Title	Connecting the continents. Power system modelling and capacity building for detailed assessments of global power sector decarbonization pathways
Author(s)	Brinkerink, Maarten
Publication date	2021
Original citation	Brinkerink, M. 2021. Connecting the continents. Power system modelling and capacity building for detailed assessments of global power sector decarbonization pathways. PhD Thesis, University College Cork.
Type of publication	Doctoral thesis
Rights	**© 2021, Maarten Brinkerink.** http://creativecommons.org/licenses/by-nc-nd/3.0/
Embargo information	Not applicable
Item downloaded from	http://hdl.handle.net/10468/11927

Ollscoil na hÉireann, Corcaigh

National University of Ireland, Cork

University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Connecting the Continents

Power System Modelling and Capacity Building for Detailed Assessments of Global Power Sector Decarbonization Pathways.

Thesis presented by

Maarten Brinkerink, B.Env.Sc, M.Sc

for the degree of

Doctor of Philosophy

University College Cork

School of Engineering

&

MaREI Centre, Environmental Research Institute

Head of School: Dr Jorge Oliveira

Supervisors: Professor Brian P. Ó Gallachóir & Dr Paul Deane

2021

Table of Contents

Declaration

This is to certify that the work I, Maarten Brinkerink, am submitting is my own and has not been submitted for another degree, either at University College Cork or elsewhere. All external references and sources are clearly acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism.

____

Maarten Brinkerink

Acknowledgements

My gratitude goes to Professor Brian Ó Gallachóir and Dr. Paul Deane for their supervision and overall guidance during all phases of my research. You've both helped me tremendously to improve the quality of the work and inspired me to become an overall better academic. Furthermore, I would like to thank my collaborators and fellow PLEXOS modellers in and outside the Energy Policy and Modelling Group without whom this work would have not been possible, Dr. Behnam Zakeri and Dr. Daniel Huppmann from IIASA as well as former EPMG colleagues Dr. James Glynn, Dr. Seán Collins, Dr. Fiac Gaffney and Laura Mehigan.

While working from home during the never-ending COVID-19 lockdown in Ireland it made me realize how much I appreciate having had the ability to work at the Environmental Research Institute with an amazing group of colleagues and friends. The PhD journey would have not been the same without the daily lunch-time chats and general banter. Big shoutout to Alessia Elia, Alparslan Zehir, Aoife Long, Archisman Bose, Connor McGookin, Conor Hickey, Davis Rusmanis, Duncan Mathews, Eamonn Mulholland, Evan Boyle, Fionn Rogan, Gideon Fadiran, Hannah Daly, Jason Mc Guire, Liliana Benitez, Mitra Kami Delivand, Nathan Gray, Parveen Kumar, Richard O'Shea, Shane McDonagh, Siddharth Joshi, Tarun Sharma, Tomás Mac Uidhir, Vahid Aryanpur, Vera O'Riordan and Xiufeng Yue, along with all others in the wider EPMG group and the Environmental Research Institute with whom I've worked over the years. Special thanks to Aoife Dunne, Helen McMahon and Tara Reddington for making things run so smoothly behind the scenes.

Thanks to Energy Exemplar for all the support I've received during my research and in particular to the London office for allowing me to join the team for an exciting three month research visit. I am grateful to IIASA for proceeding with the virtual Young Scientists Summer Program despite the inherent difficulties following the COVID-19 pandemic. Thanks to all the participants and the organizing committee, the members of the Energy Program and to Janet, Katie and Lisa for introducing me to the very effective 'Shut up and Write' sessions.

Thankfully there is also a life outside academia and in that respect there have been numerous people who have made a big impact along the way. To name just a few, Daniel, Harmeet, Jessie, Nicole, Rohil, Sarah, Sascha, Stephanie, thanks for enriching my Cork experience and for the well needed distractions from my PhD. Thanks to all my friends and extended family

in and around my birthplace Haaksbergen who have always been there for me whenever being back home.

Finally, I would like to express my gratitude to my direct family without whose support I would not have been able to successfully start nor finish my PhD journey. Jasper, you have been one of my biggest role models, both as a brother and as a successful academic. Thank you for all your insights and feedback when needed. Ma en pa, dank jullie wel voor jullie onvoorwaardelijke steun door dik en dun. Zonder jullie zou ik niet staan waar ik sta, zowel als persoon als professioneel. Anina, I am incredibly lucky to be able to call you my partner. I have no doubt not always been the easiest to be around when locked in our tiny city apartment while working on the final stretch of this thesis. Thank you for your patience and cheerfulness which from time to time was desperately needed. I am incredibly proud of your own accomplishments after all your hard work throughout the last few years. For everyone's sake, I am happy you will be the one called upon when a 'doctor' is needed.

Executive Summary

Deep decarbonization of the global energy sector is essential for reaching increasingly ambitious climate change mitigation targets. The momentum on global climate action is gathering speed, hence the need for energy research to accurately inform development pathways and decision making processes for the global energy sector is both critical and urgent. Electricity end use is expected to gain a larger role due to the potential for emission reductions in the electricity sector combined with the ability of electricity to displace fossil fuel use in other sectors. While completely decarbonised power systems based on very high penetrations of wind and solar energy are desirable, the technical and economic feasibility of power systems mostly or fully based on renewables remains a matter of debate. Furthermore, from a continental or global perspective, the role of flexible assets such as large-scale transmission interconnections are poorly understood.

This thesis develops, applies, and disseminates a number of key foundation blocks for robust assessments of global power system decarbonization pathways by means of open methods and datasets that can be used with a broad range of modelling tools. The author constructs and uses a detailed global power system model with high technical, temporal, and spatial modelling resolution to assess the technical feasibility of scenarios coming from long-term planning models. The methodological open source soft-link framework presented here is carefully designed to respond to known limitations of Integrated Assessment Models in a manner that allows for iterative model coupling to pinpoint and improve key areas of power system representation within Integrated Assessment Models. The thesis results provide insights that planning models struggle to generate, for example regarding curtailment of renewable electricity, occurrence of unserved energy and the operation of flexible assets at hourly modelling resolution. The research pays particular attention to the potential for intercontinental trade of electricity in context of a globally integrated power grid.

The main contributions of this thesis are the development, application and dissemination of new methods, datasets and models that improve power system modelling and capacity building efforts at the global scale. The foundation blocks provided by this research are currently contributing to improved assessments of power system decarbonization pathways and are enriching the evidence base underpinning global climate- and energy policy decisions.

Units and Abbreviations

AC	Alternating Current
AEO	Annual Energy Outlook EIA
ASEAN	Association of Southeast Asian Nations
BA	Balancing Authority
B2B	Back-To-Back
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CF	Capacity Factor
CIER	Comision de Integracion Energetica Regional
CO_2	Carbon Dioxide
CSP	Concentrated Solar Power
CT	Computational Time
DC	Direct Current
DOE	US Department of Energy
EC	European Commission
EIA	US Energy Information Administration
EJ	Exajoule
ENTSO-E	European Network of Transmission System Operators for Electricity
ETS	European Emissions Trading Scheme
EU	European Union
FAIR	Findability, Accessibility, Interoperability, and Reuse
FERC	Federal Energy Regulatory Commission
FLH	Full Load Hours
GCC	Gulf Cooperation Council
GDP	Gross Domestic Product
GEIDCO	Global Energy Interconnection Development and Cooperation Organization
GENI	Global Energy Network institute
GHG	Greenhouse Gas
GRAND	Global Reservoir and Dam Database
GW	Gigawatt
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IAM	Integrated Assessment Model
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre
km	Kilometre
kV	Kilovolt
kWh	Kilowatt hour
LDC	Load Duration Curve
LP	Linear Programming
m	metre
MENA	Middle East and North Africa
MIP	Mixed Integer Programming
MW	Megawatt
MWh	Megawatt hour
NEAG	North East Asia power Grid
NEB	National Energy Board of Canada

NEMS	EIA National Energy Modelling System
NTC	Net Transfer Capacity
OAS	Organization of American States
OCGT	Open Cycle Gas Turbine
OPEC	Organization of the Petroleum Exporting Countries
PASA	Projected Assessment of System Adequacy
PPP	Purchasing Power Parity
PSH	Pumped-Storage Hydro
PV	Photovoltaics
RES	Renewable Electricity Sources
RLDC	Residual Load Duration Curve
RR	Rounded Relaxation
SGCC	State Grid Corporation of China
SIEPAC	Central American Electrical Interconnection System
SRMC	Short Run Marginal Cost
SSP	Shared Socioeconomic Pathway
T&D	Transmission & Distribution
TSO	Transmission System Operator
TWh	Terawatt hour
TYNDP	ENTSO-E Ten Year Network Development Plan
UCED	Unit Commitment & Economic Dispatch
UN	United Nations
UNDESA	United Nations Department of Economic and Social Affairs
US	United States
UTC	Coordinated Universal Time
VRES	Variable Renewable Electricity Sources
WEO	IEA World Energy Outlook
WRI	World Resources Institute

Table of Figures

Table of Tables

Chapter 1 Introduction

1.1 Background

As many major economies across the world have introduced targets to achieve net-zero emissions by 2050, the momentum on global climate action is gathering speed. While the COVID-19 pandemic has led to a temporary reduction in global Carbon Dioxide (CO2) emissions (7%) [1], without structural changes in the economy and energy sectors, emissions are expected to return to- and exceed pre-COVID-19 levels [1–3]. Despite its tremendous impact on society, the pandemic provides a unique opportunity for governments to stimulate a green recovery in which short-term economic recovery can be coupled with acceleration on measures to reach medium- and long-term climate and environmental goals [4].

Approximately 76% of global Greenhouse Gas (GHG) emissions can be allocated to the energy sector [5] making deep decarbonization of the global energy sector essential for reaching set climate change mitigation targets. Electricity end use is expected to gain a significantly larger role [1,6,7] due to success in emissions reduction in electricity supply coupled with the potential to use electricity to displace fossil fuel use in heating and transportation. However, the large expected role for Variable Renewable Electricity Sources (VRES) such as wind and Solar-Photovoltaics (Solar-PV) is raising concerns on the technical feasibility and economic viability of electricity systems mostly- or completely based on Renewable Electricity Sources (RES) [8–12] as well as on the role of flexible assets such as large-scale transmission interconnection.

Model-informed assessments of development pathways for the global electricity sector are essential for the design of global climate and energy policy. Global Integrated Assessment Models (IAMs) are utilized and relied on to analyse and inform interlinked developments such as the effect of potential emission mitigation policies on climate change and the wider global economy [7,13,14]. Yet, IAMs were originally not designed to capture the technical implications of VRES integration or associated assets such as transmission interconnections or electricity storage and are significantly challenged in trying to realistically represent short term variations in electricity demand and supply [13–16]. This constrains the value of the evidence IAMs are delivering to energy and climate mitigation policy. Dedicated sectoral power system models are more suited for this exercise, but the application of power system models to date has mostly been restricted to assessments of continental size power systems as largest spatial modelling scale – e.g. [17–20]. This can be explained historically due to limitations on computational modelling complexity and restrictions in power system input data for developing regions. However, developments in recent years regarding hardware, software and solving techniques [21,22] as well as open data initiatives [23–28] has opened new doors for novel global power system modelling. Furthermore, advancements in costs and efficiency of long-distance electricity transmission infrastructure enabling the integration of cross-country or continental power markets has led to a growing interest in the concept of a globally interconnected power grid [29–31], meriting the utilization of a global power system model.

Energy research has been shown to lag behind other scientific disciplines when it comes to transparency and in moving to open and reproducible science [32,33]. Considering the critical timeframe in combatting climate change and decarbonization of the global energy system, it is important that scientific research informing energy policy can be reproduced and critically scrutinized by peers. For this to occur it is recommended to make use of 'open' models which can be freely accessed, used, modified and shared [32,34]. Where deemed infeasible to switch to fully open tools, a minimum requirement is to make the model input- and output data, supporting code and model formulation open for reproducibility by others.

A further challenge for energy systems modelling is the lack of available tools and data for capacity building purposes and a general bias in geographic origin and scope of scientific research. Assessing energy research from a geographical perspective, a review by Sovacool [35] regarding the research output of three main energy journals for the period 1999 to 2013 (4500 papers) highlighted that 87% of associated authors were affiliated to a European or North American institution. Furthermore, only 30% of case studies included areas outside Europe and North America. These statistics highlight a discrepancy in research focus and geographical urgency in clean energy- and decarbonization efforts. There is an important role for the energy modelling community to enable energy modelling capacity in the developing world. This can partly be approached by making use of existing knowledge and resources from developed countries, yet capacity building exercises to empower domestic scientists and policy workers are critical for successful locally informed sustainable development pathways [36].

The motivation for this thesis is to address the four points introduced above namely, 1) to develop a state of the art power system model capable of simulating power systems globally with a focus on assessing the role of long-distance transmission of electricity, 2) to support the improvement of power system representation in global IAMs to strengthen its accuracy in international climate policy, 3) to improve the dissemination of methods, tools and data to encourage greater transparency within the international energy research community and 4) to be an enabler of capacity building for energy research addressing climate change by providing the required methods, tools and data.

1.2 Thesis Aim

This thesis addresses a range of research questions as follows:

RQ-1. What is the present state of the art in the application of global power system models?

RQ-2. What is the status of open power systems data and what are the shortcomings for utilizing open data in global power systems modelling?

RQ-3. What insights can be provided regarding best practices in using proprietary energy systems modelling software for academic purposes?

RQ-4. What are the techno-economic benefits and limitations of long-distance transmission of electricity and the concept of a globally integrated power grid?

RQ-5. What are the main limitations in the power system representation of global IAMs?

RQ-6. How can global power system models be utilized as a complementary tool for global IAMs and facilitate methodological improvements within global IAMs?

The chapters in this thesis provide the knowledge base to address the above research questions. The questions are designed to shed light on the current status of global power systems research and to explore the potential research directions that can be accomplished by utilizing global power system models. Touching on a novel research area, this thesis is not intended to provide conclusive answers for all questions possible. Rather, it intends to enable others to build upon this work by providing a set of open datasets and methodologies that can be applied broadly.

1.3 Thesis in Brief

- **Chapter 2:** This chapter provides a comprehensive review of the existing literature regarding the concept of a globally integrated power grid and the intercontinental transmission of electricity. It scrutinizes the known benefits and challenges of the concept and assesses the current gaps in the literature from a techno-economic modelling perspective. The chapter furthermore includes a review on existing work to date related to the application of global power system models.

- **Chapter 3**: This chapter includes a proof-of-concept study for the modelling of integrated inter-continental power systems through long-distance electricity transmission by examining the functionality of a conceptual transmission line between Europe and North America. As an intermediate step to developing a global power system model, this study is designed to derive the necessary lessons regarding model building and functionality as well as the required insights on availability of data inputs and data quality.

- **Chapter 4**: Global climate and energy policy requires model informed insights in equitable global decarbonization pathways. This chapter describes the development of a reference detailed country-level global power system model dubbed PLEXOS-World that can be used as a baseline for a variety of assessments. The model has been benchmarked by emission and generation output with historical data. By making all model data openly available, this work provides a comprehensive global power system dataset that can support energy modelling activities and capacity building efforts globally.

- **Chapter 5:** This chapter provides an open-source methodological framework for soft-linking of global IAMs with global power system models. The framework can be used to assess and improve the technical feasibility of IAM power system decarbonization pathways through benchmarking with power system model simulations with enhanced spatial, technological, and temporal modelling resolution. A proof of concept application of the framework is presented by linking global IAM MESSAGEix-GLOBIOM with PLEXOS-World.

The final chapter, Chapter 6, presents the conclusions as drawn based on the content of this thesis. It furthermore includes a preview of- and recommendations for future work that builds on this thesis. Figure 1-1 shows an overview of the thesis chapters and their interlinkages.

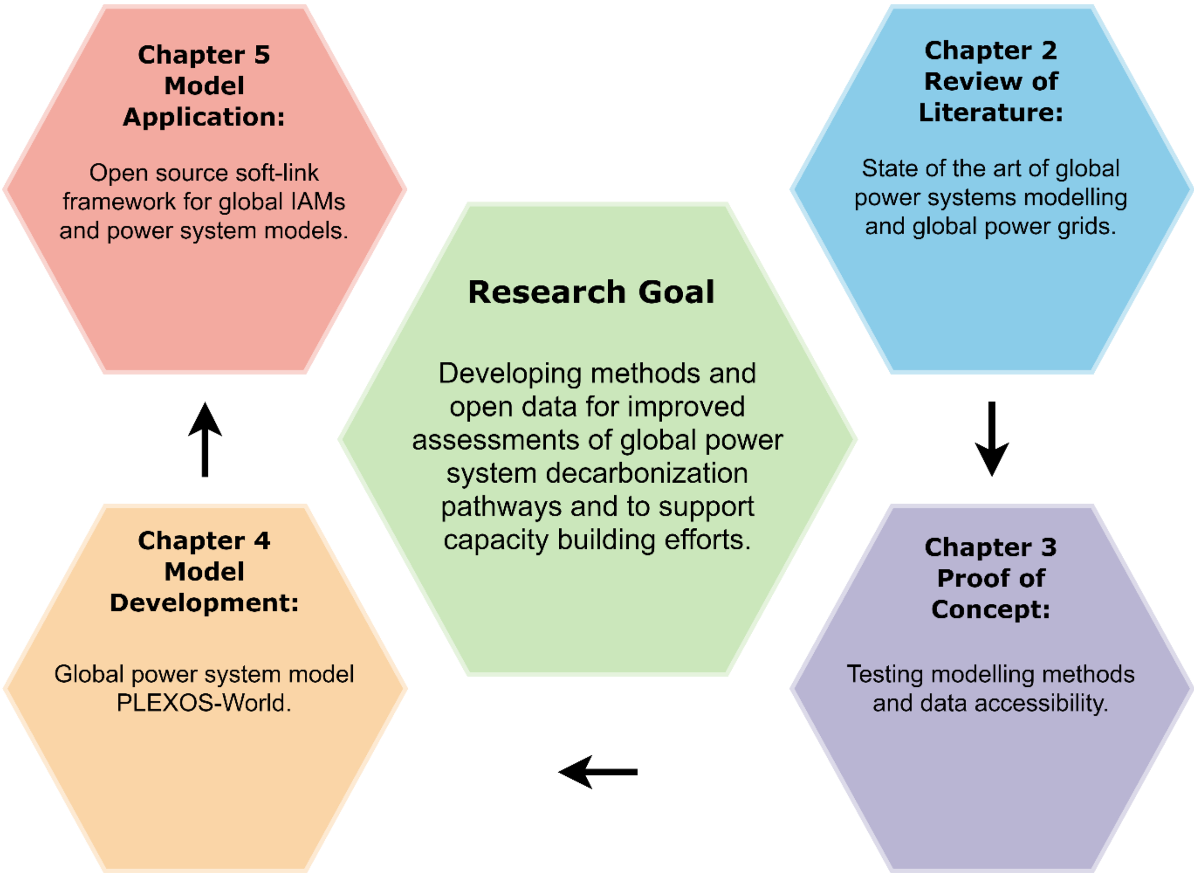


Figure 1-1 Overview map of existing, commissioned, considered and conceptually studied intercontinental transmission pathways.

1.4 Methodology

Different methodologies and methodological tools can be used to understand future decarbonisation pathways. Dedicated power system models can be used to analyse decarbonisation pathways for the power system and due to their high temporal and technical modelling resolution would provide the most accurate insights from a power sector perspective. However, to date, the computational complexity of this exercise limits the ability of power system models to perform long-term global planning studies with the level of spatial, technological, and temporal resolution required for realistic simulation of short-term power system operations[1]. Furthermore, assessing development pathways from solely a power

[1] In context of this thesis, long-term modelling covers timespans of multiple decades and short-term involves modelling at hourly resolution.

system perspective gives a narrow focus that lacks interactions with- and broader insights from other sectors relevant in the development of the overall energy system. To overcome these limitations, this thesis applies a Unit Commitment & Economic Dispatch (UCED) methodology combined with a model soft-linking approach. This means that results from a secondary model or study are fed into the power system model and used as baseline for extended assessments. Consequentially, this thesis applies detailed operational power system analyses in context of long-term global energy system decarbonization pathways.

1.4.1 Power System Unit Commitment & Economic Dispatch Modelling

Power system UCED modelling refers to the modelling exercise in which for a given generator portfolio the utilization of available capacity is optimized to match system demand while abiding to technical- and operational constraints. Within this thesis UCED modelling occurs within PLEXOS [37] which is a transparent energy- and power system modelling tool with free licenses for academic use. The fundamental linear programming equations can be viewed, modified and shared, which makes it transparent and appropriate for use in a research context. PLEXOS is used by organisations such as the IEA, IRENA, NREL and a wide range of universities for research. Model data can be shared in PLEXOS standard format for other PLEXOS users or exported for sharing in raw data format to non-PLEXOS users. Refer to Appendix A for detailed equations of the objective function of the UCED modelling as applied for this thesis.

1.4.2 Model Soft-Linking and Scenario Analysis

The baseline input data for the UCED modelling as applied in Chapter 3 and Chapter 5 is based on soft-linking to scenario data coming from external energy system models and IAMs. Soft-linking of power system models with energy systems models and IAMs has first been introduced by [38] and reviewed by [14]. Generation portfolios, electricity demand values and other power system properties from the energy system model or IAM are imported in the power system model. Operational analysis in power system models of given long-term planning scenarios can provide detailed insights in aspects such as the utilization of electricity storage and transmission infrastructure, cycling of thermal generators, electricity curtailment and more. For the soft-linking exercise as applied in Chapter 5 an intermediate step in the soft-linking workflow has been applied in which regionally aggregate scenario results from IAMs are spatially downscaled to sub-country level. An open-source methodological framework has been developed that automates model soft-linking between global IAMs and global power system models which allows for iterative feedback loops.

1.4.3 Open Data and Methods for Capacity Building

The global models as developed and used for Chapter 4 and Chapter 5 have been made publicly available in raw data format allowing for reproducibility of results in open source modelling tools. Furthermore, the methodological framework developed in Chapter 5 for soft-linking of global IAMs and global power system models has been designed to be uniformly applicable to any IAM or power system modelling tool with the supporting python script being fully open. The comprehensive global power system datasets and modelling methodologies resulting from this thesis are designed to support adoption externally as well as to contribute to energy modelling capacity building exercises globally.

1.5 Role of Collaborators

- **Chapter 2:** This chapter is based on a published peer-reviewed journal article of which I am the lead author. I performed the literature review and wrote the chapter in its entirety. Dr. Paul Deane reviewed drafts of the manuscript and together with Professor Brian Ó Gallachóir provided overall guidance.

- **Chapter 3:** This chapter is based on a published peer-reviewed journal article of which I am the lead author. I developed the power system model for North America, performed all modelling and wrote the chapter in its entirety. Dr. Seán Collins developed the power system model for Europe and reviewed drafts of the manuscript. Dr. Paul Deane reviewed drafts of the manuscript and together with Professor Brian Ó Gallachóir provided overall guidance.

- **Chapter 4:** This chapter is based on a published peer-reviewed journal article of which I am the lead author. I lead the development of the global power system model, performed all modelling, and wrote the chapter in its entirety. Dr. Paul Deane contributed to the model building and validation and together with Professor Brian Ó Gallachóir reviewed drafts of the manuscript and provided overall guidance.

- **Chapter 5:** This chapter is based on an article submitted to a peer-reviewed journal of which I am the lead author. I developed the global power system model, performed the PLEXOS model simulations, lead the methodological design of the study, developed the supporting python scripts for the workflow and wrote the chapter in its entirety. Dr. Behnam Zakeri assisted with the methodological design of the study and performed the modelling in MESSAGEix-GLOBIOM. Dr. Daniel Huppmann reviewed the developed python script. All co-authors provided guidance and reviewed drafts of the manuscript.

1.6 Thesis Outputs

1.6.1 Journal Papers

Brinkerink M, Zakeri B, Huppmann D, Glynn J, Ó Gallachóir B, Deane P (2021). Assessing global climate change mitigation scenarios from a power system perspective using a novel multi-model framework. Environmental Modelling & Software (In Review).

Brinkerink M, Ó Gallachóir B, Deane P (2021). Building and Calibrating a Country-Level Detailed Global Electricity Model Based on Public Data. Energy Strategy Reviews 33: 100592. doi: 10.1016/j.esr.2020.100592

Deane P, **Brinkerink M** (2020). Connecting the Continents-A Global Power Grid. IEEE Power and Energy Magazine 18:121–127. doi: 10.1109/MPE.2020.2974610

Brinkerink M, Ó Gallachóir B, 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

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

1.6.2 Technical Reports and Working Papers

Allington L , Cannone C, Ioannis P, Barron KC, Usher W, Pye S, Brown E, Howells M, Walker MZ, Ahsan A, Charbonnier F, Halloran C, Hirmer S, Taliotis C, Sundin C, Sridharan V, Ramos E, **Brinkerink M**, Deane P, Gritsevskyi A, Moura G, Rouget A, Wogan D, Barcelona E, Rogner H. Selected ‘ Starter Kit ’ energy system modelling data for Niger (# CCG)[2]. Research Square Preprint. doi: https://doi.org/10.21203/rs.3.rs-480051/v2

[2] Energy systems modelling ‘starter kit’ papers have been created for most developing countries as a capacity building effort. Refer to https://climatecompatiblegrowth.com/starter-kits/ for a full overview.

Huppmann D, Gidden MJ, Nicholls Z, Hörsch J, Lamboll R, Kishimoto PN, Burandt T, Fricko O, Byers E, Kikstra J, **Brinkerink M**, Budzinski M, Maczek F, Zwickl-Bernhard S, Welder L, Álvarez Quispe EF, Smith CJ. pyam: Analysis and visualisation of integrated assessment and macro-energy scenarios [version 1; peer review: awaiting peer review]. Open Research Europe 2021, 1:74 (https://doi.org/10.12688/openreseurope.13633.1)

Pye S, Butnar I, Mittal S, Giarola S, Hawkes A, Beltramo A, Usher W, **Brinkerink M**, Deane P, Benitez L, Niet T, Shivakumar A (2021). Coal phase out and renewable electricity expansion under Paris targets. Research Square Preprint. doi: https://doi.org/10.21203/rs.3.rs-380763/v3

Brinkerink M (2020). Assessing 1.5-2°C scenarios of integrated assessment models from a power system perspective - Linkage with a detailed hourly global electricity model. IIASA YSSP Report. Laxenburg, Austria: IIASA. http://pure.iiasa.ac.at/id/eprint/16957/

1.6.3 Seminar & Workshop Presentations

Brinkerink M, Zakeri B, Huppmann D, et al (2021). Assessing global climate change mitigation scenarios from a power system perspective using a novel multi-model framework. Proceedings of the 39th International Energy Workshop 2021. June 14th-17th, 2021, Webinar.

Brinkerink M (2021). PLEXOS-World. Webinar presentation as part of the 4th Openmod Online Lightning Talk Mini-workshop. May 5th, 2021.

Brinkerink M (2021). PLEXOS-World. Webinar presentation as part of the 2021 PLEXOS Academic Program. February 4th, 2021.

Brinkerink M, Zakeri B, Huppmann D, et al (2020). PLEXOS-World: Assessing 1.5-2°C scenarios of integrated assessment models from a power system perspective. Webinar presentation on 'Research Excellence' as part of the 2020 MaREI symposium. November 27th, 2020.

Brinkerink M (2020). Assessing 1.5-2°C scenarios of integrated assessment models from a power system perspective. Webinar presentation as part of the 2020 Young Scientists Summer Program (YSSP) of the International Institute for Applied Systems Analysis (IIASA). August 26th, 2020.

Brinkerink M, Glynn J, Ó Gallachóir B, et al (2019). Detailed Power System Analysis of IAM 1.5°C-2°C Scenarios with an Hourly Global Electricity Model. Proceedings of the Integrated

Assessment Modelling Consortium (IAMC) 12th Annual Meeting. December 2nd-4th, 2019, National Institute for Environmental Studies (NIES), Tsukuba, Japan.

Brinkerink M (2019). Development of a detailed global electricity model. European Utility Week. November 12th-14th, 2019, Expo Porte de Versailles, Paris, France.

Brinkerink M, Ó Gallachóir B, Deane P (2019). The Development of a Detailed Global Electricity Model at Plant and Country Level Using Open Access Data. 2019 MaREI symposium. November 6th, 2019, University of Limerick, Limerick, Ireland.

Brinkerink M (2019). Development of a detailed global electricity model: PLEXOS-World. Conseil International des Grands Réseaux Electriques (CIGRE) Ireland Next Generation Network Workshop. July 11th, 2019, ESB Networks, Dublin, Ireland.

Brinkerink M, Glynn J, Ó Gallachóir B, et al (2019). Detailed Power System Analysis of IAM 1.5°C-2°C Scenarios with an Hourly Global Electricity Model. Proceedings of the 38th International Energy Workshop 2019. June 3rd-5th, 2019, International Energy Agency, Paris, France.

1.7 Contribution of Thesis

This section briefly highlights the contributions this thesis provides in terms of added value to the scientific literature- and knowledge base, new data, methods, and models as well as its resulting impact. For the modelling work performed in this thesis a global power system model has been developed. Insights are provided regarding lessons learned in the development of a global model concerning data acquisition, automation, and management, as well as regarding trade-offs in prioritization of model detail versus computational complexity. A number of these insights are specific for energy systems modelling whereas others are applicable for any large scale modelling effort while working with large datasets.

This thesis includes a review of existing scientific literature regarding research on the role of long-distance transmission interconnectors and the concept of a globally integrated power grid. A full overview of known benefits, risks and limitations is presented. Performed power systems modelling in this thesis reveals operational complications of integrating different market types through intercontinental interconnectors. It furthermore highlights which areas in the world could potentially benefit the most from intercontinental electricity trade.

Given the limitations of global IAMs in trying to realistically represent short term variations in electricity demand and supply as well as known complications of linking IAMs with sectoral power system models, this thesis includes a methodological framework that allows for iterative and where possible automated model soft-linking. A proof of concept application shows the benefits of the framework and its ability to pinpoint and improve key areas of the power system representation in global IAMs. The use of standardized data formats allows for non-discriminatory application of the framework for a wide range of different IAMs and power system models.

Following the modelling work in this thesis insights are given regarding best practices for use and dissemination of (open) models, data, and methods. Open global power system datasets are provided to support adoption in other modelling tools and overall capacity building efforts. To date the datasets have been used in multiple projects and adopted by institutions involved in energy- and climate modelling and capacity building at the global scale.

Chapter 2 A Comprehensive Review on the Benefits and Challenges of Global Power Grids and Intercontinental Interconnectors

2.1 Abstract

Globally interconnected power grids are proposed as a future concept to facilitate decarbonisation of the electricity system by enabling the harnessing and sharing of vast amounts of renewable energy. Areas with the highest potential for renewable energy are often far away from current load centres, which can be integrated through long-distance transmission interconnection. The concept builds on the proven benefits of transmission interconnection in mitigating the variability of renewable electricity sources such as wind and solar by import and export of electricity between neighbouring regions, as well as on other known benefits of power system integration. This paper reviews existing global and regional initiatives in context of a sustainable future and presents the associated benefits and challenges of globally interconnected power grids and intercontinental interconnectors. We find that while the challenges and opportunities are clearly qualified, actual quantification of costs, benefits and environmental implications of the global grid concept remains in its infancy, imposing a significant gap in the literature.[3]

[3] Published as: Brinkerink M, Ó Gallachóir B, 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

2.2 Introduction

The Paris climate change agreement sets a long-term goal of holding global average temperature increase to well below 2 degrees and pursuing efforts to limit this to 1.5 degrees above pre-industrial levels. Substantial research gaps in attaining the 1.5-degree target have been identified, including the ability of the energy system to transition to a zero-carbon system. Electricity is emissions free at its point of use and the decarbonisation of the power sector can enable decarbonisation elsewhere in the economy. Research on low carbon pathways to avoid dangerous climate change indicate a significant increase in global electrification [6,7,39,40]. It is not known whether this increase in electrification can be managed with the current infrastructure.

Many studies show the vast theoretical potential of RES for decarbonisation of the power system [41–43], yet the extent of practical implementation and reliability of such a system in the foreseeable future is a matter of debate due to the inherently variable nature in generation of core technologies such as solar-PV systems and wind turbines [44–47]. A valid approach to tackle the variability challenge is by interconnecting adjacent power systems to be able to import or export electricity during peaks and lows in generation [48]. Even more ambitious projects examine the extent to which interconnection between continental grids can be achieved.

The origin of the concept of globally interconnected power grids dates back to the first half of the 20th century when inventor Buckminster Fuller considered the potential benefits of a global grid[4] with RES as backbone, yet also dismissed the practicality at that time due to the limited maximum distances of power transmission (around 350 miles) [49]. Decades later, Buckminster Fuller presented a first representation of his concept of the global grid at the World Game Seminar in 1969, resulting in acknowledgement of the potential of the concept by the United Nations (UN) [50]. More recently at the 2015 UN Sustainable Development Summit in New York, Chinese president Xi Jinping announced that China will take the lead on discussions about establishing a 'global energy internet', to facilitate efforts to meet the global power demand with clean and green alternatives [51]. Furthermore, current UN

[4] Within the literature a variety of terminology is applied such as Global Energy Interconnection (GEI), Global Energy Internet, Global Transnational Grid (GTG), global interconnected power grid and global grid for a similar concept. Throughout this article we refrain from using multiple terminologies and henceforth the term global grid will be used. The term intercontinental interconnectors will be used for transmission lines crossing multiple continents.

Secretary General António Guterres considered the benefits of a global grid to be in line with UN's commitment to the 2030 Agenda for Sustainable Development and its objectives in regard to climate change [52]. Although there are some clear arguments supporting the concept of a global grid, implementation of intercontinental interconnectors to date have been limited to short distance subsea Alternating Current (AC) links such as the Morocco-Spain and Egypt-Jordan interconnectors [53], and land-based interconnectors with limited flow between eastern Europe and central Asia.

This paper provides a comprehensive review, assessment and comparison of developments in- and research on global grids and intercontinental interconnectors as a potential pathway to future power system decarbonisation. To date, no such overarching review exists within the scientific literature. Section 2.3 presents an assessment of the implications of grid integration of VRES and outlines reviewed aspects of the global grid concept. Section 2.4 provides an overview of initiatives and compares projects and development trends related to the promotion or development of intercontinental interconnectors and the global grid concept. Section 2.5 provides an assessment of the arguments put forward in the literature supporting said developments, as well as potential risks and challenges. Section 2.6 incorporates an analysis of quantified results from performed techno-economic modelling studies in a global or intercontinental context. The review ends in Section 2.7 where we discuss overarching research outcomes, limitations in the assessed literature and potential research gaps.

2.3 Review of Previous Literature

Historically, hydropower has been the most mature form of RES. Yet, throughout the last decade, new additions of both solar-PV and wind energy were underlined with impressive annual growth rates [54] showing an increase in global installed capacities of (on- and offshore) wind energy from 115 Gigawatt (GW) in 2008 to 514 GW in 2017 and 15 GW to 386 GW for solar-PV [55]. The inherently variable nature of solar-PV and wind energy in generation output and its impact on the electricity grid is a well-known challenge [44,45,48,56–58]. The dispatch of flexible generators can compensate for the variability up until a certain level of penetration of VRES. At higher penetration levels, especially when VRES displaces part of the dispatchable portfolio, this becomes a significant issue in terms of securing a match between demand and supply [44,45], as well as for maintaining stable inertia levels on the grid [46,47,59]. Despite these difficulties, a variety of continental- or global 100% renewable energy scenarios have been put forward [8,42,60–62]. Although these modelling studies show the vast theoretical potential of RES for decarbonisation of the power system, the practical implementation and reliability of such a system in the foreseeable future is often questioned [9,11]. To be able to decarbonize the electricity sector to contribute to overall emission reduction targets, while maintaining power system reliability, a variety of studies indicate the importance of a diverse and flexible low-carbon generation portfolio [47,58,63,64].

RES integration in the last decades has also emerged to decrease the dependency on import of fossil fuels from distant regions and to avoid its associated risks. As Robinson argues, "most countries favour renewables because they are indigenous resources" [65]. Following this analogy, the benefits of transitioning to a RES oriented power system with a focus on optimally utilizing local resources is being researched. Kaundinya and colleagues [66] conducted an extensive review on success and failure stories for standalone- and grid-connected decentralized RES-based power systems. Pleßmann et al. [67] assessed a global, decentralized 100% RES supply scenario with optimal combinations of solar-PV, Concentrated Solar Power (CSP), wind energy and electricity storage for approximately 15.400 regions within 163 countries. This scenario, and similar power system scenarios depending on mostly storage technologies for balancing purposes (e.g. in [42,60,68]), can become viable in a situation where the availability and cost curve of storage technologies progresses significantly. Yet, to date, an assessment of such scenarios fully depending on the availability of so far mostly unproven and costly storage technologies are often considered to "represent low probability outcomes" [11].

With growing penetration of VRES, an alternative or complementary approach to tackle the variability challenge is by interconnecting adjacent power systems to be able to import or export electricity during peaks and lows in generation. Historically speaking, transmission interconnectors were initially utilized to provide additional system security [65,69], after which the demand for cross-border trading, integration of wholesale electricity markets and these days the balancing of VRES have become core arguments for new transmission interconnectors [70]. Next to providing direct flexibility, interconnectors make the sharing of peak capacity possible [69], as well as the utilization of an overall more diverse, flexible and cost-efficient generation portfolio. The European Commission (EC) has underlined the importance of further market integration by endorsing a 10% interconnection target by 2020 (import capacity over installed generation capacity per member state) and 15% by 2030 for all member states [71]. Besides the earlier mentioned benefits, the expert group initiated to provide advise on how to make the 15% target operational [72], argues “that a fundamental role of transmission infrastructure is to enable the integration of areas of high renewable energy potential with main consumption areas”. Assessing this remark from a global perspective, it becomes clear that there is a discrepancy between on the one hand main consumption areas and existing grid infrastructure, and on the other hand areas with the highest RES potential [41,43,59,69,73–75]. This observation is one of the core thoughts behind the concept of a global grid.

Certain specific aspects relevant to a global grid concept have been reviewed in detail. [53,76–83] provide an overview of the characteristics, trends and developments, prospects, reliability and commercial application of High Voltage Direct Current (HVDC) cables and convertors. Besides the former, [69] also reviews potential other required technologies for a global grid. Furthermore, [53] assesses the spatial implications, best practice of cable instalment, reliability and accident risks, and potential environmental issues for HVDC subsea power cable projects. Thomas and colleagues provide a review on the current research and prospects of superconducting transmission lines [84]. Engeland et al. [85] reviews the space-time variability of VRES generation from a regional to global perspective. Other reviewed aspects focus on the integration between backbone HVDC systems and smart grids [69,77,82], potential market models and development strategies [31,69,86–88], standardization needs for technologies in context of a global grid [69] and important treaties and laws for subsea HVDC cables [53]. Details of the elements assessed in these papers are therefore outside the scope of the current review. An assessment of previous literature demonstrates the availability of technical solutions such as HVDC cables, converters and laying equipment technology, but highlights a gap in the maturity of knowledge on the costs, benefits, challenges and opportunities of a global grid. The aim of this paper is to assess and compare these aspects to be able to determine the overall viability of the global grid concept as a means to global power system decarbonisation.

2.4 Initiatives and Projects

2.4.1 Review and Comparison of Intercontinental Interconnection Projects

On a continental scale, Europe is on the forefront in terms of power system integration through transmission interconnection. Expansion outside the borders of the European Union (EU) is an item of significant interest [89,90]. Feasibility studies conducted during the early 2000s' on Trans-Mediterranean interconnectors, such as between Algeria-Spain or Algeria-Italy (direct or indirectly through Sardinia and the already existing SAPEI HVDC interconnector), indicated that financial feasibility is highly dependent on factors such as investment costs and sales prices of electricity [91]. The original 'Desertec' project proposed to supply between 700 Terawatt hour (TWh)/year [92] and roughly 1000 TWh/year [93] of electricity generated by RES (mostly CSP) from the Middle East and North Africa (MENA) to Europe by 2050. The required investments of approximately 400 billion € [92] and the political unrest following the Arab spring revolution are often believed to be the downfall of the project [94] in its original form [95]. A similar project was The Medgrid Industrial Initiative which was formed in 2010 to support the design and promotion of a Mediterranean transmission network able to export 5 GW of electricity from MENA to Southern Europe [69,96]. This would be supported by 20 GW of mostly solar powered RES in MENA, with an overall estimated cost of the combined project between 38-46 billion € [96]. The MedGrid consortium ceased its operation in 2016 after completion of a number of planning and pre-feasibility studies [69].

Although projects on such scales have not been pursued any further, smaller scale projects between Europe and MENA - and within MENA - are in order at different stages of development, gaining support from a range of regional initiatives and organizations (e.g. Friends of the Supergrid, Med-TSO and RES4MED). By receiving environmental approval from the Cypriot government late 2017 [97], the construction of the EuroAsia interconnector, interconnecting Greece (with Crete as intermediate landing point), Cyprus and Israel, can be commenced. Once completed, this 2GW, 1518 km long transmission link [98] will be the first (partial) subsea HVDC intercontinental interconnector and will reach maximum depths of around 3000 m. Moreover, the Cypriot, Greek and Egyptian governments agreed on a route for the 2 GW EuroAfrica HVDC interconnector [99]. The proposed route would cover 1707 km in total, with Cyprus and Crete as intermediate landing points. Italian Transmission System Operator (TSO) Terna is currently assessing plans for a 600 MW HVDC interconnector between Tunisia and Sicily [74,100]. Furthermore, Morocco and Portugal agreed on conducting a feasibility study for a 1 GW interconnector [74] and a 2 GW HVDC interconnector between Libya and Greece (with again Crete as intermediate landing point) is under consideration [101]. Other plans for interconnections between Northern Africa and Europe are in earlier stages of development, such as prospects of the TuNur project combining the development of a 4.5 GW CSP project in the Tunisian part of the Sahara with three transmission pathways between Tunisia on the one hand and France, Italy and Malta on the other [102].

Next to the cross-Mediterranean subsea interconnection initiatives, a variety of land-based interconnection projects are in development to complete the so-called Mediterranean Ring of interconnected countries around the Mediterranean Sea [70]. Due to their advantageous geographical placement, Turkey is able to interconnect and synchronize their power system with Europe (synchronization with the European continental grid occurred in 2014) through AC links with Bulgaria and Greece, as well as towards Asia and the Middle East [103]. Multiple existing- and planned AC- and Back-to-Back (B2B) HVDC interconnections exist towards Armenia, Georgia, Iran, Iraq and Syria. Within the MENA region, Egypt is interconnected to Jordan with a 400 kilovolt (kV) 450 MW AC subsea power cable crossing the red sea [53] and further plans have been made to reach a total transmission capacity of 2 GW between both countries [104]. Furthermore, a 3 GW HVDC interconnector linking Egypt and Saudi Arabia is expected to be operational by 2022, with an estimated total investment cost for the project of $1.56 billion [104]. This latter development could be the beginning of a pan-Arab power pool as envisioned by the Gulf Cooperation Council (GCC) [105].

