Storage Constraints	First iteration MESSAGEix-GLOBIOM	Renewable CFs scaled to MESSAGEix-GLOBIOM values in 2050.	Storage capacity expansion freely optimized.

Table 3
Overview of MESSAGEix-GLOBIOM model simulations for the 1.5 °C scenario.

MESSAGEix-GLOBIOM simulation	Inter-regional trade
First Iteration	Inter-Regional trade based on expansion of bilateral transmission infrastructure. Input parameters uniform for all possible inter-regional transmission pathways.
Second Iteration	Inter-Regional trade based on expansion of bilateral transmission infrastructure. Transmission pathway specific input parameters are informed by PLEXOS-World.

3.1. Generation and storage

Fig. 9 shows the differences in generation mix per PLEXOS-World model simulation in comparison to the MESSAGEix-GLOBIOM output.

The main observation is that for both the 'Baseline'- as the other simulations in PLEXOS-World the total generation output is lower compared to the MESSAGEix-GLOBIOM scenario output. For example, following the given scenario in MESSAGEix-GLOBIOM the 2050 electricity generation in the CPA region equals approximately 55.5 EJ whereas generation in the PLEXOS-World simulations ranges between 43 and 45 EJ. The lower generation compared to MESSAGEix-GLOBIOM is in most cases occurring for both renewable technologies as well as for fossil fuel-based powerplants. Fig. 10 shows the technology and region specific CFs based on model output for a range of key generator technologies.

The 'Baseline' and 'No Storage Constraints' simulations have maximum CF input assumptions for hydro, solar and wind technologies in line with the MESSAGEix-GLOBIOM scenario. Yet as the graphs in Fig. 10 indicate, the equal availability of renewable resources does not always lead to comparable CFs as output. For example the regionally aggregated CF for Solar-PV based on the 'Baseline' simulation for the CPA region is 16.2% compared to 17.7% in MESSAGEix-GLOBIOM. CFs for hydro, solar and wind technologies in the 'Conservative CFs' model simulation are based on 2015 benchmarked values and lead to significantly lower VRES penetration compared to the MESSAGEix-GLOBIOM scenario output. Fossil fuel-based powerplants partly compensate for the lower availability of renewable resources in this PLEXOS-World simulation. However – besides regional outliers – all PLEXOS-World simulations indicate that CFs for these technologies are also below par compared to the MESSAGEix-GLOBIOM scenario output. The exceptions are gas and coal powerplants without Carbon Capture and Storage (CCS) from which higher utilization is required to mitigate part of the existing supply shortage from renewables. The unconstrained expansion of electricity storage in the 'No Storage Constraints' leads to lower CFs for Solar-PV yet higher CFs for other technologies compared to the 'Baseline'. This is a direct result of lower investments in storage capacity in PLEXOS-World for the 'No Storage Constraints' simulation compared to MESSAGEix-GLOBIOM as highlighted in Fig. 11.

Expansion of storage in MESSAGEix-GLOBIOM occurs based on the contribution of storage to system flexibility needs, reducing curtailment of VRES, and provision of firm capacity using stylized relationships leading to e.g. large scale investments of over 1000 GW in CPA and NAM. However, the results show that with similar capacities in PLEXOS-World, storage is utilized with lower CFs compared to MESSAGEix-GLOBIOM. When PLEXOS-World is allowed to freely optimize the expansion of storage not bound to capacities following the MESSAGEix-GLOBIOM output – as in the 'No Storage Constraints' simulation – total build capacities are approximately one third of MESSAGEix-GLOBIOM albeit with higher CFs compared to the other simulations in PLEXOS-World. The conversion of electricity into hydrogen by means of electrolysis is the only long-term storage solution integrated in MESSAGEix-

