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Assessing 1.5-2°C scenarios of integrated assessment models from a power system perspective - Linkage with a detailed hourly global electricity model

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Abstract

Integrated Assessment Models (IAMs) are vital for identifying potential pathways for the long-term development of the global energy system in line with set climate targets to keep global temperature rise well below 2°C and to further pursue efforts to limit temperature rise to 1.5°C. IAMs cover a broad spectrum of energy demand and supply sectors while simultaneously having the ability to account for interlinked impacts on ecological and economic systems. Due to their broad scope, global IAMs are limited in detail regarding spatial and temporal modelling resolution. Significant improvements have been made in recent years regarding power system representation in global IAMs. However, ongoing concerns exist within the scientific community regarding the suitability of global IAMs to properly simulate the challenges that arise with integration of vast quantities of variable renewable energy sources in the global power system.

Historically two streams of research exist in this area. One stream focuses on internal model improvements in global IAMs, whereas the other stream uses complementary sectoral power system models to benchmark the output coming from the IAM. Both approaches have its merits yet also significant limitations. Internal model improvements in IAMs without making use of dedicated power system models can lead to simplified assumptions. The lack of suitably informed data makes regional diversification of power system representation challenging. On the other hand, linking global IAMs to power system models requires two sets of model instances to be available and is generally difficult to repeat once time passes. Furthermore, until recently, power system models at the global scale weren't available in the public domain.

This study proposes a methodological soft-link framework for connecting continental- or global IAMs with detailed global power system models. With the framework, output from global IAMs can be fed into a power system model to assess given scenarios with higher spatial, technological and temporal resolution. Results from the power system model simulations can be used to identify core gaps in the IAM power system representation and can be fed back to the IAM for informed improvements. The framework is novel as it not only proposes to assess IAM scenarios, but also downscales global IAM scenarios to a higher spatial detail as required to realistically simulate power system dynamics. Furthermore, the framework promotes using IAMC data template format for linking both sets of models, making it non-discriminatory for a wide range of IAMs and power system models.

As part of this study, a proof of concept application of the soft-link framework has been applied by a first of its kind soft-linking exercise between global IAM MESSAGEix-GLOBIOM with global power system model PLEXOS-World. A 1.5°C and high VRES scenario has been chosen to critically scrutinize MESSAGEix-GLOBIOM in a setting where IAMs generally struggle the most regarding the implications of variability in electricity supply. The results highlight that MESSAGEix-GLOBIOM has significant limitations regarding realistically representing a range of power system dynamics following the limited spatial and temporal resolution. A range of parameters in MESSAGEix-GLOBIOM have been identified as potentially suitable yet could benefit from updated values based on the PLEXOS-World output. Furthermore, identified critical factors that are currently missing in MESSAGEix-GLOBIOM with a potentially large impact such as the absence of proper representation of inter-regional electricity transmission and the lack of a diverse set of investable storage technologies merits further model development of MESSAGEix-GLOBIOM.

Acknowledgments

While working on the last sections of this report it made me realize that given the challenging circumstances during the COVID-19 pandemic I’m forever grateful for this virtual YSSP to have taken place. It has given me a purpose to plough ahead despite being locked in a tiny city apartment for most of the summer. For this I’m very thankful towards the YSSP organizing committee, who despite of all the uncertainty and ever changing circumstances have given us this opportunity to be part of the IIASA YSSP family. In particular I’d like to thank Aleksandra, Brian, Fabian and Tanja for all their efforts and for making this YSSP as interactive as possible.

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1. Introduction

Planning models such as Energy System Optimization Models (ESOMs) and Integrated Assessment Models (IAMs) are widely used to assess scenarios for the long-term evolution of the global energy system over multiple decades [1,2]. Whereas ESOMs solely focus on the development of the energy system, 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 [1,3–5]. IAMs therefore not only represent different energy demand and supply sectors, but also integrate the constraints and impacts associated with land-use requirements- and emissions as well as water consumption and fossil- and renewable resource availability [3,5]. In addition to the broad sectoral representation, planning models 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 limit the overall computational requirements of model simulations, planning models are restricted in temporal resolution with a significant geographical aggregation of model regions [2,3,6].

One of the biggest challenges for leading IAMs is to deal with variability in electricity demand and supply as a result of large integration of variable renewable energy sources (VRES) in emission mitigation scenarios [1–3,6,7]. Traditional power systems can be represented in a fairly accurate manner in IAMs due to the often-predictable operation of power systems mostly based on dispatchable technologies. However, due to the limited amount- or absence of sub-annual timeslices, IAMs pitfall is to realistically represent the operation of VRES technologies and its corresponding integration challenges [1,3,6,8]. To still account for the above challenges, well-known IAMs such as AIM/GCE [9], IMAGE [10], MESSAGEix [11], POLES [12], REMIND [13] and WITCH [14] integrate generic relationships to represent the integration of VRES technologies in a stylized manner.

Significant model improvements have been made in recent years regarding power system representation in IAMs among others as a result of the ADVANCE project [1,2,8,15–20]. That said, developments are ongoing and additional improvements need to be made in multiple aspects such as the representation of storage technologies including power-to-X [1,16,18,20], parameterization of thermal power plants [15,18,20], explicit modelling of demand side management [1,16,20] and 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 due to transmission constraints [1,15–18]. Next to the above, often mentioned as 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 [1,2,16,18,20]. Regarding region specific input data, this can partly be solved by making use of advanced datasets regarding detailed historical [21,22] or synthetic [23] load data for all countries globally, yet for integration of new model assumptions it is recommenced to benchmark the assumptions by making use of model simulations in operational power system models [1,3,20,24]. Power system models can assess the operational aspects of a given power system with high spatial, temporal and technological detail. Due to the dedicated sectoral scope, a wide range of state of the art power system models such as Artelys Crystal Super Grid [25–27], EnergyPLAN [28–30], LUSYM [31,32], LUT Energy System Transition model [33], PLEXOS [22,34–38] and PyPSA [39,40] have the proven ability to simulate spatially rich continental- or global scale models with hourly temporal resolution at minimum.

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. Establishing a link with the purpose of facilitating data flows between IAMs and power system models have been occurring within the modelling community for many years. 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 [41]. 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 assumptions in the IAM. The soft-link approach is the correct choice if the intention is to assess given IAM scenarios one-off or when the aim is to improve the power system representation internally in the IAM rather than make consistent use of a power system model as complementary tool. 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 negotiates between both models [42]. The hard-link approach leads to a singular set of results and is generally the preferable approach when the linking exercise is to be repeated regularly because it's more efficient and less prone to human error. Nonetheless, what initially starts of as a soft-link can be converted into a hard-link when deemed appropriate.

Both the soft-link [41,43–49] as the hard-link [18,50] approach have proven to be successful methods for linking planning models and power system models. That said, both 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 [20,42]. On the other hand, hard-linking involves significant time and resources to develop a smooth operation of co-optimization of both models which is not always feasible [42], nor are all modelling tools computationally able to function in this setting. Furthermore, relevant for both hard- as soft-linking, traditional linking exercises are tuned to a specific link between two model instances making it complicated to switch to for examples assess scenarios from a different IAM.

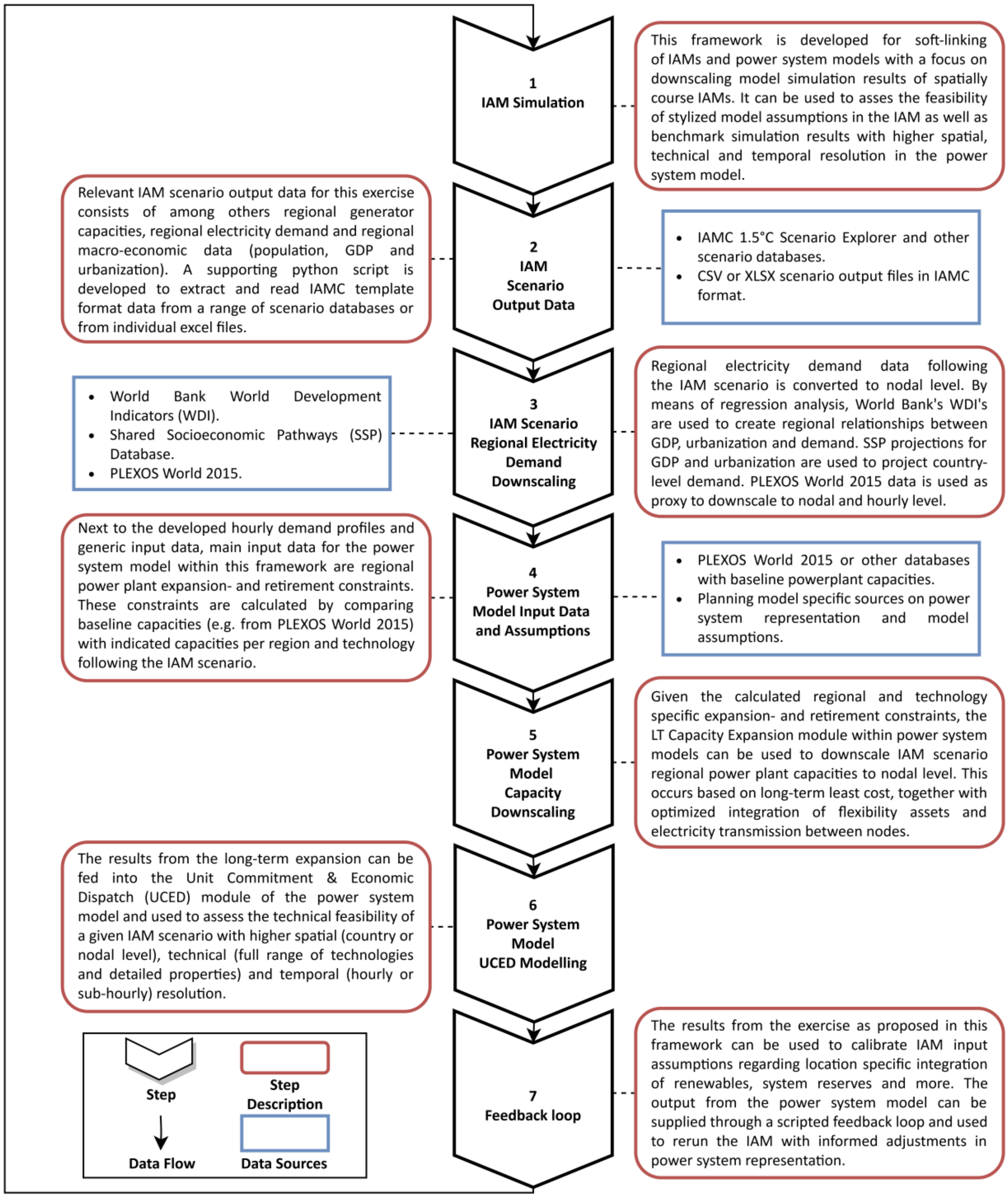
Next to the above, Collins et al. [3] argue that due to the small number of very sizable regions – each of which is assumed to be a 'copperplate' without internal network constraints – in especially global IAMs as well as the long time horizons, it can be challenging to perform power system model simulations for every region for all horizon years. 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 [18,20,24]. 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 [21–23,51–54] have made the development of detailed global power system models possible [21,22,33] from which the model input data can easily be transferred to other modelling tools [21]. Global power system models like this can be used to assist with constructing region-specific power system representation in long-term planning models as well as benchmark the overall model output explicitly by region.

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 higher spatial, technological and temporal resolution. The model output can be redirected to the IAM to use assessment outcomes for internal improvements regarding renewed region-specific power system input and model assumptions. The novelty of this framework and paper is multifold and developed in accordance with the identified limitations of IAMs and existing model linking methodologies. First, the framework is not used to assess scenarios with the often course 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 realistic assessments of local power system dynamics within the given IAM scenario. Secondly, the framework promotes using a standardized data format, making it non-discriminatory towards 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. Although the focus of the framework is particularly oriented towards the key limitations of IAMs, where needed the framework can also be applied to other long-term planning models like ESOMs.

Considering the importance of 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) [5], an ongoing theoretical debate exists within the scientific community [55,56] whether global IAMs are suitable for long-term planning of the global energy system due to among others the limitations as described in this section. The proposed framework assists with putting boundaries on this debate from a power system perspective by providing the ability to scrutinize IAM scenarios in dedicated power system models and simultaneously support internal improvement of power system representation within the IAM. As a proof of concept, the global implementation of the IAM MESSAGEix - MESSAGEix-GLOBIOM [57,58] - is soft-linked to a future oriented version of PLEXOS-World [21,22], a 258-nodal detailed global power system model developed in PLEXOS [34]. By means of a snapshot analysis for the year 2050, the MESSAGEix-GLOBIOM ENGAGE SSP2 NPI2020 500 scenario will be assessed with the aim to determine whether the generic stylized relationships regarding generator reserve requirements, generator capacity factors and transmission integration in MESSAGEix-GLOBIOM are deemed appropriate or whether this could be improved by means of regional fine-tuning. Section 2 describes the proposed methodological framework in detail and section 3 includes the results of the proof of concept application of the framework. Section 4 includes a discussion regarding the framework, its limitations, its possible future applications and a commentary on the theoretical discussion regarding the suitability of IAMs for planning exercises of the global power system.

2. Methodological Framework

The proposed methodological framework for soft-linking of spatially course IAMs with dedicated power system models allows for detailed assessments of the feasibility of given IAM scenarios with higher spatial, technological and temporal resolution. The framework can be used to perform snapshot analyses of a single data year or assess longer time horizons. Where needed, the power system model output can be used to benchmark and optimize region specific input assumptions and power system representation of the specific IAM by making use of an iterative feedback loop.



This framework is developed for soft-linking of IAMs and power system models with a focus on downscaling model simulation results of spatially course IAMs. It can be used to asses the feasibility of stylized model assumptions in the IAM as well as benchmark simulation results with higher spatial, technical and temporal resolution in the power system model.

Relevant IAM scenario output data for this exercise consists of among others regional generator capacities, regional electricity demand and regional macro-economic data (population, GDP and urbanization). A supporting python script is developed to extract and read IAMC template format data from a range of scenario databases or from individual excel files.

- IAMC 1.5°C Scenario Explorer and other scenario databases.
- CSV or XLSX scenario output files in IAMC format.

- World Bank World Development Indicators (WDI).
- Shared Socioeconomic Pathways (SSP) Database.
- PLEXOS World 2015.

Regional electricity demand data following the IAM scenario is converted to nodal level. By means of regression analysis, World Bank's WDI's are used to create regional relationships between GDP, urbanization and demand. SSP projections for GDP and urbanization are used to project country-level demand. PLEXOS World 2015 data is used as proxy to downscale to nodal and hourly level.

Next to the developed hourly demand profiles and generic input data, main input data for the power system model within this framework are regional power plant expansion- and retirement constraints. These constraints are calculated by comparing baseline capacities (e.g. from PLEXOS World 2015) with indicated capacities per region and technology following the IAM scenario.

- PLEXOS World 2015 or other databases with baseline powerplant capacities.
- Planning model specific sources on power system representation and model assumptions.

Given the calculated regional and technology specific expansion- and retirement constraints, the LT Capacity Expansion module within power system models can be used to downscale IAM scenario regional power plant capacities to nodal level. This occurs based on long-term least cost, together with optimized integration of flexibility assets and electricity transmission between nodes.

The results from the long-term expansion can be fed into the Unit Commitment & Economic Dispatch (UCED) module of the power system model and used to assess the technical feasibility of a given IAM scenario with higher spatial (country or nodal level), technical (full range of technologies and detailed properties) and temporal (hourly or sub-hourly) resolution.

The results from the exercise as proposed in this framework can be used to calibrate IAM input assumptions regarding location specific integration of renewables, system reserves and more. The output from the power system model can be supplied through a scripted feedback loop and used to rerun the IAM with informed adjustments in power system representation.

Figure 1: Overview of the proposed framework for soft-linking of IAMs and power system models**.** Details on the different steps can be found in the different sub-sections of section 2.

Figure 1 provides an overview of the different steps of the framework together with the main data flows and sources. The framework is setup in a non-discriminatory way allowing it to be applied to any specific IAM and power system model given a few base requirements. First of all, the scope of this framework from a spatial perspective is to downscale the often course regional copperplates in IAMs to a more detailed spatial resolution in the power system model. This framework is therefore more useful in the assessment of global or continental models with multi-country scale regions versus scenarios from already more spatially defined IAMs. Secondly, the used power system model requires a long-term capacity expansion module capable of integrating expansion constraints based on IAM scenario output, details on this will be provided in section 2.4.

Lastly, although not a prerequisite, the developed python script accompanying this paper that can be used to coordinate a soft-link between IAM and power system model is based on IAMC data template format[1]. Hence for the script to be used, IAM scenario output data needs to be directly exported in the IAMC data format or converted as part of the workflow. Note that the script is a helpful tool to automate data processing workflow within the soft-link but is by no means the only way to do it in context of this framework, other languages or manual data conversion (e.g. in Excel) can be applied as well. Although the methodological framework is developed in accordance with the limitations of IAMs, the framework is also suitable to assess other long-term planning models like ESOMs. The next sections describe the different parts of the framework in more detail while using the ENGAGE SSP2 NPI2020 500 scenario of the global IAM MESSAGEix-GLOBIOM as a proof of concept.