One of the outcomes of the EU-Russia energy dialogue at the beginning of this decade was an “objective of moving towards a subcontinent wide interconnected electricity system and market” [106]. The possibility to utilize the vast renewable energy potential in Russia to partly supply the European market [69,107], introduced in the literature as the RUSTEC concept [108], would be an interesting option for further decarbonisation. Russia is currently interconnected to Finland with a 1 GW interconnector and with a number of smaller (below 200 MW) interconnectors to the Baltics and Norway. Yet, besides two additional small interconnectors towards Finland and Norway, concrete plans for further integration are not in sight. More than that, political unrest and conflicts in the region has led to a movement towards reduced dependency on energy from Russia [109,110].

In recent years, State Grid Corporation of China (SGCC) has been very active in pushing the integration of regional and intercontinental power grids as part of China's 'one belt, one road' initiative to export China's industrial overcapacity and engineering expertise [111]. Liu Zhenya, (now former) chairman of SGCC, stated that wind- and thermal power in the west of China can be produced and delivered to Germany at half of the current cost of locally produced electricity [112]. Following this concept, the Joint Research Centre (JRC) of the EC studied potential routes for a future power interconnection between China and the EU to inform policy makers, potentially by utilizing a multi-terminal setup integrating a range of European and Asian countries [113]. Figure 2-1 shows a simplified representation of these routes, as well as an overview of other existing, commissioned, considered and conceptually studied (see Section 2.6) intercontinental interconnection projects.

Figure 2-1 Overview map of existing, commissioned, considered and conceptually studied intercontinental transmission pathways. Routes are indicative, they do not reflect accurate locational representation, nor do they show relative transmission capacities per pathway. Map includes intercontinental projects as described in this section as well as conceptually studied projects as mentioned in Section 2.6. Continental supergrid projects (e.g. the Gobitec proposal) are not incorporated.

On the western periphery of Europe, the development of the 1-1.2 GW, 1200 km long subsea HVDC Icelink interconnector, integrating the power systems of Iceland and Great Britain to utilize the high geothermal potential in Iceland, has been delayed. Although studies show the potential economic viability of such an interconnector depending on the setup of the business case [114,115], the progress in development is believed to be delayed by the ‘Brexit’ and fears of increasing electricity prices in Iceland [116]. Crossing the Atlantic by interconnecting Iceland and Greenland – or interconnecting Greenland and Canada – is currently deemed to be unrealistic by the relevant authorities despite the significant renewable energy potential [117]. Even more conceptual was an initiative in the early 90’s to connect load centres in Russia and the United States (US) by bridging the Bering Strait with a 10,000 km long HVDC interconnector [118,119], yet this concept hasn’t seen the light of day since then.

During the sixth summit of the Americas held by the Organization of American States (OAS, covering all 35 independent states in North- and South America) in 2012, the ‘connecting the Americas 2022’ initiative was endorsed. This includes the goal to achieve universal electricity access by 2022, among others by enhanced electrical interconnections throughout the Americas [120]. Currently, the six central American countries within the Central American Electrical Interconnection System (SIEPAC) are interconnected through a 300 MW backbone grid with plans for further expansion to 600 MW. The electricity markets of Belize and Mexico are expected to integrate with SIEPAC in the near future [121], as well as potentially Colombia after completion of the 400 MW HVDC interconnector towards Panama [74,122]. These ties link North- and South America, albeit with limited flow capacity. Additionally, the interconnectivity expansion between countries in both continents stimulates trade between the Americas even more. For example, the US signed bilateral principles with Mexico in 2017 for further power system integration [123], as of early 2017 there are 11 pending applications for new Canada-US cross-border interconnectors [124] and additional cross-border interconnectors in South America are being commissioned [125–127].

The ‘Gobitec’ proposal was put forward in 2009, fuelled by the concept of the Desertec project, to interconnect the North East Asia power grid (NEAG) by means of China, Japan, Mongolia and North- and South Korea [128]. Other NEAG advocates include Russia as well [129]. Following the Fukushima nuclear accident in 2011, the Renewable Energy Institute was initiated in Japan by the SoftBank Group to support the transition to renewables, among others by interconnecting the power systems of Asian countries [130]. The visualized Asian supergrid builds further on the NEAG concept, in addition to integrating India and the Association of Southeast Asian Nations (ASEAN). The vision of the institute is being backed by

Korea Electric Power Company, SGCC and Russian power company PSJC Rossetti after signing a memorandum of understanding in 2016 [131]. According to the International Energy Agency (IEA), the developments towards an integrated ASEAN power system remain promising, yet challenging, due to a variety of natural and man-made obstacles [132]. Although these Asian super grid initiatives focus on grid integration on a continental level, it could enable and stimulate the flow of electricity between and throughout continents, for example towards Europe [112,113,133], or towards Australia by means of an ambitious prospect of integrating Australia with the Asian mainland through a subsea HVDC interconnector [134–136].

When comparing these projects, a number of trends and developments can be observed, namely; Due to the large capital investments, most projects require political support. Despite this, until recently, projects tend to fail due to costs, political unrest, lack of support or a combination of the above. Early concept projects tended to pursue large capacities of 5GW+ whereas more recent initiatives favour capacities in the range of 2GW reflecting the current standard of HVDC projects. The bulk of projects are land-based, but recently there has been a move to investigate subsea interconnections, exploiting advances made in this area. Overall, the idea of power system integration towards an (inter)continental scale is gaining significant traction.

2.4.2 Supporting Initiatives on the Global Grid Concept

The Global Energy Network institute (GENI) was founded in 1986 to investigate the original global grid concept of Buckminster Fuller [137]. GENI's objective is to conduct research and inform the public and other relevant actors on the viability of interconnecting power systems between nations and continents.

In response to the 'one belt, one road' initiative and China's president Xi Jinping's vision of a global grid, SGCC initiated the Global Energy Interconnection Development and Cooperation Organization (GEIDCO) in March 2016 [138]. Currently, over 200 universities and research institutes, energy enterprises and other entities are engaged in membership of GEIDCO [139]. Its purpose is to conduct research and promote the development of a global grid to meet the growing global demand for electricity in a sustainable fashion and to support the UN's agenda for sustainable development [140,141]. In 2017, GEIDCO signed a memorandum of understanding with multiple international organizations, including the United Nations

Department of Economic and Social Affairs (UNDESA), to strengthen the cooperation for the purpose of sustainable development [142].

The Climate Parliament, an international cross-party network of legislators, initiated the Green Grid Initiative which among others supports the build of (inter)continental 'electricity highways' [143]. Compared to GENI and GEIDCO, this initiative utilizes a more top-down approach to create the political leadership- and will required to support the development towards a global green grid. To date, ministers of 19 countries expressed their intention to participate (e.g. of Brazil, India, Indonesia and Mexico) as well as partnerships with among others the IEA and the International Renewable Energy Agency (IRENA) to provide technical advice. Similarly, under the umbrella of the Clean Energy Ministerial, discussions on the policy- and regulatory framework required for a global grid were undertaken [144].

While these support networks and organisations promote the idea of a global grid, there is still a lack of evidence on the concept to objectively inform policy development and decision-making to justify construction of any project.

2.5 Benefits, Opportunities, Risks and Challenges

Defining possible benefits, opportunities, risks and challenges of- and for intercontinental interconnectors and a global grid is of vital importance to support necessary decision-making for a future low-carbon power system and an overall sustainable future. The chart in Figure 2-2 gives an initial overview of these aspects as mentioned within the literature, which will be discussed in more detail within this Section.

Figure 2-2 Overview of mentioned benefits, opportunities, risks and challenges for the global grid concept within the literature. The outer ring corresponds to further description of the benefits and opportunities (A) and risks and challenges (B) within this section.

2.5.1 Benefits and Opportunities

The discrepancy between on the one hand main consumption areas and existing grid infrastructure, and on the other hand areas with high renewable energy potential [41,43,59,69,73–75,145] is often regarded as a core argument for the benefits of a global grid. Considering the projected required RES capacities around the globe in line with the 1.5-2 degrees climate targets [6,7], utilizing the possibility to interconnect highly efficient-, unused- and sparsely populated regions for RES integration (A01), in parallel with optimizing the use of domestic RES resources, has gained significant interest. Czisch [146] indicates that in essence Europe has significant RES potential, yet the high population density could limit expansion towards higher RES penetration levels. Similar observations have been made for load centers in North East Asia [128] and South East Asia [134–136,147]. Norrga and Hesamzadeh [145] argue that next to the siting of RES, the possibility to install vast capacities of nuclear power plants at unpopulated and safe locations can be an important driver for a global grid and decarbonisation of the power system, however the analysis doesn't consider public acceptability as a significant challenge. Areas with significant RES potential and low population density, potentially able to supply intercontinental markets as identified in the literature, are on the outskirts of Russia for the European and Asian market [108], parts of Central and North East Asia (e.g. Kazakhstan, Mongolia and Western China) for Europe, North- and South East Asia [113,128,129,148–150], the Australian deserts for the South East Asian market [75,81,134,135,147,149–152], MENA for the European market [74,92,93,105 ,146,153–156], Greenland for Europe and North America [29,157,158] and unpopulated regions in South America for the Central and North American markets [159]. While these studies focus on spatial availability, the consideration of geopolitical or public acceptance risks is often limited. For long-distance intercontinental interconnectors it is often argued to use a multi-terminal setup with connections to secondary lines. This allows transit regions to feed in RES or take out electricity as well, making optimal use of local resources [81,113,147,160]. However, such concepts would require detailed economic analysis.

The inherent variability in generation of VRES as well as the variability in locational demand can be smoothed by utilizing time-zone diversity through longitudinal power system integration with intercontinental interconnectors (A02, e.g. [29,113,161–164]). Ardelean and Minnebo [113] highlight the potential of a China-Europe transmission pathway by indicating that periods of high consumption on either side of the pathway often occur simultaneously with off-peak hours on the other side due to a time difference of seven hours. Furthermore, the authors show that solar output in Central Asia coincides with peaks in consumption in Europe or in China depending on the time of day, allowing for constant power exchange at peak electricity prices and an overall larger market for power exchange (A09). A similar strategy is envisioned by Chatzivasileiadis and colleagues [29] for RES export from Greenland to the European and North American continents. Grossmann et al. indicate that by linking the main deserts in North- and South America the longest night (zero generation from solar-PV) can be reduced from 14 to 9 hours [159]. Conceptually, Kuwano [161] proposes to utilize the diurnal cycle of solar-PV generated electricity around the globe by linking significant solar-PV capacities with a global grid. Besides the importance of time-zone diversity, a range of studies [93,146,147,149,159,162,163,165] also indicate the potential benefits of the smoothing effect of area enlargement in VRES generation to an intercontinental scale. This is the case for longitudinal power system integration, but also for latitudinal integration by capturing seasonal and regional differences in load and VRES generation (A03). While utilizing time-zone diversity is a valid concept, it does necessitate longer interconnection distances for full exploitation. This increases the risk and complexity of such projects when compared to more local interconnections. Equally, the reviewed literature doesn't always account for future impacts of smart grid initiatives which also aim to smooth out local demand and supply, and therefore may dampen the benefit of time-zone diversity.

The ability to dispatch available low-cost generation capacity throughout larger regions by integrating continental markets can improve cost-efficiency in electricity generation (A05, e.g. [33,70,104,105,109,116,118]). Besides cost savings during dispatch, integrating continental markets allows for the sharing of costly operating reserves and an overall reduction in required generating capacity (A07, e.g. [29,69,74,81,162,167]). Furthermore, intercontinental interconnectors can support the rapid growth of electricity demand in developing regions by utilizing existing generating capacity elsewhere (A10, [69,74,129,167]). In context of interconnecting the European and North African power systems, a recent IEA report [74] argues that "interconnections are a viable option to ease the burden of North Africa's increasing demand: compared to investment in additional generation and operational costs, grid infrastructure is a low-cost solution. The structural overcapacity in Europe can help meet the North Africa's increasing need for energy." While such a concept has theoretical merit, it would be required to comply with existing European climate and energy regulations such as the European Emissions Trading Scheme (ETS) and European Renewable Energy Policy, complicating the operability of such an idea. Grossmann and colleagues [159,168] indicate that when considering an interconnected Americas power system to be solely supplied by generation from solar-PV, the total capacity required is about equal to the capacity required for supplying the North American continent alone based on purely domestic resources. Interconnections make the utilization of seasonal and diurnal differences in solar-PV generation possible, reducing the overall required capacity, as well as significantly reduce the demand for costly electricity storage (A06) compared to the original 'Solar Grand Plan' for the North American continent [169]. However, these and similar studies do not include detailed reliability and adequacy assessments to demonstrate that this type of grid could be operated with the same level of reliability as today. Until successfully completed, such ideas remain conceptual.

The possibility to invest in regions with potential highly efficient RES resources promotes foreign investment in the RES industry in developing countries, which in turn can lead to further cooperation and commitment between regions (A14, e.g. [105,108,128,129, 146,148,170,171]). Seliger and Kim [128] argue that the Gobitec proposal could be a catalyst for policy cooperation in the political tense region of North East Asia. Grossmann and colleagues [159] highlight the significant role interconnections between the Americas could have on economic development in South America. Not only due to the expected revenue flows, but also in regard to an overall economic growth following the improved energy availability in the region. Other benefits and opportunities of intercontinental interconnectors and- or a global grid as mentioned within the literature are that it can improve diversity and security of supply (A04, e.g. [29,69,83,147,163,165]) and that it brings forth a lower price volatility in the interconnected regions resulting in an overall more stable price for consumers (A08, [29,69,93]). Boute and Willems [108] argue that the export of locally produced RES from biomass in Russia further into Europe might be a more cost-efficient and sustainable alternative to exporting the raw fuel itself (A11). A range of studies highlight the potential contribution intercontinental interconnectors and intercontinental RES import could have on policy targets, such as the earlier mentioned decarbonisation- and interconnection targets within Europe (A13, [65,74,108,113,153,164]). Additional socio-economic benefits are the possibility to improve a country's image from fossil fuel exporter to RES supplier (A15, [108,134,135]), positive effects on green job growth [148,151,172] and an overall expected welfare improvement [129,164,172] (A16). Furthermore, significant environmental benefits are expected as a result of the higher RES integration and the decrease in electricity generation from fossil sources (A17, e.g. [69,73,92,129,165]). Bompard et al., [83] qualitatively benchmarks a global grid scenario to alternative decarbonization pathways and indicates that the concept could be particularly beneficial from an environmental viewpoint.

Lastly, some studies indicate that by directly interconnecting to areas with high RES potential, local grids with voltages of 110 kV and below can by bypassed (A12, [29,70]). Yet, to date, a core limit on RES integration lies within the weakness of local grids. Hence, although bypassing local grids might be an option in certain situations, for an optimally functioning intercontinental interconnector or possible (global) super grid it is essential that local Transmission and Distribution (T&D) networks are able to support and distribute these bulk flows. Both in terms of Net Transfer Capacity (NTC) as well as coordination and exchange of information between T&D networks- and operators [59,70,78,82,173,174].

2.5.2 Challenges and Risks

Although the development of interconnections between countries and continents could enhance cooperation and economic development between regions as indicated earlier, it could also bring forth risks in case of supply dependency from non-domestic sources in often unstable regions (B03, e.g. [65,83,88,175–179]). An often made argument is that import of electricity from centralized distant regions has obvious similarities to the current dependency of large parts of the world on gas and oil imports from a set number of suppliers, including the risk of supply interruptions and its consequences [65,88,175,180,181]. Despite the similarities, there are also inherent differences, such as the fact that oil and gas can potentially be rerouted from different suppliers whereas electricity is dependent on fixed grids [175]. Next to that, gas and oil can be stored, allowing importers to store buffers, but more importantly, it allows suppliers to stop exporting without an immediate monetary loss on the long-term [88,175]. Electricity needs to be consumed directly after generation, creating a different balance of power between supplier and consumer. Furthermore, unless a transmission line is physically disconnected, Kirchhoff's laws determine the flow of electricity [182], limiting the potential to alter supply directions. The vulnerability to supply interruptions in a Desertec scenario is assessed by Lilliestam and Ellenbeck [175]. They show that Europe in principle is not very susceptible to extortion following a potential export embargo from a single country. Only modest economic damage can be created, yet the exporting party might undermine its own market position in terms of direct income and long-term reputation. Only if all North African countries combined would engage in an embargo Europe's vulnerability would increase [175]. Similarly, certain politically unstable countries such as North Korea would significantly benefit from linkage into an Asian supergrid due to their poor power status [178], making it unlikely to engage in activities affecting the exchange of electricity. Czisch and Giebel [180] furthermore indicate that the amount of partners involved in a RES supergrid is much higher compared to the current relative monopolies in fossil fuel supply (e.g. the Organization of the Petroleum Exporting Countries (OPEC)), securing a higher intrinsically stable and diverse system. However, many investors are risk adverse and previous literature shows that political support and backing would be required for such projects. Overall, it can be argued that the N-1 contingency criteria for countries utilizing intercontinental interconnectors is of vital importance to limit the associated risks [128,129,175]. This can either be through interconnectivity with other regions or by securing sufficient domestic supply potential.

Utilizing potential resources in areas with high RES potential might be an attractive means to fuel decarbonisation, yet a stream of research highlights a competing development trend towards prioritization of decentral RES (B05). Certain studies advocate that it is deemed to be the cost-efficient solution [136,183–186] whereas others argue the societal preference for making use of indigenous resources [65,181]. Another societal concern is that by utilizing distant RES for import purposes, a 'sell-out' of local resources might occur which could otherwise be used for the domestic market (B06, [108,184]). Although this is a viable concern, it has also been indicated earlier that areas with some of the highest renewable energy potential are also areas with very low population density. That said, it is vital that expected trends in population growth, such as in Northern- [74,92] and Sub-Saharan Africa [187], are taken into account. Vice versa, by importing distant RES rather than making use of domestic resources, the economic- and employment opportunities that energy projects bring along are partly being lost to the exporting regions [108]. When it comes to providing flexibility for the variability of VRES, it is often argued that energy storage solutions in parallel with decentral VRES is a more economically viable solution (B09, [60,68,176]). However, because of the absence of detailed modelling of a global grid, as we'll discuss in more detail in Section 2.6, such a statement cannot be verified. Despite that, storage could provide auxiliary services required for a functioning global grid [59] and although storage and interconnectors may often compete for similar roles [48], they can also reinforce each other by optimizing the utilization rate of interconnectors [59,147,151,188]. Again, the role of storage in a future global grid is poorly understood and requires research for greater insight.

A challenge for any transmission project, especially for long-distance and often sub-sea interconnectors, are the high investment costs- and risks associated with projects of this magnitude (B01, [17,32,36,58,80,103,153]). In the past, and arguably so for the near future, it's been one of the core limiting factors on intercontinental interconnection projects [91,136]. Table 2-1 gives an overview of expected investment costs and transmission losses for intercontinental HVDC interconnectors as mentioned within the literature. Furthermore, costs of a range of installed- or planned subsea HVDC interconnectors have been included as an indication for the current state of the art.

Table 2-1 Overview of normalized investment costs, conversion- and transmission losses for existing- and conceptual HVDC (intercontinental) transmission projects.

Ref.	Year study	Status	Pathway	Specifics line	Costs Land-based line (€ Billion /1000 km)	Costs Subsea line (€ Billion / 1000 km)	Line losses / 1000 km[1] (%)	Costs Converter pair (€ Billion)	Converter pair losses (%)
[189]	-	Existing	BritNed	1 GW, 450 kV	-	-	-	-	-
[190]	-	Commissioned	EuroAsia	2 GW, 400 kV					
[191]	-	Existing	NordBalt	0.7 GW, 300 kV	-	0.675[3]	-	0.193[4]	-
[192]	-	Commissioned	NordLink	1.4 GW, 525 kV	-	1.488[3]	-	0.396	-
[53,193]	-	Existing	NorNed	0.7 GW, 450 kV	-		5% incl. conversion		5% incl. line losses
[192]	-	Commissioned	NorthSea-Link	1.4 GW, 500 kV	-	1.224[3]	-	0.409	-
[53]	-	Existing	SAPEI	1 GW, 500 kV	-	-	-	-	-
[146]	2008	Conceptual	Europe-MENA	5 GW	0.35	3.5	4	0.3	1.2
[93]	2012	Conceptual	Europe-MENA	3 GW[5]	1.98[6]	2.38[6]	1.6	0.43	1.4
[68]	2014	Conceptual	Europe-MENA	3 GW[5]	1.65[7]	1.65[7]	-	-	-
[92]	2007	Conceptual	Europe-MENA	5 GW	-	-	3.33	-	-
[29]	2013	Conceptual	Europe-Greenland-N. America	3 GW, 800 kV	-	1.15-1.8	3	0.6	1.2

[164]	2018	Conceptual	Europe-Greenland-N. America	4 GW, 640 kV	-	-	2.12	-	2
[114]	2010	Conceptual	Iceland-UK	1.2 GW	-	1.24	4.3	0.28	1
[113]	2017	Conceptual	China-Europe	-	1.8-2[8]	6-8[8]	-	0.7-0.8	-
[194]	2016	Conceptual	North East Asia	3 GW[5]	1.49[6]	2.38[6]	1.6	0.43	1.4
[148]	2014	Conceptual	North East Asia	10 GW, 1000 kV	-	-	1.63	-	2.1
[147]	2012	Conceptual	South East Asia-Australia	5 GW, 800 kV	0.77[4,7]	0.77[4,7]	3	-	2.7
[151]	2017	Conceptual	South East Asia-Australia	3 GW	0.64[4]	2.58[4]	-	0.86	-
[149]	2012	Conceptual	South East Asia-Australia	-	-	-	3	-	-
[159]	2014	Conceptual	Americas	-	-	-	2-3	-	-
[163]	2004	Conceptual	Global	3 GW[5]	0.79[7]	0.79[7]	3	-	-
				Mean	1.196	1.646	2.757	0.465	1.625
				Median	1.14	1.475	3	0.42	1.4

[1] *At full rated power, lower losses at non-full load.*

[2] *Note that total project costs can be lower than combined line and converter costs. Line costs are normalized to billion €/1000 km.*

[3] *Line costs for subsea interconnectors include line costs for land-based connections to converter stations.*

[4] *Applied exchange rate of €1-US$1.16379.*

[5] *3 GW used for conversion.*

[6] *Costs converted back from NTC with indicated 20% reserve margin* [93].

[7] *Averaged value for HVDC, no distinction between land-based and subsea interconnectors.*

[8] *Includes potential costs for high capacity HVDC interconnectors as currently commissioned in China (800-1100 kV, 10-12 GW).*

The table indicates a significant range in normalized investments costs per 1000 km of transmission distance. Expected line costs for land-based HVDC interconnectors range between 0.35-2 billion €/1000 km and line costs for subsea HVDC interconnectors between 0.675-8 billion €/1000 km. A multitude of factors influence the cost expectations, such as cable characteristics (e.g. setup, type, voltage and wattage), the geography of the route (e.g. flat, mountainous or subsea) [53,113,177] and recency of the study. Refer to Ardelean and Minnebo [53] for a detailed assessment of these factors for subsea HVDC interconnectors. The majority of normalized costs as indicated within the literature are above the investment costs of existing projects due to the generally higher voltage and wattage per line and converter. Yet, taking this and technological learning curves into account, assessment of the existing literature indicates that there's a development trend of decreasing project costs for (intercontinental) long-distance HVDC transmission. Another visible trend is the growing interest of intercontinental projects in China and other parts of Asia, reflecting the growing economy in Asia and its resulting need for power.

The median, as included in the table to limit the influence of outliers, in mentioned transmission losses normalized/1000 km is 3%, which seems to be a common assumption in intercontinental interconnector studies. Losses for a converter pair are deemed to be around 1.4-1.6%. The significant transmission losses associated with the utilization of long-distance transmission lines can be seen as a limiting factor to the overall feasibility of potential intercontinental interconnection projects (B02, [65,113,149]).

Clearly, the high capital investments required for intercontinental interconnectors and the associated risks are an obstacle to be overcome. The BritNed and NorNed projects indicate that a merchant investment mechanism, where profit margins are determined based on the price differential between interconnected regions, can be successful for long-distance HVDC transmission projects and that it might be a realistic option for future intercontinental interconnectors [88]. Yet, a merchant investment approach encounters significant limitations, such as the lack of transparency in long-term regulated planning, making it difficult to assess the viability of investments [74]. Furthermore, profits run on short-term spot- or day ahead markets and not so much on long-term contracts, adding uncertainty for investors [29]. Next to that, a significant part of the benefits of power system integration on an intercontinental scale, such as the reduction in RES curtailment [93], the strengthening of regional grid stability [74] and significant cost-reductions in electricity generation are not part of the remuneration for private interconnector investors. This can be considered as a lack of incentives for market players to make high capital investments in developments which provide system-level advantages [93]. Hence, it is often argued that interconnectors can be seen as a public good and that a regulated investment strategy could be anticipated [29,65,74,81]. Robinson [65] suggests that "interconnectors should be built as part of a multi-country planning process and that the costs and benefits of the interconnectors should be socialised – in other words, shared – according to a set of principles agreed in advance". Furthermore, Gellings [81] argues that a global tax on greenhouse gas emissions could be a financial incentive to shift to carbon-free energy and that once first segments of a global grid are in place, such a carbon tax would catalyse private funding for further power system integration and RES capacity expansion. While this argument work in theory, real world implementation of carbon taxes has been politically difficult. Whatever investment mechanism is used for intercontinental interconnectors and a global grid, the costs and benefits of any project need to be clearly defined. This aspect will be further assessed in Section 2.6.

Regulatory issues and challenges in market operations (B04) in a global grid context, such as the difficulty of integrating different types of power markets, are potential obstacles which need to be tackled [29,65,75,83,88,164,179]. Al Asaad [105] indicates the potential for a pan-Arab power pool, yet also highlights the differences in power market structures within the different countries of the GCC, from partly competitive to state-owned. In context of a possible transatlantic interconnector between Europe and North America, Purvins and colleagues [164] state that power exchange between both continents would be challenging due to often incomplete exchange of information in competitive bilateral trading. Furthermore, the to date lack of carbon pricing in power markets in large parts of North America relative to the European ETS would prevent a level playing field in the transatlantic context [195]. Allowing competition between non-harmonized countries and regions as in the examples above would affect the competitiveness of market participants and possibly create unfair situations. Defilla therefore argues for an existing or new supranational institution to be assigned to act as global regulating institution [179]. Similarly, Chatzivasileiadis and colleagues [29,88] anticipate the need for a global regulator to provide a forum for communication among interested parties, coordinate investments and ensure a global competitive market environment, but also expect the need for an independent global TSO with a similar role compared to current regional and national TSO's. The authors envision two potential market models for a global grid, a hierarchical one where the backbone DC grid is separated from the underlying AC grid, or a more horizontal model where every regional market participates as an individual player [29].

Another challenge is that by integrating power systems an improved balance in marginal electricity prices between regions will occur, and although this leads to an overall cost reduction, it also means that in certain regions the cost of electricity generation- and potentially the electricity prices for consumers will go up (B08, [69,149,164]). Besides that, concerns regarding energy sovereignty [136], influence of politics on protecting the domestic energy mix [65], resistance of market participants to new entries [65] and local resistance against interconnector development (NIMBY) [179] are all factors influencing occurrence of opposition against interconnector development or power system integration (B10). Defilla argues that local opposition is the most time-consuming and often limiting factor in interconnector development. Considering the larger range of parties involved in case of an intercontinental interconnector project, good governance and communication within all layers of involved actors is deemed to be essential [179].

The inexperience in long-distance interconnection projects, especially when considering subsea pathways, causes uncertainties in regard to the impact of the local environment, geography and terrain on the feasibility of the project (B07, [53,70,91,113,135,177]). Walter and Bosch indicate that the most optimal transmission pathway is through flat barren lands and that it becomes significantly more expensive when considering occupied terrains such as agricultural areas or woodlands, sloped corridors or subsea sections. The calculated cost optimal-route for a conceptual interconnection between the east of Morocco and Paris does therefore not run upwards through Spain, but through the Mediterranean and the Italian- and Swiss mainland, mostly due to the ability to bypass natural barriers such as mountains and rivers [177]. Ardelean and Minnebo [53] mention the importance of avoiding deep trenches and steep slopes while maintaining the shortest path possible when considering a subsea interconnection. Maximum depths expected to be feasible were set at 2000 metres about a decade ago [196] and although depths of above 1000 metres are only reached in the Mediterranean sea so far [53], the commissioned EuroAsia and EuroAfrica interconnectors will reach depths of near 3000 metres [98,99], expanding the technological boundaries. Refer to [53] for a more detailed review of environmental aspects influencing cable performance and factors affecting the physical implementation of subsea interconnection projects.

On operational aspects, the risk of propagation of disturbances becomes more prominent with enhanced interconnectivity [197–199], especially on the scale of a global grid. Using B2B HVDC interconnectors to prevent propagation between interconnected AC grids can be a solution [199,200], albeit with significant costs due to the high investments required for HVDC interconnectors as indicated earlier in this section. A collaboration between eight institutions and universities in Europe and the US engaged in 2017 in a project called the 'Global RT-Super

Lab' [199,201]. During a demo event, an HVDC transatlantic interconnector was simulated through cloud-based communication, interconnecting the transmission systems of Europe and the US represented by the locations of the collaborating institutions. Different components of the power system, such as an actual wind farm in the US, were integrated during the simulations. Main goal of the demo was to assess the robustness of the interconnection in terms of acting as a 'firewall' against the real-time propagation of disturbances between the interconnected AC grids on both side of the DC link. The results indicated that the dispersed assets can simultaneously solve a grid stability problem by making use of the interconnection [202].

Finally, according to the European Network of Transmission System Operators for Electricity (ENTSO-E), occurrence of inter-area oscillations [203] are a "major concern when enlargements of the [Continental European] system are studied or carried out" [204]. It is clear that this challenge becomes more difficult to tackle when considering power system integration towards a global scale. Within Europe, Coreso has been appointed as a centralised regional security coordinator allowing the exchange of information between TSO's among others to help prevent significant disturbances to occur. A similar role could be assigned to a global institution such as the global regulator as introduced by Chatzivasileiadis and colleagues [29,88], or a separate independent institution.

2.6 Techno-Economic Assessment

In the previous section we indicated the significant investments required for intercontinental interconnectors and a global grid. Yet, to be able to determine if these investments would be worth the capital and the associated risks, it's of vital importance that the net benefits are assessed and quantified while considering the full market impact [69]. Within this section we review and compare studies attempting to assess the techno-economic aspects of intercontinental interconnectors and the global grid.

2.6.1 Global Grid

The first ever attempt to simulate the functionality of a global grid was done by Dekker and colleagues [205] in 1995. However, the complexity of the optimization problem and the available modelling software limited the practical implementation of the envisioned nine region global model at that time. Bompard et al., [83] benchmarks the global grid concept with alternative decarbonization pathways, yet does not include a quantified assessment of system-wide techno-economic effects. Albeit the limitations of this aspect are acknowledged in the study, the claim from the authors that the global grid option seems sustainable from an economic point of view remain unverifiable based on today's knowledge and literature.

Biberacher [163] performed a linear least-cost optimization solely based on optimal utilization of available solar-PV and wind energy potential for a global grid based on 11 nodes. The author indicates that in a scenario with sufficient availability of low-cost storage, global interconnectors are mostly used to compensate for recurring geographical discrepancies in demand and supply. Storage is deemed to be the cost-efficient solution in case of peak oversupply by storing the generated electricity locally. If storage is not available, global interconnectors are utilized to balance the short-term variability in generation as well, yet as Biberacher mentions; "the grid becomes massively oversized". Following the flow dynamics of the simulated global grid, a core flow of globally generated electricity towards load centers in South East Asia and China can be identified, with Australia as main exporter.

In contrast, Aboumahboub and colleagues [162] used a optimization methodology for a global grid model consisting of 51 nodes of similar geographical size, disregarding current borders of power systems and associated generation portfolios. The results indicate that the overall required conventional backup capacity can be reduced by a factor eight when comparing the optimization of an interconnected- versus a non-interconnected scenario of the 51 regions. This shows the potential of utilizing seasonal and diurnal (time-zone differences) variability for smoothing of the global VRES generation. Similar to [163], the study showcases the importance of the duality between storage and global interconnectors. It furthermore indicates the cost-efficient RES import potential for China, India and South East Asia in the global grid context. These findings are in line with the earlier described trend of growing interest in (intercontinental) interconnection projects in Asia due to its growing need for power. In a second study by the same authors [165], the potential of global carbon pricing was assessed in context of CO_2 abatement targets. In a scenario where capacity expansion of interconnectors between the 51 regions is permitted, a shift can be seen in the cost-optimal solution from mostly biomass- and gas-based generation to increased levels of wind power penetration to reach the same abatement targets.

Ummel [73] applies a realistic limit on solar power capacity expansion while optimizing the deployment around the globe by restricting the global supply of solar powered electricity generation at 2000 TWh by 2030 (approximately 7% of 2030 global demand). The author indicates that "there is generally low correlation of optimal generating sites and the location of electricity consumption", which from an intercontinental perspective results in core power flows from MENA to Europe, the Persian Gulf to India and from Australia to Indonesia. The modelling approach utilized in this study is restricted to the least-cost optimization of solar powered generation capacity. The supply of the remaining 93% of 2030 electricity demand is not incorporated in the simulations. In a similar study Bogdanov and Breyer [60] performed a linear optimization for a 2030 100% RES global energy system consisting of 23 regions across the globe. The authors highlight that the optimal solution is highly decentral, only 4% of energy demand is supplied by import of energy. Furthermore, besides a pathway interconnecting the Americas and a pathway interconnecting Southern Europe with MENA, the authors conclude that the results are a clear indication that a global grid does not generate benefits. Yet, the view of the authors that a 100% renewable energy system (heat, power and transport) can be reached by 2030 seems optimistic.

A comparative assessment of these studies show some potential benefits of power system integration towards a global grid, however they contain a number of weaknesses which limits their value, namely; 1) the relatively low nodal representation [162,163,165,183,205], 2) low technological representation [73,163], 3) limited locational data representation (e.g. lack of input data based on actual locational load- or VRES profiles outside Europe) [73,162,163,183], 4) a focus on 100% RES modelling [162,163,183] and 5) the overall limited quantification of costs and benefits [60,73,83,205]. In a recent paper [195], we introduced a project aimed to fill this gap by developing a global interconnected power system model to assess the global grid concept with high technological and temporal resolution for a variety of future decarbonisation pathways. Furthermore, developments in open power system data [23,206,207] and computational power [21] can support improved assessments of the global grid concept.

2.6.2 Intercontinental interconnectors

Compared to studies assessing the global scale, studies focussing on the potential of separate intercontinental interconnectors or transmission pathways are more numerous and often supported by more detailed quantification. Brancucci and colleagues [153] indicate the potential for cost-efficient RES export from North Africa to the European market. Although these findings are relevant within their respective scenario, being an EU power system largely based on coal and gas, the trend in continental Europe has evolved towards a more established RES portfolio. Potentially, a reversed flow could assist in transitioning the current fossil-fuel dominated power systems in North Africa as well as support the growing demand for electricity [74]. Yet, as mentioned earlier, political instability in North Africa in the past has limited the development of potential economically feasible interconnection projects due to uncertainty regarding the return on investments. Despite the uncertainty on transmission interconnection developments between Europe and MENA, studies assessing deep decarbonization of the 2050 Pan-European power system do highlight the cost-efficiency of utilizing the RES potential across the Mediterranean [27,93,146,208,209]. The E-Highway 2050 project, funded by the EC, showcases that in the higher RES scenarios approximately 10-40 GW of transmission capacity should be integrated between North Africa and Italy, supporting the supply from up to 116 GW of installed solar capacity for demand centres in the European power market [208]. Overall, in a 2050 cost-optimal low-carbon combined energy system of Europe and MENA, Hess [210] identifies an empirical probability of technological integration of CSP export from MENA to EU through HVDC interconnectors of up to 66%.

Chatzivasileiadis and colleagues [29] assess the economics of a 3 GW transatlantic interconnector between Europe and North America with intermediate landing points in Greenland and Iceland, while also incorporating a 3 GW offshore wind farm near Greenland with a Capacity Factor (CF) of 40%. The authors assume that electricity from the wind farm can always be sold at peak prices by utilizing time-zone diversity. The remaining capacity of the 3 GW interconnector can be used for power exchange between both continents. By assuming similar revenues compared to the NorNed project, the study indicates that the income for each delivered kilowatt hour (kWh) would exceed 2-4 times the initial investments. In a follow-up study, the authors suggest that the amortization period for a direct link between the PJM interconnection (US) and Portugal is expected to be between 18-35 years [157]. Purvins and colleagues [164] simulate an interconnected European–North American power system in a 2030 power dispatch model (North America represented by a singular node). The results indicate that the majority of power exchange, being 27.4 TWh with a total CF of 78%, through the 4 GW interconnector is directed towards North America. The authors conclude that the overall socio-economic benefits for society, around 177 million €/year, are sufficient to cover the investment costs and hence that the project is welfare improving. Brinkerink et al. [195] confirms the potential for power exchange between Europe and North America in an integrated 2050 power system model. Similarly to [164], the study identifies a general direction of flow towards North America when considering standardized fuel and carbon pricing, mostly due to the higher relative RES penetration in Europe. Yet, the study also indicates the sensitivity of the combined merit order to integration of localized fuel and carbon pricing. This highlights the challenge of integrating different markets, as put forward in Section 2.5.

Grossmann et al. [159] argues that considering expected solar electricity costs by 2030, and calculated costs of HVDC transmission for respectively interconnections between San Diego in the US and the Atacama- and Sechura deserts in South America, solar electricity can be supplied for between 0.057-0.061 $c/kWh. This takes into account that 50% of installed capacity is based in South America and 50% in the US, making optimal use of time-zone- and seasonal diversity in supply and demand. In an optimized 15 region 100% RES based 2030 energy system for Central- and South America, Barbosa and colleagues [18] indicate that the overall cost can be reduced with 8.7% if transmission capacity expansion is part of the optimization. Yet, the overall flow of electricity between both continents is limited at 1 TWh. Continental generation in combination with significant storage capacities is deemed to be the cost-efficient solution.

In a similar study for the North East Asian super grid context [194], the same authoring team showcases the significance of grid integration to make optimal use of available RES resources. Highly efficient wind power displaces decentralized solar-PV capacity. Mano et al. [148] indicate that a 100 GW RES project in the Gobi desert, including transmission pathways to China, Japan, North- and South Korea, can be cost-efficient when a minimal CF of 30% can be reached, which is feasible [211]. Zhenya and colleagues [129] argue in favour of a similar concept by highlighting that the average electricity price in Eastern China in 2016 was around $0.12/kWh, whereas the feed in tariff in Eastern Russia for RES is less than $0.05/kWh. In a cost-optimized 100% RES power system for Europe and China, Wu and Zhang [133] indicate that a transmission pathway between both regions could reduce annual investments by more than 30%.

The potential feasibility of Australia-(South East) Asia interconnectors are underlined by a number of studies [147,149,151,152]. At today's prices and cost estimates, delivering solar electricity from Pilbara in Australia to Java can be delivered at an expected LCOE of $AUS 0.18-0.25/kWh [151]. Compared to the current feed-in tariff for solar electricity in Java at $AUS 0.193/kWh, the authors of the study argue that if present trends in cost reduction continue, the business case for this interconnector can be commercially viable within five to ten years. Blakers et al., [147] argues the importance of electricity storage to capture the midday solar-PV peak supply in Australia; the required capacity for an interconnector towards South East Asia can be reduced with a factor four if peak generation- and flow can be smoothed out throughout the day. Contrary to the above studies, Gulagi et al. [186] concludes that the costs associated to the transmission of generated low-cost solar and wind electricity from Australia is too high compared to the option of regional generation and storage in South East Asia.

Cova and colleagues [91] argued at the beginning of this century that financial feasibility of trans-Mediterranean interconnectors highly depends on factors such as investment costs and sales prices of electricity. Based on the analysis above, it is clear that almost two decades later the same conclusion is still valid for any intercontinental interconnection project. Although the benefits of intercontinental power system integration are obvious, the assessed studies show that actual feasibility strongly depends on among others the assumed required capex investments, assumed cost-reductions for technologies in future scenarios due to the technological learning curve and the contextual scenarios in which projects are assessed. More detailed power system modelling studies with high temporal, technical and spatial resolution, including sensitivity analyses, are a must.

2.7 Discussion

This paper provides a comprehensive review of the current literature related to the concept of a global grid. It reviews the benefits and challenges associated with a global grid- and with intercontinental interconnectors. It furthermore assesses existing initiatives supporting the concept, as well as an assessment of the state of the art of intercontinental interconnection projects.

The potential to utilize the vast quantities of efficient RES resources around the globe to decarbonize the global power system is significant. Among others, the possibility to smoothen demand and supply through area enlargement and time-zone diversity, as well as the discrepancy between consumption centres, existing grid infrastructure, and areas with high RES potential, could be valid reasons for power system integration towards a global grid and for the intercontinental exchange of electricity. Whether or not such a transformation to decarbonize the power system is worth the significant capital investments required is uncertain. A comparative assessment of literature and projects reveals that although the possible costs, benefits, challenges and opportunities of a global grid and intercontinental interconnectors are clearly qualified within the literature, actual quantification of costs and benefits remains in its infancy. Furthermore, to date performed techno-economic modelling studies attempting to assess a global grid are often limited in their regional and technological representation and are mostly focused on 100% RES assessments. The limited quantification- and scope of these studies prohibits benchmarking of the concept to alternative pathways for decarbonisation of the global power system.

Key development trends related to the global grid concept include a decrease in costs for long-distance transmission technologies, in particular land-based and subsea HVDC, partly driven by China and other Asian countries as a result of their growing economies and consequential power demand. Furthermore, a transition towards projects pursuing the development of intercontinental interconnectors with overall lower transmission capacities as a result of failed overly ambitious projects in the past (e.g. Desertec) can be witnessed. Overall, initiatives supporting the global grid concept have been gaining traction in the last years [140,143,144].

Despite these initiatives, as Robinson [65] argues; "The case for the Global Grid rests on a fundamental geopolitical principle: that physical integration of world electricity grids will lower costs and make the world a safer place". As long as the detailed costs and benefits of global grids remain largely unquantified, it is inherently impossible to objectively inform policy development and decision-making, this being an essential factor for any large-scale transition to succeed. For future work [195], we aim to contribute to the filling of this gap in the literature by developing a global interconnected power system model with high technological and temporal resolution to assess the global grid concept for a variety of decarbonisation pathways and an overall sustainable future.