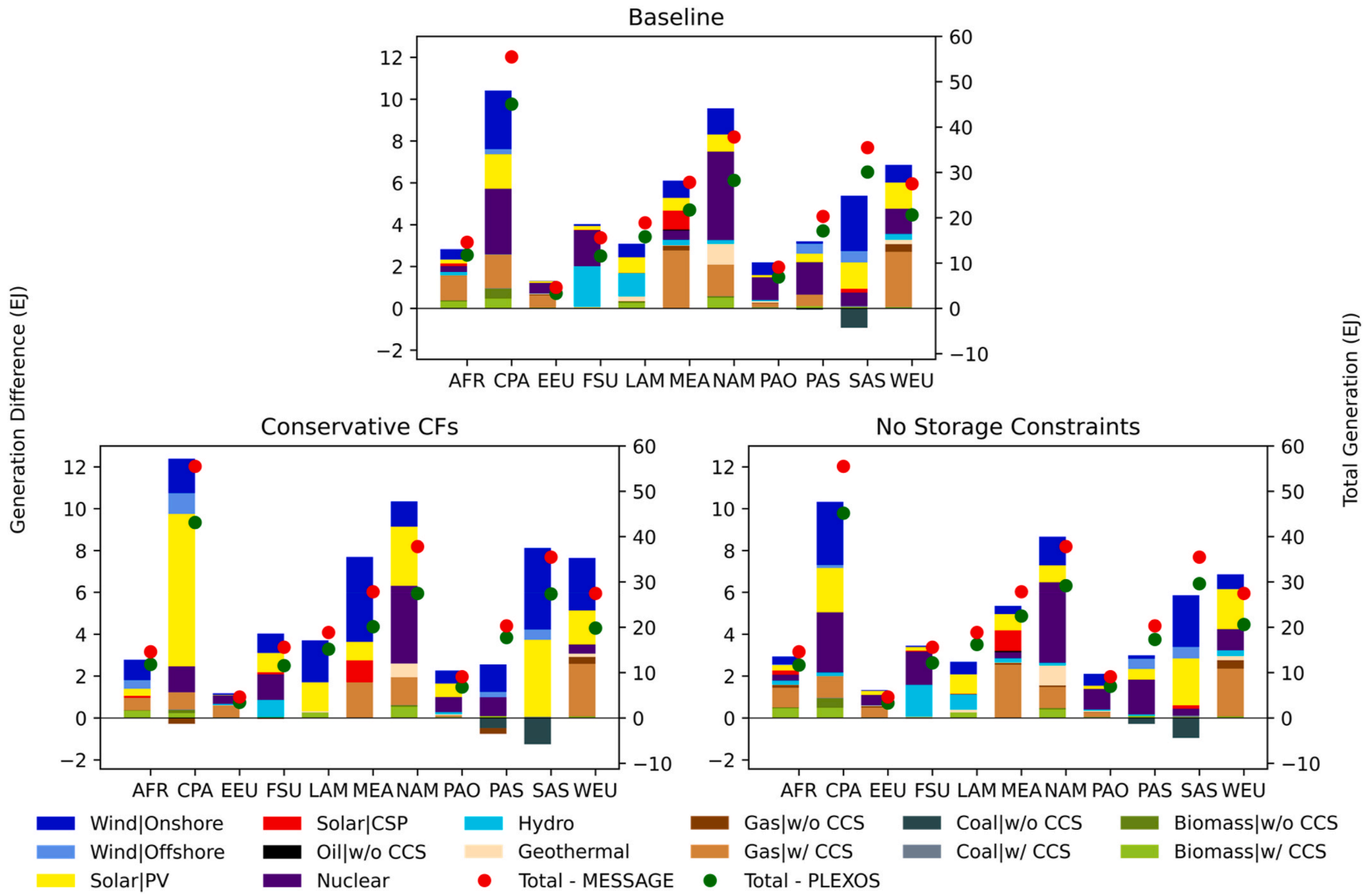

Fig. 9. Differences in generation mix per PLEXOS-World simulation in comparison to the MESSAGEix-GLOBIOM output. The bars represent generation differences per fuel type (primary Y-axis) with positive values indicating surplus generation in the MESSAGEix-GLOBIOM output compared to PLEXOS-World and negative values vice versa. The markers represent total generation values (secondary Y-axis). The X-axis region abbreviations refer to the regions as introduced in Fig. 1.

GLOBIOM for the assessed scenario. Fig. 12 however indicates that similar to short-term storage hydrogen electrolysis is underutilized in all PLEXOS-World simulations compared to MESSAGEix-GLOBIOM.

3.2. Curtailment and unserved energy

Electricity coming from VRES technologies that cannot be instantaneously used, stored, transmitted to a neighbouring area or converted to other energy carriers gets curtailed. Curtailment is an important factor in power systems with large penetration of VRES and based on the PLEXOS-World simulations an element that might be underestimated in MESSAGEix-GLOBIOM for the examined scenario. This is visualized in Fig. 13 which as an example highlights the region specific curtailment values for Solar-PV.

MESSAGEix-GLOBIOM accounts for curtailment through stylized relationships as a function of relative VRES penetration. Although this kind of stylized relationship is inherently not incorrect – the 'Baseline' and 'Conservative CFs' PLEXOS-World model simulations indicate that curtailment grows in parallel with relative VRES penetration – the observed curtailment values in PLEXOS-World are in almost all cases a magnitude higher compared to MESSAGEix-GLOBIOM. The lower investments in storage capacities in the 'No Storage Constraints' simulation lead to overall highest Solar-PV curtailment values due to reduced possibilities to mitigate peak Solar-PV supply. On the global scale, curtailment values relative to the theoretical generation potential range between 4 and 11% for Solar-PV depending on the PLEXOS-World simulation and comparatively between 4 and 8% for wind-based technologies. The combined effect of higher VRES curtailment compared to MESSAGEix-GLOBIOM in combination with the underutilization of dispatchable technologies leads to the occurrence of unserved energy in the global power system. This is visualized in Fig. 14 which showcases unserved energy values per region and model simulation.

3.3. Electricity trade

In an optimally functioning integrated global power system a spatiotemporal mismatch between demand and supply of electricity can be mitigated by sharing resources between regions by means of transmission integration. Despite significant intra-regional transmission flows within PLEXOS-World – both land-based as well as through long-distance subsea interconnectors – the built transmission infrastructure cannot sufficiently compensate for the large variability in supply. Fig. 15 shows mapped electricity flows in 2050 for the 'No Storage Constraints' simulation. For contextual purposes, 1 EJ (278 TWh) roughly equals the current-day electricity demand of Australia or Mexico.

Fig. 16 highlights the occurrence of inter-regional trade of electricity between the IAM regions for both performed iterations of MESSAGEix-GLOBIOM in comparison to the simulations in PLEXOS-World. The second iteration of MESSAGEix-GLOBIOM has adjusted input parameters based on the results of the 'No Storage Constraints' simulation in PLEXOS-World and general PLEXOS-World input parameters – refer to Table S2.5 in Section 2.4 of the Supplementary Material for a full overview. Within the PLEXOS-World results, the 'Conservative CFs' simulation has the overall largest trade. For this simulation the inter-regional transmission flows are a means to compensate for the lower CFs for renewables compared to MESSAGEix-GLOBIOM. The 'Baseline' simulation has the lowest trade values correlated to the earlier identified large capacities of electricity storage following MESSAGEix-GLOBIOM