2.1. Planning model simulation

As described in the introduction of this paper, the representation of the power system in IAMs occurs in a stylized manner. By means of this framework, these relationships as well as the general input assumptions and data can be benchmarked and optimized through power system model simulations with higher spatial, technological and temporal resolution. Among others, the model soft-link allows for enhanced insights regarding VRES integration in IAMs and provides the ability to assess the suitability of uniformly applied generic relationships and input assumptions or whether said relationships and assumptions need to be specified based on regional characteristics.

2.2. Planning model scenario output data

At minimum, the required IAM scenario output data consists of technology specific regional level powerplant capacities and regional electricity demand. Other data such as carbon- and fuel prices as well as capacities of balancing assets such as storage, power to gas and electric vehicles can either be standardized (pricing) or optimized (balancing assets) in the power system model. That said, to assess the technical feasibility of a given scenario as baseline for further optimization, it's worth mimicking most of the scenario output in the power system model. After that constraints can be softened to optimize the scenario solely from a power system perspective to assess in which areas improvements can be made regarding power system representation within the specific IAM.

The python script that accompanies this paper is based on IAMC data template format. This allows the script to directly connect to commonly used databases such as the IAMC 1.5°C Scenario Explorer [59,60] and assess scenarios from a wide range of scenario ensembles, among others the ensemble as assessed in Chapter 2 of the IPCC's Special Report on Global Warming of 1.5°C (SR15) [5]. Alternatively, it is also possible to link the script to individual csv or xlsx files.

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[1] https://data.ene.iiasa.ac.at/database/

2.3. Planning model scenario regional electricity demand downscaling

One of the core aspects of the framework is the ability to assess regionally course IAM scenarios with higher spatial and temporal resolution. For this to occur, scenario specific yearly electricity demand values need to be downscaled to a newly defined spatial resolution and converted into more detailed timeseries, for example hourly, depending on the aim of the study [61]. Although any downscaling approach can be applied, within the accompanying script we apply a forecasting methodology for country-level electricity demand based on multivariate linear regression with GDP at purchasing power parity per capita and urbanization share as independent variables and electricity consumption per capita as dependent variable. Refer to appendix 1 for details on the applied downscaling methodology for the proof of concept application of this framework.

2.4. Power system model input data and assumptions

Within the proposed framework there are three sets of required power system model input data. The first set relates to data that due to the specific characteristics of power system models regarding the ability to integrate high detail in especially temporal and technological resolution requires input data and modelling assumptions that cannot always be provided or replicated from IAMs. Examples can be temporally detailed capacity factor (CF) profiles for renewables or detailed powerplant characteristics such as ramp rates and minimal stable levels. Next to that, the second set of input data relates to data that if available from the IAM could be integrated in the power system model to mimic the specific scenario as closely as possible, yet is not critical for the overall application of the framework as this type of data can also be standardized from other sources. Examples are fuel- and carbon price projections and cost assumptions for expansion of balancing assets such as transmission infrastructure and different storage technologies. The last and most important set of input data is data that needs to be directly linked to the IAM scenario output and can be seen as constraints for the proper application of the framework.

For the latter, next to the downscaled demand profiles as described in the previous section, other main input data are regional powerplant expansion and retirement constraints which determine per scenario region and technology how much capacity needs to be expanded or retired to match the values given by the specific IAM scenario for a given year. These constraints are used as basis for the capacity expansion exercise within the power system model (more details in the next section) and can be setup in multiple ways. First, a 'greenfield' approach can be used in which existing powerplant capacity portfolios in individual (sub-)country nodes 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's therefore advisable to start with a baseline portfolio, which can be based on any preferable source, yet this paper and the accompanying script uses the PLEXOS-World 2015 dataset [21]. The dataset includes global powerplant capacities as of 2015 at individual powerplant level separated by 258 regions.

Given the high temporal resolution of power system models, Unit Commitment and Economic Dispatch (UCED) exercises are usually restricted to a year at maximum per model simulation as a snapshot analysis of the dynamics of a given power system. UCED within power system models refer to the optimal utilization of available generating capacity to match system demand within a given simulation period while abiding to technical- and operational constraints. Taking 2050 as an example as intended simulation year for the UCED, scenario specific expansion and retirement constraints for the period up to 2050 can be calculated by subtracting the regional and technology specific powerplant capacities retrieved from the IAM scenario output from the baseline powerplant capacities. If the difference is positive it means that expansion of capacity is required for that specific technology and region and vice versa retirement. For optimally realistic 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 (2015-2050) to make the capacity expansion exercise computationally less intensive. In context of global scenario assessments this latter approach is merited despite inherent limitations. For example, depending on the power system model, expansion in a single step for such a long period might not correctly represent the expansion and retirement of technologies with lifetimes shorter than the horizon of the simulation step. Figure 2 shows an example of calculated expansion and retirement constraints for the period 2015-2050 for the MESSAGEix-GLOBIOM_R11LAM region.

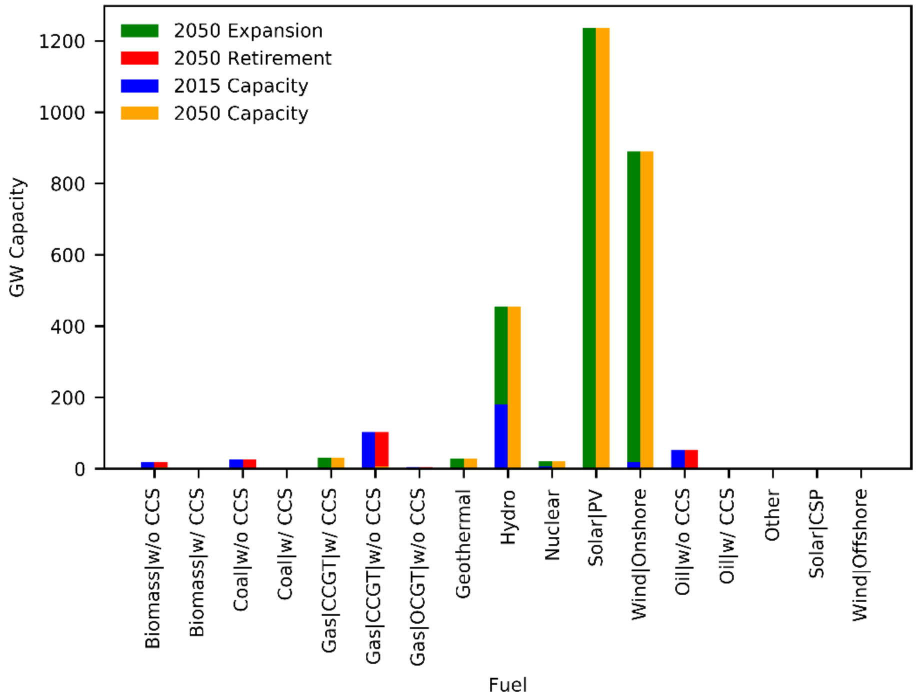

Figure 2: Example expansion and retirement constraints for the MESSAGEix-GLOBIOM_R11LAM region in the ENGAGE SSP2 NPI2020 500 scenario for the period 2015-2050. Per technology, the left bar indicates the existing baseline capacity in 2015 (blue) and the to be expanded capacity (green) in case the difference between the 2015 and 2050 capacity is positive. The right bar indicates the required capacity in 2050 (yellow) and the to be retired capacity (red) in case the difference between the 2015 and 2050 capacity is negative.

2.5. Power system model long-term capacity downscaling and system integration

In the traditional application of long-term capacity expansion modules within power system models, the objective is generally to minimize the net present value of the long-term system costs consisting of fixed capital costs as well as fixed and variable operational costs. The main difference in the application of the long-term module within the current framework is that there are no fixed costs attached to the expansion and retirement of powerplants considering these costs are already accounted for in the IAM. The module is used to downscale given powerplant capacities based on the IAM scenario output from a regional to (sub-)country level based on local characteristics and resources, in parallel with optimized expansion of balancing assets. The downscaling of powerplant capacities is constrained by the expansion and retirement constraints as constructed in the previous step. Figure 3 shows an example output of the downscaling exercise in which the regional powerplant capacities for the MESSAGEix-GLOBIOM_R11LAM region as indicated in figure 2 are downscaled to a more detailed spatial representation.

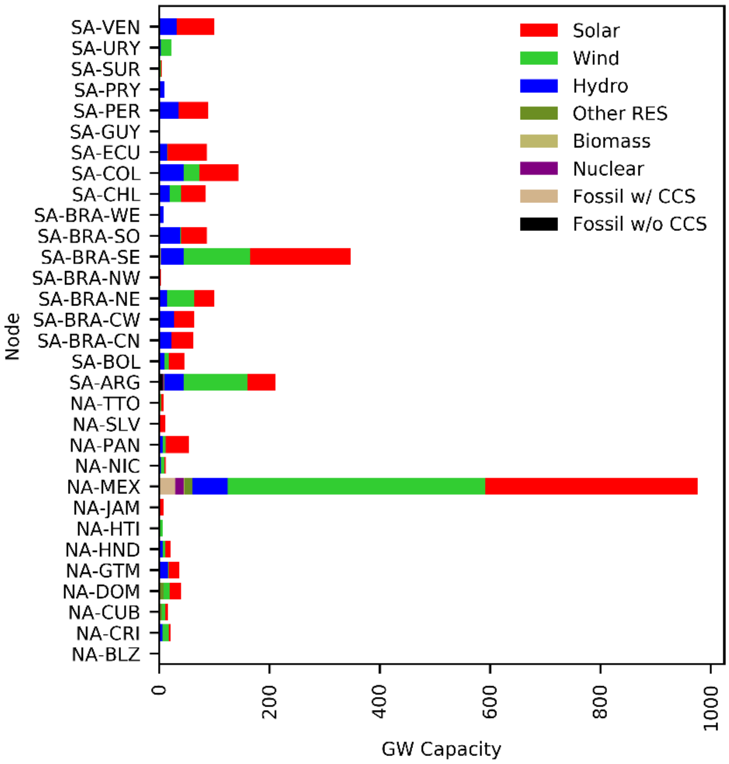

Figure 3: Example output for the MESSAGEix-GLOBIOM ENGAGE SSP2 NPI2020 500 scenario of the long-term capacity expansion module used to downscale regional power plant capacities as provided by the output of the given IAM scenario to a more detailed spatial representation. The bars indicate installed powerplant capacities per category.

The purpose of this exercise with an alternative application of power system models' long-term capacity expansion module is twofold. First, the constrained downscaling of capacities rather than unconstrained expansion forces the power system model to optimally allocate powerplant capacities based on the IAM scenario output from an often coarse regional level to a more spatially detailed setting. Especially relevant from a power system perspective, this allows for any IAM scenario to be assessed in context of local characteristics with the ability to provide detailed insights that cannot be provided with a courser representation. For example, the effect of transmission power pooling, the ability to balance electrical load over a large transmission network, can be considered when the different IAM regions are not modelled as large individual copperplates. Furthermore, it can be assessed whether generic relationships in IAMs that are uniform for all regions are representative or whether regional differences merit further fine tuning. For example, the effect of transmission power pooling can be expected to be very different in geographically dense model regions (e.g. MESSAGEix-GLOBIOM_R11WEU) versus larger regions where individual countries are often separated with large stretches of unpopulated land or water (e.g. MESSAGEix-GLOBIOM_R11PAO). Other benefits of spatial downscaling in the context of this framework among others relate to the ability of providing insights in region specific reserve- and flexibility requirements.

Next to the downscaling of powerplant capacities, the long-term capacity expansion module 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. These assets are usually accounted for in IAMs, yet not always by means of optimization that incorporates the benefits of these assets visible in model simulations with detailed temporal resolution. Integration of these assets can be very different per region and also impact earlier mentioned aspects such as required domestic system reserves and capacity factors of different technologies. Figure 4 shows an example of optimized expansion of transmission infrastructure by means of net transfer capacity for the given example scenario.

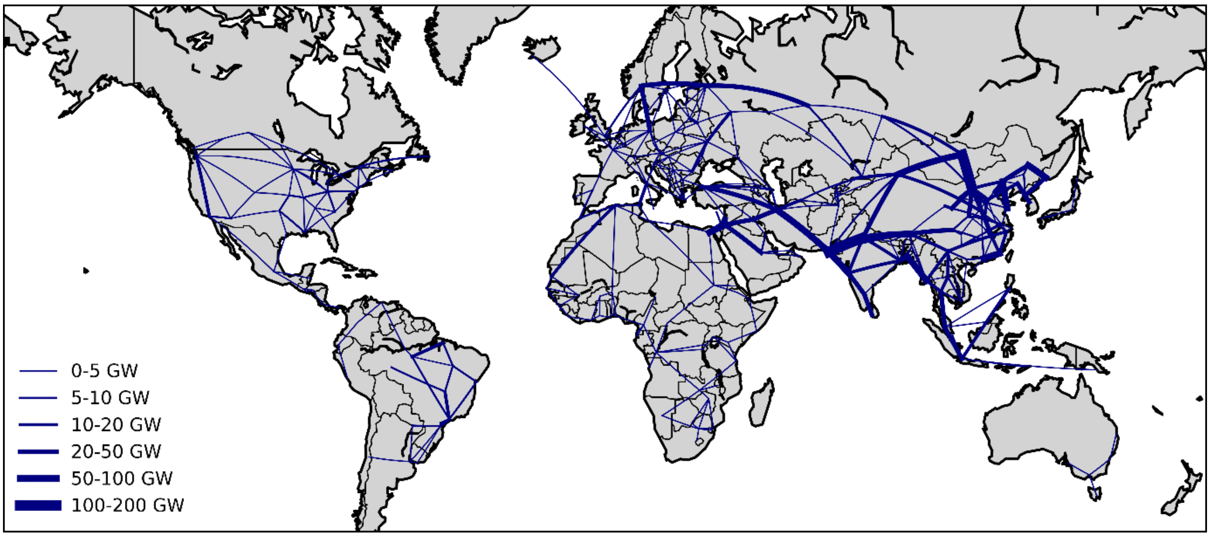

Figure 4: Example output of the long-term capacity expansion module with optimized expansion of transmission infrastructure for the MESSAGEix ENGAGE SSP2 NPI2020 500 scenario. The map indicates net transfer capacity per transmission pathway based on a model simulation with a total of 258 nodes and 545 unique potential transmission pathways spanning the globe. Details on the modelling of transmission infrastructure and its assumptions in the indicated example can be found in appendix 2.

2.6. Power system model UCED modelling

The output from the power system models' long-term capacity expansion module can be used as input for the UCED modelling. Temporally detailed model simulations, being hourly or even sub-hourly, 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 CF's and generation values, general relationships regarding curtailment and occurrence of possible unserved energy. Similar to the long-term results, the output from the UCED can indicate whether there are significant regional differences that could merit a tailored approach for the IAM input or whether generic input assumptions are viable.

2.7. Power system model scenario output data and IAM feedback loop

The results from the model soft-link exercise within this framework consist of quantified simulation output but can also include non-quantifiable observations that can assist with optimizing the power system representation in IAMs while considering the computational requirements of model simulations. The latter part cannot be automized, whereas the power system model output data flow can be converted into a readable format for the specific IAM (e.g. IAMC format) and directly integrated where appropriate. Clear examples can be region specific CF's for the different generator technologies and balancing assets as well as region specific reserve- and flexibility requirements. This scripted feedback loop allows for an iterative process between IAM and power system model until the power system representation in the IAM is deemed satisfactory.

3. Application of the framework

The previous section has described the proposed framework for downscaling- and detailed assessments of IAM scenarios in power system models. This section includes a proof of concept application of the framework with the global IAM MESSAGEix-GLOBIOM [11] being used from which the ENGAGE SSP2 NPI2020 500 scenario will be assessed in power system model PLEXOS [34]. The aim of this exemplary exercise is to determine whether the generic stylized assumptions regarding generator reserves (i.e. firm capacity requirements), generator capacity factors and transmission integration in MESSAGEix-GLOBIOM are deemed appropriate or whether this could be improved by means of regional fine-tuning. The section starts with an introduction of MESSAGEix-GLOBIOM and PLEXOS with a focus on the power system representation in both modelling tools that are relevant for the above-mentioned research questions.

3.1. MESSAGEix-GLOBIOM

MESSAGEix-GLOBIOM is a process-based IAM with a detailed representation of technological, socioeconomic and biophysical processes in energy and land-use systems [11]. The global implementation of the model is based on a 11-region spatial representation [62] as visualized in figure 5. The focus of this paper is on the power system representation in MESSAGEix-GLOBIOM, refer to [11,62] for a full description of the MESSAGEix framework and [57] for details on the MESSAGEix-GLOBIOM model. As mentioned in the introduction, one of the biggest challenges for current-day IAMs is to deal with short-term variation in electricity supply following the large-scale integration of VRES. Although MESSAGEix can perform model simulations with sub-annual timeslices, simulations of MESSAGEix-GLOBIOM generally occur with years as most detailed timeframe. Sullivan et al. [24] and Johnson et al. [20] have therefore developed methodologies for implementing relationships in MESSAGEix-GLOBIOM that capture the impact of VRES technologies in a stylized manner. Sullivan et al. introduced two sets of power system reliability constraints related to 1) capacity reserves to meet system peak load at all times and 2) operating reserves to provide a pre-defined level of system flexibility. Albeit a significant step forward compared to earlier versions of the model, the approach has a range of limitations such as the fact that the globally uniform parametrization is based on UCED simulations from a six-region power system model of the ERCOT system in Texas US [15,24,63] and that the stylized relationships were derived based on integration of wind generation without considering solar technologies. Furthermore, Johnson and colleagues [20] argue that the use of a detailed power system model for parameterization makes it difficult to reproduce the study results.