Chapter 3 Developing a Global Interconnected Power System Model

3.1 Abstract

Decarbonizing the power sector is a necessary step towards a low-carbon future. Interconnecting power systems on different continents could be a method to contribute to such a future, by utilizing highly efficient renewable resources around the globe, while simultaneously providing additional benefits of power system integration. In this paper, we describe the process of constructing and simulating a global interconnected power system model with high technological and temporal resolution. Being the first of its kind on the global scale, this paper is designed to showcase the proof of concept as an intermediate step to a high-resolution global model, by integrating an existing European power system model with the North American continent. The work to date has been focused on testing the methodology and building up necessary knowledge to realistically simulate the functionality of a possible future global grid. Some initial results are analysed to support the viability of the model and the concept in general. Furthermore, key factors influencing the development and optimal performance of the global interconnected power system model are identified.[5]

[5] Published as: 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

3.2 Introduction

Following the 2015 Paris Climate Change Agreement, ambitious climate mitigation targets have been set in place to pursue a goal of containing global average temperature increase to well below 2 degrees above pre-industrial levels, with a further aim to limit the increase to 1.5 degrees. Considering an increase in global future energy demand, as well as expected increasing shares of electricity in final energy consumption from below 20% today to between 23%-27% by 2040 [40], the power sector requires a drastic transition to a low-carbon future in response to said mitigation targets.

The theoretical potential of RES to decarbonize power systems is a well-documented aspect [41–43], yet the fluctuating characteristic in the generation of electricity from VRES such as solar-PV systems and wind energy influences the practical implementation and reliability of power systems with increasing VRES penetration [44–47,56,57]. A common approach to handle the variability in generation is by interconnecting nearby power systems to cope with peaks and lows in non-dispatchable generation output. Other advantages of transmission interconnection relate to the provision of system security [65,69], possibility of cross-border trading and the integration of wholesale power markets [70], sharing of operating reserves [69,74] and accessibility to an overall more diverse, flexible and cost-efficient generation portfolio [69,105]. Technological progress in HVDC transmission has been significant in recent years [53,76–80]. Currently, 800 kV land-based HVDC interconnectors with rated capacities of up to 8 GW exist in China, with even higher ratings of 1100 kV and 12 GW to be reached in the near future [113]. Progress in subsea HVDC transmission projects occurs as well, albeit in smaller steps, for example with the commissioning of the EuroAsia interconnector, interconnecting Greece, Cyprus and Israel. Once completed, this 2GW, 1518 km long transmission link, will be the first (partial) subsea HVDC intercontinental interconnector [190]. Ardelean and Minnebo [53] conclude that subsea HVDC power cables can now be considered a mature technology able to pay back the generally high investment costs.

A to date limitedly used application of transmission interconnection is the possibility to integrate the vast and highly efficient RES potential in distant and often unpopulated areas [29,146,147]. On a global scale, it’s clear that there’s an overall discrepancy between areas of high electricity consumption and areas with high RES potential [41,43,69,75,212]. The overall benefits of power system integration through transmission interconnection and the ability to utilize distant high RES resources are two core aspects underlying the concept of a globally interconnected power system.[6]

In this article we describe the process of constructing and simulating a globally interconnected power system model as a proof of concept. An existing European power system model is interconnected to the North American continent as an intermediate step to the global model, to test the methodology and for the purpose of knowledge building. Section 3.3 gives a short review on similar analyses done to date as an indicator of the necessity of this research. In Section 3.4 we elaborate on the applied methodology for building the model. Section 3.5 includes an overview of lessons learned during early stages of the model building and highlights implications from modelling results. In Section 3.6 we discuss future work and the possibilities for engaging with GEIDCO and its members.

3.3 Literature Review

To date, a number of studies have made efforts to simulate a global grid in a power system model. Although these studies show some potential benefits of power system integration towards a global grid, the relatively low nodal representation [162,163,165,205], low technological representation [73,163], limited locational data representation (e.g. lack of input data based on actual locational load- or VRES profiles outside Europe) [73,162,163] and the main focus on 100% RES modelling [162,163] impose a significant research gap surrounding the global grid concept.

In 1995, Dekker and colleagues [205] attempted to simulate a nine region interconnected global grid, yet the complexity of the optimization problem and the available modelling software limited the practical implementation at that time. No further research based on this model has been made public since. Biberacher [163] applied a linear least-cost optimization for the global grid with 11 nodes solely based on optimal utilization of available solar-PV and wind energy potential. They showed that in a scenario with large availability of low-cost storage, global interconnectors are primarily used to compensate for consistent geographical discrepancies in demand and supply. The high availability of storage made it more cost effective to store electricity locally in case of peak oversupply. In a scenario without storage, global interconnectors were used to handle short term variability in generation as well, but

[6] Henceforth mentioned as global grid.

as Biberacher mentions “the grid becomes massively oversized”. He furthermore indicates the compatibility of wind energy with a global grid due to the lower seasonal and diurnal variability compared to solar-PV, and a core flow of globally generated electricity (with Australia as main exporter) towards load centers in South East Asia and China.

Aboumahboub and colleagues [162] applied a similar optimization methodology for a global grid model based on 51 nodes of equal geographical size, disregarding current borders of power systems and its associated generation portfolios. The results showed that when comparing the optimization of an interconnected- versus a non-interconnected scenario of the 51 regions, the overall required conventional backup capacity can be reduced by a factor eight. This highlights the potential of smoothing global generation of VRES by utilizing seasonal and diurnal (time-zone differences) variability. Similar to [163], the authors highlight the importance of the duality between global interconnectors and regional storage, and also indicate the potential for South East Asia, China and India to become main importers in a global grid context. In a follow-up study by the same authoring team [165], the importance of a global CO2 price was reviewed in context of CO2 abatement targets. When allowing the possibility of investment in interconnections between the 51 regions, a shift can be seen in the cost-optimal solution from high capacities of biomass- and gas-based generation capacity to increasing levels of wind energy penetration to reach the same abatement targets.

By restricting the global supply of solar powered electricity generation at 2000 TWh by 2030 (approximately 7% of 2030 global demand), Ummel [73] attempts to apply a realistic limit on capacity expansion while optimizing the deployment of least-cost solar capacity around the globe. The author indicates “that there is generally low correlation of optimal generating sites and the location of electricity consumption”, which from an intercontinental perspective results in significant flows through interconnections from MENA to Europe, the Persian Gulf to India and from Australia to Indonesia. The modelling approach applied in this study is limited to the least-cost optimization of solar powered generation capacity, other parts of the power system, to supply the remaining 93% of 2030 demand, are not incorporated in the simulations.

3.4 Methodology

3.4.1 PLEXOS® Integrated Energy Model

To realistically simulate the operation of a potential future global grid, a UCED methodology will be applied by means of the power system modelling tool PLEXOS Integrated Energy Model [213]. The PLEXOS software is a market leader in large scale power and energy system optimisation and is freely available for academic research. XPRESS-MP is used as the solver. UCED within power systems refer to the optimal utilization of available power generation capacity to match system demand within the simulation period, while behaving in accordance with the technical constraints and limitations within said power system. The model optimises the dispatch of thermal and renewable generation and Pumped-Storage Hydro (PSH). It does so subject to operational constraints at hourly resolution while holding the installed capacity constant. The model seeks to minimise the overall generation cost to meet demand, subject to the mix of installed generation fleets and their technical characteristics such as ramp rates, start costs, minimum up times etc. This includes operational costs consisting of fuel and carbon costs, start-up costs consisting of a fuel offtake at start-up of a unit and a fixed unit start-up cost. In these day-ahead market simulations, a perfect market is assumed across the globe without consideration of market power or competitive bidding practices.

3.4.2 European Electricity Dispatch Model

The starting point of developing the global grid power system model is an existing European electricity dispatch model with hourly temporal resolution (EU-28[7] + Norway and Switzerland) as constructed for previous work on the implications of the potential future European power system [47]. The European model (EU model) has been developed using a soft-linking approach to provide additional insights on the European Commission's EU 2016 Reference Scenario (EU-REF) [214]. The EU model consists of a single node per country. Furthermore, generator categories as constructed in PLEXOS for the EU model also follow EU-REF. A disaggregation approach has been used to convert aggregated overall capacities per power plant and country as given in EU-REF into generator portfolios with standardized characteristics per generator unit. An overview of some of these characteristics can be found in Table 3-1. Localised hourly profiles for load and VRES are incorporated based on historical hourly data at country level. A carbon price of 88€/Tonne CO2 is incorporated following EU-

[7] Including the United Kingdom as representing the EU at time of writing.

REF. For more details on the methodology and data assumptions behind the EU model we refer to [47].

Table 3-1 Sample of standardized generator characteristics as applied for the modelling in this chapter.

Fuel Type	**Capacity (MW)**	**Start Cost (€)**	**Min Stable Factor (%)**
Biomass and Waste Fired	300	10000	30
Derived Gasses	150	12000	40
Geothermal Heat	70	3000	40
Hydro Lakes	150	0	0
Hydro Run of River (ROR)	200	0	0
Hydrogen	300	5000	40
Natural Gas CCGT	450	80000	40
Natural Gas OCGT	100	10000	20
Nuclear Energy	1200	120000	60
Oil Fired	400	75000	40
Coal Fired[1]	300	80000	30

[1] Also includes lignite-based capacity.

3.4.3 Connecting the Continents

As a proof of concept, the existing EU model has been expanded and interconnected to a combined European - North American (NAM, consisting of Canada and the United States) power system model for the 2050 reference scenario. The purpose of this intermediate step towards a globally interconnected power system model is to validate the functionality of the applied methodology and to build up relevant knowledge and experience. Thus, potential limitations can be identified in an early stage and can be regarded as lessons for the larger project resulting in an overall more efficient process. North America was chosen due to the availability of generally open access power system data, especially compared to other regions of the world.

The EU model consists of 30 nodal regions (one per country) in total. The NAM model has been constructed based on a relatively similar sized nodal representation with 20 nodes in the United States (US) following the identified regions within the National Energy Modelling System (NEMS, the three New York NEMS regions are combined into a single node) as used for the annual energy outlook (AEO) by the U.S. Energy Information Administration (EIA) [215,216], and eight nodes in Canada composing of the grid-connected provinces of Alberta, British Columbia, Manitoba, Newfoundland and Labrador, Ontario, Quebec, Saskatchewan and a combined node of the remaining Atlantic regions. Figure 3-1 shows an overview of the nodes in the combined model, together with the relative demand per node for the 2050 reference case.

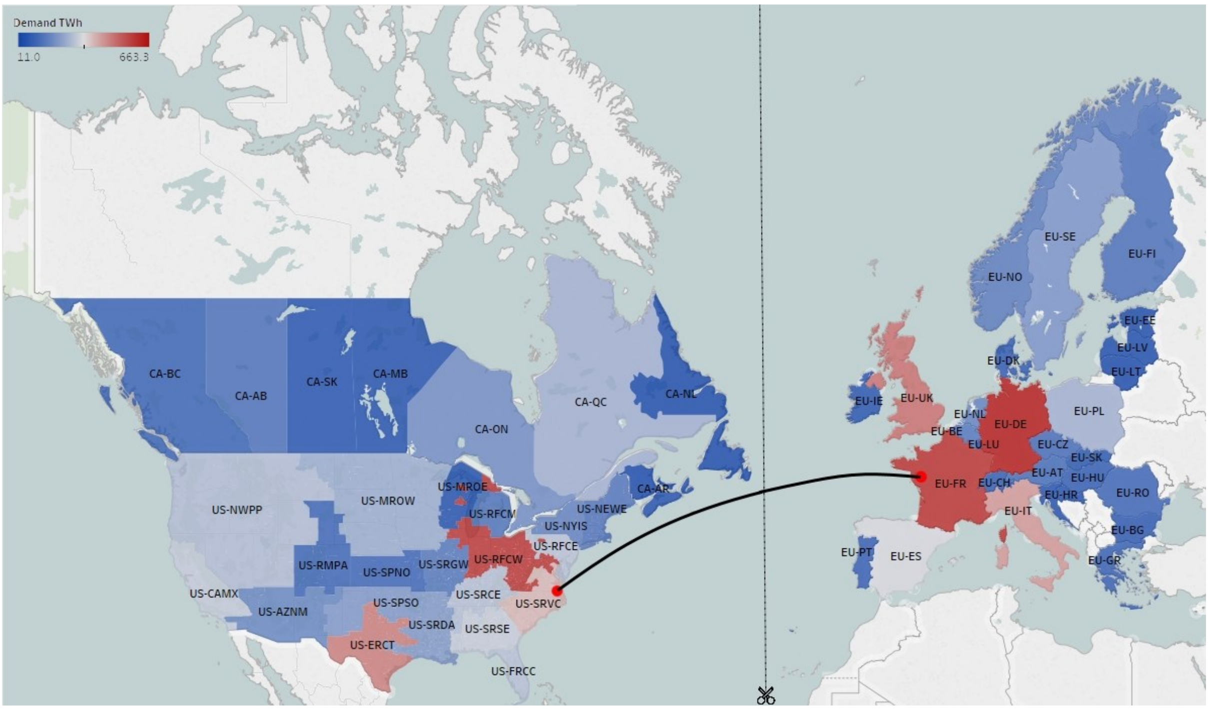


Figure 3-1 Nodal representation of the combined 2050 EU-NAM power system model. Relative demand per node is showcased by a colour scheme ranging from dark blue (EU-LT 11 TWh) to dark red (EU-DE 663 TWh). The map is cropped horizontally for visibility reasoning, the interconnector between EU-FR and US-SRVC stretches approximately 6000 km. Red sections in US-MROE are part of balancing authorities in US-RFCW.

The 2050 generator portfolio for the US, nodal fuel pricing and total demand are based on the reference scenario of the 2017 AEO of the EIA [216,217]. Compared to Europe, fuel prices in the AEO for coal and gas are significantly lower. An overview of fuel and carbon pricing for all regions can be seen in Table 3-2. Load profiles for different US nodes are developed by combining and scaling historical (mostly 2015) load profiles of the relevant balancing authorities (BA) within each node, as retrieved from the Federal Energy Regulatory Commission (FERC) [218]. BA's per node have been identified based on geographical visualizations from the EIA and FERC [219,220], and individual market reports of the BA's. For this study it has been assumed that peak loads per node scale linearly with the overall increase in load between 2015 and 2050. Due to a lack of available transmission capacity data for the US, NTCs between nodes have been determined by assuming that the maximum hourly flow between BAs during 2015 and 2016, as retrieved through EIA's data plugin [221], can be seen as representative.

Table 3-2 Overview of fuel- and carbon pricing for the 2050 reference model as used within this chapter. Applied exchange rate of €1 – US$1.16 and €1 – CA$1.525.

Region/Node	Coal price (€/GJ)	Gas price (€/GJ)	Oil price (€/GJ)	CO_2 price (€/Tonne)
Canada	2.49	3.71	11.77	18
Europe	4.1	11.08	18.5	88
US-CAMX[1]	2.24	5.38	22.93	0
US-ERCT[1]	2.19	5.34	20.90	0
US-RFCW[1]	2.15	5.74	22.30	0
US-SRSE[1]	2.49	5.35	21.99	0
US-SRVC[1]	2.75	5.70	18.47	0

[1] The AEO incorporates region specific fuel prices for the different US regions depending on accessibility to fuels and regional policies. Pricing for other US nodes fall within the range of the above sample.

The reference scenario for the Canadian nodes is based on the projected energy future by the National Energy Board of Canada (NEB) [222]. The projected future runs until 2040, hence for the purpose of this study, the trends for factors such as generator portfolios, overall demand per node and fuel prices have been extrapolated to 2050. Contrary to the US in the AEO, carbon pricing is introduced in the projected energy future scaling to CA$50/Tonne CO_2 by 2022 (€32.8/Tonne CO_2, €1 - CA$1.525) and remaining steady afterwards, equalling an inflation adjusted carbon price of €18/Tonne CO_2 by 2050.

Historical hourly load profiles for the different nodes are retrieved from the relevant system operators through online data portals [44–48] and personal communication (L. St- Laurent, Hydro Quebec, 12-02-2018 – B. Owen, Manitoba Hydro, 01-12-2017 – R. Mall, SaskPower, 21-12-2017), and scaled to expected 2050 values. Gas and oil fuel prices are based on NEB's projected energy future, yet coal prices are not included in the study. Hence to retain uniformity, an averaged coal fuel price based on the AEO is incorporated for the Canadian nodes. Interregional transmission capacities and cross-border transmission capacities towards the US are retrieved from the market reports of the Canadian system operators. For the purpose of testing the methodology in the 2050 reference scenario, a uniform increase of 25% of NTC has been applied for all existing transmission pathways between nodes in North America compared to the reference 2015 values.

Localised hourly wind and solar profiles for the North American nodes are retrieved from the Renewables Ninja database [25,26] (https://www.renewables.ninja). A single locational sample pattern per node for the 2015 meteorological year is taken to capture the diversity in profiles. A more detailed approach will be applied in a later stage to incorporate geographical differences within nodal regions. All hourly profiles, both for VRES as well as load, have been centred around Coordinated Universal Time (UTC). This means that the first hourly timestep is set at UTC 12 AM and all profiles shifted accordingly depending on the longitudinal time-zone differences.

For this proof of concept study, the European and North American systems are interconnected by a 5 GW intercontinental interconnection linking the EU-FR and US-SRVC nodes, as shown in Figure 3-1. These nodes are chosen due to their geographical location, relatively large size (demand and installed capacity) and its significant interconnectivities to other nodes in the continents. These factors influence the possibility for trade. Incremental losses of 15% for transmission and conversion are applied on the interconnection, assuming a near 6000 km transmission distance, as well as wheeling charges of €4/MWh.

3.5 Preliminary Results and Lessons Learned

This section showcases some early stage results of the possible functionality of a transcontinental interconnector between Europe and North America. It furthermore highlights the experiences to date regarding the development of a global interconnected power system model. By no means are these early stage results definitive, they are incorporated to support the proof of concept.

3.5.1 Europe – North America Interconnector Utilization

Due to the longitudinal direction of the interconnector, multiple time-zones are covered when bridging the continents. This affects the match in absolute time of occurrence of factors such as peaks in load and variable generations (especially solar-PV). An example of this is visualized in Figure 3-2, showcasing the load profiles of Germany (EU-DE) and US-RFCW as the nodes with the highest demand in 2050 in both continents (EU-DE 663 TWh, US-RFCW 608 TWh). The six-hour time-zone difference between both nodes causes peaks in demand to occur on different timesteps during the diurnal cycles. The graph shows that in some cases, peaks in one continent partially coincide with off-peak hours on the other continent. This indicates the potential benefit of utilizing intercontinental interconnectors for trade by dispatching low-cost generators on either side of the link, especially considering the total time-zone span of between UTC +2 in Eastern Europe and UTC -8 at the west coast of North America.

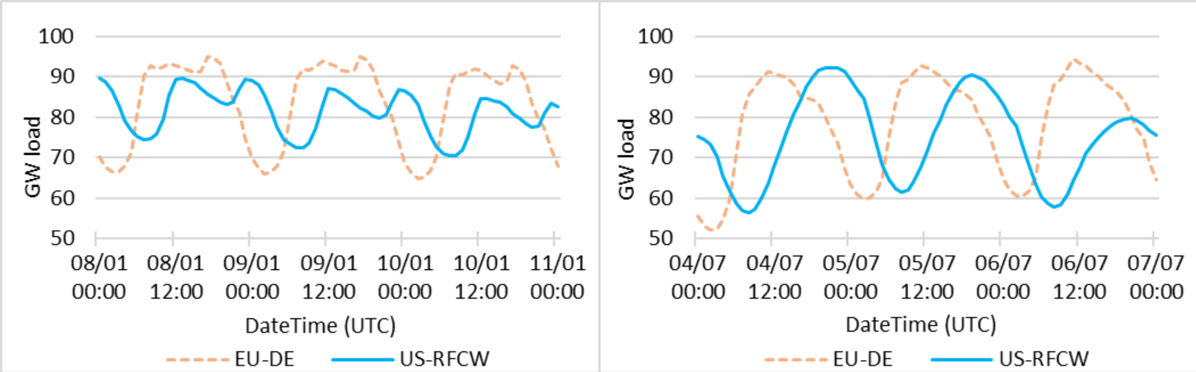


Figure 3-2 Impact of longitudinal time-zone differences on match in load profiles. The graphs shows the hourly demand for EU-DE (UTC +1) and US-RFCW (UTC-5) during three days in January (left) and July (right).

The utilization of the EU-NAM interconnector within the context of this study is visualized in Figure 3-3. The vast majority of flow in the 2050 reference scenario is oriented towards Europe, with a total flow of 39.2 TWh in the European direction and only 2.5 TWh towards North America. Overall, the interconnector has a CF of just above 95.3% with occurrence of Full Load Hours (FLH) during 91.8% of the year[8]. Due to the almost constant transmission congestion, impact of the interconnector on balancing market prices between both nodes (and continents) is limited. The high utilization of the interconnector all year round indicates that the impact of diurnal or seasonal variability on the size of flow is limited.

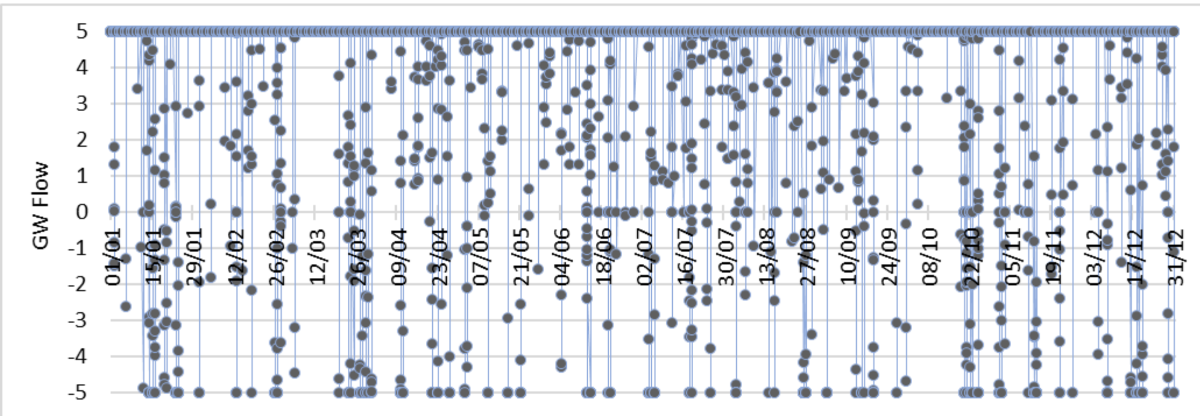


Figure 3-3 Hourly utilization of the 5 GW EU-NAM interconnector in the 2050 reference model. Positive flow is in the European direction, negative flow is in the North American direction.

The main driver for the flow towards Europe can be allocated to the significantly lower Short Run Marginal Cost (SRMC) for thermal based generation capacity in North America, mostly due to lower applied fuel and carbon pricing compared to Europe as indicated in Table 3-2. Combined Cycle Gas Turbines (CCGT) and coal power plants in North America are often

[8] FLH - here defined as the hours per year during which the interconnector operates at full rated capacity - can be used as an indicator for the occurance of transmission congestion.

dispatched before similar plants in Europe to supply the European market. To assess the sensitivity of these elements, multiple alternative scenarios are simulated with incremental carbon prices for North America, gradually increasing towards European levels. The results can be seen in Figure 3-4.

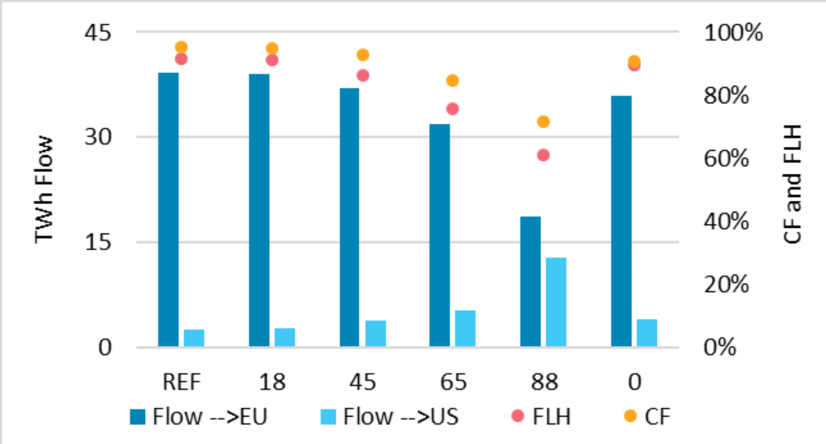


Figure 3-4 Interconnector utilization under different carbon price assumptions. Scenario names are based on applied carbon pricing in North America per scenario; REF (EU €88/Tonne CO_2, CA €18/Tonne CO_2, US €0/Tonne CO_2), 18 (EU 88, NAM 18), 45 (EU 88, NAM 45), 65 (EU 88, NAM 65), 88 (EU 88, NAM 88), 0 (EU 0, NAM 0).

Based on this graph several important observations can be made. Firstly, the incremental carbon price has limited impact on the flow direction when compared to the REF scenario, until it reaches €88/Tonne CO_2 in both continents. Overall utilization of the interconnector decreases with increasing carbon prices in North America, due to lower price differentials in SRMC between power plants on both continents. The significant increase in export towards North America in the €88/Tonne CO_2 scenario results from displacement of coal fired power plants (coal and lignite) and Open Cycle Gas Turbines (OCGT) in North America in favour of CCGTs in Europe following a shift in the merit order of the combined market. When carbon pricing is omitted from the model, as shown in the €0/Tonne CO_2 scenario, the majority of flow remains oriented towards Europe. Considering the setup of power plant portfolios in both continents, as shown in Table B-1 in Appendix B, with Europe incorporating significantly higher penetration of VRES, this is counter-intuitive. It indicates that carbon pricing is not the only impacting factor in this reference scenario, but that also the differences in baseload (US much more coal capacity) and differences in fuel pricing are of paramount importance. The impact of fuel pricing on the interconnector utilization is visualized in Figure 3-5, where the original scenarios as assessed in Figure 3-4 (REF, 0 and 88) are compared to scenarios with similar carbon pricing but with standardized fuel prices for all regions based on the reference EU fuel prices.

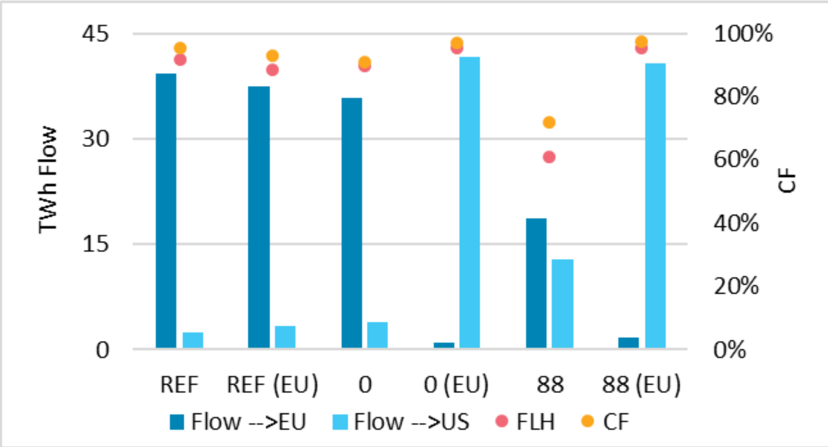


Figure 3-5 Interconnector utilization under different fuel and carbon price assumptions. REF, 0 and 88 scenarios incorporate incremental carbon pricing with reference continental (or nodal in case of US) specific fuel pricing followingTable 3-2. REF (EU), 0 (EU) and 88 (EU) scenarios incorporate incremental carbon pricing with standardized fuel pricing based on the reference European fuel prices.

The flow dynamics on the interconnector within the REF scenario with standardized European fuel prices REF (EU) are relatively similar to the baseline REF scenario. Although the differences in SMRC's on both continents are reduced, the lack of carbon pricing in the US alone remains sufficient to cost-efficiently supply the European market. Yet, when considering scenarios with equal carbon pricing and equal standardized fuel prices as in 0 (EU) and 88 (EU) the market situation changes drastically. The interconnector in both scenarios is almost fully utilized for trade in the direction of North America, with total yearly unidirectional flows of around 41 TWh. Overall interconnector CFs of above 97% are reached. The main reason for the consistent flow towards North America relates to the relatively high penetration of RES in Europe and the strong interconnectivity between European countries which allows for coordinated export of low carbon power. Within the 88 (EU) scenario, the RES capacity in Europe is able to supply 1345 TWh for the total 2050 demand of 4237 TWh (31.7% RES penetration), whereas the RES capacity in NA is limited to a supply of 860 TWh for the total 2050 demand of 5373 TWh (16% RES penetration). The higher RES penetration in Europe allows for dispatch of cost-efficient unused thermal capacity for export purposes towards North America. Depending on the carbon pricing, this can either be CCGT capacity or coal fired, next to available nuclear baseload in EU-FR during periods of high VRES generation. From a North American viewpoint, the RES capacity in North America in this reference model is insufficient to stimulate bidirectional utilization of the interconnector by making use of seasonal- or diurnal time-zone differences. That said, the high overall CF does indicate that there is potential for an EU-NAM interconnector. This is supported by findings in other studies [29,164]. Determining the market revenues and investment costs would be the next step to assess the viability in more detail.

This section shows the sensitivity of market elements on intercontinental interconnector utilization. Yet it is safe to say that the indicated unilateral export of emission intensive power from the US towards Europe in the reference scenario, without appropriate carbon pricing, would never be acceptable in a real market environment. The sensitivity and importance of clear market rules for interconnecting different regions are commonly raised points of interest, especially in context of intercontinental interconnectors and the global grid concept [74,75,81,88].

For further development of the global interconnected model, it is crucial to assess the functionality and economic utility of the global grid in a variety of possible future pathways of the power systems worldwide. This will be captured by constructing a global reference model based on current policies and developments, as well as a variety of realistic mitigation scenarios.

3.5.2 Data Availability

The decision to initially use a combined EU-NAM power system model as an intermediate step towards the global model is due to the availability of detailed power system data for both continents. To expand the model further to the global scale, a combination of approaches to retrieve necessary data must be utilized, since open-access data for other regions in the world is not always available.

Hourly load data can in some cases be accessed through data portals of representative system operators (e.g. Australia [223], Japan [224], Mexico [225] and Russia [226]). Secondly, it might be possible to retrieve profiles from system operators through personal communication, as has been done for this study for some of the Canadian provinces. Yet, it is unlikely that this is accomplishable for all regions in the world since it's a time-intensive process. Furthermore, operators are not always willing to make data publicly accessible. An alternative approach would be to make use of existing profiles of relatively similar regions (e.g. similar sectoral demand distribution or similar climate zone) by shifting and scaling the profiles based on time-zone, total demand and possibly peak demand if available. This is a commonly used approach in global power system studies [162,163], yet it does limit the accuracy of locational representation. Decisions regarding the approach will be made by balancing time-intensity and data accuracy. Hourly profiles for VRES will be developed by utilizing historical locational profiles from the Renewables Ninja database [25,26] (https://www.renewables.ninja). Samples will be taken based on a raster approach with fixed dimensions (e.g. 100 x 100 km) and aggregated to incorporate regional differences within nodal regions. Profiles will be scaled based on prospects for technology efficiency, impacting the hourly CFs.

Generation portfolios for 2050 global grid reference and mitigation scenarios could potentially be developed through two methods. The first approach would be to make use of existing scenario studies as developed for different regions in the world, with the AEO, EU-REF and the NEB energy futures as exemplary studies. Yet, this has two disadvantages. Firstly, it is difficult to accurately combine data from multiple studies into one aggregated scenario since assumptions behind the different studies are rarely in line. For example, portfolios in the studies are often optimized based on different emission reduction targets, or different assumptions are incorporated on global learning curves for generation technologies, impacting the cost-optimal capacity expansion per study in a different fashion. Furthermore, existing studies have not incorporated the possibility of power exchange between continents or accessing remote RES through global interconnectors. Hence, applied capacity expansions in these studies are not optimized in the context of the global grid concept. An alternative approach would be to make use of the capacity expansion function within PLEXOS. Performing optimizations in the global grid context in PLEXOS, by allowing capacity expansion of intercontinental interconnectors and RES capacity in distant areas, could overcome the described issues. For this approach a baseline reference model is required as a starting point for the capacity expansion. The recently published global database of power plants initiated by the World Resources Institute (WRI) and partners would be an important background source for this approach [23]. The database currently covers 62% of global installed capacity at unit level, with expected expansion to over 85% in the near future. The capacity at unit level can be manually aggregated based on the chosen nodal representation for the global model and integrated with the previously constructed 2015 European and North American reference models in PLEXOS.

Final aspect to consider is input data for the existing power grid. Power system operators are often protective of grid data, mostly for security reasons, yet also because grid data could give insights in operator revenues through power system modelling which is regarded as sensitive information [24]. Approaches to recreate transmission capacities between nodes as used for the NAM model (using hourly exchange values or market reports) are of limited applicability for other regions of the world. As an alternative, open-access grid databases such as OpenStreetMap (openstreetmap.org) can be utilized to retrieve voltage data for interconnections between nodes. The voltage data can then be converted into NTC by applying a standardized conversion based on voltage size and transmission type (AC or DC). Although the final NTCs will be simplified, it can act as a baseline for the 2050 power grid. Recently, Liang [206] introduced an initiative focused on the construction of a global database with detailed grid and generation capacity data for over 140 countries in six continents. In time, this could potentially become an important source by linking the database with the global grid model in PLEXOS.

3.5.3 Computational Time

In earlier studies for which global grid models were utilized, the Computational Time (CT) of these models has been identified as a limiting factor because of the mere size and complexity of the unit commitment and dispatch problem [163,205]. Yet, developments in hardware, software and solver since these studies, allow for significant reductions in CT for similar sized problems. Table 3-3 shows an overview of CT for a variety of scenario runs for the interconnected 2050 reference model with different unit commitment optimalities - determining how integers are treated in the unit commitment - and deviating complexity of the power system.

Table 3-3 CT in hours for multiple scenario runs in the interconnected 2050 reference model. Simulations performed with a Dell laptop (I5 processor, 8 GB RAM, 256 GB SSD) and with Xpress-MP. Results showcase CT for the full 2050 year with hourly timesteps (8760 in total).

2050 REF Detailed[1]	**CT (hours) Constrained flow[2]**	**CT (hours) Unconstrained flow**
MIP[3]	27	25.2
RR[4]	5	4.8
LP[5]	4.2	3.4
2050 REF Simplified	**CT (hours) Constrained flow[2]**	**CT (hours) Unconstrained flow**
MIP[3]	14	11.8
RR[4]	1.1	1
LP[5]	0.8	0.6

[1] *Includes PSH and multiple start states for CCGT's in the simulation.*

[2] *Flow between EU-FR and US-SRVC through the EU-NA interconnector is constrained at 5 GW.*
[3] *Mixed Integer Programming*
[4] *Rounded Relaxation.*
[5] *Linear Programming*

Depending on the complexity of the problem and the chosen unit commitment optimality, the CT ranges from below an hour to more than a day. Initial scenario runs while building and testing the global grid model, as also done for this article, will be done with limited complexity and rounded relaxation (RR) to limit the CT. Mixed Integer Programming (MIP) will only be applied in runs when quantification of final results is of importance. A CT of 27 hours for a two-continent model is acceptable for now. Yet, when the model will be expanded to the global context, simulations might potentially be performed on a high-performance computer or cloud limiting the required CT. Overall, limitations as a result of CT in context of the development and utilization of the global grid model are expected to be of modest impact.

3.6 Discussion and Future Work

The purpose of this paper has been to introduce the process of developing and simulating a global interconnected power system model as a proof of concept. The work to date has been focused on testing the methodology and building up necessary knowledge to realistically simulate the functionality of a possible future global grid. Some initial results have been analysed to support the viability of the model and the potential concept in general. Furthermore, key factors influencing the development of the global interconnected power system model are identified, as well as factors influencing the optimal performance of said model in PLEXOS.

Going forward, several steps must be taken to construct a usable global model to assess the functionality and (economic) utility of a global grid. Firstly, decisions must be made regarding the methodology for retrieving input data as well as on the spatial resolution for the different continents. A balance will be sought between time intensity and data accuracy. After that, in parallel with retrieving the input data, an unpopulated model for all continents needs to be constructed based on the template of the European and North American models. Once the empty model is created and the input data is retrieved, the model can be populated. A global reference model based on current policies and developments will be developed, as well as a variety of realistic mitigation scenarios to assess a global grid in a variety of potential future pathways.

GEIDCO consists of a broad range of member experts from academia, industry, and other associations. Within this community, considerable knowledge and data regarding the power system and power grid (e.g. [206]) for areas outside Europe and North America should be available. For the purpose of constructing the global model this experience could potentially be utilized, hence active engagement and collaboration with GEIDCO and its members is being sought.

Chapter 4 Building and Calibrating a Country-Level Detailed Global Electricity Model Based on Public Data

4.1 Abstract

Deep decarbonization of the global electricity sector is required to meet ambitious climate change targets. This underlines the need for improved models to facilitate an understanding of the global challenges ahead, particularly on the concept of large-scale interconnection of power systems. Developments in recent years regarding availability of open data as well as improvements in hardware and software has stimulated the use of more advanced and detailed electricity system models. In this paper we explain the process of developing a first-of-its-kind reference global electricity system model with over 30,000 individual power plants representing 164 countries spread out over 265 nodes. We describe the steps in the model development, assess the limitations and existing data gaps and we furthermore showcase the robustness of the model by benchmarking calibrated hourly simulation results with historical emission and generation data on a country level. The model can be used to evaluate the operation of today's power systems or can be applied for scenario studies assessing a range of global decarbonization pathways. Comprehensive global power system datasets are provided as part of the model input data, with all data being openly available under the FAIR Guiding Principles for scientific data management and stewardship allowing users to modify or recreate the model in other simulation environments. The software used for this study (PLEXOS) is freely available for academic use.[9]

[9] Published as: Brinkerink M, Gallachóir BÓ, Deane P (2021). Building and Calibrating a Country-Level Detailed Global Electricity Model Based on Public Data. Energy Strategy Reviews 33: 100592. doi: 10.1016/j.esr.2020.10 0592

4.2 Introduction

In energy systems literature, modelled global pathways limiting global warming to 1.5°C generally meet energy service demand with lower energy use and significant electrification of energy end use [6,7]. These requirements signal a potential system transition in global electricity generation and the role of increased interconnection becomes an important question. Large scale modelling of continental power systems can facilitate a better understanding of potential pathways towards a zero-carbon supply of our future energy needs, yet to date research in this area is limited by a lack of detailed global electricity models [227].

Due to limitations in either computational complexity or data availability, electricity system modelling studies tend to make a trade-off between the spatial scale of the study area and technical representation of power plant characteristics and transmission components. In modelling studies on a multi-country scale, a single node per country copperplate approach is generally applied [17,47,164,228] and technical properties such as turbine unit sizes, heat rates, and start-up costs [210,228,229] are usually represented in a standardized manner with uniform characteristics for every individual power plant of a certain type. This approach is acceptable for long-term scenario studies where development of power plants and its technological characteristics are uncertain, yet for realistic assessments of today's electricity system a finer representation of the diversity in power plant- and electricity system characteristics is preferable.

There are a limited number of modelling studies assessing electricity systems from a global perspective. This can partly be explained because of the aforementioned issues, yet an additional factor is that generally the use of a global electricity model is seen as unnecessary and even impractical. Different to most other energy carriers, electricity to-date is produced and consumed domestically or exchanged between several countries within a region or continent. That said, the interest in the concept of long-distance electricity transmission and the potential evolution towards an interconnected global grid has gained significant traction in the last few years [29,83,227], resulting in a range of modelling studies on this topic [30,73,134,162–164,195]. Other research utilizing global electricity models focuses on feasibility assessments of possible 100% renewable energy systems, without the utilization of low-carbon technologies such as nuclear energy, Carbon Capture and Storage (CCS) [42,230] or even bioenergy [42].

In order to provide improved insights in the diversity of the worlds electricity system we developed ‘PLEXOS-World’, a detailed global electricity model capable of simulating over 30,000 existing power plants using public data. Although the issues of computational intensity and data access are still relevant, developments in recent years regarding faster computers, improved solvers and solving techniques [22], as well as relevant open electricity system data initiatives [23–25] have made this project possible. An assessment by Pfenninger and colleagues of the use of open data and software within energy policy research indicates that it generally lags behind other fields of research [32]. Extended efforts are being made for this study regarding this gap by means of showing the potential of open power system data as well as openness of model. The PLEXOS-World model is openly accessible for any PLEXOS user, with the software being freely available for academic use. The model in raw data format and all model input data is openly available and can be retrieved from the supplementary datasets [231], allowing users to modify or recreate the model in other simulation environments.

In this paper we describe the process of building a detailed global electricity model at plant- and country level. Section 4.3 includes the methodology, full overview of the data inputs and any made assumptions. A benchmarking exercise of calibrated simulation results with historical emission and generation data to secure accurate model performance is included in Section 4.4. The paper concludes in Section 4.5 with a discussion of the findings, the existing limitations and data gaps and an outlook on possible future work based on the developed model.

4.3 Data Input and Methodology

This section introduces the software used to simulate the global electricity model, describes the main methods and assumptions and gives a full overview of the input data.

4.3.1 Unit Commitment & Economic Dispatch Model

The software used in this study to solve the UCED problem in the global electricity model is PLEXOS® Integrated Energy Model. PLEXOS is a transparent electricity system modelling tool used for electricity market modelling and planning. Detailed linear equations can be queried, modified and viewed by the user to facilitate a deeper understanding of model dynamics. The equations as applied for this study can be found in Appendix A. All data input is fully customizable and the tool facilitates use of a range of open source (GLPK, SCIP) and commercial (CPLEX, Gurobi, MOSEK, Xpress-MP) solvers depending on preference and accessibility to licenses. PLEXOS comes with a fully build-in user interface enabling data management, model building and simulation all to be done within, yet also supports automation of data flows and model simulation from outside the user interface by means of COM or .NET. The software package comes with detailed documentation of all features. Modelling can be carried out using MIP that aims to minimize an objective function subject to the expected cost of thermal and renewable electricity dispatch and a range of technical constraints. It is also possible to select LP for the model simulation to limit the computational complexity, albeit with lower detail in technical parameters. In the default setup of the software each time step is modelled in sequence and is linked to the previous for initial conditions. PLEXOS also provides the option to perform model simulations in a parallel fashion, meaning that otherwise chronological time steps can be simulated at once while spread out over multiple cores after which results are 'stitched' back together. This approach has the advantage of optimized utilization of computational resources with the trade-off being reduced accuracy considering cross-period parameters (e.g. number of online generator units) are not being tracked between steps. A comparison in the CT performance between both approaches in context of PLEXOS-World can be found in Table 4-1. For the simulations in this study we applied MIP with linked time steps for optimal accuracy.