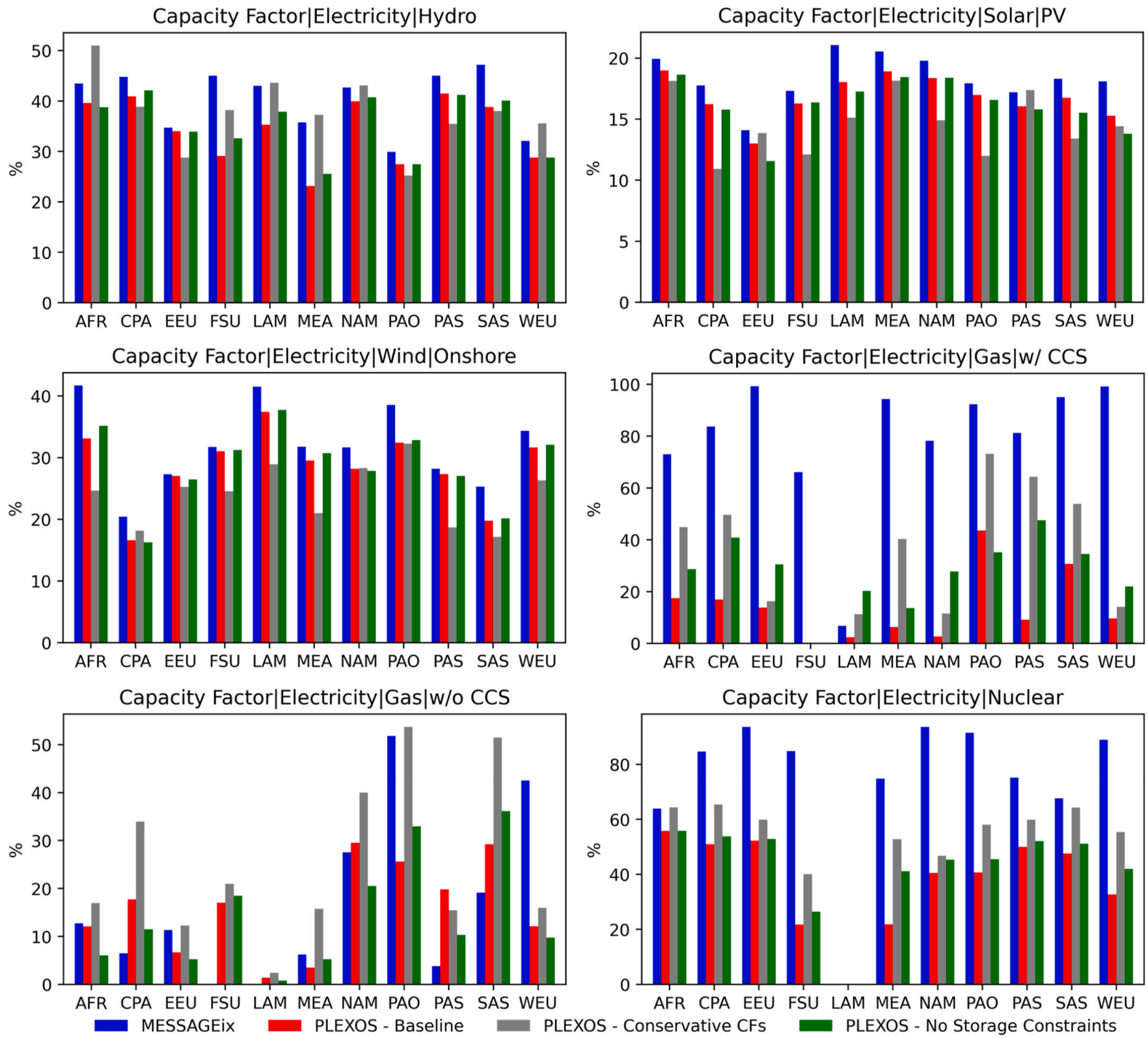

Fig. 10. Output CFs for a range of generator technologies for the different PLEXOS-World model simulations in comparison to MESSAGEix-GLOBIOM.

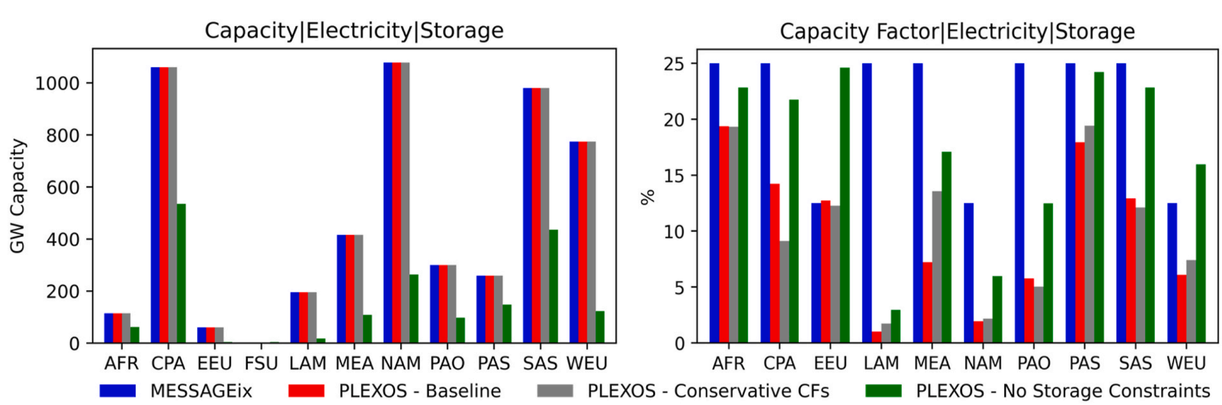

Fig. 11. Capacity (left) and CFs (right) for electricity storage for the different PLEXOS-World model simulations in comparison to MESSAGEix-GLOBIOM.

values. In the 'No Storage Constraints' simulation where the expansion of storage and transmission occurs in competition the inter-regional trade values are significantly higher compared to the 'Baseline' simulation at a net total of 6.3 EJ (1750 TWh) versus 2.5 EJ (694 TWh) globally. To put these values in context, total 2015 inter-regional trade values between the IAM regions based on simulations of PLEXOS-World (Brinkerink et al., 2021) are approximately 0.1 EJ (28 TWh). In line with MESSAGEix-GLOBIOM, the FSU region has been identified as resource rich exporting region within PLEXOS-World albeit with CPA as main importing region compared to SAS in MESSAGEix-GLOBIOM.