Due to the above limitations, Johnson et al. applied a hybrid approach using region specific Residual Load Duration Curves (RLDC'S) from [2], that allow for regional differentiation of the system reliability constraints as integrated by Sullivan et al. [24]. RLDC's represent the load of a specific region that must be met by non-VRES calculated by subtracting the projected VRES generation by the demand values per interval. These curves have been used to create regionally stylized parameterization for the impact of VRES deployment on VRES curtailment, non-VRES flexibility requirements and VRES capacity values. Regarding the representation of the elements in MESSAGEix-GLOBIOM relevant for the research questions in this proof of concept exercise, firm capacity requirements following Johnson et al. have been defined per region and decade as a multiplier of average annual load. Firm capacity represents capacity that can be guaranteed to be available at any given time. The multiplier is based on the region specific relative ratio between average load and peak load combined with a 20% reserve margin. CF's for VRES technologies are based on regional resource potentials separated per range of CF's, whereas assumed CF's for thermal powerplants are globally uniform per technology for all regions based on the ability of powerplants to operate between baseline- and flexible operational modes [20]. MESSAGEix-GLOBIOM accounts for costs of transmission within regions, yet does not actively simulate the operation of internal transmission grids. Rather it follows a copperplate approach, which means that underlying the derivation of the stylized representation of the regional power systems there are no internal network constraints assumed for electricity flow. Where internal regional electricity flows are not modelled within MESSAGEix-GLOBIOM, inter-regional exchange for electricity as a commodity occurs based on a global power pool. In essence this means that regions have the ability to either supply to- or import electricity from the global pool, without consideration of the spatial feasibility of exchange between regions. Furthermore, since MESSAGEix-GLOBIOM has no sub-annual timeslices included it means that a single decision is being made during the optimization to determine whether either import or export is merrited.

Despite Johnson and colleagues valid concerns regarding the reproducibility of soft-linking MESSAGEix-GLOBIOM to a detailed power system model, the authors mention: "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 VRE deployment". The proposed standardized framework for soft-linking IAMs and power system models makes the soft-link easier to reproduce and hence the exercise as envisioned by Johnson et al. can be applied as done in this study.

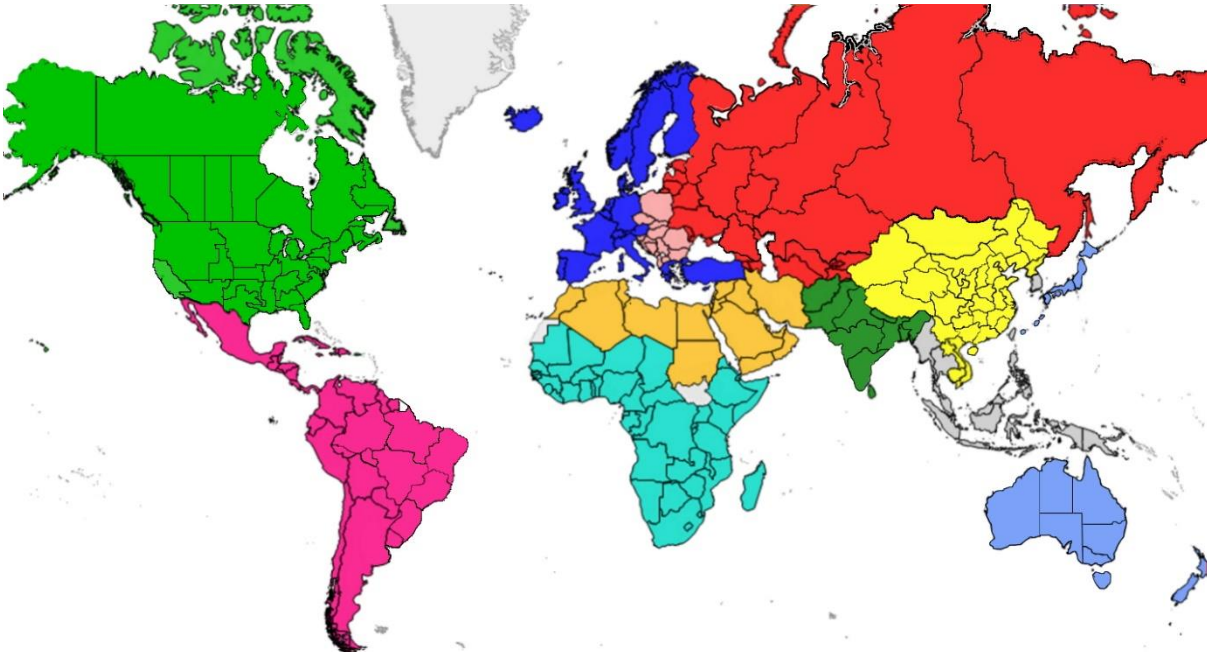

Figure 5: Spatial representation of the 11-region MESSAGEix-GLOBIOM IAM based on [62] as well as the spatial representation for MESSAGEix-GLOBIOM scenarios in PLEXOS-World. Every individual colour represents a copperplated region following MESSAGEix-GLOBIOM, whereas every area separated by borders as shown on the map represents a single (sub-)country node in PLEXOS-World with a total of 258 individual nodes. Note that certain countries are not included (e.g. South-Sudan) due to absence of required country-level data for demand projections. Refer to [21,22] for details on subdivision of sub-country nodes in PLEXOS-World.

3.2. PLEXOS-World

PLEXOS [34] 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 fully customizable and the detailed 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. For a more detailed description of the tool refer to [21,22].

The model as used for this study is based on the PLEXOS-World model, a detailed global power system model based on the 2015 global power system capable of simulating over 30,000 individual powerplants [21,22]. The spatial representation of the model specified for this study is visualized in figure 5, with a total of nodes 258 grouped per larger modelling region following the spatial representation of MESSAGEix-GLOBIOM. The existing portfolios in the different nodes consisting of aggregated powerplant capacities per technology, transmission infrastructure and storage assets are used as baseline for the downscaling and expansion exercise as described in section 2.5. Powerplants in the PLEXOS-World model are disaggregated per turbine unit to be able to incorporate technological generator characteristics. This is done by utilizing a standard unit size methodology per fuel type as applied in previous studies [38,43,64]. Table 1 shows an overview of some of the generator characteristics per technology as applied in PLEXOS-World for this study.

Table 1: Sample of standardized generator characteristics and variables as applied for this study.

Generator Type	Standard Unit Size (MW)	Minimum Stable Factor[1] (%)	Start Cost (€)	Maintenance Rate[2] (%)	Forced Outage Rate[3] (%)	Mean Time to Repair[4] (hours)
Biomass	200	30	10,000	8	3	24
Coal	300	30	80,000	8	3	24
Gas - CCGT	450	40	80,000	8	3	24
Gas - OCGT	100	20	10,000	8	3	24
Geothermal	70	40	0	8	3	24
Hydro (non-PSH)	200	10	0	3	1.5	24
Nuclear	1200	60	120,000	8	8	24
Oil	400	40	10,000	8	3	24
Other	150	-	-	8	3	24
Solar - CSP	100	-	-	-	-	-
Solar - PV	100	-	-	-	-	-
Wind - Offshore	100	-	-	-	-	-
Wind - Onshore	100	-	-	-	-	-

[1] Fraction of the maximum generator output below which a generator cannot safely operate.

[2] Fraction of the simulation horizon during which scheduled maintenance events occur per unit optimized by PLEXOS.

[3] Fraction of the simulation horizon during which unplanned stochastic forced outages occur per unit.

[4] Average time it takes for a unit to be able to become operational again.

Different to MESSAGEix-GLOBIOM, the modelling of electricity transmission in PLEXOS-World occurs based on physical transmission grids with development of new capacity compared to the 2015 baseline part of the expansion exercise. Every unique potential transmission pathway in the model – totalling 545 – has personalized associated costs and transmission losses as a function of transmission distance and potential technology. Intra-nodal grids are not modelled in PLEXOS-World. Refer to appendix 2 for full details on the modelling as well as for details on scenario integration of MESSAGEix-GLOBIOM in PLEXOS-World.

3.3. Scenarios

As mentioned in the introduction of this section, the aim of this proof of concept application of the proposed soft-link framework is to assess whether the generic stylized assumptions regarding generator reserves, generator capacity factors and transmission integration in MESSAGEix-GLOBIOM are deemed appropriate or whether this could be improved by means of the linkage with PLEXOS-World. The ENGAGE SSP2 NPI2020 500 scenario has been chosen as 1.5 degree- and high VRES scenario to critically scrutinize MESSAGEix in a setting where IAMs generally struggle the most regarding the implications of variability in electricity supply. For this to occur, a set of sub-scenarios have been created with different levels of optimization freedom as shown in table 2 that will be run in PLEXOS-World to assess the MESSAGEix-GLOBIOM scenario in different contexts.

Table 2: Overview of sub-scenarios as used in PLEXOS-World to assess the MESSAGEix-GLOBIOM ENGAGE SSP2 NPI2020 500 scenario from a power system perspective.

Sub-scenario	VRES CF's	Reserves	Storage
Sub-scenario - Baseline	VRES CF's based on PLEXOS-World 2015	Country-level 20% reserve margin following MESSAGEix-GLOBIOM	Storage capacity constrained following MESSAGEix-GLOBIOM scenario
Sub-scenario - IAM CF	VRES CF's scaled to MESSAGEix-GLOBIOM levels	Country-level 20% reserve margin following MESSAGEix-GLOBIOM	Storage capacity constrained following MESSAGEix-GLOBIOM scenario
Sub-scenario - No Reserve Constraints	VRES CF's scaled to MESSAGEix-GLOBIOM levels	No reserve margins, powerplant capacity downscaling can be fully optimized	Storage capacity constrained following MESSAGEix-GLOBIOM scenario
Sub-scenario - No Storage Constraints	VRES CF's scaled to MESSAGEix-GLOBIOM levels	No reserve margins, powerplant capacity downscaling can be fully optimized	Storage capacity freely optimized

In the 'Baseline' sub-scenario we attempt to mimic the MESSAGEix-GLOBIOM scenario as closely as possible, with the exception of CF's for VRES technologies including CSP. Baseline CF profiles for VRES technologies in PLEXOS-World are based on 2015 benchmarked values at year- and country level [21,22]. Compared to PLEXOS-World, region specific VRES CF's in MESSAGEix-GLOBIOM are significantly higher, both due to assumed technological learning as well as investment in new VRES capacity at currently untapped locations with higher solar- and wind resources. Due to the large regional copperplates in MESSAGEix-GLOBIOM, resource potential for a specific region can be informed by often very different geographical areas. For example, think of the Latin America region, which includes highly efficient wind resources in countries such as Argentina as well as enormous solar potential throughout the region all the way up to Mexico. In PLEXOS-World, if this potential in Argentina is to be used elsewhere it has to 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 very different investment dynamics, and hence it is merited to assess the specific MESSAGEix-GLOBIOM scenario in a context with more conservative VRES CF's as is the case in the 'Baseline' sub-scenario. The 'IAM CF' sub-scenario on the other hand has scaled CF's to replicate MESSAGEix-GLOBIOM levels. This has been done by comparing the regional capacity-weighted average CF per technology from the 'Baseline' sub-scenario model output in PLEXOS with the MESSAGEix-GLOBIOM scenario output. Scaling of all CF profiles occurs based on the relative difference between the two model instances by making use of a build-in tool within PLEXOS.

The 'Baseline' and 'IAM CF' sub-scenarios follow Johnson et al. [20] by integrating a 20% firm capacity reserve margin as a multiplier of region specific peak load projections. Yet, whereas in MESSAGEix-GLOBIOM this occurs on a regional level, in PLEXOS-World we apply the reserve margin at country scale to simulate a market context where every country is responsible for its own system adequacy. In line with MESSAGEix-GLOBIOM, conventional powerplants and electricity storage are assumed to contribute its full rated capacity and CSP 50% of rated capacity. Firm capacity contributions of VRES technologies are determined at a regional level following the MESSAGEix-GLOBIOM scenario output where contributions depend on the relative penetration of VRES to the supply mix. Larger penetration means that a relative lower share of the rated capacity can be designated as firm. In the 'No Reserve Constraints' sub-scenario we allow PLEXOS to fully optimize the powerplant capacity downscaling on a regional level without consideration of local reserve requirements. This simulates a market context where nodes can share reserves through transmission pooling and increases the likelihood of optimally placed powerplants including the utilization of often more efficient renewable resources compared to domestic potentials.

Finally, whereas in the first three sub-scenarios the expansion of storage capacity is constrained at a regional level following the MESSAGEix-GLOBIOM scenario output, the 'No Storage Constraints' sub-scenario allows free optimization of storage capacity with an upper limit of 100 GW per node. This allows for an assessment of how realistically storage expansion is integrated in MESSAGEix-GLOBIOM and moreover how it impacts generator CF's as well as general reserve requirements.

3.4. Results

This section includes the modelling results of PLEXOS-World for the MESSAGEix-GLOBIOM ENGAGE SSP2 NPI2020 500 scenario. The results will be compared to the model output from MESSAGEix-GLOBIOM with the aim to determine the suitability of the power system representation in MESSAGEix-GLOBIOM following assumptions regarding reserve requirements, generic CF assumptions for powerplants and regarding transmission integration. Based on this suggestions are being made for additional internal model improvements within MESSAGEix-GLOBIOM. Figure 6 showcases the generation mix per PLEXOS sub-scenario in comparison with the MESSAGEix-GLOBIOM output.

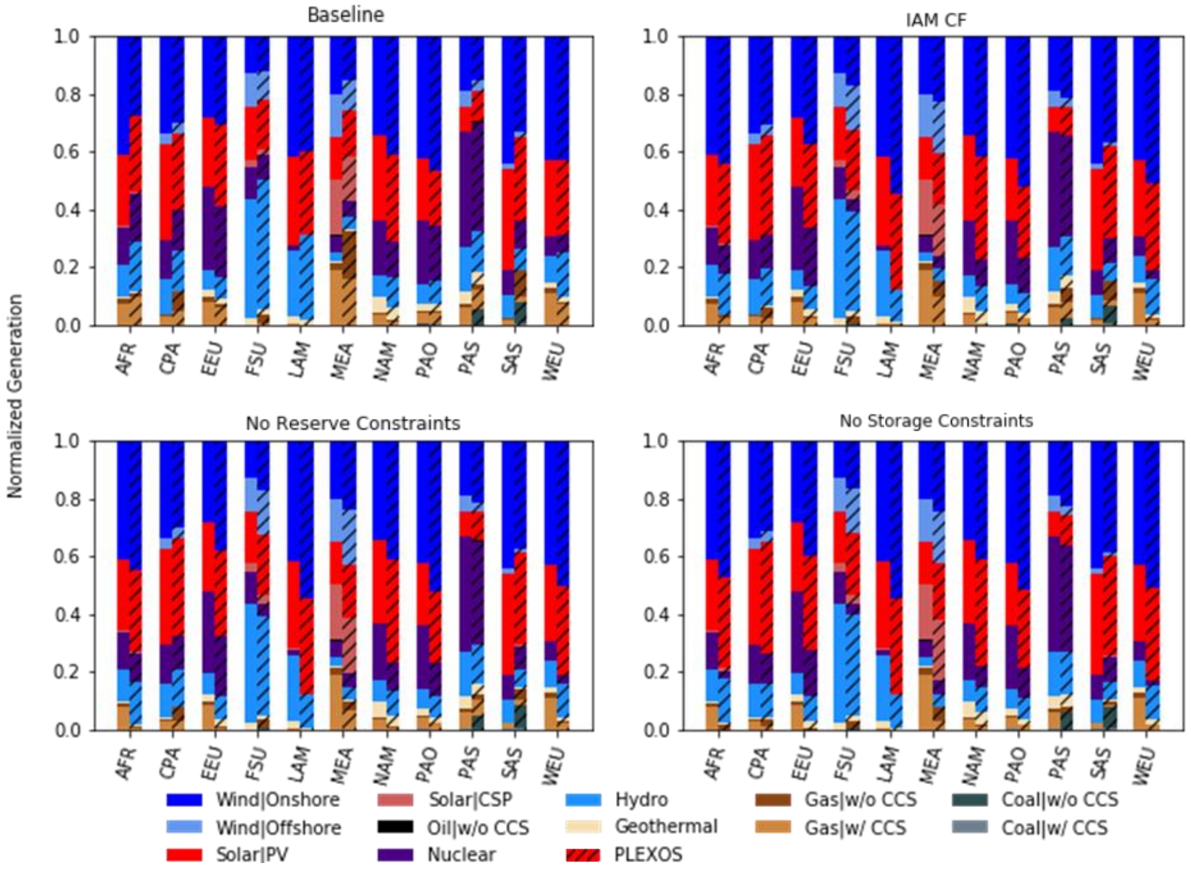

Figure 6: Normalized generation mix per PLEXOS sub-scenario in comparison to the MESSAGEix-GLOBIOM output. The hatched bars represent the output from PLEXOS. Note that due to their minor role biomass technologies have been excluded in the comparison for visibility reasoning.