Table 4-1 Runtime performance of the PLEXOS-World model. The model simulations have been performed on a Dell Intel(R) Core (TM) i7-8700K CPU @ 3.70GHz with 63.83 GB Memory with Xpress-MP 35.01.01 as solver.

Unit Commitment Optimality	Step Link Mode	Interval	Time step	CT
MIP	Linked	Hourly	Daily + 6 Hour Look-ahead	30 hrs
MIP	Parallel	Hourly	Daily + 6 Hour Look-ahead, 12 steps in Parallel	7 hrs

The objective function of the model includes operational costs, consisting of fuel costs, start-up costs consisting of a fuel offtake at start-up of a unit and a fixed unit start-up cost. Penalty costs for unserved energy and a penalty cost for not meeting reserve requirements can also be included in the objective function. Fuel consumption is calculated using piecewise linear functions based on the generator heat rate. System level constraints consist of an energy balance equation ensuring supply meets the regional demand at each simulation period. Water balance equations ensure water flow within PSH units is conserved and tracked.

Constraints on unit operation include minimum- and maximum generation, maximum- and minimum up and down time and ramp- up and down rates. A zonal pricing methodology is applied with an assumed perfect market across the globe without consideration of market power or competitive bidding practices. A large number of open energy models are available covering different energy sectors and varying geographical regions[10]. PLEXOS-World's configuration is similar in set-up to other UCED models (for example Dispa-SET) but has a simplified representation of cross border transmissions by making use of NTCs.

4.3.2 Spatial and Temporal Representation

PLEXOS-World covers the electricity systems of 164 countries, subdivided into a total of 265 nodes. Larger countries, both in terms of size as well as relative electricity demand, are spread out over multiple nodes allowing for the integration of regional diversity as well as time-zone differences. This is the case for Australia (7 nodes), Brazil (10 nodes), Canada (9 nodes), China (34 nodes), India (5 nodes), Japan (6 nodes), Russia (7 nodes) and the United States (24 nodes). Subdivision of nodes is generally based on geographical borders, operating areas of different authorities or following the availability of data. See Figure 4-1 for an overview of the nodal representation in PLEXOS-World and Section C.3 of Appendix C for a full list of nodes. Section C.1 of Appendix C can be consulted for more details on the approach of sub-country division of nodes and data.

The model is setup to run for the 2015 calendar year, with customizable timesteps adjustable for the aim of the study and the size of the simulated model. Typically, two-hourly, hourly or five-minute intervals are used. 2015 has been chosen as simulation year due to restrictions on data availability for more recent years. Continents and nodes can be manually selected or deselected based on the user's preferences, keeping in mind that changing the spatial or temporal resolution can significantly affect the CT of the simulation. Hourly simulations are generally sufficient to get a basic understanding of the optimal UCED, yet to incorporate ramping constraints of generator units or to assess aspects such as system inertia sub-hourly modelling is advisable [232]. The input data for demand- and VRES time-series are based on hourly patterns, yet the software linearly interpolates data values in case sub-hourly

[10] https://en.wikipedia.org/wiki/Open_energy_system_models

modelling is required. Hourly intervals are used for the simulations in this study based on daily time steps with a 6-hour look-ahead.

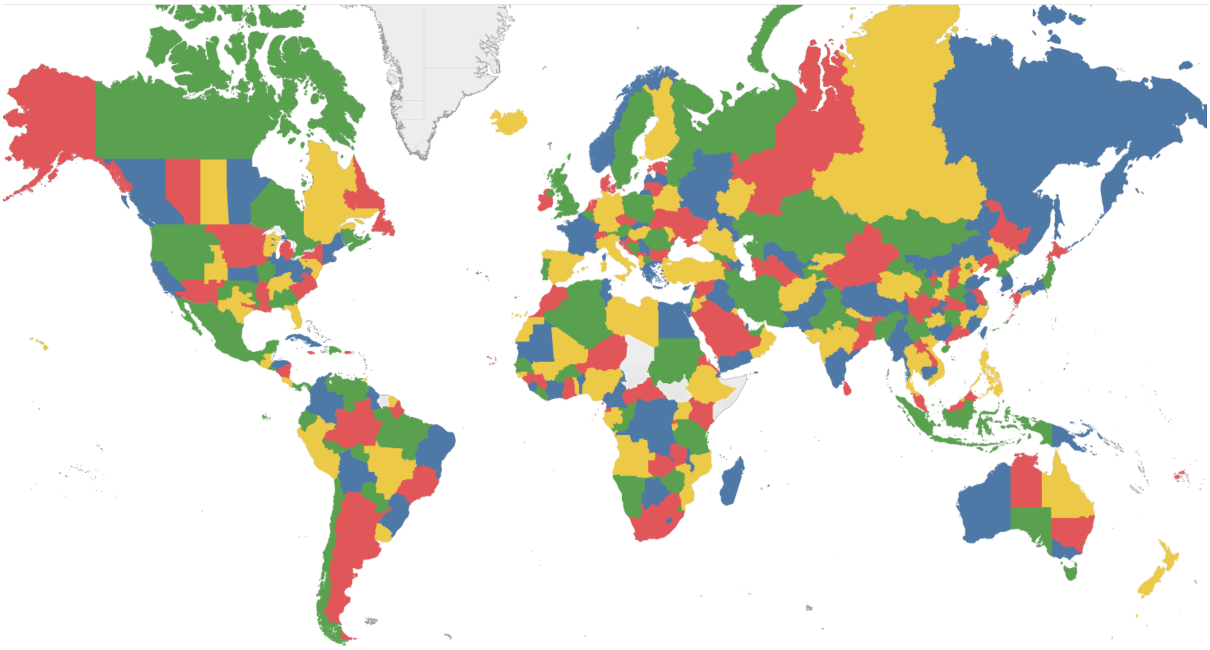


Figure 4-1 Nodal representation of PLEXOS-World. Every copperplated area of an individual colour represents a node with a total of 164 countries and 265 nodes. Australia (7 nodes), Brazil (10 nodes), Canada (9 nodes), China (34 nodes), India (5 nodes), Japan (6 nodes), Russia (7 nodes) and the United States (24 nodes) are subdivided into multiple nodes. Note that besides a range of smaller islands, certain land-based countries are also not incorporated in the model due to absence of data in the WRI Power Plant Database.

4.3.3 Technical Representation and Input Data

The model draws solely on public sources of information for input data. The sources and accompanying assumptions for this study are introduced in the next sections. Figure 4-2 gives an overview of the different steps within the modelling process as well as for the different sources and their interrelationships with the data inputs. The steps and data as used for the calibration exercise are also shown. Note that the data in the model is from best available public sources, but users of the model have freedom to change and edit any data if more advanced local or site-specific data is at hand.

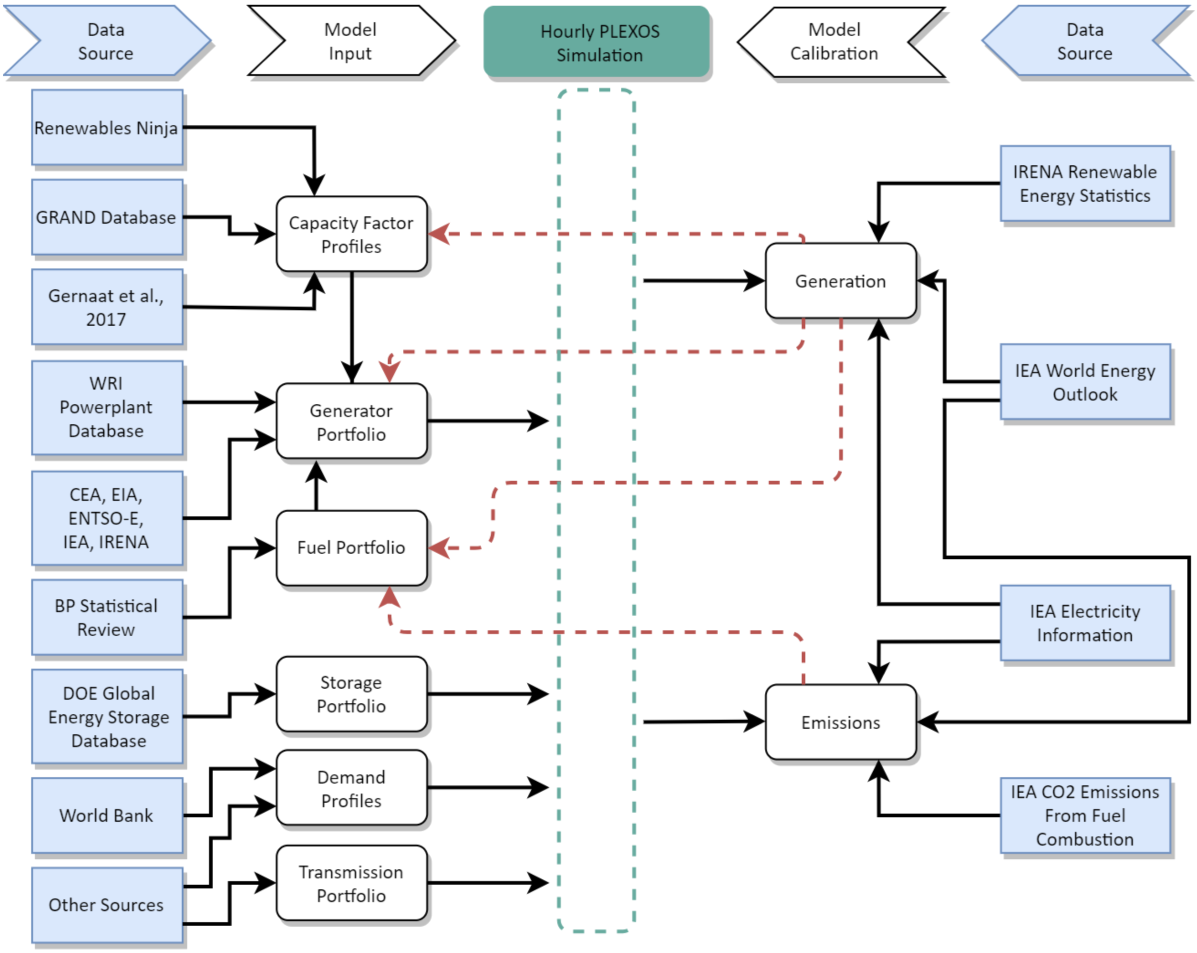


Figure 4-2 Flow chart visualizing the different methodological steps within Chapter 4. The left side indicates the main sources used for the data input of the model and their interrelationships. Hourly model simulations in PLEXOS occur based on the model input, from which among others generation and emission values per power plant are the main simulation output. These values are benchmarked on a country-level with historical data for 2015 retrieved from IEA and IRENA datasets as indicated on the right side of the chart. Through an iterative process, a range of fuel and generator properties are calibrated (indicated with the red connections) to mimic the 2015 context. These aspects are further explained in the next sections.

4.3.3.1 Power Plant Portfolios

The World Resources Institute (WRI), in collaboration with the Global Energy Observatory, Google, KTH Royal Institute of Technology in Stockholm and Enipedia, has made extended efforts to create the first open access Global Power Plant Database covering more than 85% of global capacity [23]. The WRI database differentiates power plants per fuel type and has integrated geolocations. It has been used as the primary source for power plant capacity data for PLEXOS-World. Approximately 55% of power plants in the WRI database have a commissioning year attached. For the remaining 45% it is unclear whether these power plants were already operational as of 2015. Power plants for which it is known that they became operational after 2015 are incorporated in the model yet are 'turned off' (units are set to zero) for simulations of the 2015 calendar year. The geolocations were used to allocate power plants to the relevant nodes. Figure 4-3 shows a visualization of the power plant data with the height of the bar indicating the relative capacity size. This visualization does not only reflect the differences in density of power plants between regions, but also highlights the data gap of the missing 15% of global power plant capacity. The coverage in developing regions, as well as countries such as China, India and Russia is not fully exhaustive. Furthermore, wind and solar coverage is limited due to the more decentralized nature of these technologies. The remaining power plant capacity not accounted for in the WRI database has been estimated using standardized generators per country and per technology based on a number of quality sources such as the EIA [233], ENTSO-E [234], IEA [40,235], IRENA [107] and India's Central Electricity Authority [236]. For smaller countries where no diversified fossil capacity data exists within the above sources, it is assumed that the relative share of coal, gas and oil capacity per country within the WRI database can be used to scale up to the reported aggregate fossil capacity as indicated by the EIA [233]. Due to a gap in sub-country capacity data for especially China, Japan and Russia, it is assumed that missing capacity in these larger countries can be spread out relative to the share of existing capacity per technology per sub-country node in the WRI database.

Figure 4-3 Visualization of the power plant data of the WRI database. Relative height of the bar is an indicator for the capacity of the specific power plant.

Power plant capacity data in the WRI database is supplied in an aggregate format without differentiating individual turbine unit sets per power plant. To be able to incorporate generator characteristics such as minimum stable levels, ramp rates and to assess system inertia contributions it is important to disaggregate the power plant capacity data into individual units. This is done by utilizing a standard unit size methodology per fuel type as applied in earlier studies [47,195,237], both for the WRI database data as well as for the missing capacities, with the standard turbine unit sizes per generator type indicated in Table 4-2. Other renewable power plants such as solar and wind power plants, as well as all other storage technologies other than PSH, use the capacities as given by the different databases. Note that CSP to-date is not included as a separate power plant type because the WRI database does not differentiate between different solar technologies.

It has been assumed that gas power plants in the WRI database with a capacity <130 MW represent OCGT and vice versa >130 MW CCGT. The number of units per power plant *U* (rounded upwards) can be calculated with Eq. 4-1, with *MWt* being the total nameplate capacity of the power plant and *MWst* the standard unit size of the relevant technology. Consequently, the MW capacity per unit *C* equals Eq. 4-2.

$$\text{Eq. 4-1} \qquad \mathrm{U} = \lceil \mathrm{MWt}/\mathrm{MWst} \rceil$$

$$\text{Eq. 4-2} \qquad \mathrm{C} = \mathrm{MWt}/\mathrm{U}$$

Generic relationships have been derived based on historical power plant data to calculate generator specific heat rates and start costs depending on the capacity per turbine unit. By using the constants *SCa* and *SCb* as included in Table 4-2, the specific start cost *SC* per unit *C* can be calculated with Eq. 4-3. These characteristics are modifiable by users and available as part of the model input data.

$$\text{Eq. 4-3} \qquad \mathrm{SC} = (\mathrm{C} * \mathrm{SCa}) + \mathrm{SCb}$$

Similarly, the generator specific heat rate can be calculated with Eq. 4-4, by using the constants *HRd, HRe, and HRf*.

$$\text{Eq. 4-4} \qquad \mathrm{HR} = \left((\mathrm{C}^2) * \mathrm{HRd}\right) + (\mathrm{C} * \mathrm{HRe}) + \mathrm{HRf}$$

In unconstrained model runs, baseload power plants such as coal (2015 context with higher gas prices), nuclear, biomass and geothermal are over utilized compared to historical data. In real life, generators can be limited in their operation due to a variety of factors such as outages, maintenance, limitations in fuel supply or through policy-based constraints. Data regarding restrictions in operation at power plant level are not available within the public domain, hence for these baseload technologies we've incorporated operational constraints specified per country and technology which forces generator units to be 'turned off' for part of the simulation horizon. IEA's 'Electricity Information' [235] provides insights in generation values for 2015 per country and fuel type. The difference between these values and the combined power output of all power plants per country and fuel type in the unconstrained model run can be used as indicator for the initial size of the required operational constraints. Through an iterative process with model simulations, these initial values have been calibrated up or down until further change negatively impacted the match with reported historical generation.

Table 4-2 Standard generator characteristics and variables as applied for the modelling in Chapter 4. SCa, SCb, HRd, HRe, HRf represent constants in derived relationships based on historical power plant data to calculate generator specific Heat Rates (HR) and Start Costs (SC) with the capacity per generator unit as variable.

Generator Type	MWst (MW)	SCa	SCb	HRd	HRe	HRf	Minimum Stable Level (%)
Biomass	200	246.51	1412.6	6.00E-05	-0.0392	14.432	30
Coal	300	6.2646	1166.7	-2.00E-07	-0.0016	10.892	30
CCGT	400	251.5	-9875	2.00E-06	0.0025	8.307	40
OCGT	130	91.525	-186.44	8.00E-05	-0.0235	11.516	20
Hydro (non-PSH)	400	-	-	-	-	-	-
Nuclear	600	134.55	87 091	5.00E-08	-0.0004	4.0717	60
Oil	300	91.525	-186.44	8.00E-05	-0.0235	11.516	50
PSH	200	-	-	-	-	-	-

4.3.3.2 Renewable Profiles

The supply of electricity from hydro, solar and wind is determined using location specific CFs. The Renewables Ninja database [25] has been used to extract hourly CF profiles for every on- and offshore wind (5187 in total) and solar (5929 in total) power plant location in the WRI database by making use of the geolocations. The profiles are developed by making use of NASA's MERRA-2 global reanalysis data [238]. The current set of profiles are based on the 2015 meteorological year, future updates of the model will include a wider range of data years considering that weather patterns can have significant impact on the operation of electricity systems, especially with increasing VRES integration [239]. Standardized solar- and wind power plants integrated to scale up missing capacities within the different nodes make use of an averaged profile based on all CF profiles from within that node. For nodes where no wind or solar power plants exist within the WRI database, a sample of between 4-8 patterns per node spread out over its respective geographical area have been manually extracted from the Renewables Ninja database.

Initial model simulations indicated that the overall generation of solar and wind per node as a result of the integrated CF profiles was in some cases significantly overestimated compared to historical generation data for 2015 as reported by IRENA [240]. As shown by the authors of the Renewables Ninja database [26], use of the database in particular for regions outside the EU requires bias correction. For this reason, we've applied country-level multipliers to the hourly profiles to calibrate overall generation from solar and wind in the model with historic 2015 data.

Due to the size of the model, hydro other than PSH is modelled in a simplified manner without actively simulating the use of (cascaded) reservoirs. Location specific monthly CFs for every hydro power plant (7155 in total) are developed by making use of the Global Reservoir and Dam Database (GRAND) [241] and a study by Gernaat and colleagues [242]. In this latter study, the authors identified over 60,000 potential new locations for hydro power plants and developed monthly water discharge profiles for every new location, as well as for every existing location as identified in the GRAND database based on 30-years of runoff data. The geolocations of the hydro power plants from the WRI database are matched with the nearest dam from the GRAND database, with every plant above 1 GW matched manually to secure accuracy. The coverage of the GRAND database for dams above 58 latitude is limited, hence for hydro power plants in the Scandinavian countries of Iceland, Finland, Norway and Sweden we use country average profiles as used for earlier studies assessing the European electricity system [47,195,239]. For the northern parts of Canada and Russia we use a country average fully based on GRAND data. The profiles for the standardized hydro power plants used to fill gaps in power plant capacities within the WRI database are based on an average of all profiles of the specific node. Countries without hydro power plants in the WRI database, yet with mentioned capacity following EIA data, are assigned an average profile from a neighbouring country.

Following [242], the design discharge of hydro turbines is assumed to be based on the 4th highest discharge month in the discharge profiles meaning that during at least three months of the year spillage of water occurs. Base profiles for the month specific maximum CF *CFt* per GRAND location can be calculated with Eq. 4-5, with *Qd* being the design discharge and *Qt* being the discharge of month *t*. Following on to that, to secure accuracy on the macro level, the individual profiles from Eq. 4-5 are scaled by comparing the calculated capacity weighted average CF per country with a country-level 15-year average CF based on historical capacity and generation data from IRENA [240].

Eq. 4-5 $$\mathrm{CF_t} = Qt/Qd*100$$

Hydro power plants within the WRI database do not differentiate between types of hydro, being Run-of-River or reservoir-based systems. Early stage model simulations indicated that the generation potential for a large share of hydro power plants in months with high CFs was not fully utilized, whereas the occurrence of significant unserved energy in hydro dominated regions (e.g. Canada) in months with lower CFs indicated the importance of seasonal storage of water for these regions. To mimic the possibility of having a certain flexibility in cross-monthly storage of water for more dispersed generation of electricity, the original profiles were rescaled with (eq6) to fit within a narrower range of monthly values by calibrating the original min ($\min_{old}$) and max ($\max_{old}$) of the distribution of CF_t's of the specific hydro power plant. The adjusted min ($\min_{new}$) and max ($\max_{new}$) values were determined based on an iterative process of model simulations with a hard-upper limit set at 80% of the highest *Qt* of every individual profile. At all times, the capacity weighted average of the profiles within a country equal the 15-year average country CF as identified with the IRENA data. As a last step specifically for this study, scalers have been applied in the calibration exercise to slightly in- or decrease the profiles for 2015 conditions again following reported country-level generation data from IRENA. All CF profiles as used for this study can be found in [231]. Hydro plants are constrained at a monthly level with the above profiles but are free to provide flexibility and balancing at hourly level.

Eq. 4-6 $$\mathrm{CF_t}(new) = (\mathrm{CF_t} - \min_{\text{old}})/(\max_{\text{old}} - \min_{\text{old}}) * (\max_{\text{new}} - \min_{\text{new}}) + \min_{\text{new}}$$

Yearly CFs for Ocean, Tidal and Wave based power plants have been integrated based on [235]. No seasonality or variability has been included for these technologies to-date.

4.3.3.3 Storage

Large scale electricity storage to-date is mostly based on PSH, albeit integration of other storage technologies for balancing of VRES or other ancillary services is becoming more prominent. The US Department of Energy (DOE) Global Energy Storage Database[11] is a regularly updated database of operational and commissioned electricity storage projects. The DOE database provides rated power per project yet does not consistently include storage size (MWh) or charge and discharge efficiencies. Technology specific full cycle efficiencies are incorporated based on mean values from reported data in [243]. Similarly, indicative hours of storage values from the same study are used to calculate project specific storage sizes for all technologies apart from PSH. For approximately 130 of the PSH projects, mostly in Europe and the US, actual data on storage size has been retrieved through [244,245] as well as through individual Wikipedia pages as best indication. Based on this project data, a calculated average ratio (MWh/MW) between storage size and power rating for PSH of 18.9 has been determined after exclusion of outliers with a ratio above 200. This average ratio has been applied to all PSH projects where storage size data was missing. Altogether, the model incorporates over 1100 operational electricity storage projects, of which 323 PSH.

4.3.3.4 Hourly Demand Data

Availability of hourly public demand data for countries outside Europe and North America is limited. A common approach in electricity system modelling studies for regions outside these areas is therefore to use standardized profiles from other countries (mostly European) and adapt the profiles based on locational characteristics [73,163,194]. Extended efforts have been made to integrate a more detailed spatial representation within the demand data for this study. To-date, the model includes load profiles based on actual historical hourly data for approximately 50 countries and regional specific historical load profiles for 55 sub-regions. This includes data from geographically dispersed load centres around the globe such as Canada, the US, Mexico, Brazil, Russia, South-Africa, Japan, South Korea and Australia. The data portal of the ENTSO-E includes historical hourly load data for all EU member states, as well as for most non-EU countries connected to the European synchronous grid [246,247]. Data for Ukraine has been retrieved through direct communication with the national system operator (SE NPC Ukrenergo, 29-10-2018). A range of system operators or governing entities

[11] https://www.sandia.gov/ess-ssl/global-energy-storage-database/

provide historical hourly load data on an individual (sub-)country level. A full overview of the existing publicly accessible hourly load data can be found in Section C.4 of Appendix C with all global demand profiles as used for this study to be retrieved as a separate file from [231]. Details on availability and development of hourly load profiles for all sub-country nodes can be found in Section C.1 of Appendix C.

Within the available historic data, differences exist that need to be overcome to retain uniformity in the input data for the 2015 model. Not all profiles cover the full electricity system of a country. As a best estimate for hourly demand in the respective country, we scaled the available profiles to 100% of 2015 electricity demand. Furthermore, not all available profiles are based on the 2015 calendar year, hence these profiles have been scaled and shifted to 2015 values. Shifting profiles is required to retain balance in weekdays and weekends while scaling profiles from year to year. Scaling of the hourly profiles occurs linearly with the difference in final demand between the reference year of the data and 2015 as proxy. It has been assumed that there are no changes in relative peak demand. Final electricity demand per country has been determined by multiplying consumption per capita data from the World Bank with the total population, combined with integrating country-level T&D losses [248]. All in all, 28 countries did not have a value for electricity consumption per capita. These countries were assigned a value from the nearest neighbouring country with similar Gross Domestic Product (GDP) per capita. This was done manually to verify the consistency of data.

Countries without available historic hourly demand profiles have been assigned country specific synthetic profiles as developed by Toktarova and colleagues [249]. The authors constructed a calibrated method to generate demand profiles for future years based on locational economic, technical and climatic characteristics. Profiles as developed for 2020 are scaled and shifted to the 2015 calendar year. For a number of smaller countries for which no historical or synthetic profile were available we assigned profiles from the nearest node with similar GDP per capita.

4.3.3.5 Net Transfer Capacities

Significant developments in the availability of open data regarding existing power transmission infrastructure around the globe has occurred in recent years [250,251]. Yet, no complete global dataset exists incorporating cross-border NTCs. Hence, for the 2015 global electricity system model NTCs were retrieved through a variety of sources to fill this data gap.

NTCs have been applied rather than modelling transmission infrastructure line by line due to restrictions on the availability of data as well as to set a limit on computational complexity of the model simulations. The values represent the technical potential for power flow and do not take into account possible geopolitical or market restrictions on utilization.

As part of a study on indicative scenarios of power plant investments based on potential for electricity trade in the African continent, Taliotis and colleagues [252] composed a dataset with all existing and planned NTCs between adjacent African countries. For the 2015 model we only incorporated the existing lines. The ‘Comision de Integracion Energetica Regional’ (CIER) published a report in 2016 on the current state of the energy systems within Central- and South-America, including an overview of the interconnectivity between countries with existing and planned power transmission projects [253]. Similarly, The World Bank analyzed the current power market structure and design of the electricity networks in the Middle East and Northern-Africa [254], and an overview of existing grid infrastructure for South-East Asia can be found in [255,256]. For reference NTCs between countries covered by the ENTSO-E we used the 2016 Ten Year Network Development Plan (TYNDP) as background [257]. Given 2020 values per border in [258] were taken while capacities from projects finished after 2015 have been excluded. Furthermore, the transparency platform of the ENTSO-E provides NTCs [259,260] and hourly exchange values [261] for the majority of pathways within Europe not directly covered by the TYNDP. Finally, a wide range of additional journal papers, reports and other sources contribute to a global dataset of existing cross-border and cross-regional NTCs as of 2015. This is included in Section C.5 of Appendix C, with Table C-3 showcasing NTCs per adjacent pathway as well as the references behind the values. Section C.1 of Appendix C includes a more detailed description of the approaches used regarding NTCs between sub-country nodes. Figure 4-4 highlights the cross-border transmission pathways with the highest existing NTC as of 2015.

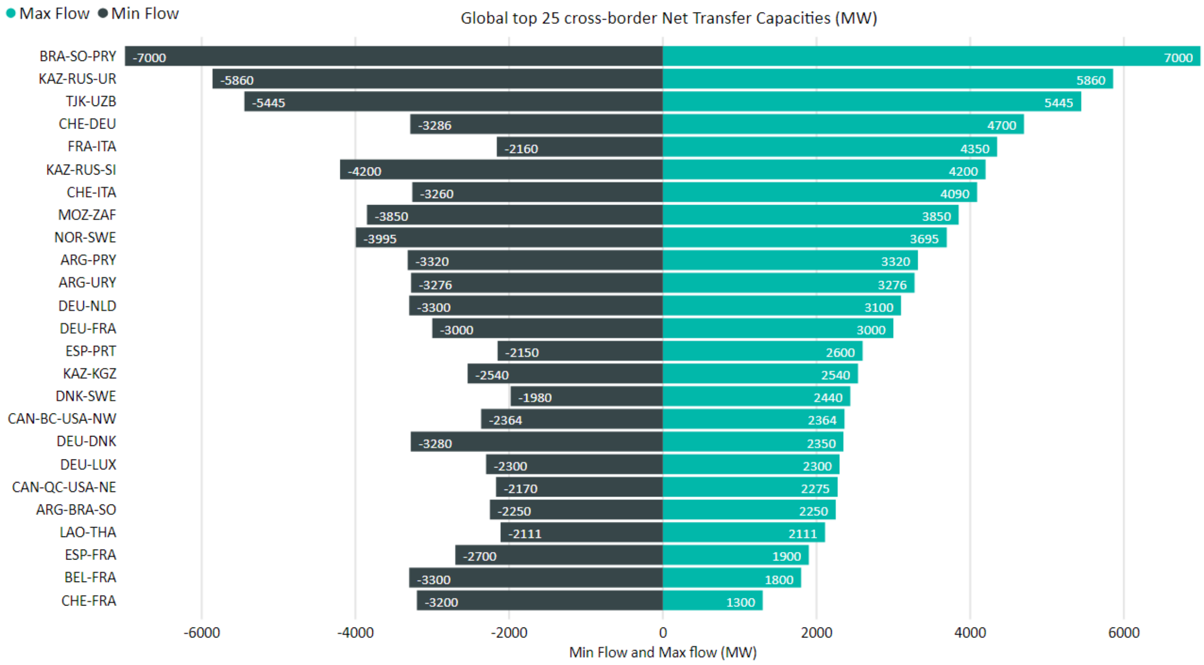


Figure 4-4 Global top 25 cross-border transmission pathways with highest NTCs as of 2015. Max Flow represents flow for direction node A - node B and Min Flow vice versa. Pathways between sub-country nodes are not included. For a full list see Table C-3 in Appendix C.

To-date, pathways with the highest NTCs are mostly used to facilitate supply of surplus electricity from hydro power plants to the power systems of neighbouring countries. Examples are the Paraguayan part of the Itaipu plant mostly used to supply Southern Brazil and a range of hydro power plants in Mozambique which are being used to supply power hungry South-Africa. Looking passed these mostly unilateral flows, Europe is on the forefront of power system integration to a combined market reflected by the generally high cross-border transmission capacities.

4.3.4 Model Calibration and Benchmarking

As described in earlier sections of this paper, part of the model input data such as renewable CFs, operational constraints of thermal power plants and fuel prices have been calibrated to secure model accuracy. This has been done through an iterative process of comparing model simulation output with 2015 benchmark data and calibrating the input data accordingly. Model calibration is important as it allows users to judge the quality of the results against international benchmarks such as the IEA. Note that users of the model can ignore the calibration by turning off the specific calibration scenario and dialling back to the raw model input. However, we believe it is a helpful asset and gives a more realistic representation of the global power system.

The sources used for the benchmark and calibration are as follows. Annex A of the World Energy Outlook (WEO) [40] provides historical CO2 emissions from power generation for the different continents. Differences in geographical coverage per continent compared to PLEXOS-World (e.g. Turkey is part of 'Europe' within the WEO whereas in PLEXOS-World it's part of 'Asia') have been adjusted by removing or adding calculated country-level power sector CO2 emissions from or to the continental totals. These country-level values were calculated based on IEA's 'CO_2 emissions from fuel combustion' [262] which provides historical CO2 emissions per generated kWh per fuel type for a range of countries, multiplied with country-level generation data per fuel type from IEA's 'Electricity Information' [235]. [235] has also been used to calibrate generation values for most fuel types. Unfortunately, the report does not differentiate generation values of solar and wind and does not include data for all countries around the world. Hence for solar and wind as well as for other renewable technologies where country-level generation data is missing we've used an additional dataset from IRENA [240]. Comparison of the benchmark data with simulation results based on the calibrated model input can be found in Section 4.4.

4.3.5 Model Availability

The full model (and its future updates) in PLEXOS- and in raw data format as well as the input datasets for PLEXOS-World are available at [231] and we use the 'FAIR Guiding Principles for scientific data management and stewardship' for dissemination [263], allowing users to modify or recreate the model in other simulation environments. FAIR encourages the findability, accessibility, interoperability, and reuse of digital assets. The principles emphasize machine-actionability, in essence the capacity of computational systems to find, access, interoperate, and reuse data with none or minimal human intervention because humans increasingly rely on computational support to deal with data as a result of the increase in volume, complexity, and creation speed of data.

4.4 Results

This section includes a benchmarking exercise in which the calibrated model simulation results of the over 30,000 simulated power plants are being compared to historical data with 2015 as base year. Benchmarking is undertaken at an aggregated continental and country level and not at plant level as this model is intended to allow users to examine large scale and continental power systems. Users have the option to downscale the spatial size of the model simulations yet would have to undertake their own calibration in this case.

Figure 4-5 showcases a comparison between the overall generation and CO_2 emissions on a continental and global level from the PLEXOS-World simulations with historically reported data. Main observations based on the graphs are that both the generation as well as the emissions are generally in line with reported data. Small deviations exist with the reported generation values, predominantly in Asia and Europe, which can be the result of a combination of factors.

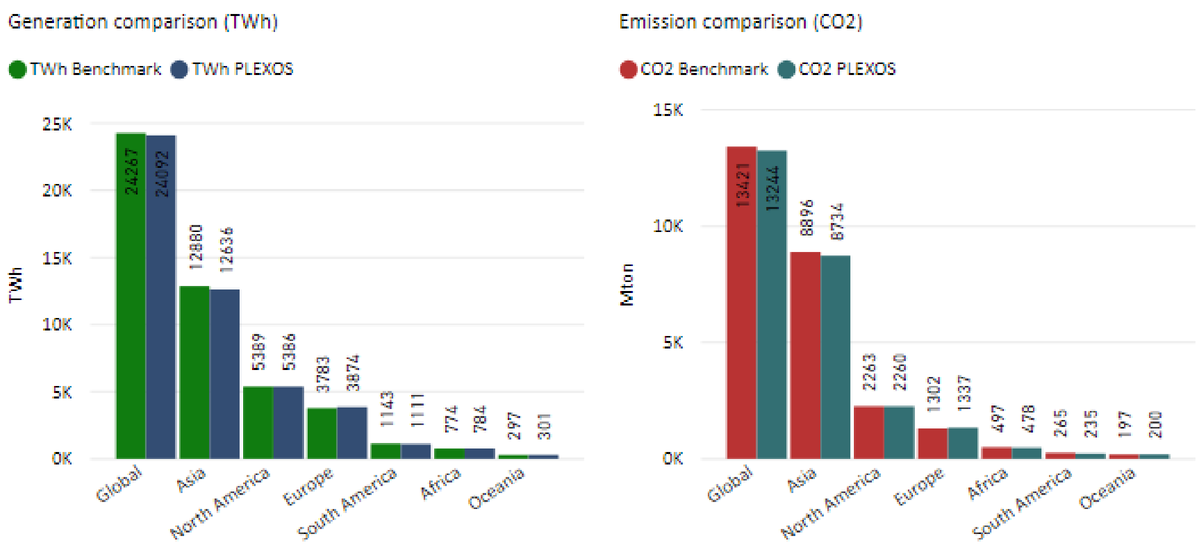


Figure 4-5 Comparison of the overall generation values and CO_2 emissions from the calibrated PLEXOS-World simulations with historically reported data for 2015.

First, the use of different datasets for input and calibration can lead to small yet insuperable differences. The overall demand for every country within the model, determining the required generation, has been based on World Bank data, whereas the reported 2015 generation values are based on IEA and IRENA datasets. Furthermore, although load shedding in mostly developing countries is not uncommon, limited occurance of unserved energy (global total of 92.4 TWh on 24,000 TWh demand) in especially sub-country nodes indicates a possible limitation of the assumption of relative distribution of missing power plant capacities based on the existing share of capacity per sub-country node within the WRI database. It is likely that as a result of said assumption slight underestimation of power plant capacity in a specific sub-country node can occur in favour of another and vice versa. Yet, due to a lack of openly available robust datasets including sub-country level power plant capacities the current approach is near optimal.

Finally, besides the technical potential for power flow, to-date there are no restrictions implemented in the model regarding trade of electricity between nodes which can lead to overestimation of flows and consequently underestimation of domestic generation. Current model results indicate a significant flow from European nodes to Asia (mostly Russia) contributing to the slight differences with historically reported data in both continents. Comparison of the overall continental emissions with reported data as shown in Figure 4-5 indicates a similar story, values are generally in line, with small differences mostly as a result of the described differences in required generation.

Figure 4-6 shows a more detailed view on both aspects by comparing the historical and simulated generation and emission values per fuel type. More detailed graphs that include comparisons with total emission- and generation values per fuel type and continent can be found in Section C.2 in Appendix C. The generation output of operationally low-cost technologies such as coal, hydro, nuclear, solar and wind has been calibrated at country level through an iterative process to come as close as possible to reported 2015 generation values. This has generally been successful, yet the earlier indicated differences in total (required) generation leads in certain cases to a mismatch in the overall use of peaking power plants based on gas and oil compared to historically reported data. These power plants are generally at the end of the merit order (2015 context with higher gas prices), and hence dispatched last or switched off first making it most susceptible of all power plant types to changes in demand.

Next to an overall deviation in use of peaking power plants, there’s also a slight mismatch in the relative use of oil versus gas in countries where both fuel types compete. The main reason for this mismatch is the approach used to scale missing power plant capacities based on relative influence of coal, gas and oil in the WRI database for countries where no capacity data is available in the IEA datasets. It is possible that the country-level power plant capacity of a specific fossil fuel is underestimated, meaning that the theoretical generation potential is insufficient to reach the benchmark values. The reason that this is especially visible in Africa is that relatively speaking Africa is underrepresented in the WRI database compared to other continents. Furthermore, to-date secondary fuels for thermal power plants are not incorporated in the model which affects the use of oil and gas.

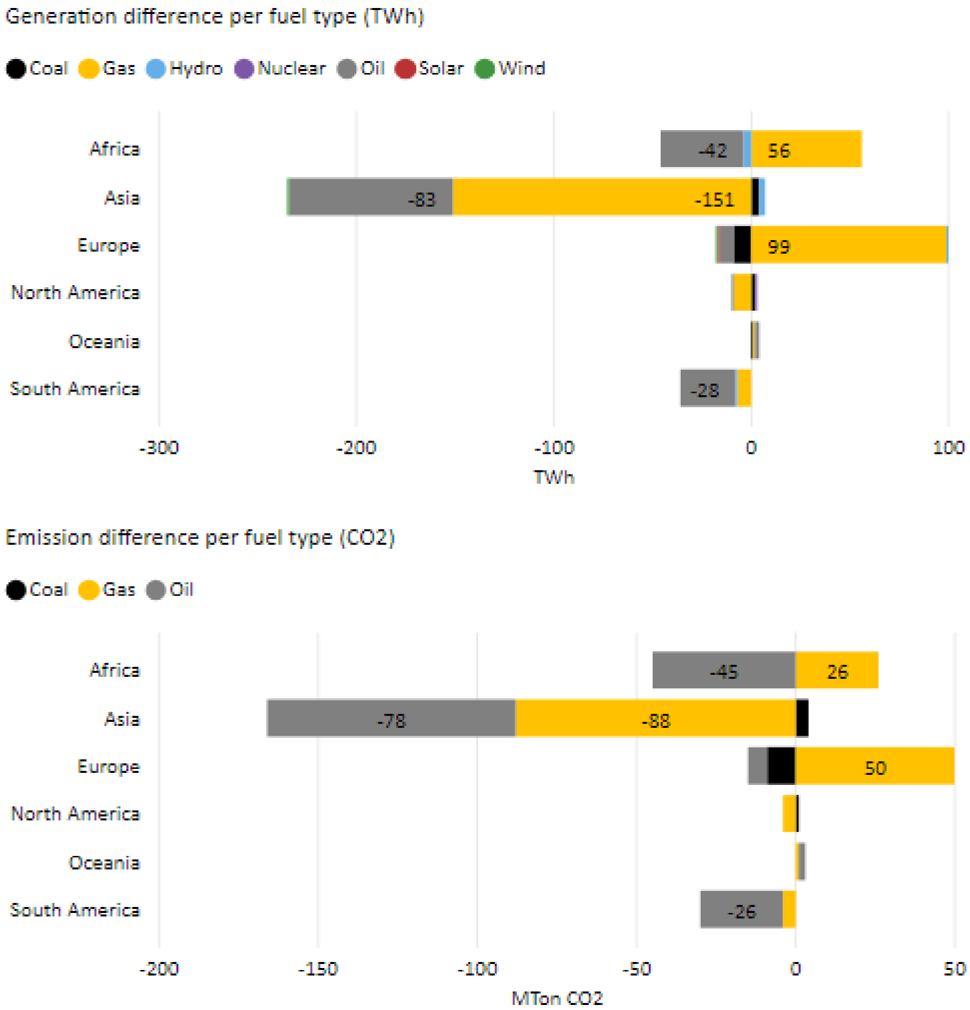


Figure 4-6 Comparison of the difference in generation- and emission values per fuel type for 2015 between the benchmark- and calibrated simulation values. Total global generation in 2015 was 24,267 TWh. A value of 0 indicates that the benchmark and simulation values are exactly equal, negative values indicate that simulation values from PLEXOS-World are lower compared to the benchmark values and positive values vice versa.

These aspects are also visible on a country-level as indicated in Figure 4-7. Utilization of gas and oil-based power plants is controlled by means of its fuel price, with oil prices calibrated at country-level to optimize the balance in use of both fuel types compared to historical data. Despite this, in certain cases oil is slightly underutilized in favour of gas and vice versa. Yet, it is important to realize that in absolute terms the role of oil for the purpose of power generation is very limited (see Section C.2 in Appendix C). Overall deviations in the use of gas compared to the benchmark values are mostly as a result of lower or higher required generation in the model. The underutilization of oil in India results from data discrepancies in the different datasets. The IEA reports a gross electricity production from oil in 2015 of almost 23 TWh [235], whereas the diesel-based installed capacity according to India's Central Electricity Authority in March 2015 was 1.2 GW [236] and in March 2016 only 0.99 GW [236].

Even at full utilization this would lead to a maximum generation potential of 8.7-10.5 TWh. The relatively low usage of gas in China is a direct result from the earlier described limitations in sub-country allocation of generator capacities as well as a slightly lower total demand compared to benchmark generation values. That said, the role of gas for power generation in China is limited compared to other fuel types. Beyond gas and oil, the graph shows that country-level total generation as well as generation from baseload- and other low-cost technologies is generally in line with historical generation values.