Compared to PLEXOS-World, the inter-regional trade values in both iterations of MESSAGEix-GLOBIOM are lower. The adjusted input

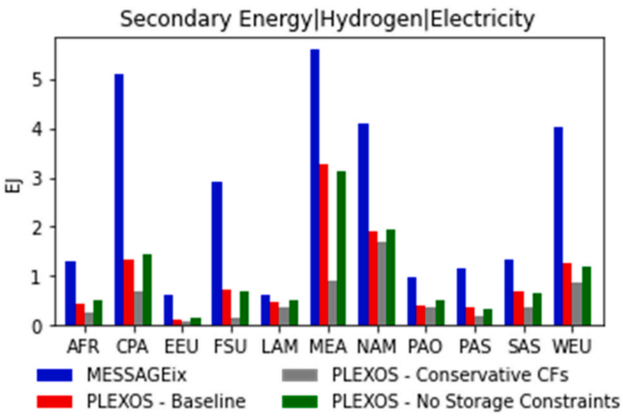

Fig. 12. Hydrogen production from electricity by means of electrolysis for the different PLEXOS-World model simulations in comparison to MESSAGEix-GLOBIOM.

parameters for the second iteration of MESSAGEix-GLOBIOM based on PLEXOS-World stimulate higher inter-regional trade between FSU and SAS as well as a modest uptake of inter-regional trade in other regions. However, considering the relatively small differences between both iterations, it is clear that the alignment of input parameters regarding inter-regional trade in MESSAGEix-GLOBIOM based on PLEXOS-World has minor impact for the examined scenario.

4. Discussion

4.1. Discussion of proof of concept results

The proof of concept application of the proposed methodological soft-link framework in this paper has revealed that the differences in modelling resolution and assumptions between MESSAGEix-GLOBIOM and PLEXOS-World can lead to different results. Note that the discussion of the results in this paper reflect on a single scenario with high shares of VRES and is not intended to shed light on the functionality of both models in all possible contexts.

The results show that generation values and generator CFs in PLEXOS-World are significantly lower than MESSAGEix-GLOBIOM. This is both the case for renewables as well as for most thermal generators and applicable for all performed PLEXOS-World simulations of the examined MESSAGEix-GLOBIOM scenario. CFs for renewables are lowest in the 'Conservative CFs' simulation which highlights the sensitivity of modelling assumptions in IAMs regarding uncertain developments such as the availability of highly efficient untapped renewable resources. Different to MESSAGEix-GLOBIOM, PLEXOS-World operates based on perfect market assumptions meaning that there are no emission constraints included that might affect how much fossil fuel-based powerplants are allowed to operate to stay within the bounds of a set emission target. This contributes to the fact that – as an outlier compared to other technologies – coal and gas powerplants without CCS in PLEXOS-World have higher generation values compared to MESSAGEix-GLOBIOM. A key factor for the overall lower generation values in PLEXOS-World is the different sectoral representation of both models. MESSAGEix-GLOBIOM is a sector-coupled model that is not only required to meet electricity demand as end-use but also has the ability to convert electricity in other energy carriers for use in for example the transport and heating sectors. PLEXOS-World focuses solely on the power sector where available generators are utilized to meet final electricity demand in addition to hydrogen electrolysis as a means to limit electricity curtailment. However, given that there is no modelled demand for hydrogen or other energy carriers in PLEXOS-World, the model can determine that it is often more efficient to curtail electricity than to invest in additional flexible technologies such as electricity storage to make optimal use of available generation for indirect use in other sectors.

That said, and despite the overall lower demand for electricity compared to MESSAGEix-GLOBIOM, the PLEXOS-World simulations indicate that demand cannot always be met leading to significant unserved energy in the global power system of between 2.5% and 5%. These findings are in line with other literature which highlights that the occurrence of unserved energy in power systems mostly reliant on VRES can be expected to become a more important factor (Tong et al., 2021). Next to unserved energy, higher VRES curtailment values can be observed compared to reported values from MESSAGEix-GLOBIOM. The more detailed temporal resolution in PLEXOS-World highlights how curtailment can occur in some hours versus unserved energy in others. Next to that, the more detailed spatial resolution in PLEXOS-World also indicates that both can occur at the same time following oversupply in some regions versus undersupply in others. This observation suggests that there is a mismatch in spatiotemporal demand and supply of electricity for the simulated scenario.