With the exception of the ‘Baseline’ sub-scenario and regional anomalies, the results indicate that the relative share of VRES technologies in the generation mix is generally higher compared to the MESSAGEix-GLOBIOM output. Yet, the high share of VRES doesn’t result from an underestimated integration potential in MESSAGEix-GLOBIOM but follows from a general supply deficiency in the simulated global power system. This is visualized in figure 7 which highlights the so-called unserved energy per region. Unserved energy represents the share of final electricity demand that cannot be met with the available resources. Different to MESSAGEix-GLOBIOM where occurrence of unserved energy is not possible, PLEXOS-World allows for unserved energy at a cost of 10,000 €/MWh which replicates a ‘willingnes-to-pay’ for consumers to reduce their demand for a given period. The model can determine that often it is more efficient for unserved energy to occur than to invest in additional flexiblity assets such as storage or in further transmission expansion to meet this unserved energy. Unserved energy is a phenomenon that occurs in the current-day global power system at limited scale, yet as indicated in the graph with largescale integration of VRES this can become a more critical issue. The Pacific OECD region (PAO) has the highest occurrence of unserved energy in relative terms. Not suprisingly, PAO consists of the islands of Australia, Japan and New Zealand meaning it has limited opportunities for sharing resources through power pooling which lowers the ability of a region to manage variability in supply and demand and hence increases the likelihood of unserved energy. In the ‘No Storage Constraints’ sub-scenario, unserved energy is signficantly lower in PAO indicating the important role of storage for sea-locked countries such as Japan as well as for geographically large countries such as Australia.

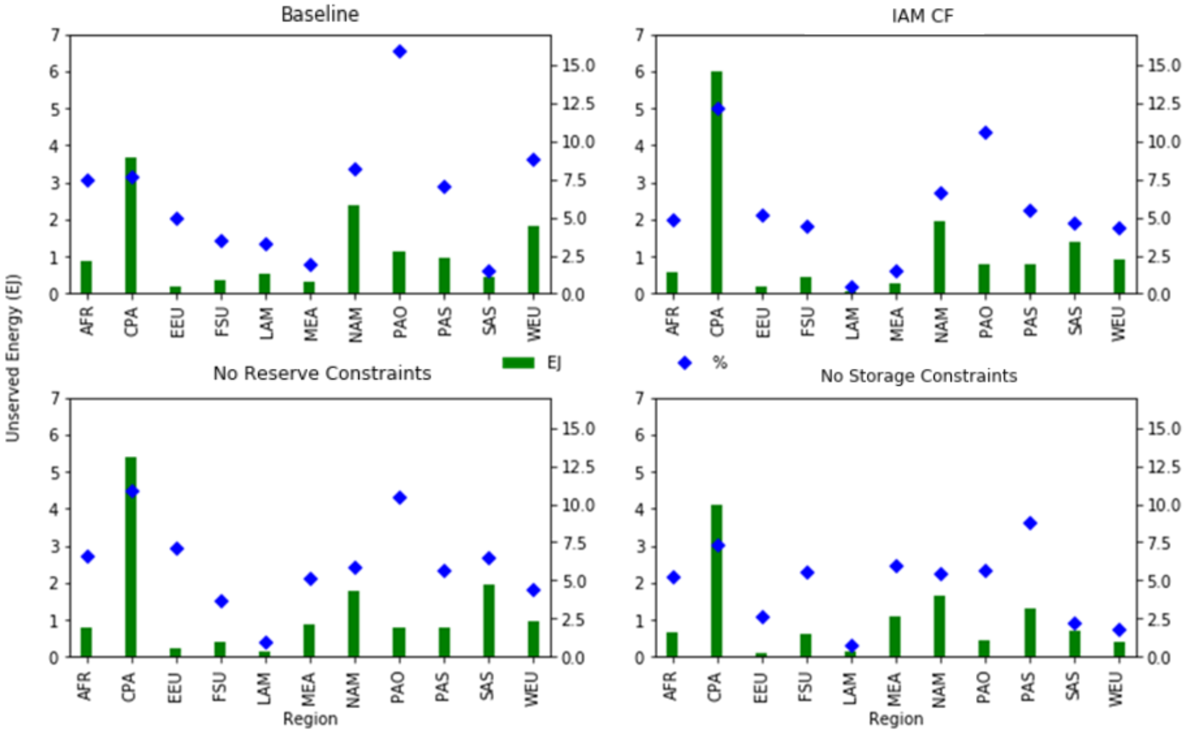

Figure 7: Occurrence of unserved energy per PLEXOS-World sub-scenario and region. The green bars represent the absolute values in EJ with the scale on the primary y-axis and the blue markers represent the relative values compared to the regional final electricity demand with the scale on the secondary y-axis.

The CPA region, consisting of China and a number of neighbouring countries, has in absolute terms the highest unserved energy and interestingly enough it increases in the sub-scenarios where VRES CF’s are higher. An important factor explaining this occurance has to do with the relative lower contribution of VRES to firm capacity at higher penetration levels. As explained earlier, firm capacity requirements in PLEXOS-World per country follow the same assumptions as MESSAGEix-GLOBIOM applies per region. These requirements are determined by taking the relative ratio between average load and peak load in addition to a standardized 20% reserve margin. Whereas in MESSAGEix-GLOBIOM these ratios are approximated, in PLEXOS-World they are determined by comparing the historic relative peak load per country based on [21,22] with the projected electricity demand. Table 3 compares the firm capacity requirements as multiplier of average load for 2050 following MESSAGEix-GLOBIOM values [20] and the regional average (demand-weighted) values in PLEXOS-World.

Table 3: Firm capacity requirements per region in MESSAGEix-GLOBIOM following [20] and in PLEXOS-World for 2050. The values are relative to average annual electricity demand.

Region	MESSAGEix-GLOBIOM	PLEXOS
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

The CPA region has the lowest required firm capacity in PLEXOS-World based on the MESSAGEix-GLOBIOM assumptions, yet following the large unserved energy for CPA and other regions in sub-scenarios with high VRES penetration, it suggests that a 20% reserve margin might not always be sufficient. It's also worth noting that the values in table x represent a regional average, but that exact values per country in PLEXOS-World can range significantly. For example values for countries in CPA range from 1.39 to 2.21. The large occurrence of unserved energy also suggests that the firm capacity contribution of VRES is often overestimated. This latter aspect becomes more clear when looking at the CF's for renewable technologies as shown in figure 8.

CF input assumptions for VRES technologies in the 'Baseline' sub-scenario are based on 2015 benchmarked values and are hence as expected significantly lower than the MESSAGEix-GLOBIOM scenario output. The other sub-scenarios have scaled CF's as input in line with the MESSAGEix-GLOBIOM scenario output as described in section 3.3. Yet, as the graphs indicate the useful electricity coming from VRES is nowhere near reported values compared to the MESSAGEix-GLOBIOM scenario output. Any electricity coming from VRES that cannot be instantaneously used, stored, transmitted to a neighbouring node or converted to hydrogen cannot be used and gets curtailed – i.e the unplanned reduction of generation output. CF's for hydro-based powerplants as a mature technology are also based on benchmarked 2015 values but are as of now not scaled to MESSAGEix-GLOBIOM values in the sub-scenarios. Compared to the 'Baseline' sub-scenario, hydro-based generation slightly decreases following the larger VRES penetration in the other sub-scenarios while retaining its core function as a zero-carbon dispatchable technology. Worth higlighting in the graphs are the relatively low CF's for the Latin America (LAM) region as a result of significant surplus capacity in the system and consequently large curtailment. This is also visualized in figure 9 which as an example higlights the scenario and region specific curtailment for Solar-PV.

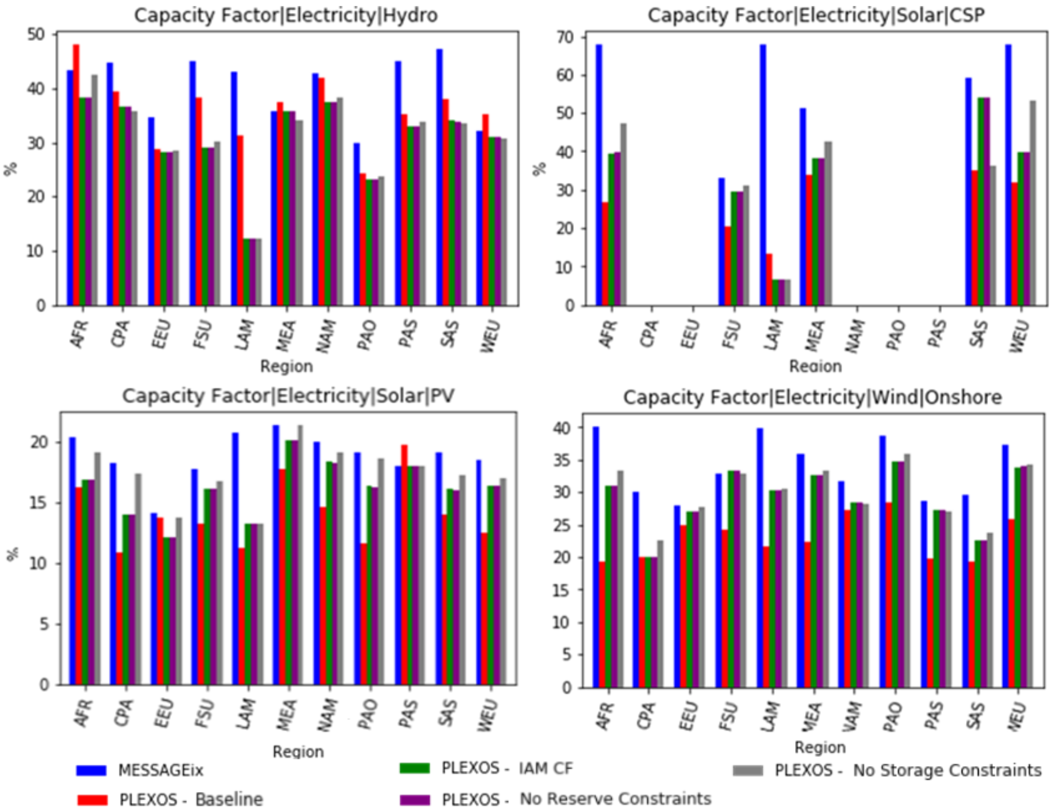

Figure 8: Capacity factors for a range of RES technologies for the different PLEXOS sub-scenarios in comparison to the MESSAGEix-GLOBIOM output. Solar and wind CF's for the 'IAM CF', 'No Reserve Constraints' and 'No Storage Constraints' are scaled based on the relative difference between region- and technology average CF's in the MESSAGEix-GLOBIOM output compared to simulation output from the PLEXOS-World 'Baseline' scenario. Hydro CF's are kept equal for all PLEXOS-World sub-scenarios.

The high curtailment in LAM is an outlier compared to the regional average, yet in all cases curtailment is signficantly higher compared to the MESSAGEix-GLOBIOM output which accounts for curtailment through stylized relationships based on relative VRES penetration [20]. In the sub-scenarios with higher VRES CF's compared to the 'Baseline' sub-scenario, curtailment grows in parallel with the larger generation potential. The exception is the 'No Storage Constraints' scenario where the larger storage capacities partly mitigate the occurance of curtailment. Curtailment on the global scale ranges between 12-23% for Solar-PV depending on the sub-scenario and compartively between 9-15% for wind based technologies.

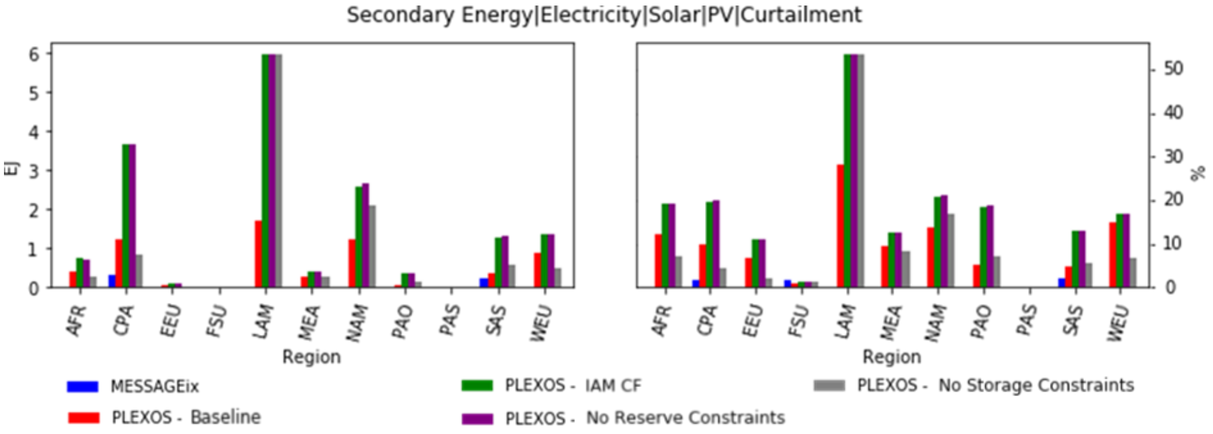

Figure 9: Curtailment values for Solar-PV specified per sub-scenario. The left graph indicates curtailment in absolute values (EJ) and the right graph indicates curtailment relative to the theoretical generation potential per region for Solar-PV.

The significant occurrence of VRES curtailment and hence lower contribution of VRES to firm capacity than expected causes further negative knock-on effects in the system. The capacity expansion in PLEXOS-World incorporates pre-defined firm capacity contributions specific per technology and region to fulfill the set minimum reserve requirements. Yet, if these values are different than expected inherently this means that the capactiy expansion is sub-optimal. Lower assumed contributions of VRES to firm capacity would have meant a more balanced allocation of dispatchable generator capacity per node to retain system adequacy. Yet, in the current situation there is a distortion of dispatchable capacity in certain nodes per region versus oversupply of VRES in others. Figure 10 showcases CF's for key non-renewable dispatchable technologies in comparison with the MESSAGEix-GLOBIOM scenario output.

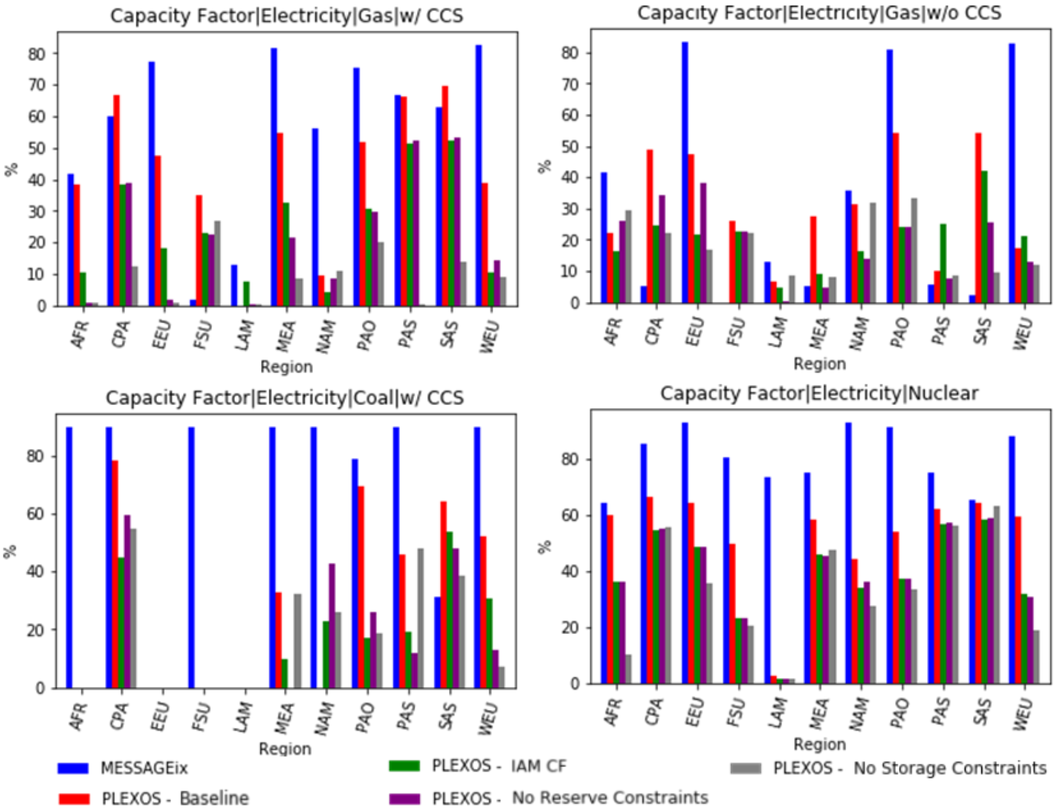

Figure 10: Capacity factors for a range of non-renewable thermal based technologies for the different PLEXOS sub-scenarios in comparison to the MESSAGEix-GLOBIOM output.

The contribution of non-renewable thermal generators to the generation mix in the PLEXOS-World sub-scenarios is undervalued compared to the MESSAGEix-GLOBIOM output as a result of the indicated capacity allocation distortion. This is in particular the case for the sub-scenarios with higher VRES CF assumptions. Furthermore, the inflexibile nature of baseload technologies such as nuclear powerplants further limits the ability of the system to compensate for the variability in supply. The dispatch of powerplants in PLEXOS-World occurs based on operational least cost with a price of above 700 US$2010/t CO2 for carbon emissions based on the ENGAGE SSP2 NPI2020 500 scenario. This means that the operational costs of generation for fossil powerplants is dominated by the cost of carbon and hence gas-based powerplants (w/ CCS) are dispatched first before coal (w/ CCS), yet still sigfnicantly lower than expected values from the MESSAGEix-GLOBIOM output.