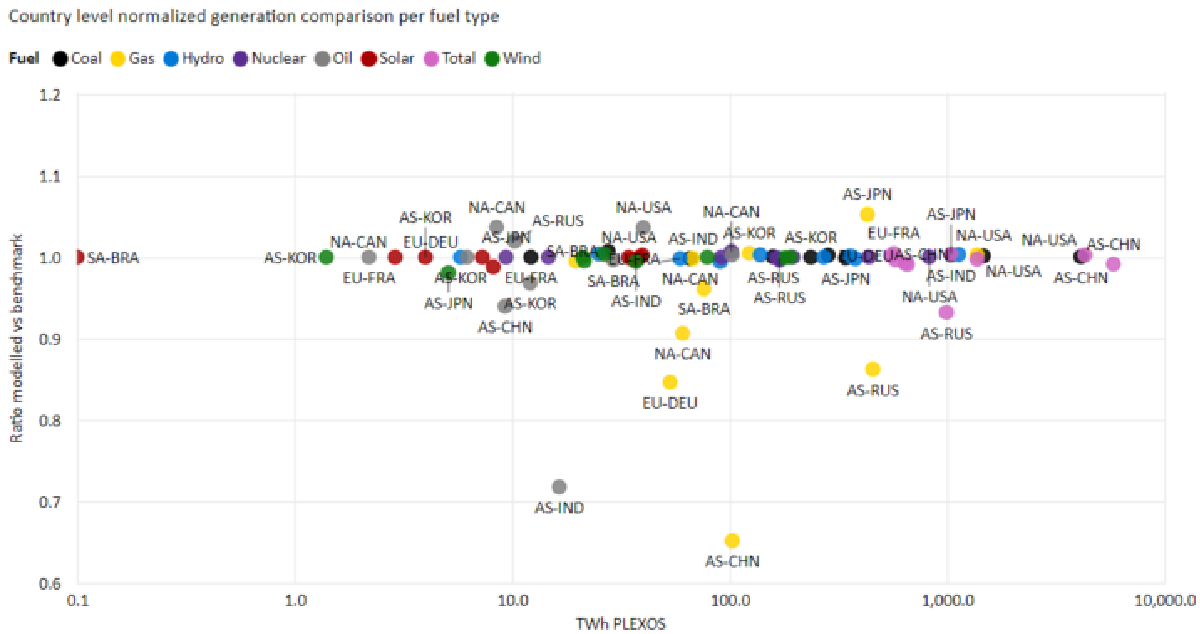


Figure 4-7 Comparison of normalized generation values per fuel type for the top 10 countries with highest 2015 electricity demand. Score of 1 indicates that the calibrated simulation value is equal to the reported benchmark value, <1 is shortage, >1 is surplus. Total generation within the PLEXOS-World simulations per fuel type and country is indicated on the X-axis with a logarithmic scale.

4.5 Discussion

This paper describes the model development of a first-of-its-kind reference detailed hourly global power system model at plant and country level. The model – dubbed PLEXOS-World after the simulation software used – can simulate the dispatch of over 30,000 individual power plants representing 164 countries spread out over 265 nodes. Alongside the existing storage facilities around the world as well as the globally existing cross-border transmission capacities, the model optimizes the supply of electricity to match the system demand by minimizing the overall operational system cost.

We've shown that the model can be a useful tool for the simulation of the global power system through a benchmarking exercise of calibrated simulation results with historical data for 2015. That said, the model is as strong as its input data and the underlying model assumptions. Significant improvements can still be made, for example regarding the representation of existing power plant portfolios, the level of spatial detail in aspects such as fuel- and carbon prices and by incorporating a wider range of data years for demand- and VRES profiles [239]. The main strength of the model is therefore not in its absolute accuracy but in its openness, adaptability and flexibility for other users. All model input is available as supplementary material [231] to allow other users to modify the model in PLEXOS or recreate the model in other simulation environments. This includes a full global dataset of cross-border transmission capacities, hourly demand profiles, and plant-specific CF profiles for existing hydro, solar and wind power plants. The model can be used for assessments on the global scale, but it is as easy to zoom in on a specific country or area in the world allowing it to be used for a wide range of research. The model is setup in a straight-forward fashion that makes it easy for users to switch to more accurate and detailed data for specific regions while modelling other areas with base data (or exclude completely).

The study has given us some valuable insights in the availability, importance- and strength of open data initiatives [32]. Nonetheless, it has also highlighted the still existing data gaps in especially areas outside Europe and North-America as well as the general difficulty of dealing with data discrepancies while using multiple large datasets. The study also showcased the clear differences in power plant portfolios and overall power system characteristics in different parts of the world. This latter aspect highlights once again that there is no single uniform pathway in the energy transition and decarbonization of the global power system, fuelling the importance of modelling tools like PLEXOS-World to support research in this area.

In future research, the model will be used as a reference model based on which a range of global decarbonization pathways will be assessed. For example, advanced analyses of the concept of a globally interconnected power grid [30,195,227] will be conducted as well as the application of known soft-linking techniques [38] to investigate the technical feasibility of projected power systems in global scenarios as constructed by IAMs.

Chapter 5 Assessing Global Climate Change Mitigation Scenarios from a Power System Perspective Using a Novel Multi-Model Framework

5.1 Abstract

There is a debate within the scientific and policy making community as to the suitability of global IAMs for long-term planning exercises of the global power system. This study informs this debate and proposes a methodological framework for soft-linking of global IAMs with detailed global power system models. With the proposed open-source framework, the scenario results from IAMs can be fed into a power system model to assess given scenarios with enhanced spatial, technological, and temporal resolution. Results from these simulations can be redirected to the IAM through iterative bi-directional soft-linking. A proof of concept application of the proposed framework is presented by linking global IAM MESSAGEix-GLOBIOM with global power system model PLEXOS-World. Among others, the results highlight that the assumption of unconstrained electricity flows inside large regional copperplates causes an overestimation of variable renewables integration potential within MESSAGEix-GLOBIOM. We propose areas for informed improvements in MESSAGEix-GLOBIOM.[12]

[12] In review as: Brinkerink M, Zakeri B, Huppmann D et al (2021). Assessing global climate change mitigation scenarios from a power system perspective using a novel multi-model framework. Environmental Modelling & Software.

5.2 Introduction

5.2.1 Background

IAMs are widely used to assess scenarios for the long-term evolution of the global energy system over multiple decades [13,264]. 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 [7,13,14,265]. 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 [7,14]. In addition to the broad sectoral representation, IAMs are commonly applied for analysing policy questions that deal with large spatial coverage – often global – and long modelling horizons of up to one century. Hence, to remain computationally tractable, limits must be placed on the overall computational details of model simulations, and as such IAMs are restricted in temporal resolution with a significant geographical aggregation of model regions [14,15,264,266,267].

A significant challenge for IAMs is the modelling of the variability in electricity demand and supply as a result of the integration of large amounts of VRES in emission mitigation scenarios [13–16,264,268]. Traditional power systems with high levels of dispatchable technologies can be well represented in IAMs due to their often-predictable operation. However, due to the limited amount- or absence of sub-annual time resolution, a weakness of IAMs lies in realistically representing the operation of VRES technologies and the corresponding integration challenges [13–15,264,269]. To account for the above challenges, global IAMs such as AIM/GCE [270], IMAGE [271], MESSAGEix-GLOBIOM [272], POLES [273], REMIND [274] and WITCH [275] integrate generic relationships to represent the integration of VRES technologies in a stylized manner. For example, in MESSAGEix-GLOBIOM the amount of solar and wind curtailment per region is accounted for as a model input based on a marginal curve with increasing curtailment at higher VRES penetration levels [276].

A number of model improvements have been made in recent years regarding power system representation in IAMs among others as a result of the ADVANCE project [13,56,264,269,276–280]. Pietzcker et al. [13] developed a set of qualitative and quantitative criteria which allows for critical scrutiny of power system representation in IAMS. Based on these criteria additional required improvements for future versions of global IAMs have been identified. This includes the overall modelling of electricity transmission infrastructure with a focus on the general pooling effect of shared generation resources through transmission integration as well as limitations on internal electricity flows in large model regions like Latin America due to power transmission constraints [13,56,277–279]. Furthermore, often mentioned as the most critical improvement in IAMs is to extend the data basis to enhance the overall spatial representation as well as refined implementation of region specific model input- and assumptions [13,264,276,278,279]. For integration of new model assumptions in IAMs, it is recommended to benchmark simulation results with operational power system dispatch models [13,14,276,281]. Power system models can assess operational aspects of a given power system with high spatial, temporal, and technological detail. Due to the dedicated sectoral scope, a range of state of the art energy or power system models such as Artelys Crystal Super Grid [48,282,283], LUSYM [284,285], LUT Energy System Transition model [230], PLEXOS [17,37,239,286,287] and PyPSA [288,289] have proven ability to simulate spatially rich continental- or global-scale models with hourly temporal resolution at minimum.

5.2.2 Model Interlinkage

By accepting that all sets of optimization and simulation models have clear limitations, it is possible to make use of the strengths of one type of model to inform and improve the other by means of inter-model linkages that facilitate data flows. 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 [38]. 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 other main approach that can be applied is a hard-link method in which the optimization occurs in a parallel fashion by means of an algorithm that communicates dynamically between both models and leads to a singular set of results [290]. Both the soft-link [38,47,291–296] and the hard-link [279,297] approach have proven to be suitable methods for linking IAMs 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

[276,290]. Hard-linking involves significant time and resources to develop a smooth operation of co-optimization of both models which is not always feasible [290], nor are all modelling tools computationally able to function in this setting. Next to the above, Collins et al. [14] argue that due to the small number of very sizable regions in global IAMs – each of which is assumed to be a "copperplate" without internal network constraints – as well as long modelling horizons, it can be challenging to perform power system model simulations for every 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 [276,279,281]. 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 [23–25,231,249,287,298,299] have made the development of detailed global power system models possible [230,231,287] from which the model input data can easily be transferred to other modelling tools [231].

5.2.3 Contribution of this Study

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

Considering the importance of global IAMs for key scientific reports such as Chapter 2 of the Special Report on Global Warming of 1.5°C by the Intergovernmental Panel on Climate Change (IPCC) [7] and Chapter 3 of the forthcoming Sixth Assessment Report, an ongoing debate exists within the scientific community [300–302] 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 informs this debate by providing the ability to scrutinize IAM scenarios in dedicated power system models while simultaneously supporting internal improvements of power system representation within the IAMs. As a proof of concept, the global implementation of the IAM MESSAGEix-GLOBIOM [303,304] is soft-linked to PLEXOS-World [231,287], a 258-nodal detailed global power system model developed in PLEXOS [37]. By means of a snapshot analysis for the year 2050, a 1.5°C and high VRES scenario from MESSAGEix-GLOBIOM is assessed with the aim to determine whether the generic stylized relationships regarding generator reserve requirements, generator capacity factors, storage- and transmission integration in MESSAGEix-GLOBIOM are deemed appropriate or whether these could be improved with more accurate regional representations. Section 2 describes the proposed methodological framework and Section 3 includes the results of the proof of concept application of the framework. Section 4 includes a discussion regarding the framework, its limitations and a commentary on the theoretical discussion regarding the suitability of IAMs for planning exercises of the global power system.

5.3 Methodological Framework

The proposed methodological framework for soft-linking spatially coarse IAMs with dedicated power system models allows for assessments of the technical feasibility of specific IAM scenarios with higher spatial, technological, and temporal resolution. This model soft-linking enables enhanced insights regarding VRES integration and provides the ability to assess the suitability of uniformly applied stylized relationships and model inputs for the power system representation in IAMs.

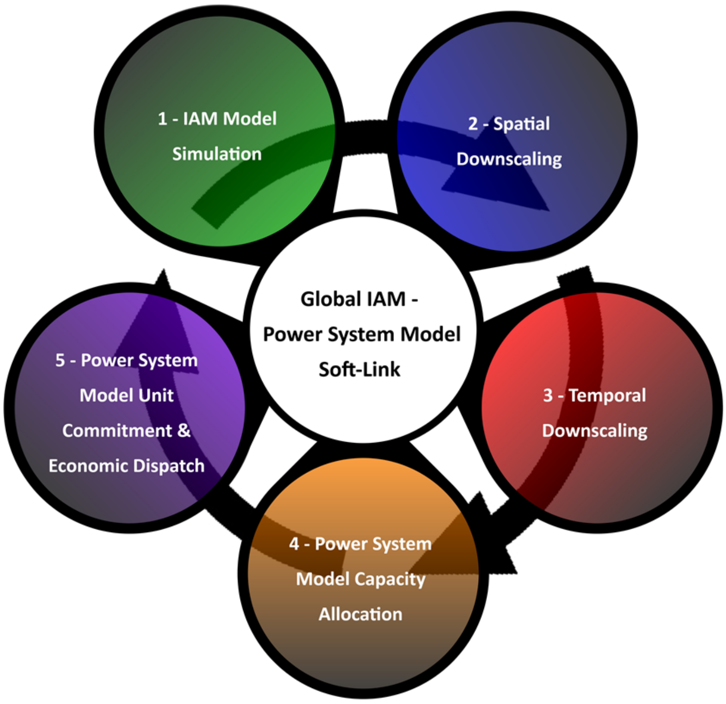


Figure 5-1 Overview of the proposed framework for soft-linking of global IAMs and power system models.

Figure 5-1 provides an overview of the different steps of the framework. The framework is setup in a non-discriminatory way allowing it to be applied to any specific IAM and power system model that meet certain base requirements. First, the scope of this framework from a spatial perspective is to downscale the coarse regional copperplates in IAMs to a detailed spatial resolution in the power system model. This framework is appropriate in the assessment of global or continental models with multi-country scale regions versus scenarios from already more spatially defined IAMs. Second, the power system model requires a long-term capacity expansion module capable of integrating expansion constraints based on IAM scenario outputs. Lastly, although not a prerequisite, the openly available python script[13]

[13] https://github.com/iiasa/IAM-powersystemmodel-linkage

accompanying this paper that can be used to coordinate the soft-link between IAMs and power system models is based on IAMC data template format[14]. Note that the script is a helpful tool to automate the data processing workflow within the soft-link yet other languages or manual data conversion (e.g. in Excel) can also be applied. Although the methodological framework is developed to address the limitations of global IAMs, the framework is also suitable for soft-linking or hard-linking to other long-term planning models like energy system optimization models. This section introduces the different parts of the framework. Refer to Sections D.1 and D.2 of Appendix D for details on the required data downscaling and conversion steps of the framework including provided examples based on a 1.5°C and high VRES scenario from the global implementation of MESSAGEix-GLOBIOM.

5.3.1 IAM Model Simulation

The minimum scope of required scenario output data from the IAM model simulations 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. To assess the technical feasibility of a given scenario, it is recommended to use as much of the IAM scenario output in the power system model as possible. After that constraints can be relaxed 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.

5.3.2 Spatial Downscaling

One of the core aspects of the framework is the ability to assess regionally coarse IAM scenarios with higher spatial resolution in the power system model. Especially relevant from a power system perspective, this allows for any IAM scenario to be assessed in the context of local characteristics with the ability to provide detailed insights that cannot be provided with a coarser representation. For this to occur IAM scenario data must be downscaled to a newly defined spatial resolution to be used as input for the power system model. An exemplary visualization of indicative spatial resolutions of both sets of models is shown in Figure 5-2.

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

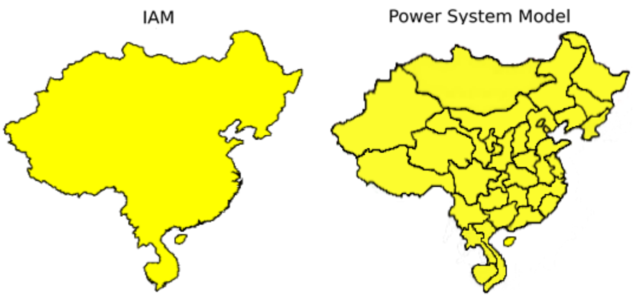


Figure 5-2 Example of indicative spatial resolutions for global IAMs and global power system models. The left side shows the CPA region of the global IAM MESSAGEix-GLOBIOM consisting of the combined area of Cambodia, China, Laos, Mongolia, North Korea, Taiwan, and Vietnam. The right side shows the spatial resolution of global power system model PLEXOS-World which represents every country in the CPA region individually and China as 34 separate nodes.

IAM scenario- and region specific yearly electricity demand values need to be downscaled and although any downscaling approach can be applied, within the accompanying script we apply a forecasting methodology to project country-level yearly 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 the dependent variable. The projected country-level values are used as proxy to downscale the IAM scenario regional electricity demand. Furthermore, for larger countries such as China, India and the United States, we use the PLEXOS-World 2015 dataset [231,287] for further downscaling to sub-country level by applying relative historical shares of electricity demand per sub-country node as proxy.

As well as electricity demand, other main IAM scenario outputs that requires downscaling are regional powerplant – and optionally balancing asset – capacities. Regional capacity expansion- and retirement constraints need to be developed that can be calculated by comparing the IAM scenario output with existing baseline capacities. These constraints determine per scenario region and technology how much capacity needs to be expanded or retired compared to the baseline to match the values provided by the specific IAM scenario for a given year. The constraints are used as boundary condition for the capacity allocation exercise within the power system model as described in Section 5.3.4.

5.3.3 Temporal Downscaling

Global IAMs and power system models have different modelling horizons and temporal resolution. An example of this is visualized in Figure 5-3. IAMs focus on the long-term development of the energy system with planning horizons of up to a century and modelling periods of between 1 to 10 years with a specified baseline year as starting point. Timesteps in global IAMs are generally applied on an annual basis with investment decisions reported at the end of every modelling period. Within the framework, the power system model is used to assess IAM model output for a specific year with detailed temporal resolution, for example on an hourly basis for the full year depending on the aim of the study [232]. Results can be reported per timestep or on a yearly basis for direct comparison with the IAM.

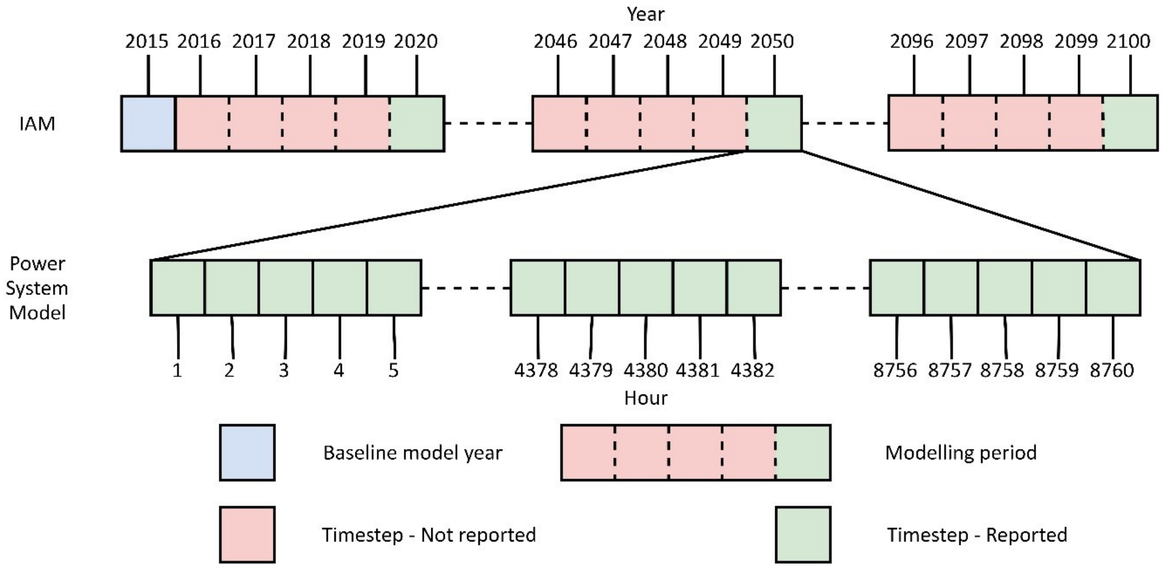


Figure 5-3 Comparison of indicative modelling horizons and temporal resolutions for global IAMs and global power system models within the framework.

The spatially downscaled yearly electricity demand values from Section 5.3.2 require additional downscaling in terms of temporal resolution. Once again multiple approaches are possible, yet for the results in this study we use historical timeseries as proxy based on the PLEXOS-World 2015 dataset [231,287] which includes hourly demand data for all countries globally as well as for a wide range of sub-country regions for the 2015 calendar year. Details on the applied methodology for electricity demand downscaling including examples can be found in Section D.1 of Appendix D. The downscaled IAM scenario data as well as other input data that can be derived from the IAM scenario output needs to be integrated in the power system model. This can be done manually or partially automated by means of scripts that can assist with the overall workflow.

5.3.4 *Power System Model Capacity Allocation*

Traditionally capacity expansion exercises in power system models are used to optimize the long-term development of the power system. In contrast to the traditional application, the framework we propose in this article does not allow powerplant capacities to be expanded and retired in an unconstrained fashion. Instead, we use the expansion and retirement decisions from the IAM by means of the developed expansion- and retirement constraints in Section 5.3.2 as boundary conditions for the power system model. The capacity expansion module is used to optimize the allocation of powerplant resources to the different nodes within a region with the IAM regional capacities as boundary. An examplary application of this exercise can be seen in Figure 5-4.

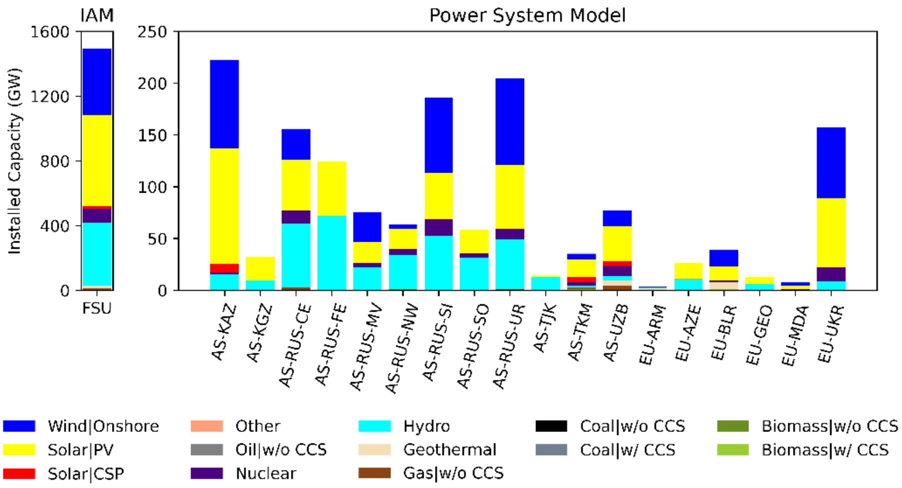


Figure 5-4 Example of the capacity allocation exercise within the framework based on the Former Soviet Union (FSU) region of the global IAM MESSAGEix-GLOBIOM. The left bar indicates the region and technology specific powerplant capacities for a given year based on the regional IAM output. These capacities are used as input for the power system model acting as boundary condition for the capacity allocation exercise. The right side shows nodal level powerplant capacities as output of the capacity allocation exercise within the power system model. Refer to [231,287] for naming conventions of nodes as used in the PLEXOS-World model.

Together with the allocation of powerplant capacities, the power system model 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. Although these assets are usually accounted for in IAMs, their operational benefits and technical limitations are only visible in model simulations with detailed spatial and temporal resolution. For example, global IAMs generally assume that there are no internal network constraints within large model regions like Latin America. This “copperplate" assumption means that intra-regional electricity exchange limitations cannot be adequately modelled. More detailed power system models can identify whether this assumption is valid or whether limitations in available electricity transmission infrastructure might necessitate different results. Details on development of the capacity expansion- and retirement constraints as well as the application of power system models' capacity expansion module for capacity allocation and balancing asset integration can be found in Sections D.2 and D.3.1 of Appendix D.

5.3.5 Power System Model Unit Commitment & Economic Dispatch

The next step in the framework is to use the output from the capacity allocation exercise as input for the UCED modelling. UCED within power system models refers to the optimal utilization of available generating capacity to match system demand within a given simulation period while abiding to technical- and operational constraints. 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 CFs and predefined technology utilization rates as well as stylized relationships regarding curtailment and occurrence of possible unserved energy. Similar to the results from the capacity expansion exercise, 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 stylized input assumptions are viable.

5.3.6 Feedback Loop

The results from the model soft-link exercise within this framework consists of quantified simulation output that can assist with optimizing the power system representation in IAMs while considering the computational requirements of model simulations. The power system model output data can be converted into a readable format for the specific IAM (e.g. IAMC data template format) and directly integrated where appropriate. The scripted feedback loop within the framework allows for an iterative process between the IAM and power system model until the power system representation in the IAM is deemed satisfactory in terms of power system adequacy.

5.4 Application of the framework

This Section includes a proof of concept application of the proposed soft-link framework with the global IAM MESSAGEix-GLOBIOM [272] being used from which the ENGAGE SSP2 NPI2020

500 scenario will be assessed in power system model PLEXOS-World [231,287]. The objective is to determine whether the generic stylized assumptions regarding generator reserves (i.e. firm capacity requirements), generator CFs, storage- and transmission integration in MESSAGEix-GLOBIOM are appropriate, or whether this could be improved by means of regional refinement. Furthermore, an iteration between MESSAGEix-GLOBIOM and PLEXOS-World will be applied to showcase the potential for informed model improvements in global IAMs by means of the framework.

5.4.1 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 [272]. The global implementation of the model has different spatial resolutions, typically ranging between 11 and 14 world regions [305], with the spatial resolution of the 11-region model as assessed in this study visualized in Figure 5-5. The focus of this paper is on the power system representation in MESSAGEix-GLOBIOM. Readers should refer to [272,305] for a full description of the MESSAGEix framework and [303] for details on the MESSAGEix-GLOBIOM model. Although MESSAGEix can perform model simulations with sub-annual timeslices, simulations of the global implementation of MESSAGEix-GLOBIOM generally occur with yearly resolution. To account for challenges associated with VRES integration only quantifiable in modelling exercises with detailed temporal resolution, Sullivan et al. [281] introduced two sets of power system reliability constraints in MESSAGEix-GLOBIOM related to (I) capacity reserves to meet system peak load at all times and (II) operating reserves to provide a pre-defined level of system flexibility relative to the installed capacity of different types of power plants. Albeit a significant step forward compared to earlier versions of the model, Johnson et al. [276] argue that 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 [277,281,306] and in general that the use of a detailed power system model for parameterization makes reproducibility difficult.

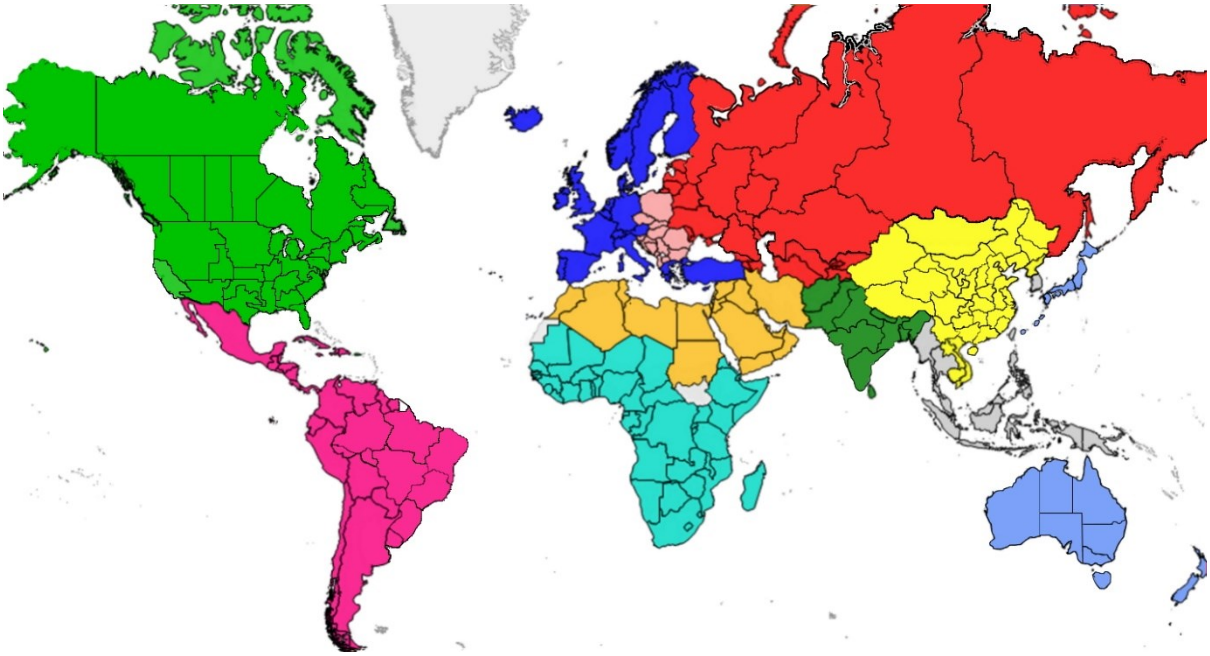


Figure 5-5: Spatial representation of the 11-region MESSAGEix-GLOBIOM global IAM based on [305] as well as the spatial representation for MESSAGEix-GLOBIOM scenarios in PLEXOS-World. Every individual colour represents a copperplated region following MESSAGEix-GLOBIOM, whereas every area separated by borders as shown on the map represents a single (sub-)country node in PLEXOS-World with a total of 258 individual nodes. Refer to Section C.1 and C.3 in Appendix C for details on sub-country nodes in PLEXOS-World.

Due to the above limitations, Johnson et al. applied a hybrid approach using region specific Residual Load Duration Curves (RLDCs) from [264]. RLDCs represent the load of a specific region that must be met by non-VRES calculated by subtracting the projected VRES generation from 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. 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 is 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. CFs for VRES technologies are based on regional resource potentials identified per range of CFs, whereas assumed CFs for thermal powerplants are globally uniform per technology for all regions based on the ability of powerplants to operate between baseload- and flexible operational modes [276].

In previous versions of MESSAGEix-GLOBIOM, inter-regional exchange of electricity occurred as any other commodity based on a global market. In essence this meant that regions had the ability to either supply to- or import electricity from the global market, without consideration of the spatial feasibility of exchange between regions. However, as part of the modelling effort in parallel to this study, the representation in MESSAGEix-GLOBIOM has been adapted to only allow for inter-regional exchange bilaterally by means of investments in transmission grid infrastructure. Iterations with PLEXOS-World have been used to inform the input parameters in MESSAGEix-GLOBIOM for this new setup as explained in more detail in Section D.3.3 of Appendix D. Intra-regional electricity flows within the regional copperplates are not modelled within MESSAGEix-GLOBIOM.

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 shown in this study.

5.4.2 PLEXOS-World

PLEXOS [37] is a transparent energy- and power system modelling tool among others used for electricity market modelling and planning freely available for academic use. All data input is customizable and the linear equations can be queried and modified by the user. PLEXOS has an integrated user interface enabling data management and model simulation to occur within the tool, yet also supports automation of data flows and model simulation by means of COM or .NET. The tool facilitates use of open source (GLPK, SCIP) and commercial (CPLEX, Gurobi, MOSEK, Xpress-MP) solvers depending on availability of licenses, with Xpress-MP being used for the simulations in this study. For a detailed description of the tool refer to [231,287].

The model used for this study is based on the PLEXOS-World model, a detailed global power system model with 2015 as baseline year capable of simulating the generation of over 30,000 individual powerplants [231,287]. The spatial representation of the model specified for this study is visualized in Figure 5-5, with a total of 258 nodes 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 capacity allocation exercise as described in Section 5.3.4. The modelling of electricity transmission in PLEXOS-World is based on physical transmission grids with development of new capacity compared to the 2015 baseline being part of the expansion exercise. Every unique potential high voltage transmission pathway in the model – totalling 545 – has customised associated costs and transmission losses as a function of transmission distance and specific transmission technology. Intra-nodal grids are not modelled in PLEXOS-World. Refer to Section D.3 of Appendix D for full details on the modelling as well as for details on scenario integration of MESSAGEix-GLOBIOM in PLEXOS-World and Appendix A for detailed equations of the UCED modelling in PLEXOS-World. The PLEXOS-World model as applied for this study including all input data and timeseries can be found in [307].

5.4.3 Scenarios

The ENGAGE SSP2 NPI2020 500 scenario is consistent with end-of-century warming of below 1.5°C after a temperature overshoot in the second half of the century. It exhibits high penetration of VRES and has therefore been chosen for this study to critically scrutinize MESSAGEix-GLOBIOM in a setting where IAMs generally struggle in terms of realistically incorporating the implications of variability in electricity supply. We perform a 'Baseline' simulation and a set of sensitivity simulations in PLEXOS-World summarized in Table 5-1. As a proof of concept for the potential of the framework to streamline informed model improvements in global IAMs, the results of the model simulations in PLEXOS-World related to inter-regional electricity trade are fed back to MESSAGEix-GLOBIOM and used as model input for a second iteration. The simulations in MESSAGEix-GLOBIOM as performed for this study can be found in Table 5-2. It is important to recall that in line with the framework, key model input in PLEXOS-World such as powerplant capacities and electricity demand are equal to the MESSAGEix-GLOBIOM model output at all times.

Table 5-1 Overview of PLEXOS-World model simulations to assess the MESSAGEix-GLOBIOM 1.5°C scenario from a power system perspective.

PLEXOS-World simulation	Soft-linked to	Renewable capacity factors	Storage assumptions
Baseline	First iteration MESSAGEix-GLOBIOM	Renewable capacity factors based on MESSAGEix-GLOBIOM	Storage capacity expansion constrained by MESSAGEix-GLOBIOM scenario
Conservative CFs	First iteration MESSAGEix-GLOBIOM	Renewable capacity factors based on PLEXOS-World 2015	Storage capacity expansion constrained by MESSAGEix-GLOBIOM scenario
No Storage Constraints	First iteration MESSAGEix-GLOBIOM	Renewable capacity factors based on MESSAGEix-GLOBIOM	Storage capacity expansion freely optimized

Table 5-2 Overview of MESSAGEix-GLOBIOM model simulations for the 1.5°C scenario.

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

The 'Baseline' simulation represents the reference for the soft-link framework in that it replicates the original MESSAGEix-GLOBIOM scenario. Input CF profiles for hydro, solar and wind technologies in the 'Baseline' simulation within PLEXOS-World are in line with MESSAGEix-GLOBIOM levels. Compared to current day CFs for renewable technologies, region specific CFs in MESSAGEix-GLOBIOM are significantly higher, both due to assumed technological learning as well as investments in new capacity at currently untapped locations with efficient hydro, solar and wind resources. Due to the large regional copperplates in MESSAGEix-GLOBIOM, renewable resource potential for a specific region can be informed by often very different geographical areas. In PLEXOS-World, if domestic resource potentials are to be used elsewhere within the region it must be physically transferred by means of transmission infrastructure including associated costs and losses whereas in MESSAGEix-GLOBIOM no intra-regional barriers for trade exist. This can lead to different investment dynamics, and hence as a sensitivity analyses it is merited to assess the specific MESSAGEix-GLOBIOM scenario in context of conservative CFs as is the case with the 'Conservative CFs' model simulation. CF profiles in this simulation are based on the PLEXOS-World 2015 dataset which includes profiles based on benchmarked values at year- and country level for 2015 [231,287].

Whereas in the 'Baseline' and 'Conservative CFs' simulations the expansion of storage capacity is bound at a regional level following the MESSAGEix-GLOBIOM scenario output, the 'No Storage Constraints' simulation allows for full optimization of storage capacity. This allows for an assessment of how realistically storage expansion is integrated in MESSAGEix-GLOBIOM and moreover how it impacts other variables such as generator CFs, generator reserve requirements and transmission utilization. Because this simulation allows for unconstrained competition between transmission and storage in the optimization it provides the best indication for the potential of inter-regional electricity trade. The results from the 'No Storage Constraints' simulation regarding interconnector CFs are therefore used as model input for a second iteration in MESSAGEix-GLOBIOM to optimize its representation of inter-regional electricity trade. This exercise can be seen as a proof of concept for the framework in terms of facilitating power system model informed adjustments of IAM power system representation and model input. Refer to Table D-4 in Section D.3.3 of Appendix D for an overview of the adjusted input parameters in MESSAGEix-GLOBIOM based on PLEXOS-World.

5.4.4 Results

This Section includes the modelling results of PLEXOS-World for the assessed MESSAGEix-GLOBIOM 1.5°C scenario. The results will be compared to the model outputs from MESSAGEix-GLOBIOM based on which suggestions are being made for additional internal model improvements regarding power system representation. Sections 5.4.4.1-5.4.4.4 are focused on simulations based on the first iteration in MESSAGEix-GLOBIOM whereas Section 5.4.4.5 analyses the differences for both iterations in MESSAGEix-GLOBIOM related to inter-regional electricity trade.

5.4.4.1 Generation and Storage

Figure 5-6 shows the differences in generation mix per PLEXOS-World model simulation in comparison to the MESSAGEix-GLOBIOM output. The main observation is that for both the 'Baseline'- as the other simulations in PLEXOS-World the total generation output is lower compared to the MESSAGEix-GLOBIOM scenario output. For example, following the given scenario in MESSAGEix-GLOBIOM the 2050 electricity generation in the CPA region – consisting of China and a number of neighbouring countries – equals approximately 55.5 EJ whereas generation in the PLEXOS-World simulations ranges between 43-45 EJ. The lower generation compared to MESSAGEix-GLOBIOM is in most cases occurring for both renewable technologies as well as for non-renewable thermal-based powerplants.

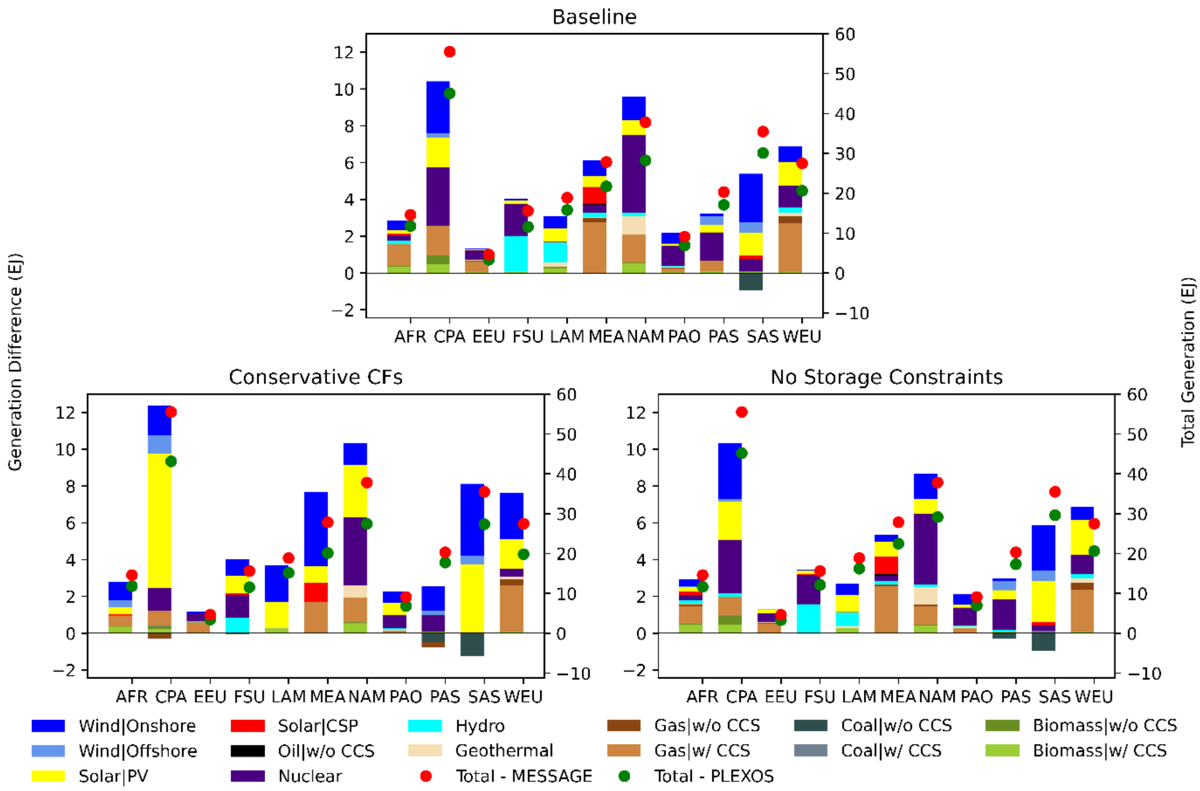


Figure 5-6 Differences in generation mix per PLEXOS-World simulation in comparison to the MESSAGEix-GLOBIOM output. The bars represent generation differences per fuel type (primary Y-axis) with positive values indicating surplus generation in the MESSAGEix-GLOBIOM output compared to PLEXOS-World and negative values vice versa. The markers represent total generation values (secondary Y-axis).

Figure 5-7 shows the technology and region-specific CFs based on model output for a range of key generator technologies. The 'Baseline' and 'No Storage Constraints' simulations have maximum CF input assumptions for hydro, solar and wind technologies in line with the MESSAGEix-GLOBIOM scenario. Yet as the graphs in Figure 5-7 indicate, the equal availability of renewable resources does not always lead to comparable CFs as output. CFs for renewable technologies in PLEXOS-World are lower following the implications of the more detailed spatial, temporal and technical modelling resolution as will be explained in the following pages. For example the regionally aggregated CF for Solar-PV based on the 'Baseline' simulation output for the CPA region is only 16.2% compared to 17.7% in MESSAGEix-GLOBIOM. CFs for hydro, solar and wind technologies in the 'Conservative CFs' model simulation are based on 2015 benchmarked values and as expected lead to signifcantly lower VRES penetration compared to the MESSAGEix-GLOBIOM scenario output. This highlights the sensitivity of modelling assumptions in IAMs regarding uncertain developments such as the availability of highly efficient untapped renewable resources.