When there is sufficient available transmission capacity within a region – or when assuming that regions are copperplates with no intra-regional network constraints such as modelled in MESSAGEix-GLOBIOM – any spatial mismatch between demand and supply can theoretically be mitigated. However, the results indicate that despite significant transmission capacities globally, network constraints are a key limiting factor that need to be overcome to enable power systems with high penetration levels of VRES. In the performed PLEXOS-World simulations based on the MESSAGEix-GLOBIOM scenario, the developed transmission portfolio together with underutilized balancing assets such as electricity storage and hydrogen electrolysis are not able to handle the spatiotemporal variability in demand and supply sufficiently to prevent largescale occurrence of curtailment and unserved energy. Future work

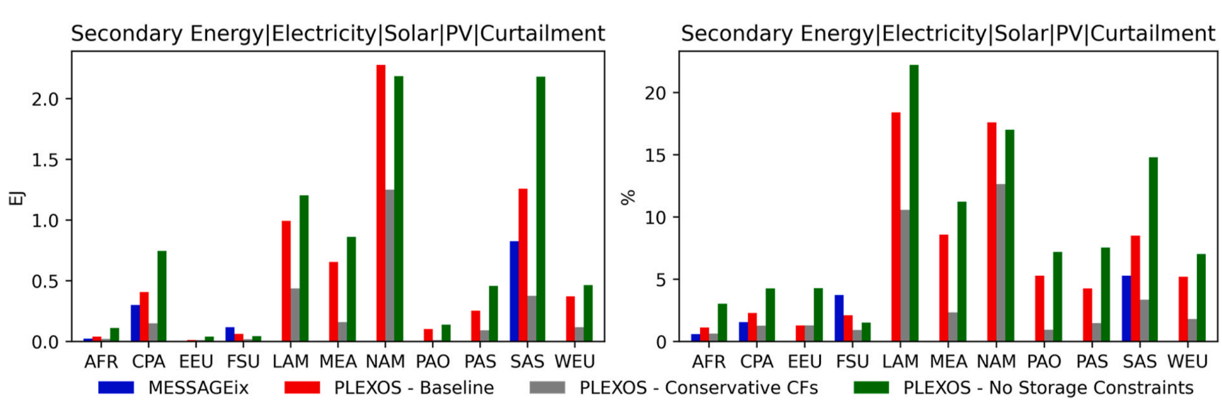

Fig. 13. Curtailment values for Solar-PV specified per model simulation. The left graph indicates curtailment in absolute values (EJ) and the right graph indicates curtailment relative to the theoretical generation potential per region for Solar-PV.

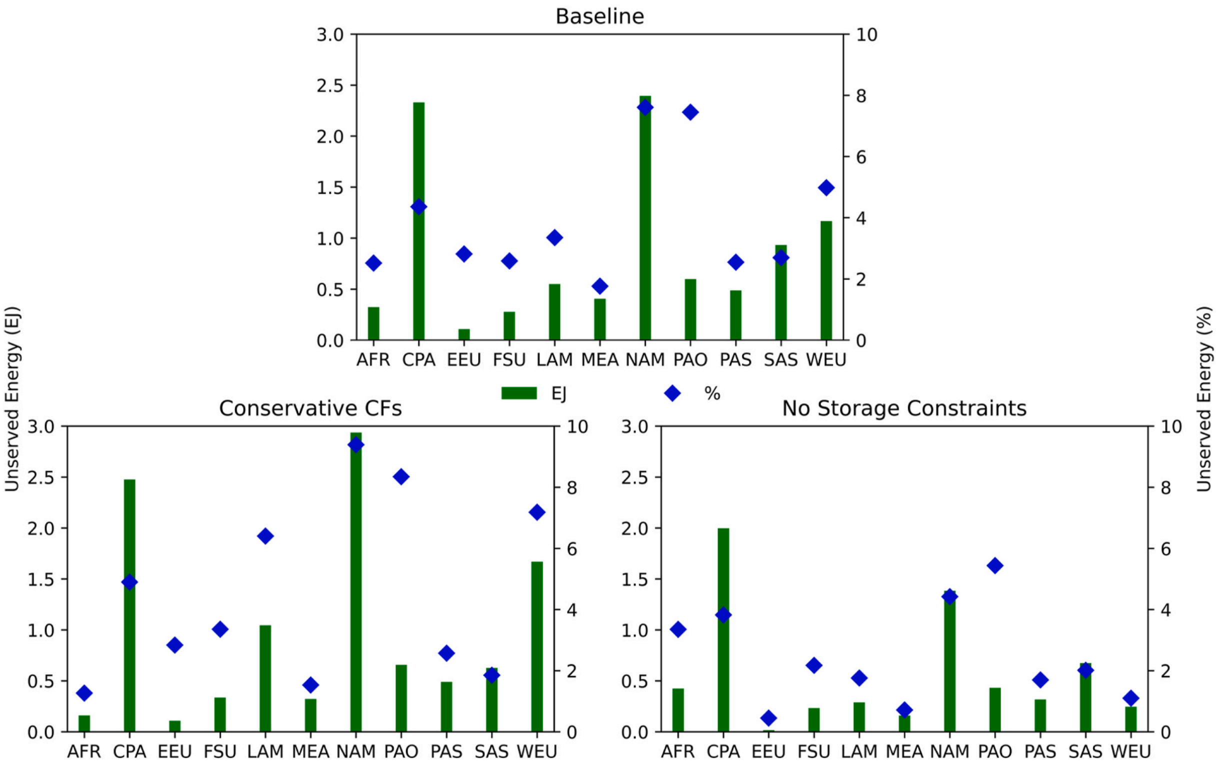

Fig. 14. Occurrence of unserved energy per PLEXOS-World simulation and region. The green bars represent the absolute values in EJ (primary Y-axis) and the blue markers represent the relative values compared to the regional final electricity demand (secondary Y-axis).