Despite the distortion in capacity allocation, in a optimally integrated global power system generator resources can be shared between nodes and regions by means of power pooling through transmision integration. Yet, as described in section 3.1, MESSAGEix-GLOBIOM does not actively simulate the operation of internal transmission grids but rather follows a copperplate approach meaning that no internal network constraints are assumed for electricity flow. That said, the results in this section based on the spatially and temporally explicit modelling in PLEXOS-World has shown that by not taking into account network constraints the difficutly of large-scale integration of VRES in MESSAGEix-GLOBIOM is underestimated. Despite significant intra-regional transmission flows within the different PLEXOS-World sub-scenarios, the transmission infrastructure cannot sufficiently compensate for the large variability in supply and sub-optimal placement of generator capacities. Figure 11 showcases mapped electricity flows in 2050 for the ‘Baseline’ sub-scenario. For contextual purposes, 1 EJ roughly equals the current-day electricity demand for a country the size of Mexico.

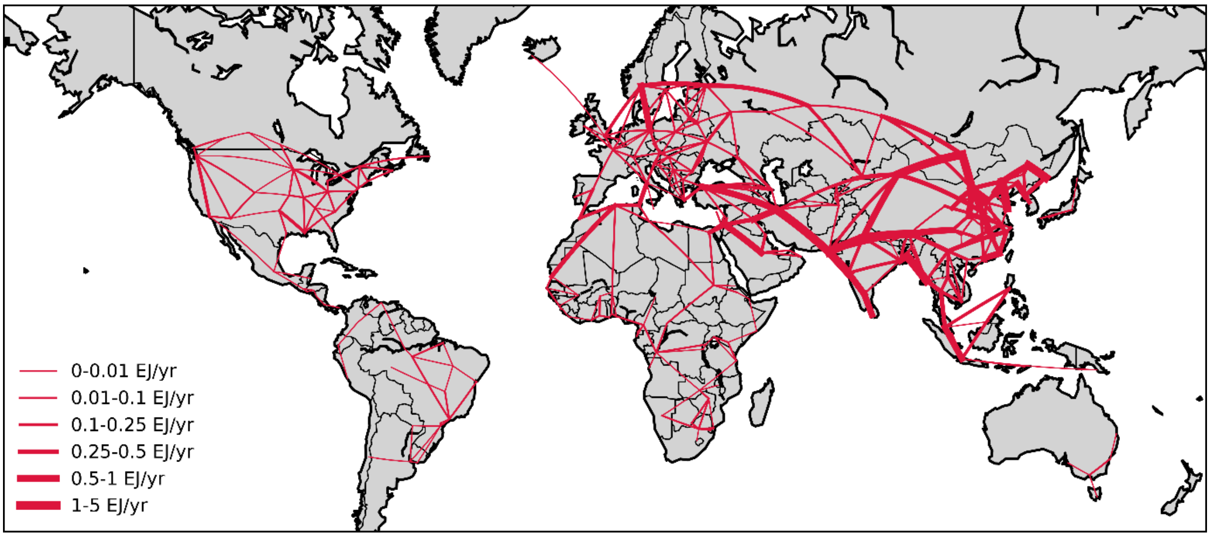

Figure 11: Electricity transmission flows for the ‘Baseline’ sub-scenario in PLEXOS-World.

As mentioned, inter-regional exchange of electricity as a commodity in MESSAGEix-GLOBIOM occurs based on a global power pool. Figure 12 compares the inter-regional electricity transmission of the different sub-scenarios in PLEXOS-World with the MESSAGEix-GLOBIOM scenario output. First observation in the MESSAGEix-GLOBIOM output is the large import of electricity in the South Asia (SAS) region of near 10 EJ, which is near twice the size of current-day electricity demand in India. Most of this is supplied from LAM, an area on the complete other end of the world and hence from a spatial perspective an unlikely situation. This observation directly explains the earlier made assessment of significant overcapacity and low CF’s in LAM. It furthermore explains the higher required generation in SAS from fossil thermal powerplants – as shown in figure 10 – to compensate for the absence of import of renewable electricity from LAM.

The requirements of utilization of physical tranmission infrastructure for the purpose of electricity exchange in PLEXOS-World does not allow for spatially unconstrained global power exchange as is the case in MESSAGEix-GLOBIOM shown by the example of LAM and SAS. The ‘Baseline’ sub-scenario indicates significant inter-regional transmission flows to compensate for the overall lower VRES CF’s compared to MESSAGEix-GLOBIOM. The other sub-scenarios require lower inter-regional exchange due to the larger generation potential within the separate regions following the scaled VRES CF’s as well as due to increased storage availability in the ‘No Storage Constraints’ sub-scenario. To put the results in context, given the lower contribution of renewables in the generation mix for all sub-scenarios and the consequential higher utilization of fossil based generation capacity, the overall CO2 emissions following fuel combustion in the PLEXOS-World simulations are signficantly higher compared to the MESSAGEix-GLOBIOM output as shown in figure 13. Special attention can be given to the SAS region, which as a result of the lack of renewable electricity import from the LAM region in the PLEXOS-World sub-scenarios has significant domestic power sector emissions. Negative emissions as indicated in the MESSAGEix-GLOBIOM scenario output aren't met in any of the PLEXOS-World sub-scenarios. Consequently, based on the current PLEXOS-World simulations, the MESSAGEix-GLOBIOM ENGAGE SSP2 NPI2020 500 scenario is from a purely power system perspective as it stands not in line with its intended target of limiting global warming to 1.5°C.

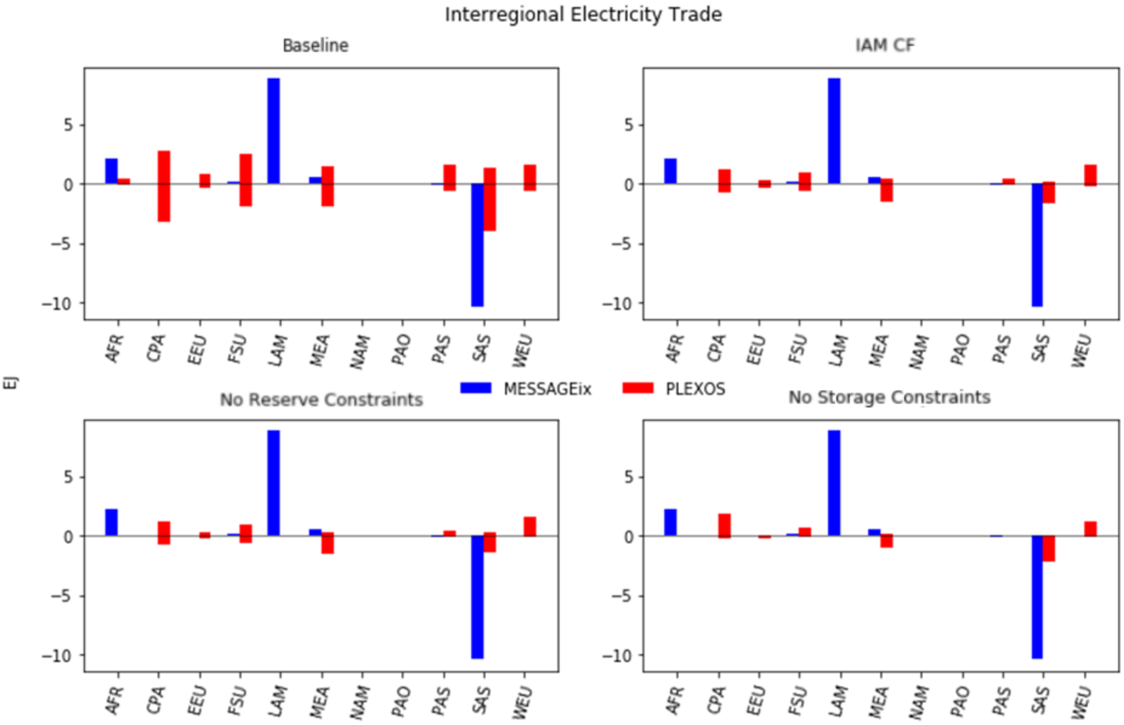

Figure 12: Inter-regional electricity trade for the different sub-scenarios in PLEXOS-World compared to the MESSAGEix-GLOBIOM scenario output. Positive values represent export and negative values import.

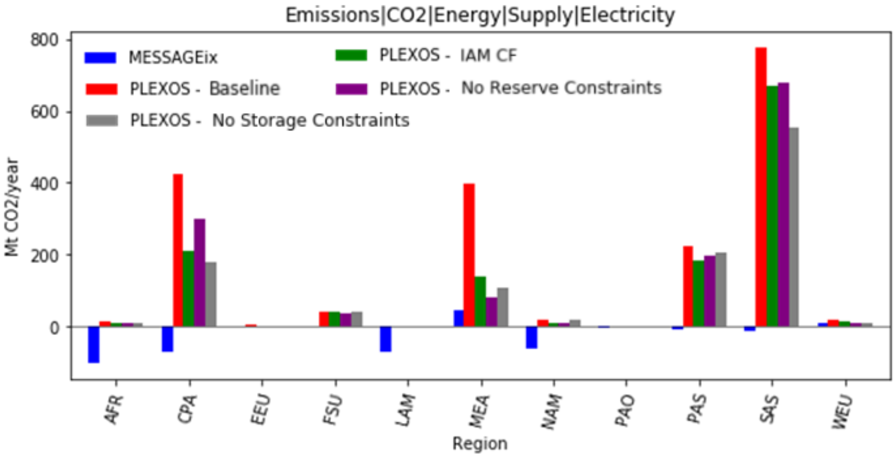

Figure 13: CO2 regional power sector emissions for the different PLEXOS-Wold sub-scenarios in comparison to the MESSAGEix-GLOBIOM output for the ENGAGE SSP2 NPI2020 500 scenario.

3.5. Study limitations

Based on the modelling results in PLEXOS-World a range of potential improvements can be identified regarding the stylized power system representation in MESSAGEix-GLOBIOM. Yet, first, it is important to mention that as all modelling tools PLEXOS-World also has its limitations that affect the accuracy of results. As of now electric vehicles and demand side management are not included in the modelling which reduces the ability of the system to compensate for variability in supply. That said, demand side management is not actively incorporated in MESSAGEix-GLOBIOM in relation to system flexibility and the overall impact of electric vehicles on bulk storage capacity is limited.

Furthermore, the choice has been made to not scale CF's for hydro-based technologies relative to the MESSAGEix-GLOBIOM output. Yet, higher hydro CF's would increase the availability of dispatchable generator resources and hence positively affect system reliability. Additional sub-scenarios are required to assess this impact in detail. Next to this, additional model runs with sensitivity analysis on a range of parameters such as costs for transmission infrastructure, forecasted demand profiles as well as switching to different weather years for VRES CF profiles could increase the robustness of the results [36].

Lastly, by attempting to mimic the MESSAGEix-GLOBIOM scenario in PLEXOS-World as closely as possible – for example by means of the expansion and retirement constraints – the risk arises of over constraining the optimization. A next step could be to apply the optimization in context of the MESSAGEix-GLOBIOM scenario by making use of projected variables such as electricity demand and commodity prices while letting PLEXOS 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 MESSAGEix-GLOBIOM versus a solely optimized planning from a power system perspective with higher detailed spatial, technical and temporal resolution in PLEXOS-World.

3.6. Feedback on power system representation in MESSAGEix-GLOBIOM

The focus of the example application of the proposed methodological soft-link framework in this paper has been on the global MESSAGEix-GLOBIOM model. Hence, suggestions for improvement of the representation of the power system in MESSAGEix-GLOBIOM are being made in this context, meaning that improvements following integration of sub-annual timeslices are not considered and that any suggested improvements need to be computationally manageable. Furthermore, it is also important to realize that suggestions are being made based on assessments of a single MESSAGEix-GLOBIOM scenario while they need to be functional for all other types of scenarios as well.

With these aspects in mind, the most straight-forward potential improvement in MESSAGEix-GLOBIOM based on the results in this study would be to move away from a global power pool approach and rather facilitate electricity exchange on an inter-regional basis. An example representation of this is visualized in figure 14. This would prevent unrealistic flows of electricity - as is the case in the current version of MESSAGEix-GLOBIOM as identified in this study - while still allowing for exchange between adjacent regions and optionally between regions with potential for subsea transmission integration [65]. It is also suggested to incorporate a transmission distance dependent loss factor specified per inter-regional power pool that replicates associated energy losses with long-distance electricity transmission. Costs and losses for inter-regional power pools can be based on PLEXOS-World output.

Besides inter-regional transmission, the spatially detailed modelling in PLEXOS-World indicates that the assumption of unconstrained power pooling in the regional copperplates is the main reason for possible overestimation of VRES integration potential in MESSAGEix-GLOBIOM. Improving the spatial resolution in the global MESSAGEix-GLOBIOM model is one way to tackle this issue yet becomes computationally difficult to manage. In most 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 penetration shares. However, as shown in the results of this study, internal transmission integration is heavily region dependent among others based on the relative region size. 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.

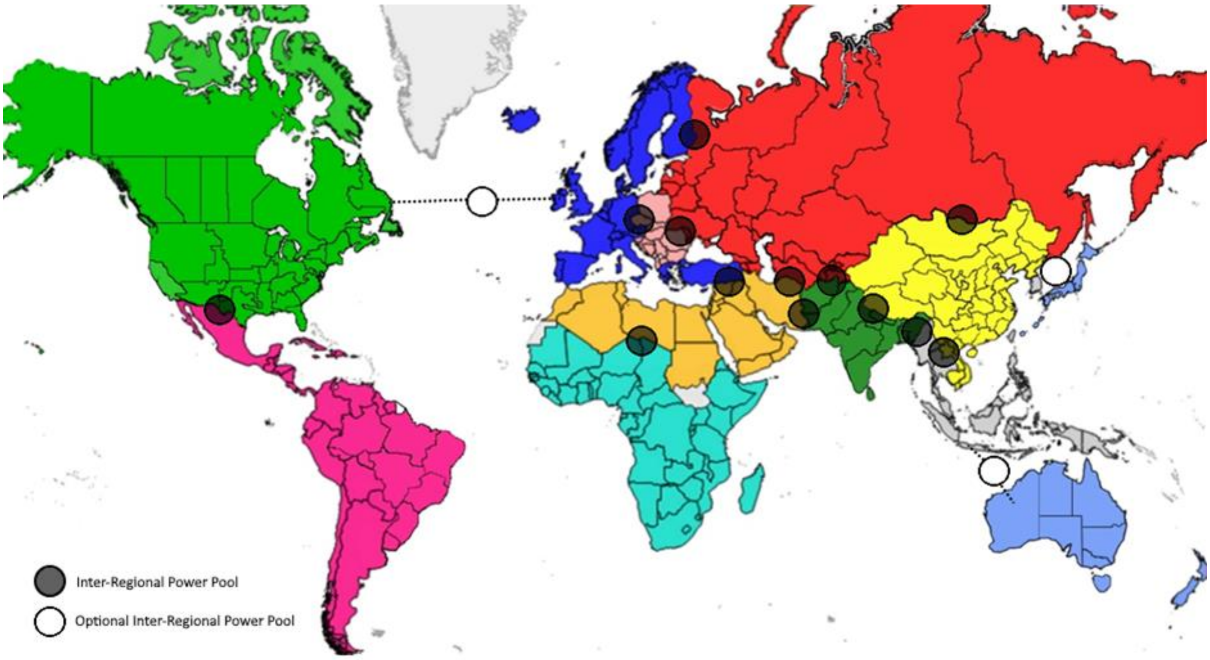

Figure 14: Example visualization of integrating inter-regional power pools for the purpose of facilitating electricity exchange between MESSAGEix-GLOBIOM regions while considering the spatial ability for transmission integration.

As of now MESSAGEix-GLOBIOM includes one generic storage technology with 24 hour storage potential. 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. Furthermore, integration of short-term storage technologies such as batteries with a relatively higher power versus storage ratio compared to the current generic storage technology in MESSAGEix-GLOBIOM would help with mitigating peaks in supply from especially Solar-PV.

Finally, the results in this study have shown that as a result of the difficulty of large-scale integration of VRES a range of other stylized parameters and input assumptions could benefit from being updated based on the spatially and temporally detailed modelling in PLEXOS-World. Examples are region specific curtailment parameters, firm capacity requirements and technology capacity factors. That said, this would first require additional model simulations in PLEXOS-World concerning the identified study limitations in section 3.5 as well as model runs for a range of other MESSAGEix-GLOBIOM scenarios to increase the accuracy of the overarching results. By means of the developed soft-link framework in this study, results from PLEXOS-World can be directly fed back into MESSAGEix-GLOBIOM in IAMC data format.

4. Discussion

To-date, a large part of the global analysis on climate change mitigation is based on modelling results from global IAMs. Among others, the IPCC assessment reports including chapter 2 of the Special Report on Global Warming of 1.5°C [5] are underpinned with analyses from global IAMs. However, within the scientific community an ongoing theoretical debate exists regarding the suitability of IAMs for among others the long-term planning of the global energy system [55,56]. From a power system perspective, the critique focuses on the lack of proper representation of geographically dispersed wind and solar resources in spatially coarse global IAMs. Furthermore, the limited replication of system integration- and operation challenges following high levels of variable renewable energy sources in global IAMs with limited amount- or absence of sub-annual timeslices gives rise to further criticism [55].