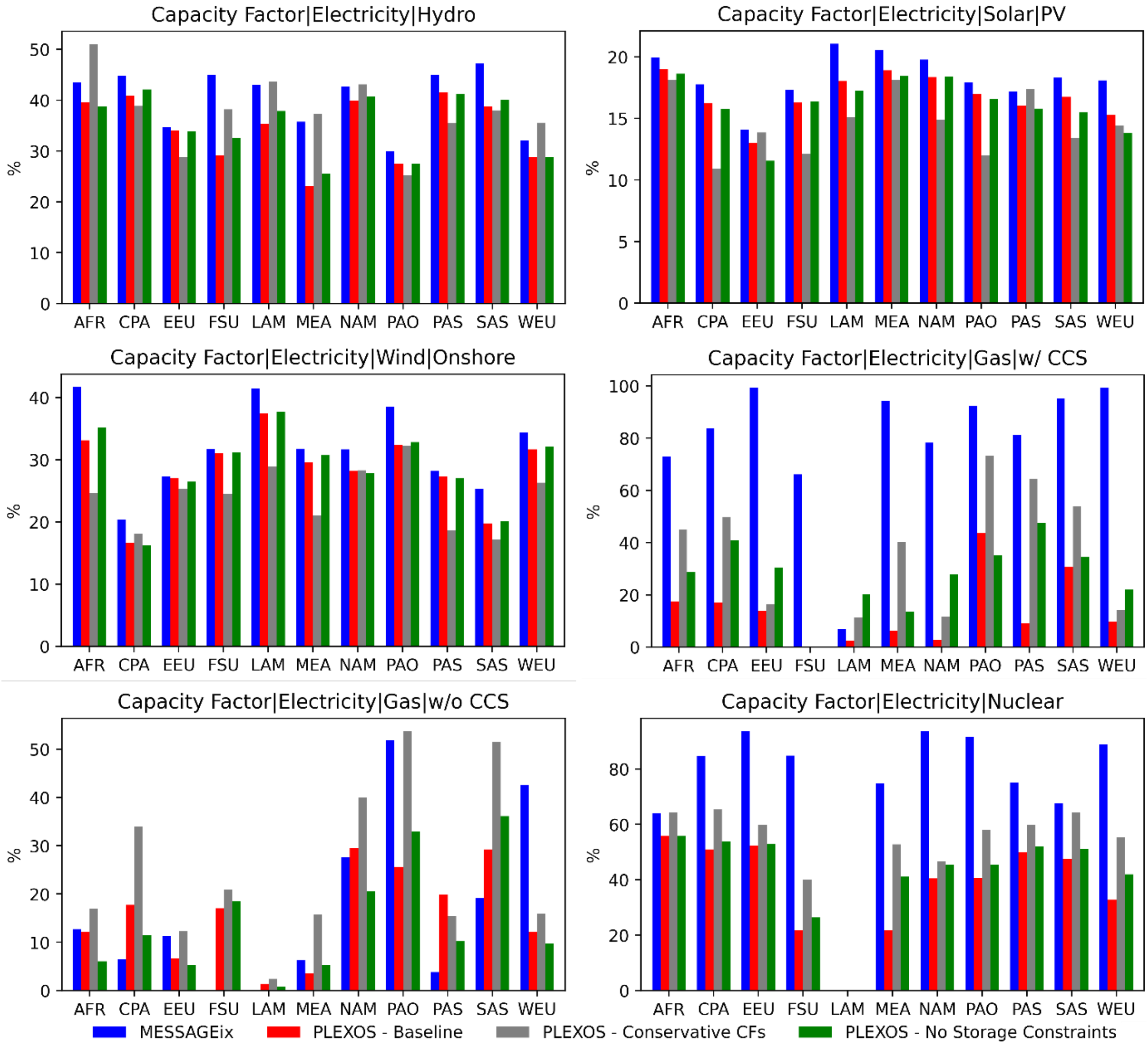


Figure 5-7 Output CFs for a range of generator technologies for the different PLEXOS-World model simulations in comparison to MESSAGEix-GLOBIOM.

Non-renewable thermal-based powerplants partly compensate for the lower availabilty of renewable resources. However – with the exception of regional outliers – all PLEXOS-World simulations indicate that CFs for these technologies are below par compared to the MESSAGEix-GLOBIOM scenario output. Even in a case with less efficient renewable resources as in the 'Conservative CFs' model simulation CFs are not comparable to assumed values in MESSAGEix-GLOBIOM. The exceptions are Gas and Coal powerplants without CCS from which higher utilization is required to mitigate part of the existing supply shortage from renewables. The unconstrained expansion of electricity storage in the 'No Storage Constraints' leads to lower CFs for Solar-PV yet higher CFs for other technologies compared to the 'Baseline'. This is a direct result of lower investments in storage capacity in PLEXOS-World for the 'No Storage Constraints' simulation compared to MESSAGEix-GLOBIOM as higlighted in Figure 5-8 compensated by larger investments in transmission infrastructure. This observation ties in with recent literature which highlights that at a regional or continental level the sharing of resources through transmission integration is favourable compared to mostly domestic generation and storage [308].

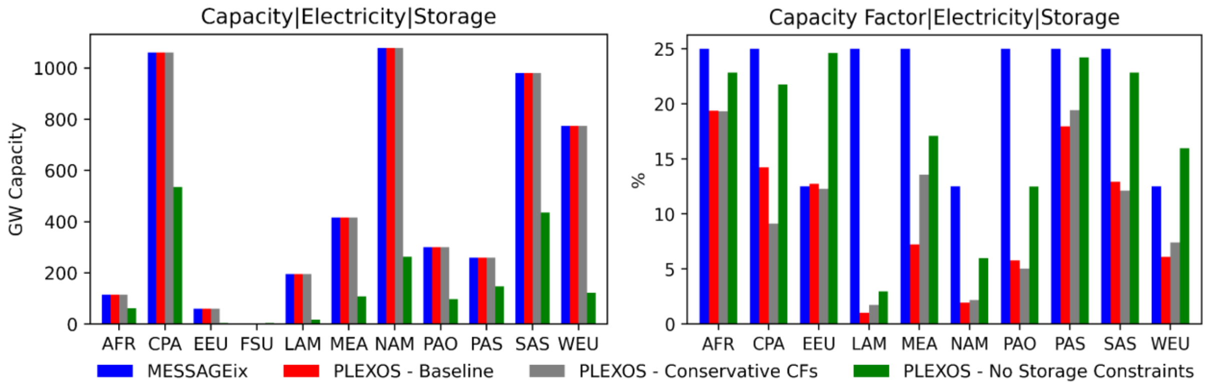


Figure 5-8 Capacity (left) and discharge CFs (right) for electricity storage for the different PLEXOS-World model simulations in comparison to MESSAGEix-GLOBIOM.

Expansion of storage in MESSAGEix-GLOBIOM occurs with predefined energy balance and firm capacity contributions leading to e.g. large scale investments of over 1000 Gigawatt (GW) in CPA and the North America (NAM) region. However, the results show that with similar capacities in PLEXOS-World the discharge CFs following MESSAGEix-GLOBIOM are not being met. When PLEXOS-World is allowed to freely optimize the expansion of storage not bound to capacities following the MESSAGEix-GLOBIOM output – as in the 'No Storage Constraints' simulation – total build capacities are approximately one third of MESSAGEix-GLOBIOM, albeit with higher CFs compared to the other simulations in PLEXOS-World. There are multiple aspects that contribute to the underutilization of available storage, however the main factor is the lack of diversity in storage technologies following MESSAGEix-GLOBIOM which to date is represented by a single technology with 24-hour storage potential [276]. Integration of storage technolgies in MESSAGEix-GLOBIOM with higher power versus storage ratios – for example batteries – that can be utilized on a diurnal basis to mitigate peaks in supply from Solar-PV would be beneficial. Similarly, other long-term storage technologies next to hydrogen electrolysis such as PSH could assist with seasonal storage purposes for especially wind based generation.

5.4.4.2 Curtailment and Unserved Energy

Any electricity coming from VRES technologies that cannot be instantaneously used, stored, transmitted to a neighbouring node or converted to hydrogen gets curtailed – i.e the unplanned reduction of generation output. Curtailment is an important factor in power systems with large penetration of variable renewables and based on the PLEXOS-World simulations an element that is underestimated in MESSAGEix-GLOBIOM. This is visualized in Figure 5-9 which as an example higlights the region specific curtailment values for Solar-PV.

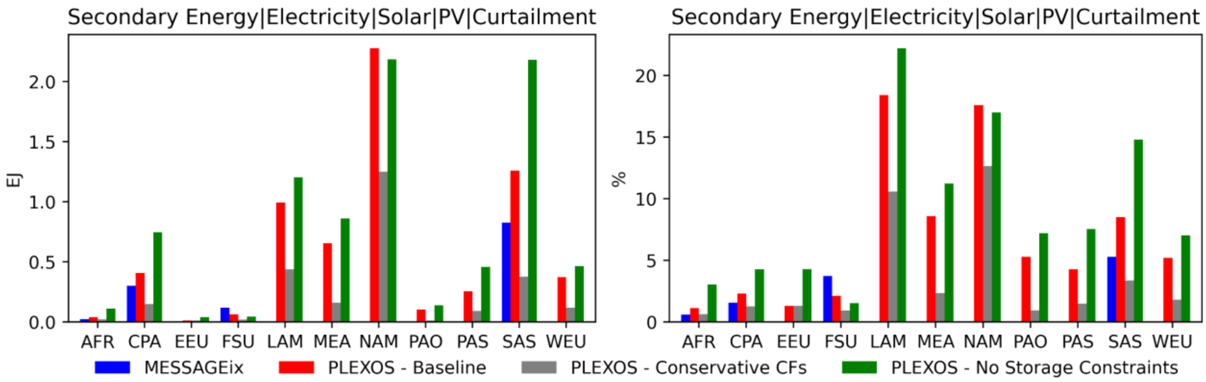


Figure 5-9 Curtailment values for Solar-PV specified per model simulation. The left graph indicates curtailment in absolute values (EJ) and the right graph indicates curtailment relative to the theoretical generation potential per region for Solar-PV.

In almost all cases curtailment is signficantly higher compared to MESSAGEix-GLOBIOM which accounts for curtailment through stylized relationships ex ante as a function of relative VRES penetration [276]. Although this kind of stylized relationship is inherently not incorrect – the 'Baseline' and 'Conservative CFs' PLEXOS-World model simulations indeed indicate that curtailment grows in parallel with relative VRES penetration – the observed curtailment values in PLEXOS-World are a magnitude higher. The lower investments in storage capacities in the 'No Storage Constraints' simulation lead to overall highest Solar-PV curtailment values due to reduced possibilities to mitigate peak Solar-PV supply. On the global scale, curtailment values relative to the theoretical generation potential ranges between 4-11% for Solar-PV depending on the PLEXOS-World simulation and compartively between 4-8% for wind based technologies.

The combined effect of VRES curtailment and the underutilization of dispatchable technologies leads to the occurance of unserved energy[15] in the global power system. Unserved energy represents the share of final electricity demand that cannot be met with the available resources. This is visualized in Figure 5-10 which highlights the occurrence of unserved energy per region and model simulation. Note that in power systems the occurance

[15] 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. 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 mitigate this unserved energy.

of unserved energy can be partly mitigated by load shifting or shedding through demand side management. However, demand side management is not actively incorporated in MESSAGEix-GLOBIOM in relation to system flexibility.

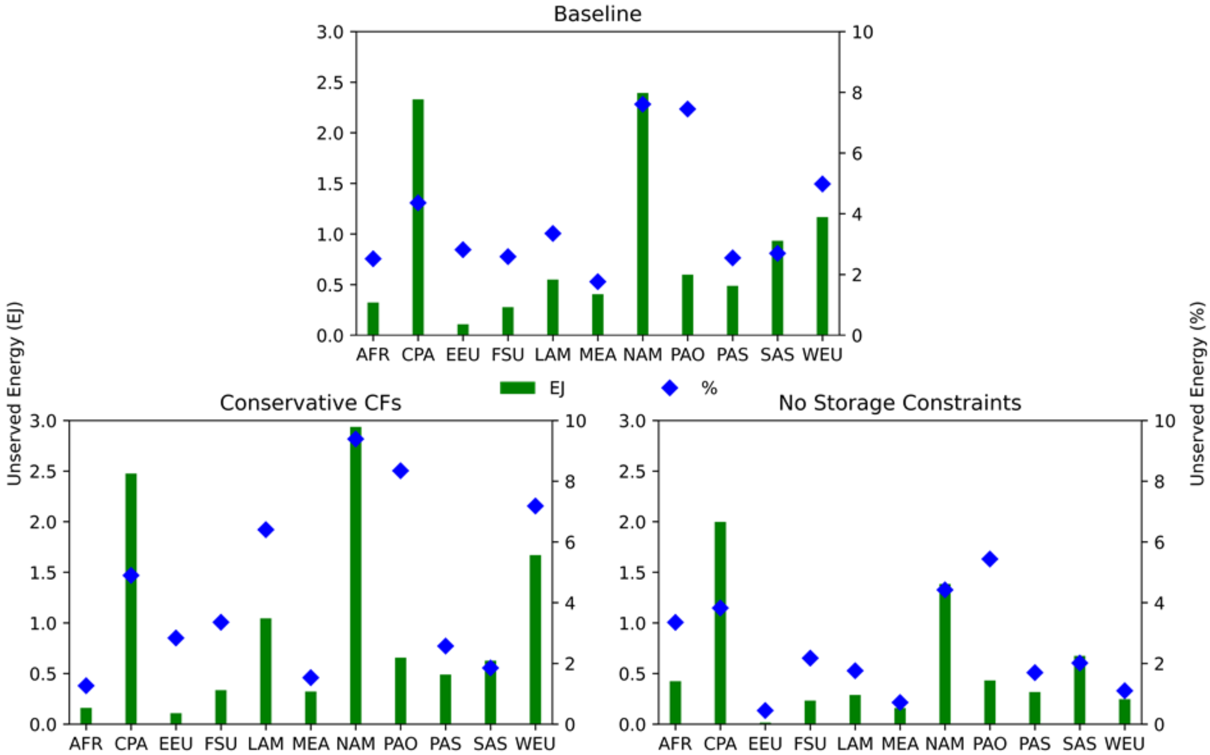


Figure 5-10 Occurrence of unserved energy per PLEXOS-World simulation and region. The green bars represent the absolute values in EJ (primary Y-axis) and the blue markers represent the relative values compared to the regional final electricity demand (secondary Y-axis).

At a global level unserved energy ranges between 2.5-5% of final electricity demand depending on the PLEXOS-World simulation. Unserved energy is lowest in the 'No Storage Constraints' simulation due to the unconstrained competition in investments for storage- and transmission infrastructure. Within this simulation, regions such as NAM who rely for a large share of its electricity supply on operationally low-cost hydro-, nuclear- and wind based powerplants within the given MESSAGEix-GLOBIOM scenario see the largest drop in unserved energy. To optimally utilize these resources it is beneficial to have the ability to share resources through a well integrated regional power system. More details on transmission utilization within the different model simulations will be provided in Sections 5.4.4.4 and 5.4.4.5.

The simultaneous occurance of significant curtailment as well as large scale unserved energy could be seen as paradoxical. The PLEXOS-World simulations indicate that generator capacity and storage are often available in the wrong place at the wrong time leading to both surplus-as shortage of electricity supply. This observation leads to the conclusion that from a regional and temporally coarse perspective following MESSAGEix-GLOBIOM the projected global power system is deemed technically feasible, however the application of the soft-link framework by means of temporally and spatially detailed model simulations in PLEXOS-World higlight that the power system adequacy is insufficient. There are a few key factors that contribute to this aspect which will be discussed next.

5.4.4.3 Firm Capacity

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 matching the relative peak load per country based on [231,287] with the projected electricity demand. Table 5-3 compares the firm capacity requirements as multiplier of average load for 2050 following MESSAGEix-GLOBIOM values [276] and the regionally aggregated demand-weighted values in PLEXOS-World.

Table 5-3 Firm capacity requirements per region in MESSAGEix-GLOBIOM following [18] and in PLEXOS-World for 2050. The values are relative to average annual electricity demand. Values for PLEXOS-World are regional aggregates based on country-level demand weighted values.

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

Compared to MESSAGEix-GLOBIOM, firm capacity requirements per region in PLEXOS-World have a much wider range. It’s also worth noting that the values in Table 5-3 represent a regional average, but that values per country in PLEXOS-World can range significantly. For example values for countries in CPA range from 1.39 to 2.21. Firm capacity requirements in MESSAGEix-GLOBIOM affect the long-term development of the regional generator portfolios. However, the different values in PLEXOS-World creates a situation where for some regions available firm capacity based on the MESSAGEix-GLOBIOM scenario is insufficient to meet peak demand. Furthermore, the widespread occurance of unserved energy for basically all regions suggests that the standardized 20% reserve margin in MESSAGEix-GLOBIOM might not be sufficient.

Next to firm capacity requirements, the largescale VRES curtailment following the PLEXOS-World simulations is an indicator that the assumed contributions of VRES technologies to firm capacity in MESSAGEix-GLOBIOM are overestimated. This overestimation causes negative knock-on effects in the simulated global power system within PLEXOS-World. The capacity allocation in PLEXOS-World incorporates pre-defined firm capacity contributions specific per technology and region in line with MESSAGEix-GLOBIOM to fulfill the set minimum reserve requirements. Yet, if the actual contributions to firm capacity are lower than expected inherently this means that the capacity allocation 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 following MESSAGEix-GLOBIOM assumptions there is a distortion of dispatchable capacity in certain nodes per region versus oversupply of VRES in others explaining the overall low CFs and high curtailment values.

5.4.4.4 Intra-Regional Trade

Despite the distortion in capacity allocation, in an optimally functioning integrated global power system a mismatch between real-time demand and supply of electricity can be mitigated by sharing resources between nodes and regions by means of power pooling through transmision integration. However, the results have shown that because MESSAGEix-GLOBIOM doesn't take intra-regional network constraints into account within the regional copperplates the difficulty of large-scale integration of VRES in terms of matching demand and supply is underestimated. Despite significant intra-regional transmission flows within PLEXOS-World – both land-based as well as through long-distance subsea interconnectors – the built transmission infrastructure cannot sufficiently compensate for the large variability in supply and sub-optimal placement of generator capacities. Other flexibility assets such as electricity storage and hydrogen electrolysis assist with mitigating the mismatch but are not able to handle the required quantities in the simulated global power system based on the MESSAGEix-GLOBIOM scenario. Figure 5-11 shows mapped electricity flows in 2050 for the

'No Storage Constraints' simulation. For contextual purposes, 1 EJ roughly equals the current-day electricity demand of Australia or Mexico.

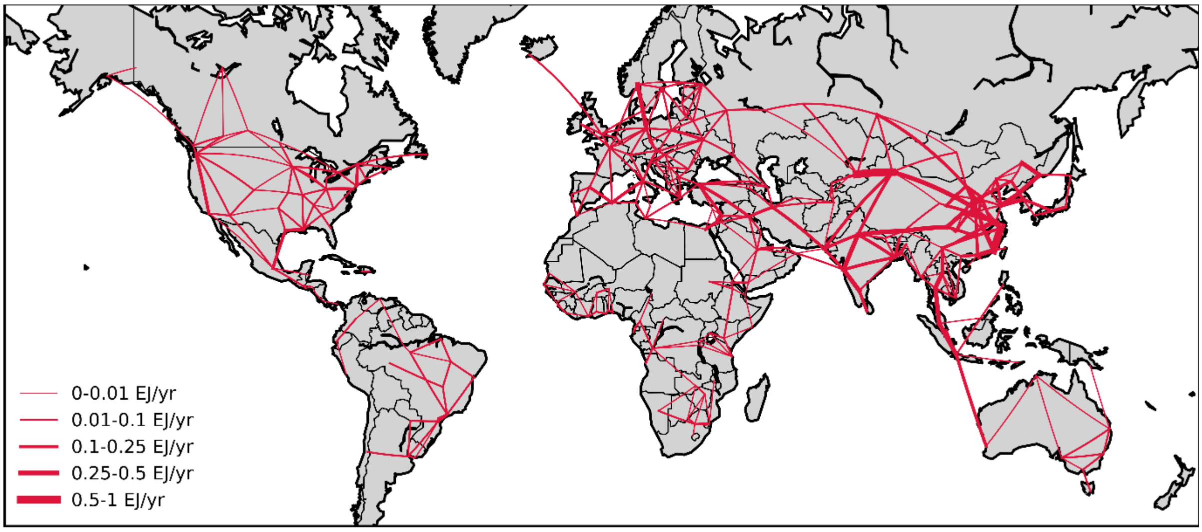


Figure 5-11 Cumulative electricity transmission flows in 2050 for the 'No Storage Constraints' model simulation in PLEXOS-World. Locations of transmission pathways are indicative and do not reflect a geographically accurate representation.

5.4.4.5 Inter-Regional Trade

Figure 5-12 highlights the occurance of inter-regional trade of electricity for both iterations of MESSAGEix-GLOBIOM in comparison to the simulations in PLEXOS-World. The Second Iteration of MESSAGEix-GLOBIOM has adjusted input parameters based on the results of the 'No Storage Constraints' simulation in PLEXOS-World and general PLEXOS-World input parameters – refer to Table D-4 in Section D.3.3 of Appendix D for a full overview. Within the PLEXOS-World results, the 'Conservative CFs' simulation has the overall largest trade. For this simulation the inter-regional transmission flows are a means to compensate for the lower input RES CFs compared to MESSAGEix-GLOBIOM. The 'Baseline' simulation has the lowest trade values correlated to the earlier identified surplus capacity of electricity storage following MESSAGEix-GLOBIOM values. In the 'No Storage Constraints' simulation where the expansion of storage and transmission occurs in competition the inter-regional trade values are significantly higher compared to the 'Baseline' simulation at a net total of 6.3 EJ versus 2.5 EJ globally. To put these values in context, total 2015 inter-regional trade values based on simulations of PLEXOS-World [287] are approximately 0.1 EJ. In line with MESSAGEix-GLOBIOM, the FSU region has been identified as resource rich exporting region within PLEXOS-World albeit with CPA as main importing region compared to South Asia (SAS) in MESSAGEix-GLOBIOM.

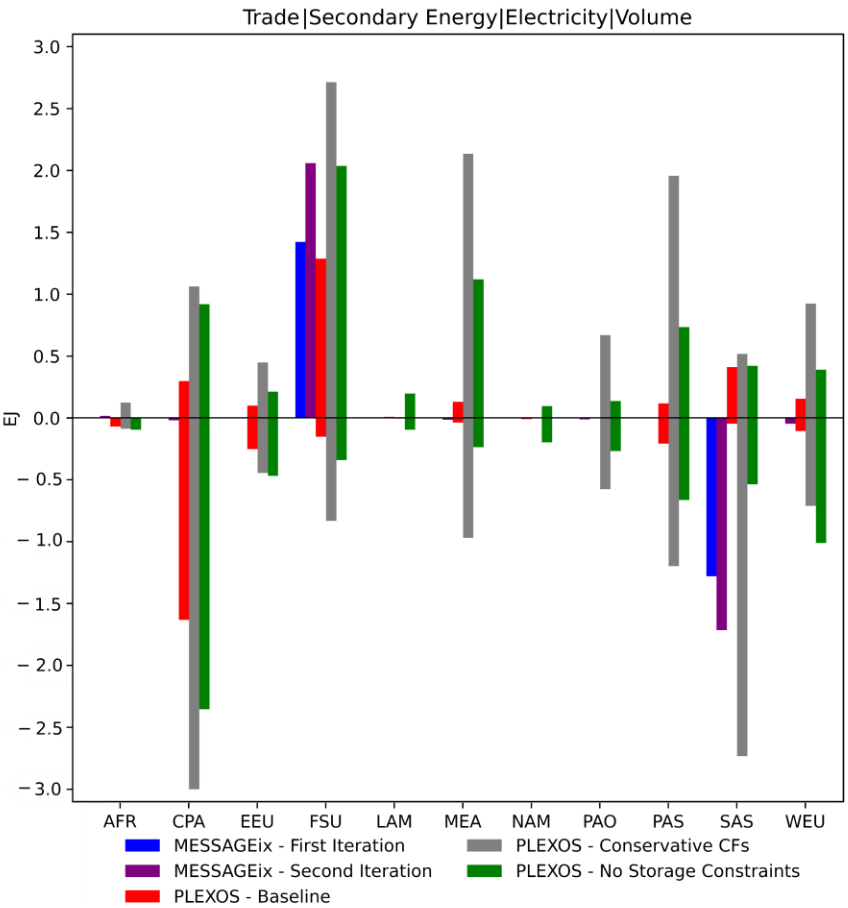


Figure 5-12 Inter-regional electricity trade for the different PLEXOS-World simulations compared to both iterations of the MESSAGEix-GLOBIOM output. Positive values represent export and negative values import.

Compared to PLEXOS-World, the inter-regional trade values for both iterations of MESSAGEix-GLOBIOM are lower. The adjusted input parameters in MESSAGEix-GLOBIOM based on PLEXOS-World stimulate higher inter-regional trade between FSU and SAS as well as a modest uptake of inter-regional trade in other regions. However, considering the relatively minor differences between both iterations, it is clear that the allignment of input parameters in MESSAGEix-GLOBIOM based on PLEXOS-World has minor impact. It can therefore be concluded that the differences in spatial and temporal modelling resolution between MESSAGEix-GLOBIOM and PLEXOS-World are a direct cause for the underutilization of inter-regional trade in MESSAGEix-GLOBIOM. Due to the absence of sub-annual timeslices in the global implementation of MESSAGEix-GLOBIOM, there is a singular decision in the optimization to determine whether inter-regional import or export of electricity is cost-optimal within the modelling period. This means that transmission is solely utilized for bulk unilateral flows of electricity within the modelling period, yet on an aggregate level it does not provide additional flexibility for the power systems involved in the inter-regional trade.

PLEXOS-World for this study operates based on hourly intervals and hence is not only able to assess unilateral flows but also the occurance of bilateral flows for the purpose of balancing electricity demand and supply between regions and for contributions to the mitigation of VRES variability. Furthermore, whereas a singular inter-regional transmission pathway exists between regions in MESSAGEix-GLOBIOM, PLEXOS-World has transmission pathways between all bordering nodes meaning that multiple inter-regional transmission lines between two regions can be operational at any given time. The restrictions in spatial and temporal resolution in MESSAGEix-GLOBIOM inherently means that there is a model bias against the uptake of inter-regional electricity trade.

5.4.5 Study Limitations

Like all modelling tools, PLEXOS-World has its limitations that affect the accuracy of the 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 impact of electric vehicles on bulk storage capacity is limited. 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.

Furthermore, the sampling approach used for deriving representative timeslices as applied for the capacity allocation exercise in PLEXOS-World – see Section D.3.1 of Appendix D for details – has to be assessed in more detail. Increasing the number of timeslices for the full global model is computationally challenging, hence it would have added value to benchmark the results with single-region model simulations with enhanced time slicing. Lastly, by attempting to replicate the MESSAGEix-GLOBIOM scenario in PLEXOS-World as closely as possible 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 allowing PLEXOS-World to optimize the long-term development of generator portfolios and balancing assets without further constraints. This would allow for an actual comparison of the optimal long-term planning in the integrated context in MESSAGEix-GLOBIOM versus a solely optimized planning from a power system perspective with higher detailed spatial, technical, and temporal resolution in PLEXOS-World.

5.4.6 Feedback on Power System Representation in MESSAGEix-GLOBIOM

The proof of concept application of the proposed methodological soft-link framework in this paper has revealed that the differences in modelling resolution between MESSAGEix-GLOBIOM and PLEXOS-World can lead to different results. From a regionally and temporally coarse perspective following MESSAGEix-GLOBIOM the projected global power system is deemed technically feasible. However, the temporally and spatially detailed model simulations in PLEXOS-World higlight that the power system adequacy of the assessed scenario is insufficient. The focus in this paper has been on the global implementation of the MESSAGEix-GLOBIOM model. Hence, suggestions for improvement of the power system representation in MESSAGEix-GLOBIOM are being made in this context. The use of sub-annual timeslices would be beneficial for the representation of VRES, however, to date its integration has been hampered due to its impact on computational complexity and resulting model runtime. Continuous developments regarding faster computers, cloud-based solutions, improved solvers and solving techniques merits a regular reassessment of the feasibility of implementing sub-annual timeslices in the global implementation of MESSAGEix-GLOBIOM.

As part of the modelling effort in parallel to this study, the power system representation in MESSAGEix-GLOBIOM regarding inter-regional trade of electricity has been adapted by integrating bilateral trade through investments in region specific transmission grid infrastructure. Model data and simulation results from PLEXOS-World have been used to inform the input parameters in MESSAGEix-GLOBIOM for this new setup. However, modelling results from the updated version of MESSAGEix-GLOBIOM indicate an underestimation of inter-regional trade potential as a result of the limited spatial and temporal modelling resolution. All technologies in MESSAGEix-GLOBIOM have pre-defined values relative to their capacity for assumed positive or negative contributions to power system flexibility. To date it is assumed that inter-regional trade of electricity has positive contributions to system flexibility for the exporting region whereas inter-regional trade for the importing region has an equal negative contribution – i.e. it needs equally sized additional domestic flexibility to compensate for the import of electricity from another region. On a macro level this means that inter-regional trade does not contribute to flexibility in the power system within

MESSAGEix-GLOBIOM which may restrict investments in new transmission capacity. Studies assessing the benefit of large-scale transmission integration in power systems with high VRES penetration higlight the potential for cross-border transmission as a means to provide flexbility, among others due to often asynchronous occurences of peaks and lows in electricity demand and VRES generation in different regions [227]. Transmission integration in this context can decrease the need for domestic reserves providing flexibility [168,308–310]. With this in mind it is recommended to reassess whether an equal negative contribution to flexibility for importing regions in MESSAGEix-GLOBIOM is overly conservative. The trade values in PLEXOS-World can act as a baseline to calibrate the flexibility contributions for inter-regional trade in MESSAGEix-GLOBIOM.

As of now MESSAGEix-GLOBIOM includes a single generic electricity storage technology with 24-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 PSH 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 would help with mitigating peaks in supply from especially Solar-PV. Next to storage, the integration of demand side management could assist with shifting of peaks in electricity demand to decrease the likelihood of occurance of unserved energy.

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

The PLEXOS-World simulations have shown that the large-scale integration of VRES based on the MESSAGEix-GLOBIOM scenario is accompanied by the occurance of both significant electricity curtailment as well as unserved energy in electricity demand. Hence, it can be argued that the contribution of VRES technologies to firm capacity in MESSAGEix-GLOBIOM is overvalued and that a standardized reserve margin of 20% might not be sufficient. From a power system adequacy perspective, given the limitations in modelling resolution and model assumptions within global IAMs such as the unconstrained intra-regional power pooling, it is merited to be rather conservative when it comes to estimating parameters for the integration of VRES. The above aspects and a range of other stylized parameters and input assumptions such as region-specific curtailment parameters and technology CFs could benefit from being updated based on the spatially and temporally detailed modelling in PLEXOS-World. By means of the developed soft-link framework in this study, results from PLEXOS-World can be directly fed back into MESSAGEix-GLOBIOM as has been shown by the proof of concept for inter-regional electricity trade.

5.5 Conclusions and Discussion

To date, a large part of global analyses on climate change mitigation is based on modelling results from global IAMs. However, within the scientific community an ongoing debate exists regarding the suitability of IAMs for among others the long-term planning of the global energy system [300,301]. From a power system perspective, the critique focuses among others on the limited replication of integrational- and operational challenges following high levels of VRES [300]. In recent years the IAM community has made efforts to improve the power system representation in global IAMs [13,56,264,269,276–280] as well as general efforts regarding model evaluation and transparency [302,311–313]. However, 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 [300]. To fill this gap, 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. Within the framework, scenarios are not assessed based on the regionally coarse spatial representation of global IAMs as is. Rather, the long-term capacity expansion capabilities of power system models are used to downscale the regional copperplates as used in the IAM to a more spatially defined level. The use of standardized data formats and where possible automated workflows within the framework allow for efficient replication of the soft-link exercise. The proposed soft-link framework can be used as a method to put boundaries on the theoretical debate regarding the suitability of global IAMs for the long-term planning of power systems. It can furthermore be used as a template for soft-linking of global IAMs to other dedicated sectoral models.

By means of a proof of concept application of the soft-link framework through soft-linking of global IAM MESSAGEix-GLOBIOM with global power system model PLEXOS-World, the results of this paper reflect that global IAMs are not constructed with the aim to perform spatially and temporally detailed assessments of power system operations. That said, it is the authors' view that this not necessarily means that global IAMs are unsuitable for providing boundaries in possible mitigation pathways for the development of the global 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 do not permit simulations for long-term horizons – an average model run of PLEXOS-World based on the 2050 snapshot analysis in context of this study takes approximately 12 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, we conclude that IAMs can be applied for long-term planning of the global power system assuming benchmarking with dedicated sectoral models occurs regularly. By making use of the soft-link framework proposed in this study, power system models like PLEXOS-World can be used in a complimentary fashion to pinpoint areas for model-informed improvements in global IAMs.

Chapter 6 Conclusions

This thesis provides a foundation for assessments of global power system decarbonization pathways by developing open methods and datasets that can be applied to a broad range of modelling tools. In order, Chapters 2-5 bring forth a review of relevant literature, a proof of concept of modelling methodologies, insights in model development and calibration and finally an example model application. The developed global power system model PLEXOS-World is used to analyse the potential role of long-distance electricity transmission in context of a globally integrated power grid. It is furthermore being used to assess the technical feasibility of power system representation in global IAMs and to provide suggestions for model-informed improvements. This final chapter concludes the thesis by summarizing gained insights from the different chapters. The original aim of this thesis was defined in a set of research questions as stated below. These questions will be answered in the following sections by topic, being i) state of the art in global power system modelling, ii) the use of open data, methods and models, iii) intercontinental electricity transmission and iv) analysis of power system representation in global IAMs.

- **RQ-1.** What is the present state of the art in the application of global power system models?
- **RQ-2.** What is the status of open power systems data and what are the shortcomings for utilizing open data in global power systems modelling?
- **RQ-3.** What insights can be provided regarding best practices in using proprietary energy systems modelling software for academic purposes?
- **RQ-4.** What are the techno-economic benefits and limitations of long-distance transmission of electricity and the concept of a globally integrated power grid?
- **RQ-5.** What are the main limitations in the power system representation of global IAMs?
- **RQ-6.** How can global power system models be utilized as a complementary tool for global IAMs and facilitate methodological improvements within global IAMs?

6.1 Conclusions on State of the Art in Global Power System Modelling (RQ-1)

The scientific discipline of power systems modelling is novel at the global scale. Chapter 4 highlights how until recently the application of global power system models could have been seen as impractical. Electricity to date is mostly produced and consumed domestically or within integrated power markets at a multi-country scale which does not necessitate the use of global models. However, as argued in Chapter 2, required decarbonization efforts in power systems globally have led to a growing interest in the concept of sharing of resources by means of long-distance transmission of electricity at a continental or inter-continental scale [18,75,113]. The potential role and feasibility of transmission interconnectors in this context merits the utilization of a detailed global power system model.

Existing techno-economic modelling studies of a future global power grid are shown to be limited, both in terms of quantity of studies and moreover regarding spatial and technological resolution applied in the modelling that lead to over simplified results and conclusions. There is a gap within the modelling community regarding tools that are able to assess this concept with sufficient detail. The developed PLEXOS-World global power system model following this thesis contributes to this gap by means of (ongoing) research in the feasibility and functionality of a global grid. The open source Supergrid[16] model that recently surfaced has the same potential. Next to global grid modelling, other existing applications of global power system models relate to the assessment of power- and full energy systems based on 100% RES [8,42,60–62]. Although very relevant from a feasibility perspective, the inherent technology bias in these modelling studies provides a narrow scope on potential cost-efficient decarbonization pathways. In recent past, IRENA has developed a novel global power system model build in PLEXOS that has the integrated ability for co-optimization of global hydrogen production, transport and conversion next to temporally detailed power system modelling [314].

Compared to other existing global power system models, PLEXOS-World is state of the art when it comes to its ability to run spatially detailed power system simulations at high temporal resolution. It is therefore most suitable to perform assessments of the technical feasibility of projected developments such as the integration of high shares of variable renewables or the coupling of power systems through transmission interconnection. In the proof of concept application of PLEXOS-World in Chapter 3 it was stated that going forward, limitations as a result of computational modelling complexity for the global model were

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

expected to be of modest impact. Looking back this observation can partly be confirmed. Indeed, computational time for UCED simulations in PLEXOS-World are manageable due to advanced solvers and solving techniques. The possibility of parallelizing simulation steps in detailed models for example as applied in Chapter 4 allows for simulations to be performed in a matter of hours without utilizing high performance computers or cloud-based solutions. However as highlighted in Chapter 5, the main limitation of the model besides a lack of interactions with other sectors is its limited ability to perform long-term planning exercises of the global power system. For the latter, a trade-off would have to be made by reducing the spatial, technical, and temporal detail which would hamper the main strengths of the model based on which it is designed. As it stands, other global models such as the recently developed OSeMOSYS global[17] are more suitable for this purpose.

Rather than reducing detail to allow for long-term planning in global power system models, an alternative approach is to make use of scenario data from dedicated planning models like IAMs or energy system models through model soft-linking. The developed methodological framework following Chapter 5 is designed to automate this process. The applied model soft-link between PLEXOS-World and global IAM MESSAGEix-GLOBIOM to assess and improve the power system representation in MESSAGEix-GLOBIOM is a novelty in terms of the application of power system models.

Overall global power system modelling as a new area of research has significant room for growth. Both in terms of extending the scope and detail of studies on existing topics as well as by interlinking with other modelling disciplines in the space of climate-, environmental- and wider energy systems modelling. It furthermore has the potential to directly contribute to informing global energy policy alongside other proven energy modelling tools.

6.2 Conclusions on Open Data, Methods and Models (RQ-2 and RQ-3)

In the introduction of this thesis it has been argued that energy research tends to lag behind other scientific disciplines when it comes to open and reproducible science [32,33]. Focussing on global power systems modelling, the majority of existing global modelling tools are indeed not available in the public domain with the exception of the Supergrid model[16]. The developed PLEXOS-World model cannot be categorized as either a fully open or fully closed tool. The

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

software used PLEXOS is freely available for academic use with subscription based fees for commercial application. The formulation of the model is transparent – refer to Appendix A – and the PLEXOS-World models as used for Chapter 4 and Chapter 5 including all input data have been made available in raw data format to be FAIR compliant.

Chapter 4 highlights relevant open data initiatives for the modelling of power systems globally. However, both Chapter 3 and Chapter 4 indicate that gaps still exist for areas outside Europe and North America for example when it comes to aspects such as details on powerplant portfolios and demand timeseries. The PLEXOS-World dataset developed in Chapter 4 feeds into this gap by providing an entry level comprehensive global dataset that can be used in PLEXOS or plugged into other modelling tools. Furthermore, the in 2019 published GlobalEnergyGIS package[18] enables the automated development of renewable energy input data and synthetic demand timeseries for arbitrary world regions to be used for scenario analysis in energy system models [28]. Although there is still a need for enhanced insights and transparency in operational power systems data especially for developing countries, the wide range of open data initiatives in recent years have pushed the boundaries for energy systems modelling globally [23–25,28,251].

One of the original objectives of this thesis was to develop tools, methods and data that can support capacity building efforts to enable researchers around the world to contribute to energy and climate science. The PLEXOS-World model and dataset have been widely adopted externally through its public repository [231]. IRENA makes use of the datasets as one of the sources to populate their global hydrogen and power system model [314]. To push for open models able to assess power system developments from a global perspective, the open source OSeMOSYS global model generator[17] is being constructed that uses the PLEXOS-World dataset as foundation [315]. Furthermore, the dataset is also being used for the development of energy modelling country starter kits in OSeMOSYS for developing countries globally (e.g. [316]) as part of the Climate Compatible Growth initiative[19]. Finally, the open source methodological framework for soft-linking of global IAMs with global power system models as developed in Chapter 5 has been used to inform and improve the power system representation in global IAM MESSAGEix-GLOBIOM. By extension, the work in this thesis

[18] https://github.com/niclasmattsson/GlobalEnergyGIS
[19] https://climatecompatiblegrowth.com/starter-kits

indirectly contributes to the work done globally with MESSAGEix-GLOBIOM. In a similar manner, the framework is currently being used in ongoing collaboration with other leading IAM teams as part of the ENGAGE project[20].

Next to openness, reproducibility of data and methods is key for energy research and science in general. The PLEXOS-World dataset following Chapter 4 is developed with the 2015 calendar year as baseline. There is interest to expand and update the dataset for more recent years, yet the wide range of sources with often very different data formats makes automation complicated and hence reproducibility time intensive. Chapter 3 applied a soft-link methodology to integrate scenario data from a range of different studies into a proof of concept version of PLEXOS-World. This exercise showed the complications of repeating a soft-link exercise, especially when it comes to integrating data from different sources. A review on linking methodologies as conducted in Chapter 5 highlights how concerns regarding repeatability of soft-linking techniques is often a key argument against its application [276,290]. The soft-link framework for linking global IAMs with global power system models as developed in Chapter 5 overcomes this argument by partly automating and standardizing the link between both model types. That said, the key to its success is the fact that scenario data from a wide range of IAMs is reported in a consisted manner by means of the IAMC data template format in openly accessible data depositories. This data consistency is unique for IAMs and not directly applicable to other model types which makes soft-linking not always straight-forward.

To conclude, significant efforts have been made in recent years to push for open and reproducible science within the energy research community. The use of open source modelling tools is key in terms of transparency, however the work in this thesis has also brought forth insights regarding best practices in the application of tools like PLEXOS. Aspects such as its large user base, available support system, convenient user interface and wide application potential for modelling of the full energy system allows you to hit the ground running. This is especially relevant for smaller research groups where the time and resources are not always available to develop inhouse tools or integrate a wider set of open source models for diverse research questions. Whatever tool is being used, it is critical to be fully

[20] https://www.engage-climate.org/

transparent in model formulation, data inputs, applied methods and to support the adoption and shareability of model data as emphasised in the literature [24,32,33,313].

6.3 Conclusions on Intercontinental Electricity Transmission (RQ-4)

An emerging global trend is visible in the integration of electricity markets by means of cross-border transmission of electricity. Due to its success in for example Europe and China, the logical next step would be to assess the feasibility of extending this integration across continents to a globally interconnected power grid. However, opinions are divided on the technical feasibility as well as on the overall benefits compared to alternative solutions for deep decarbonization of the global electricity supply [65,66,317]. During the last two decades, overly ambitious transmission projects aimed to interconnect different continental power markets have failed due to uncertainty regarding investment costs-, benefits- and risks as well as a lack of political support.

Techno-economic modelling can provide the necessary insights for objective assessments of the technical- and economic feasibility of proposed interconnection projects and the global grid concept as a whole. A review of scientific literature in Chapter 2 indicates potential benefits of power system integration towards a global grid, however, the accuracy of performed modelling studies to date are affected by limitations in spatial and technological modelling resolution. Until now, no single techno-economic assessment exists based on a globally optimized power system with sufficient detail to provide insights from a global perspective, while also capturing local dynamics needed to ensure system adequacy or to assess domestic welfare implications. Furthermore, there is a lack of benchmarking of envisioned cost-benefits compared to alternative system setups such as decentralized demand and supply of electricity or a global interconnected electricity system with transportable green hydrogen as main energy carrier rather than physical transmission infrastructure. Chapter 3 introduced a project aimed to do the above, however this work is ongoing at the time of writing among others as a result of the identified complexity of capacity expansion exercises in a detailed global power system model.

Following the review in Chapter 2, the ability to integrate areas with high potential for RES with larger demand centers around the world as well as the potential to smooth demand and supply by means of time-zone and seasonal differences are often considered as main arguments for intercontinental interconnectors and the global grid concept [29,113,161–

164]. The modelling as performed in Chapter 5 confirms this potential by optimizing the capacity expansion and operation of transmission infrastructure in a given scenario from MESSAGEix-GLOBIOM. The results show how resource rich regions like Australia, the Middle East and Russia can be used to supply growing markets in among others Asia. The results also indicate the benefits of latitudinal transmission integration within Asia and between Asia and Europe to make optimal use of time-zone differences. Chapter 3 also highlights how by means of a conceptual transmission interconnector between the East coast of the US and Western Europe the dispatch of powerplants can be optimized through a larger region among others due to different occurrences of peaks in demand following the time zone differences. Similar observations have been made by [164].