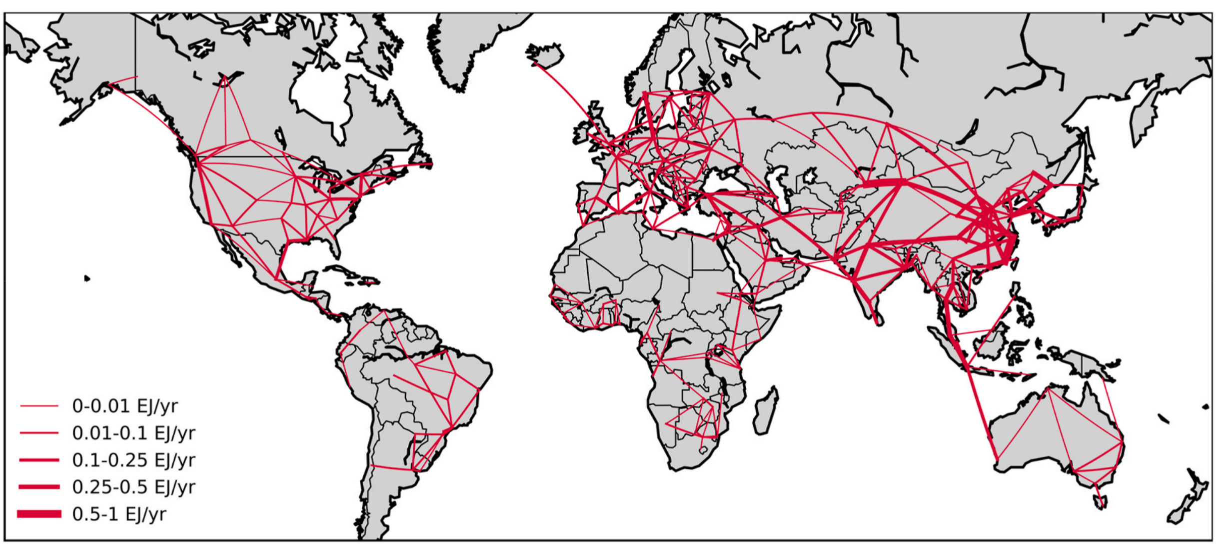

Fig. 15. Cumulative electricity transmission flows in 2050 for the 'No Storage Constraints' model simulation in PLEXOS-World.

is essential to provide more insights in model uncertainties as a result of the regional copperplates in global IAMs. Overall it can be observed that from a regionally and temporally coarse perspective following MESSAGEix-GLOBIOM the projected global power system is deemed technically feasible. However, the temporally and spatially detailed model simulations in PLEXOS-World highlight that the power system adequacy of the assessed scenario in terms of unserved energy, without taking into account potential contributions of electric vehicles to load management, may be insufficient.

As part of the modelling effort in parallel to this study, the power system representation in MESSAGEix-GLOBIOM regarding inter-regional trade of electricity has been adapted by integrating bilateral trade through investments in region specific transmission grid infrastructure. Model data and simulation results from PLEXOS-World have been used to inform the input parameters in MESSAGEix-GLOBIOM for this new setup. However, modelling results from the updated version of MESSAGEix-GLOBIOM still indicate an underestimation of inter-regional trade potential. It can therefore be concluded that the differences in spatial and temporal modelling resolution between MESSAGEix-GLOBIOM and PLEXOS-World are a direct cause for the underutilization of inter-regional trade in MESSAGEix-GLOBIOM. Due to the absence of sub-annual timeslices in the global implementation of MESSAGEix-GLOBIOM, there is a singular decision in the optimization to determine whether inter-regional import or export of electricity is

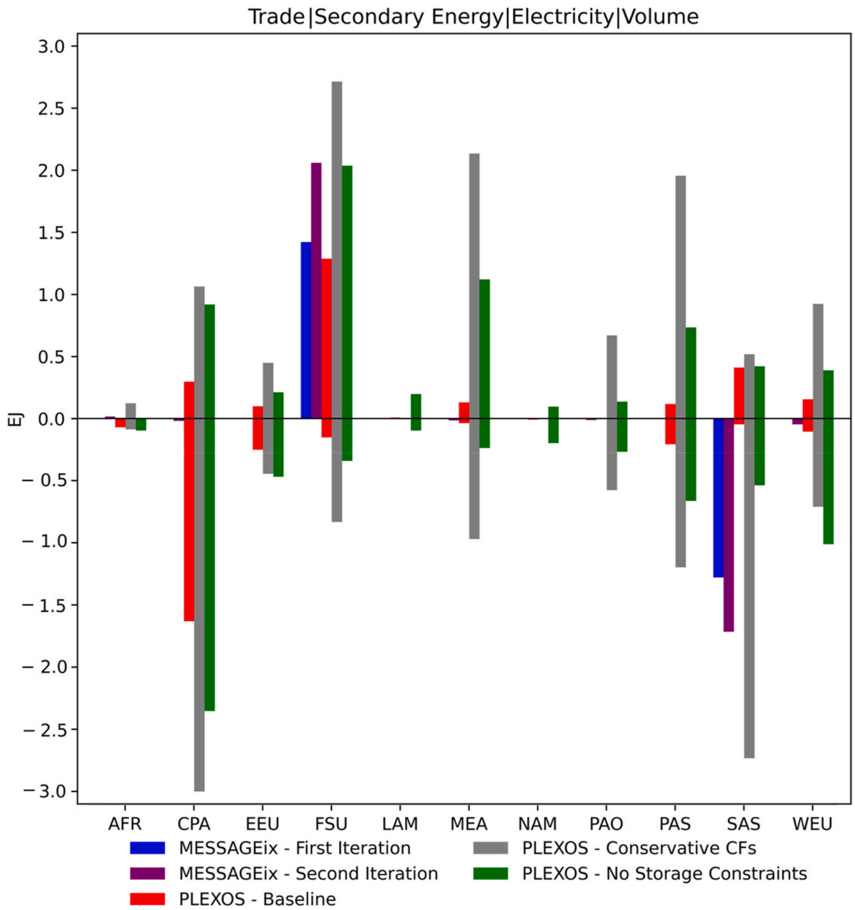

Fig. 16. Inter-regional electricity trade for the different PLEXOS-World simulations compared to both iterations of the MESSAGEix-GLOBIOM output. Positive values represent export and negative values import.