In recent years the IAM community has made significant efforts to improve the power system representation in global IAMs [1,2,8,15–20]. Pietzcker et al. [1] have defined a set of qualitative and quantitative criteria based on which the performance of power system representation in IAMS can be evaluated. Based on these criteria, additional required improvements for future versions of global IAMs have been identified. Among others, these relate to the modelling of internal and inter-regional transmission of electricity to properly reflect the potential for power pooling through shared generation resources while simultaneously accounting for transmission constraints. Furthermore, improvements are needed regarding the overall data basis based on which the spatial representation in global IAMs can possibly be extended and based on which region specific power system representation and input assumptions can be optimized. That said, considering the wide scope of global IAMs, there will always be a trade-off in terms of technological representation versus tempo-spatial resolution to keep computational requirements manageable. Hence, as Gambhir and colleagues rightly argue, there is a limit on internal IAM model improvement both regarding computational functionality as regarding available time resources for model development [55]. To ease the pressure on global IAMs, additional modelling tools can be utilized to complement IAMs regarding assessments of sectoral specific detailed dynamics.

This study proposes a methodological framework for soft-linking of continental- or global IAMs with detailed global power system models. With the soft-link framework, output from IAMs can be fed into a power system model to assess given scenarios with enhanced spatial, technological and temporal resolution. Results from the power system model simulations can be used to identify core gaps in power system representation and can be fed back for further internal improvements in the IAM while considering computational requirements. By supporting bi-directional model coupling, the soft-link exercise can be repeated until power system model representation in the global IAM is deemed satisfactory. The framework is developed while considering known limitations in IAMs as well as known limitations in existing model linking methodologies. Within the framework, scenarios are not assessed based on the regionally coarse spatial representation of global IAMs as is. Rather, the long-term expansion capabilities of power system models are proposed to be used to downscale the regional copperplates as used in the IAM to a more spatially defined level. The framework promotes using a standardized data format[2] for the model soft-linking making it non-discriminatory for a wide range of IAMs and power system models. Furthermore, it allows the soft-link exercise to be easily repeated – often indicated as core limitation for soft-link methodologies [20,42] – and it smoothens the process of transitioning the soft-link to other model instances, for example to assess scenarios from other IAMs.

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[2] https://data.ene.iiasa.ac.at/database/

The proposed soft-link framework can be seen as an attempt to put boundaries on the theoretical debate regarding the suitability of global IAMs for the long-term planning of power systems. It is furthermore a method to overcome the discussion on whether inhouse improvements in the IAM are sufficient or whether complementary sectoral modelling tools are merited. The framework helps with preventing exclusivity of a single approach – being inhouse IAM improvement or linking to a sectoral model – but rather standardizes possibilities for inhouse IAM improvement through model soft-linking. It also opens doors to act as a template for similar soft-link frameworks for global IAMs with other types of sectoral models.

As part of this study a proof of concept application of the soft-link framework has been applied by soft-linking global IAM MESSAGEix-GLOBIOM with global power system model PLEXOS-World. A 1.5°C and high VRES scenario has been chosen to critically scrutinize MESSAGEix-GLOBIOM in a setting where IAMs generally struggle the most regarding the implications of variability in electricity supply. The long-term capacity expansion module within the PLEXOS-World model has been used to downscale projected regional powerplant capacities to a detailed spatial level together with optimized expansion of balancing assets and transmission infrastructure. This is followed by a detailed snapshot analysis for the year 2050 based on hourly model simulations for the full global power system. This kind of exercise has been setup to identify three assessment outcomes. It is capable of highlighting those aspects in the MESSAGEix-GLOBIOM power system representation that already replicate regional power system dynamics appropriately, those aspects that are in essence functional yet require regional fine-tuning of parameters based on the PLEXOS-World simulation output and those aspects that are missing in the MESSAGEix-GLOBIOM power system representation that are essential for proper replication of global power system dynamics.

Based on the results in this study it is clear that MESSAGEix-GLOBIOM struggles with realistically representing certain power system dynamics following the different spatial and temporal resolution compared to a detailed power system model like PLEXOS-World. Occurance of significant unserved energy and high curtailment values for variable renewables that are a multifold higher than expected values based on the MESSAGEix-GLOBIOM scenario output are indicators that the ability of variable renewable energy integration in the current version of MESSAGEix-GLOBIOM is overestimated. Existing regionally stylized parameters in MESSAGEix-GLOBIOM dependent on relative penetration of variable renewable energy sources like curtailment values, firm capacity requirements and internal transmission costs are deemed appropriate yet require updated values which can be based on the PLEXOS-World output. Identified factors that are currently missing in MESSAGEix-GLOBIOM with a large impact such as the proper representation of inter-regional electricity transmission and the absence of a diverse set of investable storage technologies merits further model development.

To round off with a reflection on the theoretical debate regarding the suitability of Global IAMs for long-term development of the global energy system, this paper highlights that it is critical to objectively analyse the functionality of modelling tools in relation to its intended goal. Global IAM's are not constructed with the aim to perform spatially and temporally detailed assessments of power system dynamics which is reflected in the results of this study. That said, it is the author's view that this not necessarily means that global IAM's are unsuitable for providing boundaries in possible mitigation pathways for the development of the global power 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 temporally detailed model simulations in global power system models like PLEXOS-World do not permit simulations for long-term horizons – an average model run of PLEXOS-World based on a 2050 snapshot analysis in context of this study takes approximately 24 hours. Furthermore, the lack of interaction with other sectors and ecological- and economical systems gives power system models a narrow scope. Hence, considering limitations of both sets of models, it leads to the conclusion that IAM's can be applied for long-term planning of the global energy system assuming regular benchmarking with dedicated sectoral models occurs. By making use of the soft-link framework as introduced in this study, dedicated power system models like PLEXOS-World can be used in a complimentary fashion to pinpoint potential areas for improvement.

Appendix 1: Details on applied electricity demand downscaling methodology

Although any downscaling approach can be applied for the demand downscaling in the proposed soft-link framework, within the accompanying script of this paper we apply a forecasting methodology for country-level electricity demand based on multivariate linear regression with GDP at purchasing power parity (GDPppp) per capita and urbanization share as independent variables and electricity consumption per capita as dependent variable. Historical country level values for the above variables can be retrieved by means of the World Banks World Development Indicators [66]. Country level values are grouped per region according to the spatial representation of the specific scenario (e.g. R5 regions[3]) followed by the regression being applied per region for the period 1980-2014 (later years are not available for electricity consumption per capita). The regression has been applied per region and not per country because historical data is not available for all countries globally. Then, for country-level projections of the independent variables as well as population projections we used the Shared Socioeconomic Pathways (SSPs) [4] and the accompanying quantifications [67–71], all retrievable through the SSP Public Database[3]. The SSPs are developed based on five different narratives that describe alternative global socio-economic developments. The choice for a specific SSP 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 projections for the independent variables, per capita electricity demand at country-level can be projected specific per SSP. An example of this is visualized in figure A1.1 in for the Latin America region in the 11-region MESSAGEix-GLOBIOM IAM.

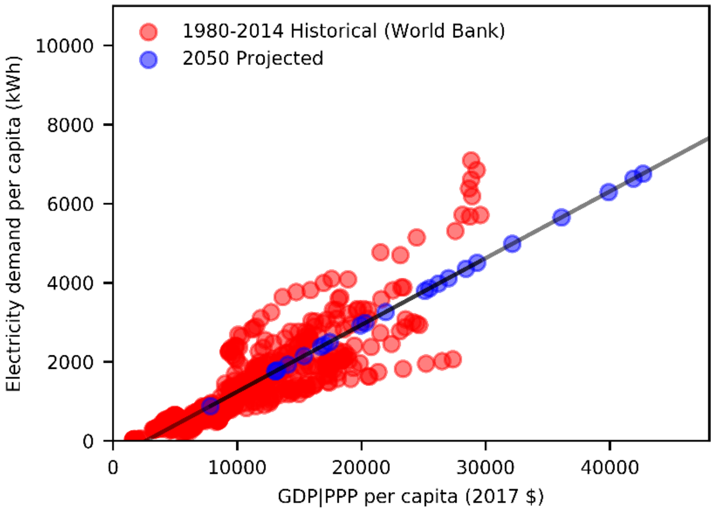

Figure A1.1: Regression example with GDPppp per capita as independent variable (2017 $) and electricity demand per capita (kWh) as dependent variable. Every red dot in the graph represents a single year value for one of the countries in the MESSAGEix-GLOBIOM_R11LAM region for the period 1980-2014. The blue dots represent the country-level projected values based on SSP specific projections for the independent variables.

By multiplying the projected per capita demand values with country-level population projections for the corresponding SSP, aggregate projected country-level electricity demand can be calculated. These values can then be used as a proxy to downscale IAM scenario regional demand values. Within the python script this occurs by making use of downscaling functionalities within pyam, an open source python package for analysis and visualization of IAM scenario data [72]. Figure A1.2 showcases an example comparison of the projected demand, the downscaled scenario demand and 2015 baseline demand based on the PLEXOS-World 2015 dataset [21,22] for contextual purposes.

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

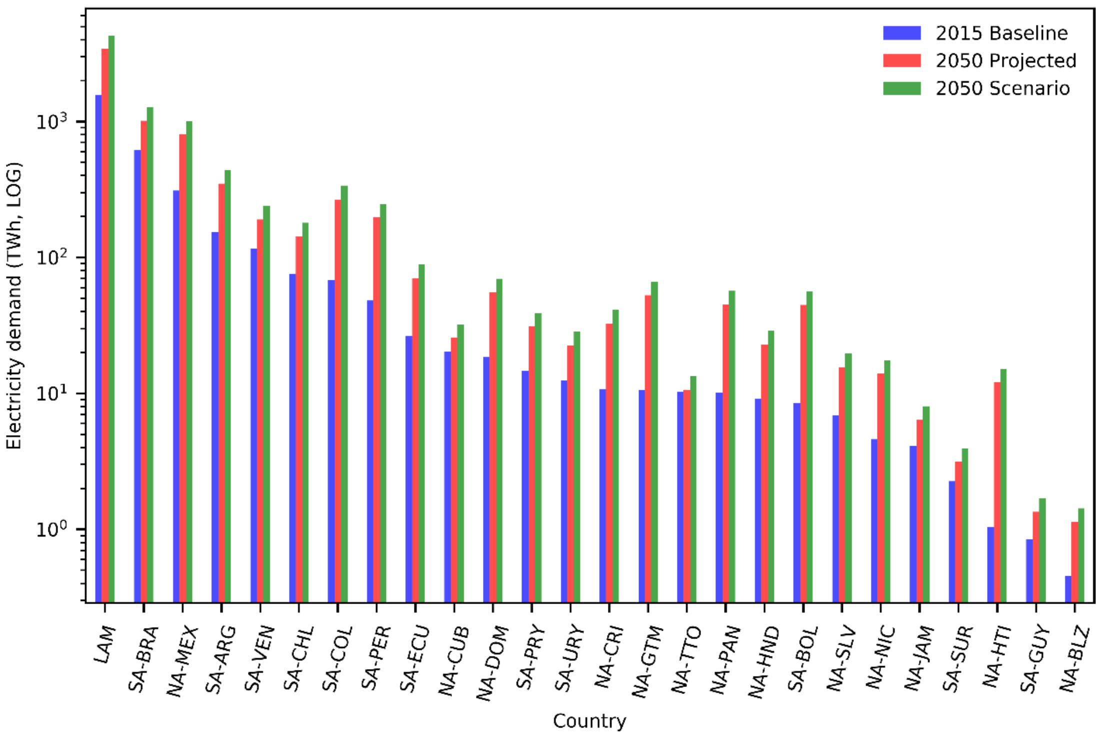

Figure A1.2: Comparison of regional- and country-level projected electricity demand, the downscaled scenario demand (with the projected demand as proxy) and the 2015 baseline demand for the MESSAGEix-GLOBIOM_R11 LAM region. The MESSAGEix-GLOBIOM ENGAGE SSP2 NPI2020 500 scenario is used as a proof of concept for the framework.

Compared to the baseline demand, the graph indicates different growth ratios as a result of different 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 [73]. 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 [5,74].

Contrary to model runs for most continental or global IAM scenarios, power system models have the ability to perform model simulations with highly detailed hourly or even sub-hourly temporal resolution. This requires further downscaling of the country-level yearly electricity demand, and while there are multiple approaches possible, the most straightforward way to do this is to use temporally detailed historical electricity demand data as proxy. For this paper we use the PLEXOS-World 2015 dataset [21,22], which includes hourly demand data for all countries globally and a wide range of sub-country regions – with approximately 50% of profiles based on actual historical data –based on the 2015 calendar year. Figure A1.3 shows an example of the downscaled yearly electricity demand for Brazil for the specific scenario, both temporally but also spatially to sub-country level. The shape for the baseline profile for Brazil, in this case for 2050, is based on the reference 2015 profile with all hourly values scaled based on the relative difference of the final electricity demand in 2015 versus the calculated scenario demand for 2050. Note that the occurance of periods with relative lower demand (i.e. weekends) does not coincide in both calendar years. The relative peak demand for the baseline profile is kept equal to 2015 and grows in parallel with the total demand. That said, peak demand can also be altered either exogenously as indicated in figure A1.3 with a relative peak demand of 90% or endogenously in the power system model by allowing market participants to adjust their demand for a given price through demand side management. Optionally, depending on availability of data and the aim of a particular study, it's possible to downscale country-level demand profiles to sub-country level as shown in the figure by using historical relative demand shares as proxy and scaling the sub-country specific demand profiles.

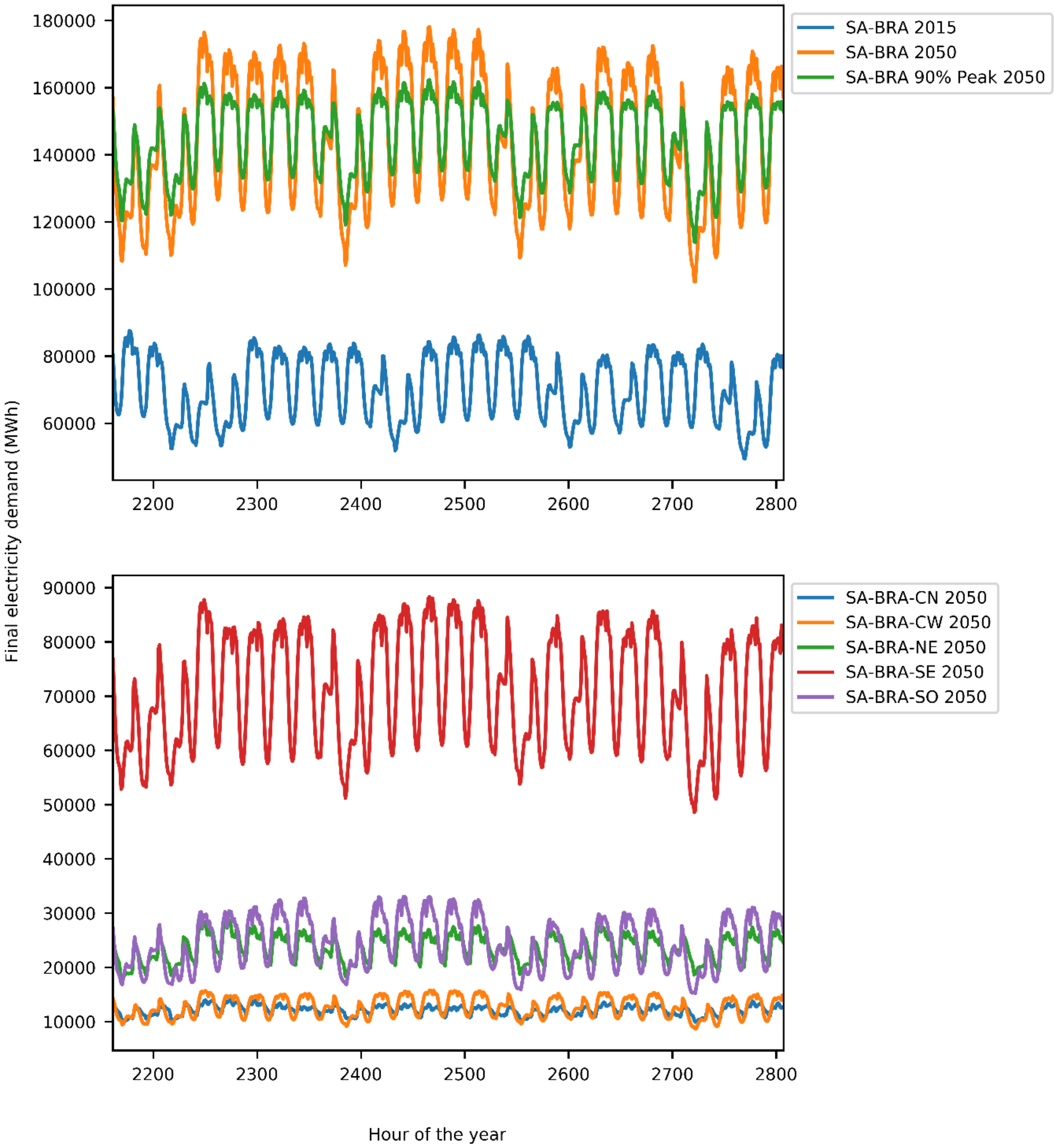

Figure A1.3: Downscaled hourly final electricity demand for South-America - Brazil (SA-BRA) in the MESSAGEix-GLOBIOM ENGAGE SSP2 NPI2020 500 scenario. The upper graph showcases the baseline 2050 hourly demand profile for Brazil, an exemplary profile with adjusted peak demand at 90% and the 2015 demand profile for reference. The lower graph shows the hourly demand profiles of the largest sub-country nodes within Brazil (Central North (CN), Central West (CW), North East (NE), South East (SE), South (SO)). The sum of all demand values of the sub-country nodes per interval equals the baseline profile of Brazil, whereas the sum of all interval values of the country-level profiles (both the baseline as the profile with adjusted peak demand) equals the yearly country-level value based on the spatially downscaled IAM scenario output.