The significant investment costs and transmission losses of long-distance transmission infrastructure projects are one of the key arguments negating the potential benefits of the global grid concept. However, Chapter 5 shows that from a central planner perspective objectively speaking investments in intercontinental transmission lines can be merited. That said, the results also indicate that there is a limit on the marginal benefits of additional investments in transmission infrastructure. Despite significant unserved energy and occurance of electricity curtailment, the benefits of additional transmission infrastructure does not always outweigh the required investments. Overall, it can be concluded that the feasibility of projects need to be determined on a case by case basis. Following the review in Chapter 2, besides costs and losses, a big factor in this is also the appropriate investment mechanism to determine whether projects are feasible from a merchant investment perspective or whether a regulated investment strategy should be anticipated since the system wide advantages of transmission infrastructure justifies projects to be treated as public good.

A second hurdle that needs to be overcome are aspects related to the integration of power systems with different market structures. For example, Chapter 3 shows the sensitivity of applied carbon pricing mechanisms on electricity flows of the modelled interconnector between the East coast of the US and Western Europe. Following a reference scenario in the US without carbon pricing, the interconnector is mostly used to facilitate the dispatch of fossil fuel based thermal powerplants in the US to supply the European market while displacing cleaner alternatives in Europe. From a market and policy perspective this seems unacceptable. Chapter 4 indicates how from a purely technical perspective with existing transmission infrastructure the benefits of electricity trade between for example Europe and Russia are significant. However, despite the technical potential being there, political considerations or different market structures in the real world hamper its full potential. Given the spatial scale of electricity markets in context of the global grid concept, the implementation of clear market rules and appointment of regulating authorities are critical as also emphasised in the literature [30,65,88].

In the review in Chapter 2 it has been concluded that the challenges and opportunities of the global grid concept are clearly qualified, yet that the actual quantification of costs, benefits and environmental implications of the concept remains in its infancy, imposing a significant gap in the scientific literature. Roughly three years after publication this conclusion still stands. Despite a growing number of papers on the topic in recent years [30,317], the identified limitations in among others techno-economic modelling are still applicable. Hence, as argued, as long as the detailed costs and benefits of the global grid concept remain largely unquantified, it is inherently impossible to objectively inform policy development and decision-making.

6.4 Conclusions on Analysis of Power System Representation in Global IAMs (RQ-5 and RQ-6)

Due to their long track record and ability to analyse interlinked sectoral developments, IAMs are the main tools used to assess potential pathways for the long-term evolution of the global energy system. In Chapter 5 it has been argued that from a purely power system perspective dedicated sectoral power system models might be more suited for this exercise given the importance of accurately representing power system integration challenges with rapidly growing shares of VRES. However, for the time being, limitations on computational complexity for temporally detailed model simulations as well as a narrow modelling scope due to a lack of interactions with other sectors sets a limit on the usefulness of power system models in this context.

Continuous improvement of power system representation within global IAMs is essential due to its known limitations in spatial, technical, and temporal modelling resolution. Improvements can be sought internally, for example by assessing whether the integration of sub-annual timeslices is feasible. Yet, there are limits to the extent of feasible internal improvements both regarding computational complexity as well as available time resources [300]. A useful approach is therefore to make use of complementary power system models to benchmark IAM simulation results and to assist with optimizing the power system representation within the IAM. Most common is to apply a one-directional model soft-link due to the complexity of facilitating data exchange between models. However, bi-directional soft-linking should be encouraged to support power system model informed improvements of long-term planning exercises within IAMs.

A review of scientific literature in Chapter 5 regarding existing IAM and power system model soft-linking exercises indicates that the main concern for its application are difficulties to repeat a soft-link among others due to changing data formats or different users involved [276,290]. The soft-link exercise as applied in Chapter 3 highlights the complications of integration scenario data based on different data formats into PLEXOS-World. Following these observations, a standardized methodological soft-link framework has been developed in Chapter 5 that enables the bi-directional soft-linking of global IAMs with global power system models in an iterative fashion.

Limitations in the power system representation of global IAMs and potential areas for improvement are generally well documented and fall in two larger categories. The first category relates to extending the data basis to enhance the overall spatial representation as well as refined implementation of region specific IAM data input- and assumptions. Datasets such as the PLEXOS-World 2015 dataset as developed in Chapter 4 can assist with that, for example by using detailed country-level electricity demand timeseries to improve the RLDCs as used in most global IAMs. Furthermore, power system model simulation output can be used to finetune generic IAM model inputs at a regional level. As an example, in Chapter 5 it has been shown how model output from PLEXOS-World has been used to inform global IAM MESSAGEix-GLOBIOM regarding the modelling of bilateral electricity transmission infrastructure with region specific input parameters.

The second category of potential IAM model improvements relates to the representation of power system technologies and the general model structure of stylized relationships that replicate power system integration challenges within IAMs. Following the literature, examples that merit prioritization are the representation of storage technologies including power-to-X, parameterization of thermal power plants, explicit modelling of demand side management 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 [13]. By means of a proof of concept application of the soft-link framework in Chapter 5 linking PLEXOS-World and MESSAGEix-GLOBIOM it has been shown that the assumption of unconstrained electricity flows inside large regional copperplates causes an overestimation of VRES integration potential within MESSAGEix-GLOBIOM. In the case of MESSAGEix-GLOBIOM the soft-link has also shown that some stylized relationships are inherently not incorrect, for example the assumption that accounted costs for T&D should increase relative to the area size of the specific region and the relative VRES penetration. However, the parameters could benefit from model informed adjustments by means of the soft-link framework.

Overall, it can be concluded that global IAMs are useful tools to provide boundaries on potential development pathways for the global energy system. That said, it is essential that the power system representation is regularly benchmarked with dedicated power system models to secure model accuracy.

6.5 Future Work

This thesis provides an initial introduction to the wide range of possibilities in the application of global power system models, however it is by no means designed to give conclusive answers to all questions possible. Future work lies in two directions, the first being improvements and extensions of model data and applied methods and the second relates to the application of the PLEXOS-World model and its underlying datasets.

6.5.1 Data and Methods

The PLEXOS-World model and dataset as developed in Chapter 4 including all used demand- and renewables timeseries are fully based on the 2015 calendar year. For model calibration purposes this is justifiable, however for application in feasibility studies as for example in Chapter 5 it is recommended to make use of a wider set of data years to assess the robustness of a given system under different conditions. Future applications of PLEXOS-World require a wider range of timeseries to be applied, this can either be done by means of different calendar years or through stochastic modelling. Furthermore, expected electrification in among others the heating- and transportation sectors will affect the relative shape of demand timeseries which to date has not been incorporated. This, as well as the potential for flexible load in these sectors, is a subject for further examination.

The PLEXOS-World dataset following Chapter 4 has proven to be successful in terms of external adoption and overall engagement. In a next phase the model and datasets will be updated to a more recent baseline year, for example 2020. Albeit challenging due to a wide range of data sources, the aim is to do this in a mostly automated fashion to allow for more regular updates in the years to come.

It has been argued that until now the application of long-term planning exercises within PLEXOS-World is computationally not feasible at its high spatial, technological, and temporal modelling resolution. However, there are sufficient arguments to keep pursuing this goal for example to objectively compare long-term planning pathways from a purely power system perspective to those from cross sector models like IAMs. To achieve this, one solution would be to make use of cloud-based solutions for advanced computational power yet this would put restrictions on the external useability of the model. An alternative is to reduce the complexity of the optimization by finding the optimal balance in modelling resolution suitable for the scope of the specific research question [318,319].

6.5.2 Model Application

Given the identified limitations of the PLEXOS-World model – i.e. the complexity of long-term planning exercises, the lack of interactions with other sectors in the energy system and its restrictions in openness – the open source OSeMOSYS global model generator[17] is currently being developed that uses the PLEXOS-World datasets as foundation. Once completed, OSeMOSYS global can be used for the long-term planning of energy systems and can be applied to any combination of countries and regions or for the full global energy system. It can be used standalone or as shown in a recent proof of concept application soft-linked to PLEXOS-World [320]. By using similar techniques as in Chapter 5, the results from the long-term planning in OSeMOSYS global can be fed to PLEXOS-World for an operational analysis of the projected power system.

One of the applications of the OSeMOSYS global and PLEXOS-World soft-link in the pipeline is focused on the global grid concept. Based on the earlier identified limitations of existing techno-economic modelling studies of global grids, OSeMOSYS global will be used to perform long-term planning exercises at detailed spatial resolution with different levels of allowed power system integration ranging from local demand and supply to a fully integrated global power system. This will provide insights on the cost-optimality of a global grid and simultaneously allows for benchmarking with alternative system setups. PLEXOS-World will be used to benchmark the feasibility of results, perform assessments of overall system adequacy and to provide detailed insights in electricity trade and flows within the global market.

Finally, the methodological soft-link framework from Chapter 5 will be further utilized in ongoing collaboration with nine global IAM teams as part of the ENGAGE project. A set of scenarios as designed for the IPCCs forthcoming Sixth Assessment Report will be assessed in PLEXOS-World regarding the technical feasibility of the projected power systems globally. Furthermore, following the recommendations in Chapter 5 regarding the power system representation in MESSAGEix-GLOBIOM, PLEXOS-World will be used for further benchmarking of simulation results from MESSAGEix-GLOBIOM to assess the effect of integrated improvements such as the addition of sub-annual timeslices. Additional work that needs to be carried out relates to the application of the soft-link framework to power system models other than PLEXOS-World to test its overall robustness.

Bibliography

[1] Cozzi L, Gould T, Bouckart S, et al (2020). World Energy Outlook 2020. International Energy Agency, Paris, ISBN: 0872625710

[2] Le Quéré C, Jackson RB, Jones MW, et al (2020). Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nature Climate Change 10: 647–653. doi: 10.1038/s41558-020-0797-x

[3] IMF (2020). World Economic Outlook, April 2020: The Great Lockdown. International Monetary Fund, Washington DC, ISBN: 1557757402

[4] OECD (2020). Making the Green Recovery work for jobs, income and growth

[5] WRI (2020). Climate Watch Historical GHG Emissions. World Resources Institute, Washington DC. Available online at: https://www.climatewatchdata.org/ghg-emissions

[6] 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

[7] 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

[8] Jacobson MZ, Delucchi MA, Cameron MA, et al (2015). Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes. Proceedings of the National Academy of Sciences 112: 15060–15065. doi: 10.1073/pnas.1510028112

[9] Clack CTM, Qvist SA, Apt J, et al (2017). Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar. Proceedings of the National Academy of Sciences 114: 6722–6727. doi: 10.1073/pnas.1610381114

[10] Jacobson MZ, Delucchi MA, Cameron MA, et al (2017). The United States can keep the grid stable at low cost with 100% clean, renewable energy in all sectors despite inaccurate claims. Proceedings of the National Academy of Sciences 114: E5021–E5023. doi: 10.1073/pnas.1708069114

[11] Heard BP, Brook BW, Wigley TML, et al (2017). Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems. Renewable and Sustainable Energy Reviews 76: 1122–1133. doi: 10.1016/j.rser.2017.03.114

[12] Brown TW, Bischof-Niemz T, Blok K, et al (2018). Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems.' Renewable and Sustainable Energy Reviews 92: 834–847. doi: 10.1016/j.rser.2018.04.113

[13] 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

[14] 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

[15] 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

[16] 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

[17] 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

[18] Barbosa L de SNS, Bogdanov D, Vainikka P, et al (2017). Hydro, wind and solar power as a base for a 100% renewable energy supply for South and Central America. Plos One 12: doi: 10.1371/journal.pone.0173820

[19] Aghahosseini A, Bogdanov D, Breyer C (2017). A Techno-Economic Study of an Entirely Renewable Energy-Based Power Supply for North America for 2030 Conditions. Energies 10: 1171. doi: 10.3390/en10081171

[20] He G, Avrin AP, Nelson JH, et al (2016). SWITCH-China: A Systems Approach to Decarbonizing China's Power System. Environmental Science and Technology 50: 5467–5473. doi: 10.1021/acs.est.6b01345

[21] Sharma T, Glynn J, Panos E, et al (2019). High performance computing for energy system optimization models: Enhancing the energy policy tool kit. Energy Policy 128: 66–74. doi: 10.1016/J.ENPOL.2018.12.055

[22] Barrows C, Hummon M, Jones W, et al (2014). Time Domain Partitioning of Electricity Production Cost Simulations. doi: NREL/TP-6A20-60969

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

[24] 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

[25] 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

[26] Staffell I, Pfenninger S (2016). Using bias-corrected reanalysis to simulate current and future wind power output. Energy 114: 1224–1239. doi: 10.1016/j.energy.2016.08.068

[27] Zickfeld F, Wieland A, Bartolot J, et al (2013). Desert Power : Getting Started. ISBN: 978-3-944746-09-8
[28] Mattsson N, Verendel V, Hedenus F, et al (2021). An autopilot for energy models – Automatic generation of renewable supply curves, hourly capacity factors and hourly synthetic electricity demand for arbitrary world regions. Energy Strategy Reviews 33: 100606. doi: 10.1016/j.esr.2020.100606
[29] Chatzivasileiadis S, Ernst D, Andersson G (2013). The Global Grid. Renewable Energy 57: 372–383. doi: 10.1016/j.renene.2013.01.032
[30] Yu J, Bakic K, Kumar A, et al (2019). TB 775 - Global electricity network - Feasibility study. ISBN: 9782858734771
[31] GEIDCO (2017). White Paper on Global Energy Interconnection; Development Strategy. Beijing
[32] Pfenninger S, DeCarolis J, Hirth L, et al (2017). The importance of open data and software: Is energy research lagging behind? Energy Policy 101: 211–215. doi: 10.1016/j.enpol.2016.11.046
[33] Huebner GM, Fell MJ, Watson NE (2021). Improving energy research practices: guidance for transparency, reproducibility and quality. Buildings and Cities 2: 1–20. doi: 10.5334/bc.67
[34] Open Knowledge Foundation (2021). Open Definition; Defining Open in Open Data, Open Content and Open Knowledge. http://opendefinition.org/od/2.1/en/. Accessed 26 Jan 2021
[35] Sovacool BK (2014). What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda. Energy Research and Social Science 1: 1–29. doi: 10.1016/j.erss.2014.02.003
[36] IRENA (2020). Energy Planning and Modelling Support in Africa. Abu Dhabi
[37] Energy Exemplar (2020). PLEXOS Market Simulation Software. https://energyexemplar.com/solutions/plexos/. Accessed 8 Oct 2020
[38] 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
[39] Eurelectric (2018). Decarbonization pathways; European economy; EU electrification and decarbonization scenario modelling; Synthesis of key findings
[40] International Energy Agency (2017). World Energy Outlook 2017. Paris, doi: 10.1787/weo-2017-en, ISBN: 9789264243668
[41] Deng YY, Haigh M, Pouwels W, et al (2015). Quantifying a realistic, worldwide wind and solar electricity supply. Global Environmental Change 31: 239–252. doi: 10.1016/j.gloenvcha.2015.01.005
[42] Jacobson MZ, Delucchi MA, Bauer ZAF, et al (2017). 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. Joule 1: 108–121. doi: 10.1016/j.joule.2017.07.005
[43] Edenhofer O, Pichs Madruga R, Sokona Y, et al (2012). Renewable Energy Sources and Climate Change Mitigation (Special Report of the Intergovernmental Panel on Climate Change). Cambridge University Press, Cambridge, doi: 10.5860/CHOICE.49-6309, ISBN: 9781107607101
[44] Denholm P, Margolis RM (2007). Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems. Energy Policy 35: 2852–2861. doi: 10.1016/j.enpol.2006.10.014
[45] Pierre I, Bauer F, Blasko R, et al (2011). Flexible generation: Backing up renewables. Brussels
[46] Ulbig A, Borsche TS, Andersson G (2014). Impact of low rotational inertia on power system stability and operation. In: Proceedings of the 19th World Congress The International Federation of Automatic Control Cape Town, South Africa. August 24-29, 2014. IFAC, pp 7290–7297
[47] 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
[48] 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
[49] Fuller RB, Kuromiya K (1982). Critical Path. St. Martin’s Griffin, ISBN: 0312174918
[50] UN (1971). Committee on natural resources, report on the 1st session, 22 February - 10 March 1971, Economic and Social official records, 50th session, supplement no.6. New York, ISBN: 0309291291
[51] UN (2015). Towards Win-win Partnership for Sustainable Development; Remarks by H.E. Xi Jinping, President of the People’s Republic of China. In: United Nations Sustainable Development Summit, New York, 26 September 2015. p 5
[52] UN (2017). Advancing the Sustainable Development Goals, António Guterres, United Nations Secretary General. UN
[53] Ardelean M, Minnebo P (2015). JRC technical reports; HVDC Submarine Power Cables in the World; State-of-the-Art Knowledge. doi: 10.2790/95735, ISBN: 9789279527852
[54] International Renewable Energy Agency (IRENA) (2017). REthinking Energy: Accelerating the global energy transformation. Abu Dhabi, ISBN: 978-92-95111-06-6
[55] International Renewable Energy Agency (IRENA) (2018). Renewable capacity statistics 2018. Abu Dhabi, ISBN: 9789295111905
[56] 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
[57] Cochran J, Bird L, Heeter J, et al (2012). Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience, Summary for Policymakers. Golden, Colorado
[58] Bertsch J, Growitsch C, Lorenczik S, et al (2016). Flexibility in Europe’s power sector — An additional requirement or an automatic complement? Energy Economics 53: 118–131. doi: 10.1016/j.eneco.2014.10.022
[59] Guo B, Niu M, Lai X, et al (2018). Application research on large-scale battery energy storage system under Global

Energy Interconnection framework. Global Energy Interconnection 1: 79–86.
[60] Ram M, Bogdanov D, Aghahosseini A, et al (2017). Global energy system based on 100% renewable energy - power sector. Lappeenranta, ISBN: 978-952-335-171-4
[61] 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
[62] Fthenakis V, Mason JE, Zweibel K (2009). The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US. Energy Policy 37: 387–399. doi: 10.1016/j.enpol.2008.08.011
[63] Mileva A, Johnston J, Nelson JH, et al (2016). Power system balancing for deep decarbonization of the electricity sector. Applied Energy 162: 1001–1009. doi: 10.1016/j.apenergy.2015.10.180
[64] MacDonald AE, Clack CTM, Alexander A, et al (2016). Future cost-competitive electricity systems and their impact on US CO2 emissions. Nature Climate Change 6: 526–531. doi: 10.1038/nclimate2921
[65] Robinson D (2017). Economic and Geopolitical Determinants of Trade in Electricity. In: International Trade in Sustainable Electricity; Regulatory Challenges in International Economic Law. Cambridge University Press, Cambridge, pp 54–73
[66] Kaundinya DP, Balachandra P, Ravindranath NH (2009). Grid-connected versus stand-alone energy systems for decentralized power—A review of literature. Renewable and Sustainable Energy Reviews 13: 2041–2050. doi: 10.1016/j.rser.2009.02.002
[67] Pleßmann G, Erdmann M, Hlusiak M, et al (2014). Global Energy Storage Demand for a 100% Renewable Electricity Supply. Energy Procedia 46: 22–31. doi: 10.1016/j.egypro.2014.01.154
[68] Bussar C, Moos M, Alvarez R, et al (2014). Optimal allocation and capacity of energy storage systems in a future European power system with 100% renewable energy generation. In: Energy Procedia. The Authors, pp 40–47
[69] IEC (2017). Global Energy Interconnection. Geneva, doi: 978-2-8322-3680-2
[70] Bompard E, Fulli G, Ardelean M, et al (2014). It's a Bird, It's a Plane, It's a … Supergrid!; Evolution, Opportunities, and Critical Issues for Pan-European Transmission. IEEE power energy Mag. doi: 0.1109/MPE.2013.2294813
[71] EC (2014). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL; European Energy Security Strategy; {SWD(2014) 330 final}. Brussels, doi: 10.1007/978-3-531-19201-7, ISBN: 978-3-531-19200-0
[72] EC (2017). Towards a sustainable and integrated Europe; Report of the Commission Expert Group on electricity interconnection targets. Brussles
[73] Ummel K (2010). Global Prospects for Utility-Scale Solar Power : Toward Spatially Explicit Modeling of Renewable Energy Systems Working Paper 235 December 2010
[74] IEA (2016). Large-scale electricity interconnection - Technology and prospects for cross-regional networks. Paris
[75] Zhenya L (2015). Global Energy Interconnection. Elsevier Academic Press, doi: 10.1016/B978-0-12-804405-6.00007-5, ISBN: 9780128044056
[76] Chen G, Hao M, Xu Z, et al (2015). Review of high voltage direct current cables. CSEE Journal of Power and Energy Systems 1: 9–21. doi: 10.17775/CSEEJPES.2015.00015
[77] Barnes M, Van Hertem D, Teeuwsen SP, et al (2017). HVDC Systems in Smart Grids. Proceedings of the IEEE 105: 2082–2098. doi: 10.1109/JPROC.2017.2672879
[78] Kangwa N, Venugopal C, Davidson I (2017). A Review of the Performance of VSC-HVDC and MTDC Systems. In: 2017 IEEE PES-IAS PowerAfrica. IEEE, pp 267–273
[79] Qin X, Zeng P, Zhou Q, et al (2016). Study on the Development and Reliability of HVDC Transmission Systems in China. In: 2016 IEEE International Conference on Power System Technology (POWERCON). IEEE, pp 1–6
[80] Sutton SJ, Lewin PL, Swingler SG (2017). Review of global HVDC subsea cable projects and the application of sea electrodes. International Journal of Electrical Power and Energy Systems 87: 121–135. doi: 10.1016/j.ijepes.2016.11.009
[81] Gellings CW (2015). A Globe-Spanning Supergrid. IEEE Spectrum August: 48–54.
[82] Rafique SF, Shen P, Wang Z, et al (2018). Global Power Grid Interconnection for Sustainable Growth: Concept, Project and Research Direction. IET Generation, Transmission & Distribution 12: 1–12. doi: 10.1049/iet-gtd.2017.1536
[83] Bompard E, Grosso D, Huang T, et al (2018). World decarbonization through global electricity interconnections. Energies 11: 1–29. doi: 10.3390/en11071746
[84] Thomas H, Marian A, Chervyakov A, et al (2016). Superconducting transmission lines - Sustainable electric energy transfer with higher public acceptance? Renewable and Sustainable Energy Reviews 55: 59–72. doi: 10.1016/j.rser.2015.10.041
[85] Engeland K, Borga M, Creutin JD, et al (2017). Space-time variability of climate variables and intermittent renewable electricity production – A review. Renewable and Sustainable Energy Reviews 79: 600–617. doi: 10.1016/j.rser.2017.05.046
[86] Wang L, Gao Y, Zhou Y, et al (2018). Research on the future electricity market model for GEI based on the analysis of typical electricity market operation mechanisms. Global Energy Interconnection 1: 197–208.
[87] Zhao Q, Liu G, Li Z, et al (2018). Simplified model of design of transnational and intercontinental electricity trading for Global Energy Interconnection. Global Energy Interconnection 1: 209–216.
[88] Chatzivasileiadis S, Ernst D (2017). The State of Play in Cross-Border Electricity Trade and the Challenges towards a

Global Electricity Market Environment. In: International Trade in Sustainable Electricity: Regulatory Challenges in International Economic Law. Cambridge, pp 21–45
[89] EC (2003). EUROMED REPORT; MINISTERIAL DECLARATION BY THE EURO-MEDITERRANEAN ENERGY FORUM Rome, 1 and 2 December 2003. Rome
[90] JRC (2018). Transcontinental and global power grids. https://ses.jrc.ec.europa.eu/transcontinental-and-global-power-grids. Accessed 18 Nov 2017
[91] Cova B, Pincella C, Simioli G, et al (2006). HVDC Interconnections in the Mediterranean Basin. In: Inaugural IEEE PES 2005 Conference and Exposition in Africa. IEEE, pp 143–148
[92] Trieb F, Müller-steinhagen H (2006). Sustainable Electricity and Water for Europe, Middle East and North Africa
[93] Zickfeld F, Wieland A, Blohmke J, et al (2012). 2050 Desert Power; Perspectives on a Sustainable Power System for EUMENA
[94] Reuters (2012). Germany's Bosch pulling out of Desertec renewable energy project. http://www.reuters.com/article/bosch-desertec/germanys-bosch-pulling-out-of-desertec-renewable-energy-project-idUSL5E8MCI0T20121112. Accessed 19 Sep 2017
[95] Desertec Foundation (2013). Desertec Foundation is leaving the industrial consortium Dii. http://www.desertec.org/press/press-releases/130701-desertec-foundation-is-leaving-the-industrial-consortium-dii/. Accessed 19 Sep 2017
[96] EC (2014). Medgrid - interconnecting the Mediterranean. SETIS Mag.
[97] EuroAsia Interconnector (2017). EuroAsia Interconnector secures Cyprus government environmental approval. http://www.euroasia-interconnector.com/news-euroasia_interconnector_secures_cyprus_government_environmental_approval1079period2017-12/?Period. Accessed 11 Jan 2018
[98] EuroAsia Interconnector (2017). A Trans-European Energy Infrastructure Project; The EuroAsia Interconnector
[99] EuroAfrica (2018). EuroAfrica Interconnector final electricity cable route agreed between Cyprus and Egypt. https://www.euroafrica-interconnector.com/euroafrica-interconnector-final-electricity-cable-route-agreed-between-cyprus-and-egypt/. Accessed 20 Jun 2018
[100] TERNA (2016). Piano di Sviluppo della Rete 2017
[101] ENTSO-E (2016). Project 284 - LEG1. https://docstore.entsoe.eu/Documents/TYNDP documents/TYNDP 2016/projects/P0284.pdf. Accessed 22 Jun 2018
[102] Neslen A (2017). Huge Tunisian solar park hopes to provide Saharan power to Europe. In: Guard. https://www.theguardian.com/environment/2017/sep/06/huge-tunisian-solar-park-hopes-to-provide-saharan-power-to-europe. Accessed 22 Nov 2017
[103] Saglam MA, Yilmaz M (2017). Turkish electricity Network. In: Netw. Assess. Work. Athens, Greece. https://rekk.hu/downloads/events/2017_SEERMAP_Turkish_system_Saglam_Yilmaz.pdf. Accessed 5 Jan 2018
[104] Farag M (2018). Egypt becoming electricity hub between region, Europe: minister of electricity. In: Dly. News Egypt. https://dailynewsegypt.com/2018/02/06/egypt-becoming-electricity-hub-region-europe-minister-electricity/. Accessed 20 Jun 2018
[105] Al-Asaad HK (2009). Electricity Power Sector Reform in the GCC Region. The Electricity Journal 22: 58–64. doi: 10.1016/j.tej.2009.08.013
[106] EC and the Ministry of Energy of the Russian Federation (2013). Roadmap EU-Russia Energy Cooperation until 2050
[107] IRENA (2017). REmap 2030 Renewable Energy Prospects for Russian Federation, Working Paper. Abu Dhabi, ISBN: 978-92-9260-022-8
[108] Boute A, Willems P (2012). RUSTEC: Greening Europe's energy supply by developing Russia's renewable energy potential. Energy Policy 51: 618–629. doi: 10.1016/j.enpol.2012.09.001
[109] Reuters (2017). EU to work with Baltic states on decoupling from Russian power grid. https://www.reuters.com/article/baltics-energy-eu-russia/eu-to-work-with-baltic-states-on-decoupling-from-russian-power-grid-idUSL8N1IY455. Accessed 7 Feb 2018
[110] Varfolomeyev O (2017). Ukraine Moves to Integrate Its Power Grid With European Network. In: Eurasia Dly. Monit. Vol. 14 Issue 91. https://jamestown.org/program/ukraine-moves-integrate-power-grid-european-network/. Accessed 7 Feb 2018
[111] Eric Ng (2016). World power: Why China's State Grid is charged up over global interconnection dream. In: South China Morning Post. http://www.scmp.com/business/china-business/article/1903687/world-power-why-chinas-state-grid-charged-over-global. Accessed 12 Oct 2017
[112] Hornby L (2016). China looks to export surplus energy to Germany. In: Financ. Times. https://www.ft.com/content/68cdef50-f66a-11e5-803c-d27c7117d132. Accessed 13 Feb 2018
[113] Ardelean M, Minnebo P (2017). JRC science for policy report; A China-EU electricity transmission link; Assessment of potential countries and routes. Petten, doi: 10.2760/67516, ISBN: 9789279793585
[114] Hammons TJ, Hreinsson EB, Kacejko P (2010). Proposed Iceland/UK (Peterhead) 1.2 GW HVDC cable. In: Universities Power Engineering Conference (UPEC), 2010 45th International
[115] Kvika and Poyry (2016). Interconnector between Iceland and GB, cost benefit analysis and impact assessment; Presentation. London
[116] Karagiannopoulos L (2017). Iceland magma drilling project may revive giant UK power cable link. In: Reuters.

https://www.reuters.com/article/us-iceland-energy-britain/iceland-magma-drilling-project-may-revive-giant-uk-power-cable-link-idUSKBN17C17E. Accessed 21 Jun 2018
[117] Orkostofnun (2016). North Atlantic Energy Network. Reykjavik
[118] GENI (1992). The Potential of an Electrical Interconnection Between Russia and North America. http://www.geni.org/globalenergy/library/newsletters/1992/the-potential-of-an-electrical-interconnection-between-russia-and-north-america.shtml#Potential. Accessed 30 Mar 2018
[119] Belyaev LS (1994). Rational use and efficiency of intercontinental electricity connections. International Journal of Global Energy Issues, Special Issue on Central and Eastern European Energy Policy 6: 268–274.
[120] OAS (2012). MANDATES ARISING FROM THE SIXTH SUMMIT OF THE AMERICAS. Cartagena
[121] IRENA (2015). CLEAN ENERGY CORRIDOR OF CENTRAL AMERICA (CECCA) Strategy
[122] BNamericas (2018). Colombia-Panama interconnection line. https://www.bnamericas.com/project-profile/en/linea-de-interconexion-electrica-colombia-panama-interconexion-colombia-panama. Accessed 22 Jun 2018
[123] Energy.gov (2017). U.S. Energy Secretary and Mexico Energy Minister Sign Bilateral Principles to Promote Electricity Reliability of Interconnected Power Systems. In: DOEnews. https://energy.gov/articles/us-energy-secretary-and-mexico-energy-minister-sign-bilateral-principles-promote. Accessed 22 Dec 2017
[124] Parfomak, Paul W.; Campbell, Richard J. & Pirog R, Ratner M, Brown P, et al (2017). Cross-Border Energy Trade in North America: Present and Potential. Washington DC
[125] Teixeira M (2016). The Brazilian Energy Distribution System. In: TechinBrazil. https://techinbrazil.com/the-brazilian-energy-distribution-system. Accessed 22 Jun 2018
[126] Casallas D (2017). Andean interconnection plans take shape. In: BNamericas. https://www.bnamericas.com/en/news/electricpower/andean-interconnection-plans-take-shape. Accessed 22 Jun 2018
[127] IADB (2017). Peru and Chile Move Forward with Electrical Interconnection Project. http://conexionintal.iadb.org/2017/08/02/peru-y-chile-avanzan-en-proyecto-de-interconexion-electrica/?lang=en. Accessed 22 Jun 2018
[128] Seliger B, Kim PG (2009). Tackling climate change, increasing energy security, engaging North Korea and moving forward Northeast Asian integration – “Green Growth” in Korea and the Gobitec project
[129] Zhenya L, Chen G, Guan X, et al (2016). A concept discussion on northeast asia power grid interconnection. CSEE Journal of Power and Energy Systems 2: 87–93. doi: 10.17775/CSEEJPES.2016.00053
[130] Renewable Energy Institute About “Asia Super Grid (ASG).” https://www.renewable-ei.org/en/asg/about/. Accessed 30 Mar 2018
[131] Boyd J (2016). Trio of Nations Aims to Hook Asia Super Grid to Grids of the World. In: IEEE Spectr. https://spectrum.ieee.org/energywise/energy/the-smarter-grid/trio-of-nations-aim-to-hook-asia-super-grid-to-grids-of-the-world. Accessed 27 Dec 2017
[132] IEA (2015). Development Prospects of the ASEAN Power Sector: Towards an Integrated Electricity Market
[133] Wu C, Zhang X-P (2018). Economic analysis of energy interconnection between Europe and China with 100% renewable energy generation. Global Energy Interconnection 1: 529–536. doi: 10.1417/j.2096-5117.gei.2018.05.001
[134] Halawa E, James G, Shi X, et al (2018). The Prospect for an Australian–Asian Power Grid: A Critical Appraisal. Energies 11: 200. doi: 10.3390/en11010200
[135] Mella S (2015). Does Australia Energy Export Future Lie with the Asian Supergrid ? Glob. Energy Monit. 3:1–9
[136] Blanch S, Law R, Campbell A, et al (2013). Scoping workshop on Australia-South East Asia grid connection to catalyse regional generation and distribution of renewable energy. Darwin
[137] Global Energy Network institute (2016). About Us. http://www.geni.org/globalenergy/about_us/index.shtml. Accessed 11 Oct 2017
[138] SGCC (2017). Implementation of “The Belt and Road” Initiative - Promote China-Nepal Power Interconnection
[139] GEIDCO (2018). List of members. http://geidco.org/html/qqnyhlwen/col2017080782/column_2017080782_1.html. Accessed 28 Jun 2018
[140] GEIDCO (2018). Overview. http://geidco.org/html/qqnyhlwen/col2017080765/2017-09/23/20170923162727440712239_1.html. Accessed 28 Jun 2018
[141] GEIDCO (2017). Global Energy Interconnection Action Plan to Promote the 2030 Agenda for Sustainable Development. Beijing
[142] SGCC (2017). GEIDCO Chairman Liu Zhenya Visits the Laos, Myanmar and Bangladesh Promoting Gird Interconnection. http://www.sgcc.com.cn/ywlm/mediacenter/corporatenews/07/341836.shtml. Accessed 28 Jun 2018
[143] Climate Parliament (2018). Green Grid Leadership Forum; Engineering a Climate Solution. Clim. Parlimanet/LEGISLATORS Work. Worldw. TO Combat Clim. Chang.
[144] Clean Energy Ministerial Regional and Global Energy Interconnection (RGEI) Initiative. http://www.cleanenergyministerial.org/initiative-clean-energy-ministerial/regional-and-global-energy-interconnection-rgei-initiative. Accessed 28 Jun 2018
[145] Norrga S, Hesamzadeh M (2013). INTERGRID - Enabling a sustainable energy system by large-scale intercontinental power transmission. In: IEEE Power and Energy Society General Meeting

[146] Czisch G (2008). Low Cost but Totally Renewable Electricity Supply for a Huge Supply Area - a European/Trans-European Example -. In: 4th CLAVERTON ENERGY GROUP CONFERENCE – 24th to 26th October 2008. Bath

[147] Blakers A, Luther J, Nadolny A (2012). Asia Pacific Super Grid – Solar electricity generation, storage and distribution. Green 2: 189–202. doi: 10.1515/green-2012-0013

[148] Mano S, Ovgor B, Samadov Z, et al (2014). Gobitec and Asian Super Grid for renewable energies in Northeast Asia. ISBN: 9789059481435

[149] Taggart S, James G, Dong Z, et al (2012). The Future of Renewables Linked by a Transnational Asian Grid. Proceedings of the IEEE 100: 348–359. doi: 10.1109/JPROC.2011.2159089

[150] Grenatec (2013). A "Pan-Asian Energy Infrastructure" By 2050

[151] Mella S, James G, Chalmers K (2017). Pre-feasibility study 2017; Evaluating the potential to export Pilbara solar resources to the proposed ASEAN grid via a subsea high voltage direct current interconnector

[152] Wang C, Dargaville R, Jeppesen M (2018). Power system decarbonisation with Global Energy Interconnection – a case study on the economic viability of international transmission network in Australasia. Global Energy Interconnection 1: 507–519. doi: 10.14171/j.2096-5117.gei.2018.04.011

[153] Brancucci Martínez-Anido C, L'Abbate A, Migliavacca G, et al (2013). Effects of North-African electricity import on the European and the Italian power systems: A techno-economic analysis. Electric Power Systems Research 96: 119–132. doi: 10.1016/j.epsr.2012.11.001

[154] Fulli G, Purvins A, L'Abbate A, et al (2011). Evolutions and challenges towards a potential Pan-European HVAC / HVDC SuperGrid. CIGRE Int Symp

[155] Scholz Y (2012). Renewable energy based electricity supply at low costs - Development of the REMix model and application for Europe. University of Stuttgart

[156] Bogdanov D, Koskinen O, Aghahosseini A, et al (2016). Integrated renewable energy based power system for Europe, Eurasia and MENA regions. In: 2016 International Energy and Sustainability Conference, IESC 2016

[157] Chatzivasileiadis S, Ernst D, Andersson G (2017). Global Power Grids for Harnessing World Renewable Energy. In: Renewable Energy Integration. Elsevier, pp 161–174

[158] Claverton Energy Research Group (2010). Prospects for Trans-Atlantic Undersea Power Transmission. https://claverton-energy.com/prospects-for-trans-atlantic-undersea-power-transmission.html. Accessed 14 Jan 2018

[159] Grossmann WD, Grossmann I, Steininger KW (2014). Solar electricity generation across large geographic areas, Part II: A Pan-American energy system based on solar. Renewable and Sustainable Energy Reviews 32: 983–993. doi: 10.1016/j.rser.2014.01.003

[160] Purvins A, Wilkening H, Fulli G, et al (2011). A European supergrid for renewable energy: Local impacts and far-reaching challenges. Journal of Cleaner Production 19: 1909–1916. doi: 10.1016/j.jclepro.2011.07.003

[161] Kuwano Y (1994). The PV Era is coming — the way to GENESIS. Solar Energy Materials and Solar Cells 34: 27–39. doi: 10.1016/0927-0248(94)90021-3

[162] Aboumahboub T, Schaber K, Tzscheutschler P, et al (2010). Optimization of the Utilization of Renewable Energy Sources in the Electricity Sector. In: EE'10 Proceedings of the 5th IASME/WSEAS international conference on Energy & environment. World Scientific and Engineering Academy and Society (WSEAS), Wisconsin, pp 196–204

[163] Biberacher M (2004). Modelling and optimisation of future energy system using spatial and temporal methods. Dissertation. University of Augsburg

[164] Purvins A, Sereno L, Ardelean M, et al (2018). Submarine power cable between Europe and North America: A techno-economic analysis. J Clean Prod. doi: 10.1016/j.jclepro.2018.03.095

[165] Aboumahboub T, Schaber K, Wagner U, et al (2012). On the CO2 emissions of the global electricity supply sector and the influence of renewable power-modeling and optimization. Energy Policy 42: 297–314. doi: 10.1016/j.enpol.2011.11.088

[166] Nikolai Voropai, Sergei Podkovalnikov KO (2018). From interconnections of local electric power systems to global energy interconnection. Global Energy Interconnection 1: 4–10.