cost-optimal within the modelling period. This means that transmission is solely utilized for bulk unilateral flows of electricity within the modelling period, yet on an aggregate level it does not provide additional flexibility for the power systems involved in the inter-regional trade. The UCED modelling in PLEXOS-World for this study operates based on hourly intervals and hence is not only able to assess unilateral flows but also the occurrence of bilateral flows for the purpose of balancing electricity demand and supply between regions and for contributions to the mitigation of VRES variability. Furthermore, whereas a singular inter-regional transmission pathway exists between regions in MESSAGEix-GLOBIOM, PLEXOS-World has transmission pathways between all bordering areas meaning that multiple inter-regional transmission lines between two IAM regions can be operational at any given time. The low spatial and temporal resolution in MESSAGEix-GLOBIOM inherently means that there is a model bias against the uptake of inter-regional electricity trade.

4.2. Feedback on power system representation in MESSAGEix-GLOBIOM

There are a number of underlying assumptions in the model structure of MESSAGEix-GLOBIOM as well as general data inputs that affect its accuracy of results. The remainder of this section is dedicated to discussing these and to provide suggestions for improvements. The focus in this paper has been on the global implementation of the MESSAGEix-GLOBIOM model. Hence, suggestions for improvement of the power system representation in MESSAGEix-GLOBIOM are being made in this context. The use of sub-annual timeslices would be beneficial for the representation of VRES, however, to date its integration has been hampered due to its impact on computational complexity and resulting model runtime. Continuous developments regarding faster computers, cloud-based solutions, improved solvers and solving techniques merits a regular reassessment of the feasibility of implementing sub-annual timeslices in the global implementation of MESSAGEix-GLOBIOM. Besides refining the temporal- or spatial resolution in MESSAGEix-GLOBIOM, there are a number of low-hanging fruits that could be implemented for improved power system representation without affecting computational complexity too severely.

The previous sections have highlighted that the absence of network constraints within the regional copperplates within MESSAGEix-GLOBIOM is one of the main reasons for possible overestimation of VRES integration potential. In most global IAMs internal grid expansion is accounted for in terms of costs as a function of total build generator capacity or as a function of final electricity demand. The latter is the case for MESSAGEix-GLOBIOM, in addition to a cost premium for grid integration of VRES depending on the relative penetration and the size of the region. It is fair to assume that with longer transmission distances the costs - as well as losses - for internal electricity transmission increases. The results from the modelling in PLEXOS-World can benchmark the cost premiums in MESSAGEix-GLOBIOM for internal transmission integration to make sure they are not underestimated, which in turn would lead to overestimation of VRES integration potential. Where needed, values can be informed and updated on a regional basis.

All technologies in MESSAGEix-GLOBIOM have pre-defined values relative to their capacity for assumed positive or negative contributions to power system flexibility. To date it is assumed that inter-regional trade of electricity has positive contributions to system flexibility for the exporting region whereas inter-regional trade for the importing region has an equal negative contribution – i.e. it needs equally sized additional domestic flexibility to compensate for the import of electricity from another region. On a macro level this means that inter-regional trade does not contribute to flexibility in the power system within MESSAGEix-GLOBIOM which may restrict investments in new transmission capacity. Studies assessing the benefit of large-scale transmission integration in power systems with high VRES penetration highlight the potential for cross-border transmission as a means to provide flexibility, among others due to often asynchronous occurences of peaks and lows in electricity demand and VRES generation in different regions (Brinkerink et al., 2019). Transmission integration in this context can decrease the need for domestic reserves providing flexibility as highlighted among others from a pan-European (Rodríguez et al., 2014; Becker et al., 2014) and global (Grossmann et al., 2013) perspective. With this in mind it is recommended to reassess whether an equal negative contribution to flexibility for importing regions in MESSAGEix-GLOBIOM is overly conservative. The electricity trade values in PLEXOS-World can act as a baseline to calibrate the flexibility contributions for inter-regional trade in MESSAGEix-GLOBIOM.

As of now MESSAGEix-GLOBIOM includes a single generic electricity storage technology with 24 h storage potential. The underutilization of storage in the PLEXOS-World simulations can partly be explained by the fact that at a regional or continental level the sharing of resources through transmission integration can be favourable compared to mostly domestic generation and storage as also observed in recent literature for the African (Wu et al., 2017), Southeast Asian (Siala et al., 2021) and European (Tröndle et al., 2020) context. However the absence of other short- and longer-term storage technologies in MESSAGEix-GLOBIOM prevents the proper allocation of storage technologies depending on the requirements in the specific power system. Expansion of long-term storage technologies such as pumped hydro storage would be beneficial for seasonal storage purposes for wind-based generation. Furthermore, integration of short-term storage technologies such as batteries with a relatively higher power versus storage ratio would help with mitigating peaks in supply from especially Solar-PV. Next to storage, the integration of demand side management technologies could assist with shifting of peaks in electricity demand to decrease the likelihood of occurrence of unserved energy or to provide a better match with peaks in VRES generation.

The PLEXOS-World simulations have shown that the large-scale integration of VRES based on the MESSAGEix-GLOBIOM scenario is accompanied by the occurrence of both significant electricity curtailment as well as unserved energy in electricity demand. From a power system adequacy perspective, given the limitations in modelling resolution and model assumptions within global IAMs such as the unconstrained intra-regional power pooling, a range of stylized parameters and input assumptions such as region-specific curtailment parameters and technology CFs could benefit from being updated based on the spatially and temporally detailed modelling in PLEXOS-World. By means of the developed soft-link framework in this study, results from PLEXOS-World can be directly fed back into MESSAGEix-GLOBIOM as has been shown by the proof of concept for inter-regional electricity trade.