Appendix 2: PLEXOS-World and MESSAGEix-GLOBIOM scenario integration

PLEXOS long-term capacity expansion

There are two main simulation modules in PLEXOS relevant for this study, the long-term capacity expansion module and the short term UCED module. The objective function of the long-term module in PLEXOS is to minimize the net present value of asset build costs, plus fixed operations and maintenance costs as well as production costs. As described in section 2.5, in context of the soft-link framework, the long-term module is used to downscale given regional powerplant capacities from the MESSAGEix-GLOBIOM ENGAGE SSP2 NPI2020 500 scenario to nodal level in parallel with optimizing the expansion of balancing assets such as transmission and storage.

To limit the computational complexity of the downscaling and expansion exercise, linear optimization is applied with the expanded generator units rounded to the nearest integer. Traditionally Mixed Integer Linear Programming (MILP) is used in power system expansion planning exercises but the problem size following the global spatial scale of this study merits linearization. Furthermore, whereas in UCED modelling simulations generally occur at (sub-)hourly temporal resolution, for capacity expansion a trade-off has to be made between the temporal detail and the computational complexity. A common method in planning exercises is to use LDC's to determine the optimal generator portfolio expansion together with an approximation of required system reserves and flexibility, yet with increased variability and uncertainty following the large-scale integration of VRES it becomes critical that the chronology of demand and capacity factor profiles is being kept. Following recommendations in the literature [75,76], we apply a sampling approach that picks representative periods while keeping chronology. PLEXOS has the built-in ability to select samples statistically such that 'like' periods (days/weeks/months) are removed leaving a sample set that is representative of the variation in the original demand and VRES profiles. Figure A2.1 shows an example of different sampling combinations for demand and VRES series.

For the analysis in this paper we apply a sampling approach using 4-weeks per year at 4-hourly time resolution (total of 168 4-hourly timeslices) for the different profiles in the expansion exercise. In essence, this means that PLEXOS selects 4 weekly timeseries per original profile, aggregated per 4 hours, and applies these timeseries throughout the horizon based on a best fit compared to the original profile. Following figure A2.1, generally speaking sampling for demand and solar timeseries can be reasonably accurate due to the relative predictability of diurnal cycles. Picking representative days per month results in a better fit for especially demand and solar profiles, yet due to the variability of wind-based resources beyond diurnal cycles sampling is more tedious. As shown in the graph, using representative days for on- and offshore wind leads to a sample profile with a consistent 'peaky' behaviour that is not realistic in terms or real world dynamics. Hence, the choice has been made to apply samples in terms of weeks per year. Despite the occurrence of peaks and lows in wind not always matching with the base profiles, the occurrence of longer term peaks in the sample profiles triggers PLEXOS to invest in technologies that are compatible with this type of variability such as transmission infrastructure versus short-term storage.

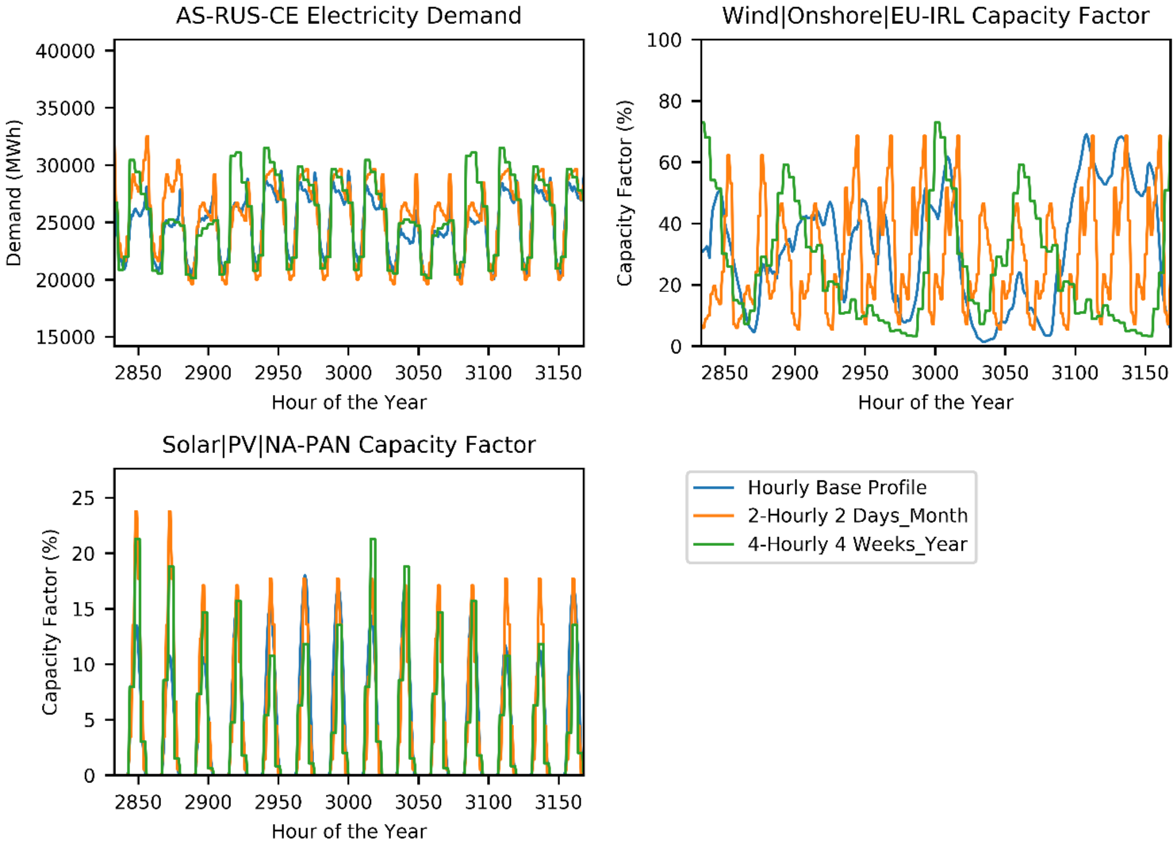

Figure A2.1: Examples of sampling combinations for a variety of demand and VRES series in Asia - Central Russia (AS-RUS-CE), Europe - Ireland (EU-IRL) and North-America - Panama (NA-PAN).

Next to the expansion- and retirement constraints and the load profiles developed based on the MESSAGEix-GLOBIOM scenario data, input data for PLEXOS based on MESSAGEix-GLOBIOM for this exercise consists of regional specific carbon- and fuel prices, generator heat rates and storage capacities- and characteristics. All data input is integrated by making use of a python script that converts and directs MESSAGEix-GLOBIOM model output. The expansion of storage in PLEXOS follows the representation of MESSAGEix-GLOBIOM where storage is modelled as a single generic technology with a cycle efficiency of 80%, storage capacity of 24 hours and a capital cost of $800/kW [20]. Hydrogen electrolysis is included but not part of the expansion. Electrolysis is constrained at a 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. Electric vehicles and demand side management are not integrated in PLEXOS-World for this proof of concept application of the framework.

Due to the absence of explicit modelling of intra-regional electricity transmission in MESSAGEix-GLOBIOM, expansion of transmission infrastructure requires additional sources and assumptions. Following Zappa et al. [37], we use a 'centre-of-gravity' approach to model electricity transmission, with the to-be expanded transmission lines located between the main population-weighted demand centers in adjacent nodes with all capacity standardized as a combined interface rather than individual lines. Similar to powerplant capacities, baseline transmission capacities are retrieved from the PLEXOS-World dataset [21,22]. Expansion candidates exist for all land-based adjacent nodes, for interfaces with existing subsea transmission capacity as well as for interfaces with planned subsea transmission capacity following an earlier review on the concept of a globally interconnected power grid [65]. An overview of the techno-economic parameters as used for the transmission capacity expansion can be seen in table A2.1.

Table A2.1: Assumed techno-economic parameters for transmission infrastructure capacity expansion. All parameters are based on [37] with the exception of CAPEX line costs for land-based HVDC which is based on [77]. All costs are in €/2016.

Parameter	HVAC	HVDC	HVDC Subsea
CAPEX Line (€/MW/KM)	634	185	240
CAPEX Substations/Converter pair (€/MW)	77600	242000	242000
Fixed Operation & Maintenance cost (% of CAPEX/year)	3.5	3.5	3.5
Line losses (%/100 km)	0.675	0.35	0.35
AC/DC Converter pair losses (%)	0	1.3	1.3

For bulk power flow, high voltage transmission lines are generally used with High Voltage Alternating Current (HVAC) lines for shorter transmission distances and High Voltage Direct Current (HVDC) lines for longer distances. HVDC becomes only efficient at longer distances because of its high base costs for AC/DC converters as well as due to significantly lower transmission losses compared to HVAC. The so-called break-even distance is the transmission distance after which HVDC becomes the more efficient solution, with values in the literature ranging between 200-800 km depending on the project specifics [78–81]. This break-even distance includes not only CAPEX investment costs but also indirect costs due to conversion and transmission losses of transmitted electricity. Yet, because the exact utilization (and hence the transmission losses) of a potential transmission line is not known before model simulation we calculate the break-even distance solely based on CAPEX costs. Based on the parameters in table A2.1, the break-even distance is calculated to be 370 km, well within the range as identified within the literature. Within PLEXOS-World, depending on the absolute distance between demand centers in neighbouring nodes compared to the break-even distance, a land-based transmission pathway is deemed to be suitable either for HVAC or HVDC. Pathways are restricted to a single technology to limit the amount of expansion candidates and hence the overall computational intensity of model simulations. Subsea transmission pathways are assumed to use solely HVDC subsea power cables in line with current real world standards [65]. Following this approach, every transmission pathway has personalized associated costs and transmission losses.

For the downscaling of renewable powerplant capacities from regional to nodal level limits have been set on the resource potential per node. To retain uniformity, resource potential is based on the same sources as used in MESSAGEix-GLOBIOM. Country-level resource potential for Solar-PV and CSP is based on a study by Pietzcker et al. [82] and country-level potential for onshore- and offshore wind based on a global assessment by Eurek and colleagues [19]. Where necessary, further downscaling from country- to nodal level has been done by taking the relative area and shoreline size of sub-country nodes as proxy as a best estimate without applying detailed GIS based assessments. Nodal potential for new hydro-based capacity is based on a study by Gernaat et al. that identifies 60,000 potential locations for new economically viable projects [83]. In addition, in cases where the identified potential by Gernaat et al., is not sufficient compared to the regional powerplant capacities following the simulation output from the specific IAM scenario, additional theoretical potential following [84] is used as limit for the capacity downscaling. For geothermal and biomass no nodal level restrictions are placed due to the limited influence of geothermal based electricity generation and the transportability of biomass between regions.

PLEXOS UCED

The UCED simulations in PLEXOS use the results from the long-term capacity expansion exercise in an automated fashion after the long-term simulation finishes. Yet, before this occurs two separate modelling phases are applied as preparation for the UCED. First, a Medium Term (MT) schedule decomposes constraints with time horizons longer than the intended UCED horizon. For example, within PLEXOS-World we use monthly CF profiles for hydropower plants based on the seasonal availability of water resources specified per node. The MT schedule decomposes these constraints to a horizon that is computationally manageable for the UCED, for example to daily constraints. Furthermore, a Projected Assessment of System Adequacy (PASA) phase is applied that among others optimizes scheduled maintenance events while retaining system reliability. The PASA also provides reliability indicators as output that can be used to assess the feasibility of reserve assumptions following the MESSAGEix-GLOBIOM scenario. After the MT and PASA the UCED simulation can be applied. The detailed objective function of the UCED simulations in PLEXOS can be found in appendix 3. For the UCED we use MILP at hourly resolution. Optimization steps for the full year (2050) occur based on a daily horizon starting at 12 AM with a six-hour look-ahead providing the most efficient starting state of generators for the simulation step of the next day.

Appendix 3: PLEXOS UCED Detailed Equations

Indices

j	Generation Unit
t	Time Period
stor	Index related specifically to pumped storage unit
RES^{up}	Upper Storage Reservoir
RES_{low}	Lower storage Reservoir

Variables

Vjt	Integer on/off decision variable for unit j at period t
Xjt	Integer on/off decision variable for pumped storage pumping unit j at period t
Ujt	Variable that = 1 at period t if unit j has started in previous period else 0
Pjt	Power output of unit j (MW)
Hjt	Pump load for unit j period t (MW)
Wint	Flow into reservoir at time t (MWh)
Woutt	Flow out of reservoir at time t (MWh)
Wt	Volume of storage at a time t (MWh)

Parameters

vl	Penalty for loss of load (€/MWh)
vs	Penalty for Reserve not met
use	Unserved Energy (MWh)
usr	Reserve not met (MWh)
D	Demand (MW)
obj	Objective Function
njt	No load cost unit j in period t (€)
cjt	Start cost unit j in period t (€)
mjt	Production Cost unit j in period t (€)
estor	Efficiency of pumping unit (%)
pmaxj	Max power output of a unit j (MW)
pminj	Mini stable generation of unit j (MW)
pmpmaxstor	Max pumping capacity of pumping unit
Jj	Available units in each generator
Jstor	Number of pumping units
MRUj	Maximum ramp up rate (MW/min)
MRDj	Maximum ramp down rate (MW/min)
MUTj	Minimum up time (hrs)
Ap	Number of hours a unit must initially be online due to its MUT constraint (hrs)
WINT	Initial Volume of reservoir (GWh)
W	Maximum volume of storage (GWH)

Objective Function:

$$OBJ = Min \sum \sum_{t \in T} c_{jt}.U_{jt} + n_{jt}.V_{jt} + m_{jt}.P_{jt} + vl.use_t + vs.usr_t$$

The objective function of the UCED in PLEXOS is to minimise the start-up cost of each unit (start cost (€)* number of starts of a unit) + the no load cost of each online unit + production costs of each online unit + the penalty for unserved load+ the penalty of unserved reserve. The objective function is minimised within each simulation period. The simulation solution must also satisfy the constraints below:

Energy Balance Equation:

$$\sum\sum_{t\in T} P_{jt} - H_{jt} + use_t = D_t$$

Energy balance equation states that the power output from each unit at each interval minus the pump load from pumped storage units for each interval + unserved energy must equal the demand for power at each interval. (Note that line losses can also be included here but is not shown). As the penalty for unserved energy is high and part of the objective function, the model will generally try to meet demand.

Operation Constraints on Units:

Basic operational constraints that limit the operation and flexibility of units such as maximum generation, minimum stable generation, minimum up/down times and ramp rates.

$$-V_{jt} + U_{jt} \ge -1 \qquad \forall t = 1$$

$$V_{jt} - V_{jt+1} + U_{jt+1} \ge 0$$

These two equations define the start definition of each unit and are used to track the on/off status of units.

$$P_{jt} - P\max{}_j .V_{jt} \le 0$$

Max Export Capacity: A units power output cannot be greater than it maximum export capacity.

$$P_{jt} - P\min{}_j .V_{jt} \ge 0$$

Minimum Stable Generation: A units output must be greater than its minimum stable generation when the unit is online.

$$H_{jt} - Pmp\max{}_{Stor}.X_{jt} \le 0$$

Pumping load must be less than maximum pumping capacity for each pumping unit

$$V_{jt} + X_{jt} \le 1 \quad \text{where } j \in stor$$

$$V_j \le J_j \quad X_j \le J_{Stor} \quad j \in J$$

These constraints limit a pumped storage unit from pumping and generating at same time.

$$A_{p,j} \ge V_{j,t} - V_{j,t-1} \forall t.t - MUT_j - 1$$

$$V_{j,t} \ge A_{p,j} - \sum_{t}^{t-MUT_j+1} V_{j,t} / MUT_j \forall t$$

Minimum Up Times[4]: (Note the following text is directly from the PLEXOS Help files). The variable A_p tracks if any starts have occurred on the unit inside the periods preceding *p* with a window equal to MUT. *i.e.* if no starts happen in the last MUT periods then A_p will be zero, but if one (or more) starts have occurred then A_p will equal unity. The MUT constraints then set a lower bound on the unit commitment that is normally below zero, but when a unit is started, the bound rises above zero until the minimum up time has expired. This fractional lower bound when considered in an integer program forces the unit to stay on for its minimum up time.

$$A_{p,j} \geq V_{j,t-1} - V_{j,t} \forall t.t - MDT_j + 1$$

$$V_{j,t} \leq 1 + \sum_{t}^{t-MDT_j+1} V_{j,t} / MDT_j - A_{p,j} \forall t$$

Minimum Down Times: The variable A_p tracks if any units have been shut down inside the periods preceding *p* with a window equal to MDT. *i.e.* if no units are shut down in the last MDT periods then A_p will be zero, but if one (or more) shutdown then A_p will equal unity. The MDT constraints then set an upper bound on the unit commitment that is normally above unity, but when a unit is stopped, the bound falls below unity until the minimum down time has expired.

$$P_{jt} - P_{j.t-1} - MRU_j.V_{jt} - p_{\min j}.U_j \leq 0$$

$$p_{\min j}.P_{jt} + P_{jt} - P_{j.t-1} - P_{jt}.(MRD_j - p_{\min j}) \leq 0$$

Maximum Ramp up and down constraints: These constraints limit the change in power output from one time period to another.