4.3. Study limitations and modelling uncertainties

The proposed soft-link framework is designed to assess and benchmark existing IAM scenarios by means of a snapshot analysis in a power system model with enhanced spatial and temporal resolution. The main limitation of this method is that by attempting to replicate the IAM scenario as closely as possible in the power system model the risk arises of over constraining the optimization that affects its optimality. A complementary approach could be to apply the optimization in context of the IAM scenario by making use of projected variables such as electricity demand and commodity prices, while allowing the power system model to optimize the long-term development of generator portfolios and balancing assets without further constraints. This would allow for an actual comparison of the optimal long-term planning in the integrated context in the IAM, versus an optimized long-term planning in the power system model from a solely operational power system perspective. However, modelling in PLEXOS-World indicates that performing long-term planning exercises in detailed global power system models can be computationally challenging and requires further examination to find appropriate trade-offs between modelling resolution and computational time – an average model run of PLEXOS-World based on the 2050 snapshot analysis in context of this study takes approximately 12 h.

Other study limitations are specific to the proof of concept linking MESSAGEix-GLOBIOM and PLEXOS-World, for example related to the practical implementation of the different framework steps. The applied spatial demand downscaling uses projected demand values as proxy retrieved by means of multivariate linear regression. Besides the fact that the used values for the regression are for the period 1980–2014, the main limitation of this approach is that historic values are not fully representative for future developments when it comes to electricity demand forecasting due to among others expected increasing electrification in final energy demand. That said, the projected values are solely used as proxy for the downscaling, actual final demand values at an aggregate regional level are equal to the scenario output from MESSAGEix-GLOBIOM. More advanced energy downscaling methods designed for IAM scenario data have become recently available that can be used for future studies (Sferra et al., 2021). Another simplification is the fact that for the temporal demand downscaling, demand timeseries in the PLEXOS-World model for 2050 are linearly scaled compared to historical timeseries whereas it can be expected that the shape of diurnal electricity demand in the future might change among others due to uptake of electric vehicles. Future work can address this by using reported sectoral electricity demand from IAMs as foundation for adjusting demand timeseries.

Like all modelling tools, PLEXOS-World has its limitations and uncertainties that affect the accuracy of results for the proof of concept. As of now the model does not include demand for other energy carriers that indirectly affect how much electricity needs to be supplied – for example green hydrogen demand for transport and heating. These differences in sectoral coverage contribute to observed differences in model outputs for factors such as technology generation values and CFs for PLEXOS-World compared to a sector-coupled model like MESSAGEix-GLOBIOM. Future applications of the model will need to take these intersectoral dynamics into account to be able to compare model outputs with IAMs in a level playing field. Furthermore, in the used version of PLEXOS-World electric vehicles and demand side management are not included which reduces the ability of the power system to compensate for variability in supply. Demand side management is not actively incorporated in MESSAGEix-GLOBIOM in relation to system flexibility yet electric vehicles can contribute to curtailment reduction and overall system flexibility. Another important factor is that the sampling approach used for deriving representative timeslices as applied for the capacity allocation exercise in PLEXOS-World has to be assessed in more detail. Increasing the number of timeslices for the full global model is computationally challenging, hence it would have added value to benchmark the results with single-region model simulations with enhanced time slicing. Next to the above, additional model runs to assess sensitivities and uncertainties on a range of parameters and assumptions such as costs for transmission infrastructure, perfect market and foresight assumptions, power system adequacy and reliability constraints, climatic impact on renewable resource potential, switching to different weather years for VRES CF timeseries (Collins et al., 2018) and overall to analyse a wider range of scenarios and snapshot years could increase the robustness of the results.

5. Conclusion

This study proposes a novel methodological framework for soft-linking of continental- or global IAMs with detailed global power system models. By means of a proof of concept application of the soft-link framework linking global IAM MESSAGEix-GLOBIOM with global power system model PLEXOS-World, the results of this paper highlight the usefulness of the framework by feeding in to known limitations of global IAMs as a result of limited modelling resolution and power system representation. The spatially and temporally detailed modelling in PLEXOS-World of scenarios coming from MESSAGEix-GLOBIOM has identified a number of key limitations in MESSAGEix-GLOBIOMs' power system representation that affect its accuracy of results.

Overall, the results reflect that MESSAGEix-GLOBIOM and global IAMs in general are not constructed with the aim to perform spatially and temporally detailed assessments of power system dynamics. That said, it is the authors' view that this not necessarily means that global IAMs are unsuitable for providing boundaries in possible mitigation pathways for the development of the global energy system from a multi-disciplinary perspective. From a solely power system point of view, tools like PLEXOS-World would be better suited to optimize the long-term planning of the global power system. Yet, as it stands, computational requirements for global model simulations without compromising on modelling resolution do not permit simulations for long-term horizons. Furthermore, the lack of interaction with other sectors in the energy system and with ecological- and economical systems gives power system models a narrow scope.

Considering limitations of both sets of models, we conclude that IAMs can be applied for providing insights in possible long-term development pathways for the global energy system and to inform global climate- and energy policy assuming benchmarking with dedicated sectoral models occurs regularly. By making use of the soft-link framework proposed in this study, power system models like PLEXOS-World can be used in a complimentary fashion to pinpoint areas for model-informed improvements in global IAMs. The framework can furthermore be used as a template for soft-linking of global IAMs to other dedicated sectoral models.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envsoft.2022.105336.

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