Water Balance Equations:

These equations track the passage of water from the lower reservoir to the upper reservoir. In this set-up there is no inflow and water volume is conserved.

$$W_{tR} + W_{out.tR} - W_{in.tR} = W_{INT,R} \quad \forall t = 1, R \in RES_{Up,} RES_{low}$$

$$W_{t.RES^{up}} + W_{out,RES^{up}} - W_{in,RES^{up}} = 0$$

$$e_{stor}.H_{jt.RES^{up}} - W_{in.tRES^{up}} = 0$$

$$P_{stor.t} - W_{out.t.RES^{up}} = 0$$

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[4] PLEXOS Help Files

Bibliography

[1] Pietzcker RC, Ueckerdt F, Carrara S, et al (2017). System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches. Energy Economics 64: 583–599. doi: 10.1016/j.eneco.2016.11.018

[2] Ueckerdt F, Pietzcker R, Scholz Y, et al (2017). Decarbonizing global power supply under region-specific consideration of challenges and options of integrating variable renewables in the REMIND model. Energy Economics 64: 665–684. doi: 10.1016/j.eneco.2016.05.012

[3] Collins S, Deane JP, Poncelet K, et al (2017). Integrating short term variations of the power system into integrated energy system models: A methodological review. Renewable and Sustainable Energy Reviews 76: 839–856. doi: 10.1016/j.rser.2017.03.090

[4] Riahi K, van Vuuren DP, Kriegler E, et al (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change 42: 153–168. doi: 10.1016/j.gloenvcha.2016.05.009

[5] Rogelj J, Shindell D, Jiang K, et al (2018). Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. pp 93–174

[6] Pfenninger S, Hawkes A, Keirstead J (2014). Energy systems modeling for twenty-first century energy challenges. Renewable and Sustainable Energy Reviews 33: 74–86. doi: 10.1016/j.rser.2014.02.003

[7] Ueckerdt F, Brecha R, Luderer G, et al (2015). Representing power sector variability and the integration of variable renewables in long-term energy-economy models using residual load duration curves. Energy 90: 1799–1814. doi: 10.1016/j.energy.2015.07.006

[8] Scholz Y, Gils HC, Pietzcker RC (2017). Application of a high-detail energy system model to derive power sector characteristics at high wind and solar shares. Energy Economics 64: 568–582. doi: 10.1016/j.eneco.2016.06.021

[9] Fujimori S, Masui T, Matsuoka Y (2012). AIM/CGE [basic] manual. doi: 10.1016/S1043-2760(97)84344-5, ISBN: 2012-01

[10] Stehfest E, Vuuren D van, Kram T, et al (2014). Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications. ISBN: 9789491506710

[11] Huppmann D, Gidden M, Fricko O, et al (2019). The MESSAGEix Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development. Environmental Modelling & Software 112: 143–156. doi: https://doi.org/10.1016/j.envsoft.2018.11.012 LB - huppmann_2019_MESSAGEix

[12] Després J, Keramidas K, Schmitz A, et al (2017). POLES-JRC model documentation. European Commission, doi: 10.2760/225347, ISBN: 9789279718014

[13] Luderer G, Leimbach M, Bauer N, et al (2015). Description of the REMIND Model (Version 1.6). SSRN Electron J. doi: 10.2139/ssrn.2697070

[14] Emmerling J, Reis LA, Bevione M, et al (2016). The WITCH 2016 Model - Documentation and Implementation of the Shared Socioeconomic Pathways. SSRN Electron J. doi:

10.2139/ssrn.2800970

[15] Carrara S, Marangoni G (2017). Including system integration of variable renewable energies in a constant elasticity of substitution framework: The case of the WITCH model. Energy Economics 64: 612–626. doi: 10.1016/j.eneco.2016.08.017

[16] Dai H, Fujimori S, Silva Herran D, et al (2017). The impacts on climate mitigation costs of considering curtailment and storage of variable renewable energy in a general equilibrium model. Energy Economics 64: 627–637. doi: 10.1016/j.eneco.2016.03.002

[17] de Boer HS (H S)., van Vuuren D (D P). (2017). Representation of variable renewable energy sources in TIMER, an aggregated energy system simulation model. Energy Economics 64: 600–611. doi: 10.1016/j.eneco.2016.12.006

[18] Després J, Mima S, Kitous A, et al (2017). Storage as a flexibility option in power systems with high shares of variable renewable energy sources: a POLES-based analysis. Energy Economics 64: 638–650. doi: 10.1016/j.eneco.2016.03.006

[19] Eurek K, Sullivan P, Gleason M, et al (2017). An improved global wind resource estimate for integrated assessment models. Energy Economics 64: 552–567. doi: 10.1016/j.eneco.2016.11.015

[20] Johnson N, Strubegger M, McPherson M, et al (2017). A reduced-form approach for representing the impacts of wind and solar PV deployment on the structure and operation of the electricity system. Energy Economics 64: 651–664. doi: 10.1016/j.eneco.2016.07.010

[21] Brinkerink M, Deane P (2020). PLEXOS-World 2015. Harvard Dataverse, V4. UNF6+rCz+q2zqJyLE0VRQCABZA== [fileUNF]. doi: https://doi.org/10.7910/DVN/CBYXBY

[22] Brinkerink M, Gallachóir BÓ, Deane P (2020). Building and Calibrating a Country-Level Detailed Global Electricity Model Based on Public Data. Manuscr Submitt Publ

[23] Toktarova A, Gruber L, Hlusiak M, et al (2019). Long term load projection in high resolution for all countries globally. International Journal of Electrical Power and Energy Systems 111: 160–181. doi: 10.1016/j.ijepes.2019.03.055

[24] Sullivan P, Krey V, Riahi K (2013). Impacts of considering electric sector variability and reliability in the MESSAGE model. Energy Strategy Reviews 1: 157–163. doi: 10.1016/j.esr.2013.01.001

[25] Artelys (2020). Multi-energy planning of interconnected systems. https://www.artelys.com/crystal/super-grid/. Accessed 8 Oct 2020

[26] Artelys (2019). Investigation on the interlinkage between gas and electricity scenarios and infrastructure projects assessment. Paris

[27] Brinkerink M, Shivakumar A (2018). System dynamics within typical days of a high variable 2030 European power system. Energy Strategy Reviews 22: doi: 10.1016/j.esr.2018.08.009

[28] Lund H, Thellufsen JZ (2020). EnergyPLAN Advanced Energy Systems Analysis Computer Model Documentation Version 15.1

[29] Connolly D, Lund H, Mathiesen B V. (2016). Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renewable and Sustainable Energy Reviews 60: 1634–1653. doi: 10.1016/j.rser.2016.02.025

[30] Østergaard PA (2015). Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. Applied Energy 154: 921–933. doi:

10.1016/j.apenergy.2015.05.086

[31] Van Den Bergh K, Bruninx K, Delarue E, et al (2015). LUSYM: a Unit Commitment Model formulated as a Mixed-Integer Linear Program. Energy Syst Integr Model Gr Work Pap Ser No EN2014-07

[32] Delarue E, Van den Bergh K (2016). Carbon mitigation in the electric power sector under cap-and-trade and renewables policies. Energy Policy 92: 34–44. doi: 10.1016/j.enpol.2016.01.028

[33] Bogdanov D, Farfan J, Sadovskaia K, et al (2019). Radical transformation pathway towards sustainable electricity via evolutionary steps. Nature Communications 10: 1–16. doi: 10.1038/s41467-019-08855-1

[34] Energy Exemplar (2020). PLEXOS Market Simulation Software. https://energyexemplar.com/solutions/plexos/. Accessed 8 Oct 2020

[35] Gaffney F, Deane JP, Drayton G, et al (2020). Comparing negative emissions and high renewable scenarios for the European power system. BMC Energy 2: 1–13. doi: 10.1186/s42500-020-00013-4

[36] Collins S, Deane P, Ó Gallachóir B, et al (2018). Impacts of Inter-annual Wind and Solar Variations on the European Power System. Joule 2: 2076–2090. doi: 10.1016/j.joule.2018.06.020

[37] Zappa W, Junginger M, van den Broek M (2019). Is a 100% renewable European power system feasible by 2050? Applied Energy 233–234: 1027–1050. doi: 10.1016/j.apenergy.2018.08.109

[38] Brinkerink M, Deane P, Collins S, et al (2018). Developing a global interconnected power system model. Global Energy Interconnection 1: 330–343. doi: 10.14171/j.2096-5117.gei.2018.03.004

[39] Brown T, Hörsch J, Schlachtberger D (2018). PyPSA: Python for power system analysis. Journal of Open Research Software 6: doi: 10.5334/jors.188

[40] Brown T, Schäfer M, Greiner M (2019). Sectoral interactions as carbon dioxide emissions approach zero in a highly-renewable european energy system. Energies 12: 1–16. doi: 10.3390/en12061032

[41] Deane JP, Chiodi A, Gargiulo M, et al (2012). Soft-linking of a power systems model to an energy systems model. Energy 42: 303–312. doi: 10.1016/j.energy.2012.03.052

[42] Wene CO (1996). Energy-economy analysis: Linking the macroeconomic and systems engineering approaches. Energy 21: 809–824. doi: 10.1016/0360-5442(96)00017-5

[43] Collins S, Deane JP, Ó Gallachóir B (2017). Adding value to EU energy policy analysis using a multi-model approach with an EU-28 electricity dispatch model. Energy 130: 433–447. doi: 10.1016/j.energy.2017.05.010

[44] Pina A, Silva CA, Ferrão P (2013). High-resolution modeling framework for planning electricity systems with high penetration of renewables. Applied Energy 112: 215–223. doi: 10.1016/j.apenergy.2013.05.074

[45] Poncelet K, Delarue E, Six D, et al (2016). Impact of the level of temporal and operational detail in energy-system planning models. Applied Energy 162: 631–643. doi: 10.1016/j.apenergy.2015.10.100

[46] Brouwer AS, van den Broek M, Seebregts A, et al (2015). Operational flexibility and economics of power plants in future low-carbon power systems. Applied Energy 156: 107–128. doi: 10.1016/j.apenergy.2015.06.065

[47] Zeyringer M, Price J, Fais B, et al (2018). Designing low-carbon power systems for Great Britain in 2050 that are robust to the spatiotemporal and inter-annual variability of weather. Nature Energy 3: 395–403. doi: 10.1038/s41560-018-0128-x

[48] Soria R, Lucena AFP, Tomaschek J, et al (2016). Modelling concentrated solar power (CSP) in the Brazilian energy system: A soft-linked model coupling approach. Energy 116: 265–280. doi: 10.1016/j.energy.2016.09.080

[49] Lap T, Benders R, van der Hilst F, et al (2020). How does the interplay between resource availability, intersectoral competition and reliability affect a low-carbon power generation mix in Brazil for 2050? Energy 195: doi: 10.1016/j.energy.2020.116948

[50] Schmid E, Knopf B, Bauer N (2012). Remind-D: A Hybrid Energy-Economy Model of Germany. SSRN Electron J. doi: 10.2139/ssrn.2026443

[51] Byers L, Friedrich J, Hennig R, et al (2018). A Global Database of Power Plants. Washington DC

[52] Pfenninger S, Staffell I (2016). Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy 114: 1251–1265. doi: 10.1016/j.energy.2016.08.060

[53] Medjroubi W, Müller UP, Scharf M, et al (2017). Open Data in Power Grid Modelling: New Approaches Towards Transparent Grid Models. Energy Reports 3: 14–21. doi: 10.1016/j.egyr.2016.12.001

[54] Sadovskaia K, Bogdanov D, Honkapuro S, et al (2019). Power transmission and distribution losses – A model based on available empirical data and future trends for all countries globally. International Journal of Electrical Power and Energy Systems 107: 98–109. doi: 10.1016/j.ijepes.2018.11.012

[55] Gambhir A, Butnar I, Li PH, et al (2019). A review of criticisms of integrated assessment models and proposed approaches to address these, through the lens of BECCs. Energies 12: 1–21. doi: 10.3390/en12091747

[56] Pindyck RS (2017). The use and misuse of models for climate policy. Review of Environmental Economics and Policy 11: 100–114. doi: 10.1093/reep/rew012

[57] Krey V, Havlik P, Fricko O, et al (2016). MESSAGE-GLOBIOM 1.0 Documentation. International Institute for Applied Systems Analysis (IIASA), International Institute for Applied System Analysis (IIASA), Schlossplatz 1, 2361 Laxenburg, Austria

[58] Fricko O, Havlik P, Rogelj J, et al (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Global Environmental Change 42: 251–267. doi: 10.1016/j.gloenvcha.2016.06.004

[59] Huppmann D, Kriegler E, Krey V, et al (2018). IAMC 1.5°C Scenario Explorer and Data hosted by IIASA

[60] Huppmann D, Rogelj J, Krey V, et al (2018). A new scenario resource for integrated 1.5 °C research. Nat Clim Chang. doi: 10.1038/s41558-018-0317-4

[61] Holttinen H, Orths A, Abildgaard H, et al (2013). IEA Wind Expert Group Report on Recommended Practices: 16. Wind Integration Studies. 89.

[62] IIASA Energy Program (2020). Regions -- MESSAGE-GLOBIOM. https://docs.messageix.org/projects/global/en/latest/overview/spatial.html. Accessed 13 Oct 2020

[63] Sioshansi R (2010). Evaluating the impacts of real-time pricing on the cost and value of wind generation. IEEE Transactions on Power Systems 25: 741–748. doi: 10.1109/TPWRS.2009.2032552

[64] Deane JP, Ó Ciaráin M, Ó Gallachóir BP (2017). An integrated gas and electricity model of the EU energy system to examine supply interruptions. Applied Energy 193: 479–490. doi: 10.1016/j.apenergy.2017.02.039

[65] Brinkerink M, Gallachóir BÓ, Deane P (2019). A comprehensive review on the benefits and challenges of global power grids and intercontinental interconnectors. Renewable and Sustainable Energy Reviews 107: doi: 10.1016/j.rser.2019.03.003

[66] World development indicators. Washington, D.C. : The World Bank.

[67] KC S, Lutz W (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Global Environmental Change 42: 181–192. doi: 10.1016/j.gloenvcha.2014.06.004

[68] Dellink R, Chateau J, Lanzi E, et al (2017). Long-term economic growth projections in the Shared Socioeconomic Pathways. Global Environmental Change 42: 200–214. doi: 10.1016/j.gloenvcha.2015.06.004

[69] Crespo Cuaresma J (2017). Income projections for climate change research: A framework based on human capital dynamics. Global Environmental Change 42: 226–236. doi: 10.1016/j.gloenvcha.2015.02.012

[70] Leimbach M, Kriegler E, Roming N, et al (2017). Future growth patterns of world regions – A GDP scenario approach. Global Environmental Change 42: 215–225. doi: 10.1016/j.gloenvcha.2015.02.005

[71] Jiang L, O'Neill BC (2017). Global urbanization projections for the Shared Socioeconomic Pathways. Global Environmental Change 42: 193–199. doi: 10.1016/j.gloenvcha.2015.03.008

[72] Gidden M, Huppmann D (2019). pyam: a Python Package for the Analysis and Visualization of Models of the Interaction of Climate, Human, and Environmental Systems. Journal of Open Source Software 4: 1095. doi: 10.21105/joss.01095

[73] Schandl H, Hatfield-Dodds S, Wiedmann T, et al (2016). Decoupling global environmental pressure and economic growth: scenarios for energy use, materials use and carbon emissions. Journal of Cleaner Production 132: 45–56. doi: 10.1016/j.jclepro.2015.06.100

[74] McCollum DL, Zhou W, Bertram C, et al (2018). Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. Nature Energy 3: 589–599. doi: 10.1038/s41560-018-0179-z

[75] Sisternes FJ de, Webster MD (2013). Optimal selection of sample weeks for approximating the net load in generation planning problems optimal selection of sample weeks for approximating the net load in generation planning problems. Massachusetts Institute of Technology Engineering Systems Division 12.

[76] Abdin IF, Zio E (2018). An integrated framework for operational flexibility assessment in multi-period power system planning with renewable energy production. Applied Energy 222: 898–914. doi: 10.1016/j.apenergy.2018.04.009

[77] Droste-Franke B, Paal BP, Rehtanz C, et al (2012). Balancing Renewable Electricity. Springer Berlin Heidelberg, Berlin, Heidelberg, doi: 10.1007/978-3-642-25157-3, ISBN: 978-3-642-25156-6

[78] Bahrman M, Johnson B (2007). An Overview of High Voltage Direct Current Systems and Applications. IEEE power & energy magazine 32–44.

[79] Kalair A, Abas N, Khan N (2016). Comparative study of HVAC and HVDC transmission systems. Renewable and Sustainable Energy Reviews 59: 1653–1675. doi: 10.1016/j.rser.2015.12.288

[80] Barnes M, Hertem D Van, Teeuwsen SP, et al (2017). HVDC Systems in Smart Grids. Proceedings of the IEEE 105: 2082–2098. doi: 10.1109/JPROC.2017.2672879

[81] EIA (2018). Assessing HVDC Transmission for Impacts of Non-Dispatchable Generation. Washington DC

[82] Pietzcker RC, Stetter D, Manger S, et al (2014). Using the sun to decarbonize the power sector: The economic potential of photovoltaics and concentrating solar power. Applied Energy 135: 704–720. doi: 10.1016/j.apenergy.2014.08.011

[83] Gernaat DEHJ, Bogaart PW, Vuuren DPV, et al (2017). High-resolution assessment of global technical and economic hydropower potential. Nature Energy 2: 821–828. doi: 10.1038/s41560-017-0006-y

[84] Zhou Y, Hejazi M, Smith S, et al (2015). A comprehensive view of global potential for hydro-generated electricity. Energy and Environmental Science 8: 2622–2633. doi: 10.1039/c5ee00888c