[167] Rudenko Y, Yershevich V (1991). Is it possible and expedient to create a global energy network ? International Journal of Global Energy Issues 3: 1–10. doi: 10.1504/IJGEI.1991.063683

[168] Grossmann WD, Grossmann I, Steininger KW (2013). Distributed solar electricity generation across large geographic areas, Part I: A method to optimize site selection, generation and storage. Renewable and Sustainable Energy Reviews 25: 831–843. doi: 10.1016/j.rser.2012.08.018

[169] Zweibel K, Mason J, Fthenakis V (2008). A Solar Grand Plan. Scientific American 298: 64–73. doi: 10.1038/scientificamerican0108-64

[170] Shen H, Dai Q, Wu Q, et al (2018). The state-of-the-arts of the study on grid interconnection between Iberian Peninsula and West Maghreb region. Global Energy Interconnection 1: 20–28. doi: 10.14171/j.2096-5117.gei.2018.01.003

[171] Komoto K, Enebish N, Song J (2013). Very large scale PV systems for North-East Asia: Preliminary project proposals for VLS-PV in the mongolian gobi desert. In: 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC). IEEE, pp 2376–2379

[172] Calzadilla A, Wiebelt M, Blohmke J, et al (2014). Desert Power 2050: Regional and sectoral impacts of renewable electricity production in Europe, the Middle East and North Africa. ISBN: 1891

[173] Nykamp S (2013). Integrating Renewables in Distribution Grids : Storage, regulation and the interaction of

different stakeholders in future grids. University of Twente
[174] Verzijlbergh RA, De Vries LJ, Dijkema GPJ, et al (2017). Institutional challenges caused by the integration of renewable energy sources in the European electricity sector. Renewable and Sustainable Energy Reviews 75: 660–667. doi: 10.1016/j.rser.2016.11.039
[175] Lilliestam J, Ellenbeck S (2011). Energy security and renewable electricity trade-Will Desertec make Europe vulnerable to the "energy weapon"? Energy Policy 39: 3380–3391. doi: 10.1016/j.enpol.2011.03.035
[176] Koskinen O, Breyer C (2016). Energy Storage in Global and Transcontinental Energy Scenarios: A Critical Review. Energy Procedia 99: 53–63. doi: 10.1016/j.egypro.2016.10.097
[177] Walter K, Bosch S (2013). Intercontinental cross-linking of power supply - calculating an optimal power line corridor from North Africa to Central Europe. Energy, Sustainability and Society 3: 14. doi: 10.1186/2192-0567-3-14
[178] Song J (2014). Super Grid in North - East Asia Through Renewable Energy. Tech Monit. 24–27
[179] Defilla S (2017). Good Governance for a Global Electricity Grid : What Are the Ingredients? In: International Trade in Sustainable Electricity; Regulatory Challenges in International Economic Law. Cambridge University Press, pp 74–98
[180] Czisch G, Giebel G (2007). Realisable Scenarios for a Future Electricity Supply based 100% on Renewable Energies. In: Energy solutions for sustainable development. Risø National Laboratory, pp 186–195
[181] Elliott D (2013). Emergence of European supergrids - Essay on strategy issues. Energy Strategy Reviews 1: 171–173. doi: 10.1016/j.esr.2012.04.001
[182] Murillo-Sanchez CE, Zimmerman RD, Thomas RJ (2001). Kirchhoff vs. competitive electricity markets: a few examples. In: 2001 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.01CH37194). IEEE, pp 1256–1261
[183] Bogdanov D, Breyer C (2016). Global grid for 100% renewable energy supply. In: conference proceedings during the NEO-CARBON ENERGY 6th RESEARCHERS' SEMINAR. Lappeenranta
[184] Pearce F (2009). Sunshine superpower; Is building a gigantic electricity plant in the Sahara really such a good idea. New Scientist 204: 38–41. doi: 10.1016/S0262-4079(09)62825-6
[185] Hollain V (2009). Kraftwerke in der Wüste: Ein Luftschloss auf Sand gebaut. SOLARZEITALTER 1: 74–77.
[186] Gulagi A, Bogdanov D, Fasihi M, et al (2017). Can Australia power the energy-hungry asia with renewable energy? Sustainability 9: doi: 10.3390/su9020233
[187] Barasa M, Bogdanov D, Oyewo AS, et al (2016). A Cost Optimal Resolution for Sub-Saharan Africa powered by 100% Renewables for Year 2030 Assumptions. In: 32nd European Photovoltaic Solar Energy Conference and Exhibition. Munich, pp 2570–2611
[188] Zhao L, Wang W, Zhu L, et al (2018). Economic analysis of solar energy development in North Africa. Global Energy Interconnection 1: 53–62.
[189] 4coffshore (2018). BritNed Interconnector. https://www.4coffshore.com/transmission/interconnector-britned-icid19.html. Accessed 16 Sep 2018
[190] EC (2016). EuroAsia Interconnector - Design, Implementation and Environmental Studies. Brussels
[191] Reuters (2010). UPDATE 1-ABB wins $580 mln Nordic-Baltic power order. https://uk.reuters.com/article/abb/update-1-abb-wins-580-mln-nordic-baltic-power-order-idUKLDE6BJ0Y520101220. Accessed 16 Sep 2018
[192] Härtel P, Vrana TK, Hennig T, et al (2018). Estimation of investment model cost parameters for VSC HVDC transmission infrastructure. Electric Power Systems Research 160: 99–108. doi: 10.1016/j.epsr.2018.02.007
[193] T&D World (2008). NorNed, the Longest Electricity Cable in the World, is Operational. In: T&D World Mag. https://www.tdworld.com/projects-progress/norned-longest-electricity-cable-world-operational. Accessed 16 Sep 2018
[194] Bogdanov D, Breyer C (2016). North-East Asian Super Grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options. Energy Conversion and Management 112: 176–190. doi: 10.1016/j.enconman.2016.01.019
[195] 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
[196] Gevorgian V (2011). Renewable Energy and Inter-island Power Transmission. CIEMADeS IV Int. Conf.
[197] Liu X, He J, Ding J, et al (2017). A Review on Research Methods of Disturbance Propagation in Large-Scale Power Grids. IOP Conference Series: Materials Science and Engineering 199: 012112. doi: 10.1088/1757-899X/199/1/012112
[198] Pagnier L, Jacquod P (2018). Disturbance propagation, inertia location and slow modes in large-scale high voltage power grids. 1–11.
[199] Bompard E (2017). GLOBAL RT-SUPER LAB DEMO EVENT A real-time multisite co-simulation across the Atlantic for supporting Energy Transition. In: 7th IEEE International Conference on Innovative Smart Grid Technologies. Idaho Falls, Turin
[200] Setreus J, Bertling L (2009). Introduction to HVDC Technology for Reliable Electrical Power Systems. In: Proceedings of the 10th International Conference on Probablistic Methods Applied to Power Systems. IEEE
[201] Mohanpurkar M, Hovsapian R, Suryanarayanan S (2017). Real-time SuperLab. In: Fourth International Grid Simulator Testing Workshop National Renewable Energy Laboratory. Denver

[202] Wagman D (2017). Stress-Testing a Hypothetical Global Grid. In: IEEE Spectr. https://spectrum.ieee.org/energywise/energy/the-smarter-grid/testing-the-systems-to-link-grids-across-continents. Accessed 14 Oct 2017
[203] Grebe E, Kabouris J, López Barba S, et al (2010). Low frequency oscillations in the interconnected system of Continental Europe. IEEE PES General Meeting, PES 2010 1–7. doi: 10.1109/PES.2010.5589932
[204] ENTSO-E (2017). Analysis of CE Inter-Area Oscillations of 1st December 2016
[205] Dekker P-M, Meisen P, Bruton AB (1995). THE GENI MODEL: The Interconnection of Global Power Resources to Obtain an Optimal Global Sustainable Energy Solution. SIMULATION 64: 244–253. doi: 10.1177/003754979506400407
[206] Liang X (2018). Application and research of global grid database design based on geographic information. Global Energy Interconnection 1: 87–95.
[207] EIA (2018). International Energy Statistics. https://www.eia.gov/beta/international/data/browser/. Accessed 24 Aug 2018
[208] E-Highway 2050 (2015). Europe's future secure and sustainable electricity infrastructure
[209] Czisch G (2005). Szenarien zur zukünftigen Stromversorgung; Kostenoptimierte Variationen zur Versorgung Europas und seiner Nachbarn mit Strom aus erneuerbaren Energien. University of Kassel
[210] Hess D (2018). The empirical probability of integrating CSP and its cost optimal configuration in a low carbon energy system of EUMENA. Solar Energy 166: 267–307. doi: 10.1016/j.solener.2018.03.034
[211] Komoto K, Ehara H, Lv F, et al (2015). Energy from the Desert: Very Large Scale PV Power Plants for Shifting to Renewable Energy Future. ISBN: 978-3-906042-29-9
[212] IEA (2016). World Energy Outlook 2016. Paris, ISBN: 9789264045606
[213] Energy Exemplar (2018). . https://energyexemplar.com/. Accessed 5 May 2018
[214] EC (2016). EU Reference Scenario 2016; Energy, transport and GHG emissions - Trends to 2050. Brussels, doi: 10.2833/9127, ISBN: 978-92-79-52373-1
[215] EIA (2017). The Electricity Market Module of the National Energy Modeling System : Model Documentation 2016. Washington DC
[216] EIA (2017). Annual Energy Outlook 2017. Washington DC, doi: DOE/EIA-0383(2012) U.S., ISBN: 2025869592
[217] EIA (2017). Annual Energy Outlook 2017; Electricity and Renewable fuel tables (tables 55-58.22). https://www.eia.gov/outlooks/archive/aeo17/supplement/excel/sup_elec.xlsx. Accessed 14 Feb 2018
[218] FERC (2018). Form No. 714 - Annual Electric Balancing Authority Area and Planning Area Report. https://www.ferc.gov/docs-filing/forms/form-714/data/form714-database.zip?csrt=6396829886107945880. Accessed 9 Nov 2017
[219] EIA (2019). U.S. Electric System Operating Data; Status Map. https://www.eia.gov/realtime_grid/#/status?end=20170905T00. Accessed 17 Nov 2017
[220] FERC (2017). Electric Power Markets: National Overview. https://www.ferc.gov/market-oversight/mkt-electric/overview.asp. Accessed 17 Nov 2017
[221] EIA (2018). API Query Browser. https://www.eia.gov/opendata/qb.php?category=2122632. Accessed 24 Nov 2017
[222] National Energy Board of Canada (2017). Canada's Energy Future 2017; Energy Supply and Demand Projections to 2040. Calgary
[223] AEMO (2018). DATA DASHBOARD
[224] METI (2011). Past power demand record. http://warp.da.ndl.go.jp/info:ndljp/pid/3487098/www.meti.go.jp/setsuden/performance.html%0A. Accessed 21 Mar 2019
[225] Secretariat of Energy Mexico (2017). Programa de Desarrollo del Sistema Eléctrico Nacional; base de datos de demanda horaria
[226] SO-CDU UES (2018). Generation and consumption (hours) (Translated)
[227] Brinkerink M, Ó Gallachóir B, 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
[228] Deane JP, Drayton G, Ó Gallachóir BP (2014). The impact of sub-hourly modelling in power systems with significant levels of renewable generation. Applied Energy 113: 152–158. doi: 10.1016/j.apenergy.2013.07.027
[229] Brouwer AS, van den Broek M, Zappa W, et al (2016). Least-cost options for integrating intermittent renewables in low-carbon power systems. Applied Energy 161: 48–74. doi: 10.1016/j.apenergy.2015.09.090
[230] 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
[231] Brinkerink M, Deane P (2020). PLEXOS-World 2015. Harvard Dataverse, V6, UNF6fyT1L5t+sHlvSHolxelaVg== [fileUNF]. doi: https://doi.org/10.7910/DVN/CBYXBY
[232] Holttinen H, Orths A, Abildgaard H, et al (2013). IEA Wind Expert Group Report on Recommended Practices: 16. Wind Integration Studies. 89.
[233] EIA (2018). International. https://www.eia.gov/international/data/world/electricity/electricity-capacity/. Accessed 24 Aug 2018
[234] ENTSO-E (2019). Installed Capacity per Production Type. https://transparency.entsoe.eu/generation/r2/installedGenerationCapacityAggregation/show. Accessed 18 Oct

2019
[235] IEA (2017). Electricity Information 2017. Paris, ISBN: 978-92-64-27813-4
[236] CEA (2016). All India installed capacity (in MW) of power stations (As on 31.03.2016). http://cea.nic.in/reports/monthly/installedcapacity/2016/installed_capacity-03.pdf. Accessed 21 Apr 2019
[237] 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
[238] Molod A, Takacs L, Suarez M, et al (2015). Development of the GEOS-5 atmospheric general circulation model: Evolution from MERRA to MERRA2. Geoscientific Model Development 8: 1339–1356. doi: 10.5194/gmd-8-1339-2015
[239] 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
[240] IRENA (2019). Renewable Energy Statistics 2019. Abu Dhabi, ISBN: 978-92-9260-033-4
[241] Lehner B, Liermann CR, Revenga C, et al (2011). High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Frontiers in Ecology and the Environment 9: 494–502. doi: 10.1890/100125
[242] 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
[243] Luo X, Wang J, Dooner M, et al (2015). Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied Energy 137: 511–536. doi: 10.1016/j.apenergy.2014.09.081
[244] Geth F, Brijs T, Kathan J, et al (2015). An overview of large-scale stationary electricity storage plants in Europe: Current status and new developments. Renewable and Sustainable Energy Reviews 52: 1212–1227. doi: 10.1016/j.rser.2015.07.145
[245] MWH Americas (2009). Technical Analysis of Pumped Storage and Integration with Wind Power in the Pacific Northwest Final Report
[246] ENTSO-E (2019). Consumption data: Hourly load values 2006-2015. https://docstore.entsoe.eu/Documents/Publications/Statistics/Monthly-hourly-load-values_2006-2015.xlsx. Accessed 11 Nov 2018
[247] ENTSO-E (2020). Total Load - Day Ahead / Actual. https://transparency.entsoe.eu/load-domain/r2/totalLoadR2/show. Accessed 11 Dec 2018
[248] The World Bank (2019). DataBank. https://databank.worldbank.org/home.aspx. Accessed 4 Sep 2019
[249] 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
[250] Openmod Transmission network datasets. https://wiki.openmod-initiative.org/wiki/Transmission_network_datasets. Accessed 13 Mar 2019
[251] Arderne C, Zorn C, Nicolas C, et al (2020). Predictive mapping of the global power system using open data. Scientific Data 7: 19. doi: 10.1038/s41597-019-0347-4
[252] Taliotis C, Shivakumar A, Ramos E, et al (2016). An indicative analysis of investment opportunities in the African electricity supply sector - Using TEMBA (The Electricity Model Base for Africa). Energy for Sustainable Development 31: 50–66. doi: 10.1016/j.esd.2015.12.001
[253] CIER (2016). Síntesis Informativa Energética de los Países de la CIER; Información del sector energético en países de America del Sur, America Central y El Caribe. Montevideo
[254] The World Bank (2013). Middle East and North Africa; Integration of Electricity Networks in the Arab World; Regional Market Structure and Design. doi: Report No: ACS7124
[255] Sumranwanich T (2014). Development of Cross – Border Trade between Thailand and Neighboring Countries. https://dokumen.tips/documents/development-of-cross-border-trade-between-thailand-and-4-bangkokdevelopmedevelopment.html. Accessed 11 Nov 2018
[256] Toh E (2016). Interconnections in Southeast Asia : Implications for Singapore and the region. https://www.ceer.eu/documents/104400/-/-/4738276b-5fe6-88f3-48f7-47eab474ed8c%0A. Accessed 11 Nov 2018
[257] ENTSO-E (2015). TYNDP 2016 Scenario Development Report. Brussels
[258] ENTSO-E (2016). Project list TYNDP2016 assessments. https://www.entsoe.eu/Documents/TYNDP documents/TYNDP 2016/rgips/Project list TYNDP2016 assessments.xlsx. Accessed 12 Mar 2019
[259] ENTSO-E (2019). Forecasted Transfer Capacities - Month Ahead. https://transparency.entsoe.eu/transmission-domain/r2/forecastedTransferCapacitiesMonthAhead/show. Accessed 25 Feb 2019
[260] ENTSO-E (2019). Forecasted Transfer Capacities - Year Ahead. https://transparency.entsoe.eu/transmission-domain/ntcYear/show. Accessed 25 Feb 2019
[261] ENTSO-E (2019). Cross-Border Physical Flow. https://transparency.entsoe.eu/transmission-domain/physicalFlow/show. Accessed 25 Feb 2019
[262] IEA (2017). CO2 Emissions from Fuel Combustion 2017. Paris, doi: 10.1787/co2_fuel-2007-en-fr
[263] Wilkinson MD, Dumontier M, Aalbersberg IjJ, et al (2016). Comment: The FAIR Guiding Principles for scientific data management and stewardship. Scientific Data 3: 1–9. doi: 10.1038/sdata.2016.18
[264] 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
[265] 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
[266] Iwanaga T, Wang H-H, Hamilton SH, et al (2020). Socio-technical scales in socio-environmental modeling: managing a system-of-systems modeling approach. Environmental Modelling & Software 135: 104885. doi: 10.1016/j.envsoft.2020.104885
[267] Hamilton SH, ElSawah S, Guillaume JHA, et al (2015). Integrated assessment and modelling: Overview and synthesis ofsalient dimensions. Environmental Modelling and Software 64: 215–229. doi: 10.1016/j.envsoft.2014.12.005
[268] Yalew SG, van Vliet MTH, Gernaat DEHJ, et al (2020). Impacts of climate change on energy systems in global and regional scenarios. Nature Energy 5: 794–802. doi: 10.1038/s41560-020-0664-z
[269] 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
[270] Fujimori S, Masui T, Matsuoka Y (2012). AIM/CGE [basic] manual. doi: 10.1016/S1043-2760(97)84344-5, ISBN: 2012-01
[271] 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
[272] Huppmann D, Gidden M, Fricko O, et al (2019). The MESSAGE 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: 10.1016/j.envsoft.2018.11.012
[273] Després J, Keramidas K, Schmitz A, et al (2017). POLES-JRC model documentation. European Commission, doi: 10.2760/225347, ISBN: 9789279718014
[274] 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
[275] 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
[276] 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
[277] 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
[278] 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
[279] 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
[280] 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
[281] 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
[282] Artelys (2020). Multi-energy planning of interconnected systems. https://www.artelys.com/crystal/super-grid/. Accessed 8 Oct 2020
[283] Artelys (2019). Investigation on the interlinkage between gas and electricity scenarios and infrastructure projects assessment. Paris
[284] 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
[285] 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
[286] 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
[287] Brinkerink M, Ó Gallachóir B, Deane P (2021). Building and Calibrating a Country-Level Detailed Global Electricity Model Based on Public Data. Energy Strategy Reviews 33: 100592. doi: 10.1016/j.esr.2020.100592
[288] Brown T, Hörsch J, Schlachtberger D (2018). PyPSA: Python for power system analysis. Journal of Open Research Software 6: doi: 10.5334/jors.188
[289] 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
[290] 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

[291] 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
[292] 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
[293] 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
[294] 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
[295] 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
[296] 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
[297] Schmid E, Knopf B, Bauer N (2012). Remind-D: A Hybrid Energy-Economy Model of Germany. SSRN Electron J. doi: 10.2139/ssrn.2026443
[298] 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
[299] Chang M, Zink J, Zakeri B, et al (2021). Trends in tools and approaches for modelling the energy transition. 290: doi: 10.1016/j.apenergy.2021.116731
[300] 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
[301] 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
[302] Schwanitz VJ (2013). Evaluating integrated assessment models of global climate change. Environmental Modelling and Software 50: 120–131. doi: 10.1016/j.envsoft.2013.09.005
[303] 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
[304] 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
[305] IIASA Energy Program (2020). Regions -- MESSAGE-GLOBIOM. https://docs.messageix.org/projects/global/en/latest/overview/spatial.html. Accessed 13 Oct 2020
[306] 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
[307] Brinkerink M (2020). PLEXOS-World - MESSAGEix-GLOBIOM Soft-Link. Harvard Dataverse, V2. doi: https://doi.org/10.7910/DVN/O6ICJP
[308] Tröndle T, Lilliestam J, Marelli S, et al (2020). Trade-Offs between Geographic Scale, Cost, and Infrastructure Requirements for Fully Renewable Electricity in Europe. Joule 4: 1929–1948. doi: 10.1016/j.joule.2020.07.018
[309] Becker S, Rodriguez RA, Andresen GB, et al (2014). Transmission grid extensions during the build-up of a fully renewable pan-European electricity supply. Energy 64: 404–418. doi: 10.1016/j.energy.2013.10.010
[310] Rodríguez RA, Becker S, Andresen GB, et al (2014). Transmission needs across a fully renewable European power system. Renewable Energy 63: 467–476. doi: 10.1016/j.renene.2013.10.005
[311] IAMC wiki; The common Integrated Assessment Model (IAM) documentation. https://www.iamcdocumentation.eu/index.php/IAMC_wiki. Accessed 24 Jan 2019
[312] Huppmann D, Kriegler E, Krey V, et al (2018). IAMC 1.5°C Scenario Explorer and Data hosted by IIASA
[313] Koomey J, Schmidt Z, Hummel H, et al (2019). Inside the Black Box: Understanding key drivers of global emission scenarios. Environmental Modelling and Software 111: 268–281. doi: 10.1016/j.envsoft.2018.08.019
[314] IRENA (2021). World Energy Transitions Outlook: 1.5°C Pathway. International Renewable Energy Agency, Abu Dhabi, ISBN: 9789292603342
[315] Shivakumar A, Brinkerink M, Niet T, et al (2021). OSeMOSYS/osemosys_global: Development release for CCG (Version v0.2.b0). In: Zenodo. http://doi.org/10.5281/zenodo.4636742. Accessed 25 Mar 2021
[316] Allington L, Cannone C, Pappis I, et al (2021). Selected ' Starter Kit ' energy system modelling data for Niger (# CCG). Res Sq Prepr. doi: https://doi.org/10.21203/rs.3.rs-480051/v2
[317] Breyer C, Bogdanov D, Aghahosseini A, et al (2020). On the Techno-economic Benefits of a Global Energy Interconnection. Economics of Energy & Environmental Policy 9: doi: 10.5547/2160-5890.9.1.cbre
[318] 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.
[319] 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
[320] Pye S, Butnar I, Mittal S, et al (2021). Coal phase out and renewable electricity expansion under Paris targets. Res Sq Prepr. doi: https://doi.org/10.21203/rs.3.rs-380763/v3
[321] AEMO (2010). An introduction to Australia's national electricity market. doi: ISBN 0-646-41233-7
[322] AEMO (2019). Aggregated Price and Demand Data - Historical. https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Data-dashboard#aggregated-data. Accessed 21 Mar 2019
[323] AEMO (2019). Market Data Western Australia. http://data.wa.aemo.com.au/#load-summary. Accessed 14 Jan 2019
[324] Department of the Environment and Energy (2018). Australian Energy Update 2018. https://www.energy.gov.au/publications/australian-energy-update-2018. Accessed 14 Jan 2019
[325] AEMO (2017). Interconnector Capabilities for the National Electricity Market
[326] AEMO (2019). Map. https://www.aemo.com.au/aemo/apps/visualisations/map.html. Accessed 14 Jan 2019
[327] Cabezon JH y S de (2011). Biodiesel in Brazil Becomes a Booming Business as Oil Reserves Dwindle. https://jherrerosdc.typepad.com/jhsdc/2011/07/index.html. Accessed 21 Feb 2019
[328] ONS (2019). Mapa dinamico do SIN. http://www.ons.org.br/paginas/sobre-o-sin/mapas. Accessed 21 Feb 2019
[329] Gils HC, Simon S, Soria R (2017). 100% Renewable energy supply for Brazil-The role of sector coupling and regional development. Energies 10: doi: 10.3390/en10111859
[330] ONS (2019). Curva de carga horaria. http://www.ons.org.br/Paginas/resultados-da-operacao/historico-da-operacao/curva_carga_horaria.aspx. Accessed 21 Mar 2019
[331] IBGE (2014). Estimativas da população residente no Brasil e unidades da federação com data de referência em 1º de Julho de 2014. ftp://ftp.ibge.gov.br/Estimativas_de_Populacao/Estimativas_2014/estimativa_dou_2014.pdf. Accessed 21 Feb 2019
[332] SPP (2015). EI-WECC Seams Study Needed. http://cigre-usnc.tamu.edu/wp-content/uploads/2015/10/1-2C-Caspary.pptx. Accessed 9 Mar 2019
[333] NERC (2017). Reliability Coordinators. https://www.nerc.com/pa/rrm/TLR/pages/reliability-coordinators.aspx. Accessed 8 Mar 2019
[334] Gilbert A (2016). The U.S. Electricity System in 15 Maps. https://www.energycentral.com/c/ec/us-electricity-system-15-maps. Accessed 8 Mar 2019
[335] NRCAN (2018). Canada's Electric Reliability Framework. https://www.nrcan.gc.ca/energy/electricity-infrastructure/18792. Accessed 25 Feb 2018
[336] Nova Scotia Power (2019). Hourly total net Nova Scotia load. http://oasis.nspower.ca/en/home/oasis/monthly-reports/hourly-total-net-nova-scotia-load.aspx. Accessed 20 Dec 2017
[337] NB Power (2019). System Information Archive. https://tso.nbpower.com/Public/en/system_information_archive.aspx. Accessed 20 Dec 2017
[338] IESO (2019). Data Directory. http://www.ieso.ca/en/power-data/data-directory. Accessed 20 Dec 2017
[339] AESO (2016). 2016 hourly load data. https://www.aeso.ca/market/market-and-system-reporting/data-requests/2016-hourly-load-data/. Accessed 20 Dec 2017
[340] BC Hydro (2019). Historical Transmission Data; LOAD: British Columbia. https://www.bchydro.com/energy-in-bc/operations/transmission/transmission-system/balancing-authority-load-data/historical-transmission-data.html. Accessed 20 Dec 2017
[341] NB Power (2016). Annual Report 2015-2016. Fredericton, doi: 10.1017/CBO9781107415324.004, ISBN: 1800111363
[342] NB Power (2011). NB Power strategic plan 2011-2040. Fredericton
[343] SaskPower (2016). SaskPower 2015-16 annual report. Regina
[344] Department of Natural Resources (2012). Gull Island: Why not develop Gull Island first? St. John's
[345] AESO (2015). AESO 2015 Long-term Transmission Plan. Calgary
[346] Li T, Rai R (2016). Rating Report; The Manitoba Hydro-Electric Board. https://www.dbrsmorningstar.com/research/302749/manitoba-hydro-electric-board-the-rating-report. Accessed 12 Mar 2019
[347] Hydro-Quebec (2018). Transmission System Overview. http://www.hydroquebec.com/transenergie/en/reseau-bref.html. Accessed 12 Feb 2018
[348] BC Hydro (2019). Actual Flow Data. https://www.bchydro.com/energy-in-bc/operations/transmission/transmission-system/actual-flow-data.html. Accessed 4 Nov 2017
[349] State Utility Forecasting Group (2014). MISO Allocation Factors: State Level and MISO Local Resource Zone Contents
[350] Santee Cooper (2013). Integrated Resource Plan. http://www.energy.sc.gov/files/view/2013_IRP_SCPSA.pdf. Accessed 13 Mar 2019
[351] KCP&L (2019). Service Area Map. https://www.kcpled.com/about-us/service-area-map/. Accessed 4 Nov 2017
[352] NorthWestern Energy (2016). About Us. http://www.northwesternenergy.com/our-company/about-us. Accessed 4 Nov 2017
[353] PacifiCorp (2019). Western Grid coordination. http://www.pacificorp.com/about/eim.html. Accessed 4 Nov 2017
[354] PowerSouth (2017). Our members. http://www.powersouth.com/our-members/. Accessed 4 Nov 2017
[355] BANC (2019). Balancing Authority of Northern California. http://www.thebanc.org/. Accessed 4 Nov 2017

[356] Duke Energy (2019). Economic Development. https://www.duke-energy.com/partner-with-us/economic-development. Accessed 4 Nov 2017
[357] GSEC (2018). Golden Spread Service Area. https://www.gsec.coop/Public/About-Us/OurMembers.aspx. Accessed 4 Nov 2017
[358] Missouri River (2019). About Missouri River Energy Services. https://www.mrenergy.com/about. Accessed 4 Nov 2017
[359] Midwest Energy (2019). Service Area. https://www.mwenergy.com/about/service-area. Accessed 4 Nov 2017
[360] Tennessee Valley Authority (2019). About TVA. https://www.tva.gov/About-TVA. Accessed 4 Nov 2017
[361] Monitoring Analytics (2017). 2016 State of the Market Report for PJM; Volume 2: Detailed analysis
[362] Nebraska Energy Office (2019). Lincoln Electric System Service Area Boundary. http://www.neo.ne.gov/hers/srvarea.pdf%0A. Accessed 13 Mar 2019
[363] American Electric Power (2015). Ohio Valley Electric Corporation 2015 transmission plan
[364] GRDA (2017). Re: Request for Emergency Order Pursuant to Section 202(c) of the Federal Power Act
[365] LG&E/KU (2019). LG&E/KU Shared electric service area. https://lge-ku.com/sites/default/files/documents/lgeku_shared.pdf%0A. Accessed 13 Mar 2019
[366] SPP (2017). State of the market 2016
[367] We Energies (2018). Service area map. https://www.we-energies.com/home/ServiceMap.pdf%0A. Accessed 13 Mar 2019
[368] OMPA (2013). Member Cities. https://ompa.com/about/member-cities/. Accessed 4 Nov 2017
[369] PJM (2019). Data Directory. http://www.pjm.com/markets-and-operations/data-dictionary.aspx%0A. Accessed 13 Mar 2019
[370] Potomac Economics (2017). 2016 State of the Market Report for the MISO Electricity Markets
[371] California Energy Commission (2016). Electricity Consumption by Planning Area. http://www.ecdms.energy.ca.gov/elecbyplan.aspx. Accessed 4 Nov 2017
[372] WEC (2017). Focused on the fundamentals; 2016 annual report. Chicago
[373] Southern Company (2017). 2016 Annual Report. Atlanta, doi: 10.1039/C1DT90165F, ISBN: 0121559920
[374] EIA (2015). State Electricity Profiles. https://www.eia.gov/electricity/state/archive/2015/. Accessed 4 Nov 2017
[375] U.S. Department of Homeland Security (2017). Electric Power Transmission Lines. https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-power-transmission-lines?geometry=-180.264%2C24.362%2C-13.008%2C48.687. Accessed 12 Mar 2019
[376] OATI (2019). SWPP OASIS Interface values. http://www.oasis.oati.com/SWPP/SWPPdocs/Interface_Values.xls%0A. Accessed 4 Nov 2017
[377] SWPA (2006). Southwestern Power System Map. https://www.swpa.gov/PDFs/SWPASystemMap2006.pdf. Accessed 13 Mar 2019
[378] SPP (2016). 2016 Integrated transmission planning near-term assessment
[379] TVA (2011). NERC Transmission planning map. http://www.oatioasis.com/TVA/TVAdocs/TVA_Transmission_Map_2011_r2.pdf%0A. Accessed 13 Mar 2019
[380] LG&E and KU Energy LLC (2011). PPL companies. https://lge-ku.com/sites/default/files/2017-09/LGE KU Service Territory ma.pdf%0A. Accessed 13 Mar 2019
[381] DOE (2018). Annual U.S. Transmission Data Review. Washington DC
[382] He G, Kammen DM (2016). Where, when and how much solar is available? A provincial-scale solar resource assessment for China. Renewable Energy 85: 74–82. doi: 10.1016/j.renene.2015.06.027
[383] He G, Kammen DM (2014). Where, when and how much wind is available? A provincial-scale wind resource assessment for China. Energy Policy 74: 116–122. doi: 10.1016/j.enpol.2014.07.003
[384] Wei C, Feng Z, Xin-yang H, et al (2008). Analysis on Load Characteristics of State Grid. Electric Power Technologic Economics 20: 25–30.
[385] 3E Information Development & Consultants (2008). Chinese Electricity Market Monthly. http://www.3-eee.net/File/CRES Sample/China Electricity Monthly.pdf. Accessed 20 Mar 2019
[386] CEIC (2018). China Electricity Consumption. https://www.ceicdata.com/en/china/electricity-consumption. Accessed 20 Mar 2019
[387] CEIC (2019). Macau SAR, China Electricity: Consumption. https://www.ceicdata.com/en/macau/electricity-statistics/electricity-consumption. Accessed 20 Mar 2019
[388] CEIC (2019). Hong Kong SAR, China Electricity Consumption: Total. https://www.ceicdata.com/en/hong-kong/electricity-production--consumption/electricity-consumption-total. Accessed 20 Mar 2019
[389] Ministry of Power (2019). Creation of National Grid. https://powermin.nic.in/en/content/creation-national-grid. Accessed 11 Apr 2019
[390] Ministry of Power (2017). Inter Regional Transmission Capacity --- Program of National Grid Development (in MW). https://powermin.nic.in/sites/default/files/uploads/IRTC_English_May_2017.pdf. Accessed 11 Apr 2019
[391] Ministry of Power Central Electricity Authority (2019). Monthly Peak Demand for Power. https://data.gov.in/catalog/monthly-peak-demand-power?filters%5Bfield_catalog_reference%5D=89757&format=json&offset=0&limit=6&sort%5Bcreated%5D=desc. Accessed 11 Apr 2019
[392] Lund PC (2016). Realizing the Asia Super Grid - Japan' s situation and challenges. https://www.renewable-

ei.org/en/activities/events/img/20160908/Per_Chrster_Lund_GlobalInterconnections.pdf. Accessed 7 Oct 2019
[393] Shimabukuro K Distributed Energy on the Remote Islands of Okinawa. http://www.env.go.jp/nature/biodic/ecdisso2014/en/pdf/subcommittee2/shimabukuro.pdf. Accessed 7 Oct 2019
[394] Belobrov V (2018). Electricity Markets in Russia (upd. 2018). https://www.academia.edu/2204254/Electricity_Markets_in_Russia_english_updated_2018_. Accessed 14 Apr 2019
[395] Volkov EP, Barinov VA, Krzhizhanovsky ASM, et al (2010). Prospects for development of Russia' s power industry up to 2030. In: Joint symposium within the framework of the APEC project "ENERGY RELATIONS BETWEEN RUSSIA AND EASTERN ASIA: DEVELOPMENT STRATEGIES IN THE XXI CENTURY." APEC
[396] SO UES JSC (2020). Generation and consumption (hour). http://www.so-cdu.ru/index.php?id=ees_gen_consump_hour&no_cache=1. Accessed 21 Mar 2019
[397] University of Cape Town (2015). TIME_SLICES 1.0 UNEP. http://energydata.uct.ac.za/it/dataset/satim-timeslices/resource/d721079d-f06d-4601-86f6-5538b05678d1. Accessed 4 Sep 2019
[398] Data.go.kr (2019). Korea Electricity Exchange Information on Electricity Trading Volume by Time Zone (2001.04 ~ 2017.12). https://www.data.go.kr/dataset/3043737/fileData.do. Accessed 12 Nov 2019
[399] GSO (2019). System demand profile. https://www.gso.org.my/SystemData/SystemDemand.aspx. Accessed 21 Mar 2019
[400] OPWP (2016). MIS Demand Data. http://www.omanpwp.com/new/Documents.aspx?Pid=114. Accessed 21 Mar 2019
[401] Energy Market Authority (2019). Half-hourly system demand data. https://www.ema.gov.sg/statistic.aspx?sta_sid=20140826Y84sgBebjwKV. Accessed 21 Mar 2019
[402] EXIST (2020). Real Time Consumption. https://seffaflik.epias.com.tr/transparency/tuketim/gerceklesen-tuketim/gercek-zamanli-tuketim.xhtml. Accessed 14 Apr 2019
[403] ENTSO-E (2019). Monthly Hourly Load Values. https://www.entsoe.eu/data/power-stats/hourly_load/. Accessed 21 Mar 2019
[404] GSE (2019). Electricity demand tracking. http://www.gse.com.ge/for-customers/data-from-the-power-system/production-and-consumption. Accessed 21 Mar 2019
[405] CENCE (2020). National Electric System - Costa Rica Real Time Operation. https://apps.grupoice.com/CenceWeb/CenceCurvaDemandaSEN.jsf?init=true. Accessed 13 Feb 2020
[406] Administrador del Mercado Mayorista (2020). Results of the Operation. http://www.amm.org.gt/portal/?page_id=145. Accessed 18 Nov 2019
[407] SENER (2018). National Electric System Development Program. https://www.gob.mx/sener/acciones-y-programas/programa-de-desarrollo-del-sistema-electrico-nacional-33462. Accessed 21 Mar 2019
[408] CNDC (2020). Planning and Daily Operation of the National Interconnected System and Administration of the Wholesale Electricity Market. http://www.cndc.org.ni/. Accessed 11 Nov 2019
[409] CND (2019). Comportamiento del Sistema. http://www.cnd.com.pa/informes.php?tipo_informe=31&cat=5. Accessed 21 Mar 2019
[410] UT (2020). Daily Demand Curve. http://estadistico.ut.com.sv/CurvaDemanda.aspx. Accessed 11 Nov 2019
[411] EMI (2019). Grid demand trends. https://www.emi.ea.govt.nz/Wholesale/Reports/W_GD_C?_si=v%7C3. Accessed 21 Mar 2019
[412] CAMMESA (2013). Demanda horaria neta por region. http://portalweb.cammesa.com/_layouts/XlViewer.aspx?id=http%3A%2F%2Fportalweb.cammesa.com%2FArchivosExcel%2FEstadisticas%2FGenerales%2FDem-hor.xlsx&cookie=UCwgdlm%252BweHG2WFHMQ%252BSRbO63L%252FgTD8NwWsuhiBqxXhm8ZLqwUUbpymj%252B%252FzgVpQuXMnvdIwXu0bFQ03b. Accessed 21 Mar 2019
[413] Coordinador Electrico Nacional (2019). Operación real diaria. https://sic.coordinador.cl/informes-y-documentos/fichas/operacion-real/. Accessed 21 Mar 2019
[414] COES (2019). Demanda. http://www.coes.org.pe/Portal/portalinformacion/demanda. Accessed 21 Mar 2019
[415] UTE (2020). History of Power Balance by Source. https://apps.ute.com.uy/SgePublico/ConsHistBalancePotXFuente.aspx. Accessed 21 Mar 2019
[416] Batmunkh Y-U (2016). Renewable potential in Gobi desert, Gobitec and Asian Super Grid Initiative. In: 4th Northeast Asia Energy Secur. Forum 2016. http://www.unescap.org/sites/default/files/Session 1.2. Yeren-Ulzii Batmunkh_Mongolia.pdf. Accessed 14 Apr 2019
[417] Vucetic V, Krishnaswamy V (2006). Development of Electricity Trade in Central Asia – South Asia Region 1
[418] SIGAR (2018). Afghanistan's energy grid: Planned and existing infrastructe, as of September 2018. https://www.sigar.mil/pdf/quarterlyreports/2018-10-30qr-power-infrastructure.pdf%0A. Accessed 12 Mar 2019
[419] Panda RR (2018). Trans-regional energy connectivity between the ASEAN power grid and the South-Asia power grid: Prospects and opportunities. https://sari-energy.org/wp-content/uploads/2018/05/PRESEN1-2.pdf%0A. Accessed 12 Mar 2019
[420] Bhutan Power Corporation (2014). Status of Bhutan cross border interconnection with India & Expected Benefits. https://www.usea.org/sites/default/files/event-/Bhutan Power Corporation.pdf. Accessed 11 Apr 2019
[421] NEXANS (2007). Nexans wins Euro 140 million contract to supply a high voltage subsea cable in China. https://www.nexans.no/eservice/Norway-en/navigatepub_142646_-

7836/Nexans_wins_Euro_140_million_contract_to_supply_a_.html. Accessed 14 Apr 2019
[422] The Government of the Hong Kong Special Administrative Region (2018). Power and Gas Supplies. https://www.enb.gov.hk/en/about_us/powerandgas.html. Accessed 14 Apr 2019
[423] Henderson J, Mitrova T (2016). Energy Relations between Russia and China: Playing Chess with the Dragon. ISBN: 9781784670641
[424] EIA (2018). Korea, North; Overview. https://www.eia.gov/beta/international/analysis.php?iso=PRK. Accessed 24 Feb 2019
[425] Sakato F, Fisher J, Hoole P, et al (2017). A Design of a 345-kV Electric Power Transmission Line Interlinking Ramu and Rouna Grids in Papua New Guinea. In: MATEC Web of Conferences. p 05003
[426] Shrestha P (2016). Cross-border transmission line between Nepal and India: A test-case for the analysis of HVDC integration into an existing HVAC system. Norwegian University of Science and Technology
[427] Alam F, Alam Q, Reza S, et al (2017). Regional Power Trading and Energy Exchange Platforms. Energy Procedia 110: 592–596. doi: 10.1016/j.egypro.2017.03.190
[428] Pearce A, Harlow I, Hussain MA, et al (2010). Iraq electricity masterplan; Final report. ISBN: 9780199552047
[429] Ahmad A (2015). Regional Power Interconnections in South Asia. http://www.saarcenergy.org/wp-content/uploads/2016/03/Regional-Power-Interconnections-by-Mr.-Anjum-Ahmad.pdf%0A. Accessed 14 Apr 2019
[430] Financialtribune (2016). New line will triple Iran's electricity export to Turkmen Republic. https://financialtribune.com/articles/energy/53436/new-line-will-triple-electricity-export-to-turkmen-republic. Accessed 24 Feb 2019
[431] Export.gov (2018). Israel - Energy. https://www.export.gov/article?id=Israel-Energy. Accessed 24 Feb 2019
[432] The Jordan Times (2019). Jordan, Saudi agree on feasibility of connecting power grids. http://www.jordantimes.com/news/local/jordan-saudi-agree-feasibility-connecting-power-grids. Accessed 25 Feb 2019
[433] Rault E, Perrakis K, Tourlis N, et al (2016). Activity Completion Report "Market Design Options of Kazakhstan and its Role in the Central Asia Regional Electricity Market" (89.KZ, 107.KZ,108.KZ&117.UZ). http://www.inogate.org/documents/ACR_89_107_108KZ_117UZ.pdf. Accessed 12 Mar 2019
[434] Myroshnychenko Y (2016). Regional Power Trade Unrealized Benefits for Central Asia for 2010-2014. https://www.carecprogram.org/uploads/Regional-Power-Trade-Unrealized-Benefits-for-Central-Asia-for-2010-2014.pdf%0A. Accessed 12 Mar 2019
[435] Otsuki T, Mohd Isa AB, Samuelson RD (2016). Electric power grid interconnections in Northeast Asia: A quantitative analysis of opportunities and challenges. Energy Policy 89: 311–329. doi: 10.1016/j.enpol.2015.11.021
[436] Xinhuanet (2018). Laos to sell electricity to myanmar: offical. http://www.xinhuanet.com/english/2018-01/16/c_136899158.htm. Accessed 24 Feb 2019
[437] Rawea AS, Urooj S (2018). Strategies, current status, problems of energy and perspectives of Yemen's renewable energy solutions. Renewable and Sustainable Energy Reviews 82: 1655–1663. doi: 10.1016/j.rser.2017.07.015
[438] UKRENERGO (2019). The balance of flows between the power system of Ukraine and the power systems of neighboring countries. https://ua.energy/activity/dispatch-information/transborder-flows/. Accessed 24 Feb 2019
[439] Hasnie S, Aguilar A, Beauchamp M, et al (2018). Proposed load and administration of technical assistance grant Turkmenistan: National power grid strengthening project
[440] OST (2012). An overview of the Albanian TSO, and cross-border trading and allocation of capacities. http://www.ere.gov.al/doc/Luan_Aranitasi_APS_-_OST_sh.a._-_v1.pdf%0A. Accessed 12 Mar 2019
[441] Aslanidze A (2016). The role of the energy charter in promoting electricity cooperation in the South Caucasus. Brussels
[442] Erten IE (2015). Cross-border Trade - Turkish Electricity Import and Export Rules. https://pubs.naruc.org/pub.cfm?id=256E2667-974E-5EC1-D92D-82B42FF3116E%0A. Accessed 12 Mar 2019
[443] Koktashvili A, Vakhtangadze G (2015). Ten-Year Network Development Plan of Georgia for 2016-2026. http://www.gse.com.ge/sw/static/file/TYNDP_GE-2016-2026_ENG.pdf. Accessed 13 Mar 2019
[444] Perrakis K, Vassilaki L, Tourlis N, et al (2016). Activity Completion Report "AZERBAIJAN: Legal, regulatory and market assessment regarding the export prospects towards the Turkish market" (AHEF 121.AZ, & 122.GE). http://www.inogate.org/documents/ACR_121AZ.pdf. Accessed 12 Mar 2019
[445] Teias (2017). ENTSO-E (European Network of Transmission System Operators for Electricity). https://www.teias.gov.tr/en/node/221. Accessed 25 Feb 2019
[446] ENTSO-E (2011). Indicative values for Net Transfer Capacities (NTC) in Continental Europe. https://www.entsoe.eu/fileadmin/user_upload/_library/ntc/archive/NTC-Values-Winter-2010-2011.pdf. Accessed 20 Mar 2019
[447] Staltmanis A (2006). Congestion management and capacity allocation methods used in the Baltic region. https://www.ceer.eu/documents/104400/3648831/MF_RIGA_DCBALTIJA.PDF/f7bbd986-7708-765d-2cb1-667a80d1ae0e?version=1.0%0A. Accessed 12 Mar 2019
[448] Purvins A, Fulli G, Covrig C-F, et al (2016). The Baltic Power System between East and West Interconnections; First results from a security analysis and insights for future work. doi: 10.2790/411653, ISBN: 9789279568466
[449] ENTSO-E (2019). ENTSO-E Transmission System Map. https://www.entsoe.eu/data/map/. Accessed 25 Feb 2019
[450] CEER (2013). Priorities of national power market of Belarus.

https://www.ceer.eu/documents/104400/3726591/02_03_Belarus+%5BKompatibilitätsmodus%5D.pdf/5d26bf4f-5362-3ae0-23d4-40dcd15149d3?version=1.0. Accessed 14 Apr 2019
[451] Fingrid (2019). Cross-border Connections between Russia and Finland. https://www.fingrid.fi/en/services/power-transmission/400-kv-cross-border-connections-between-russia-and-finland/. Accessed 25 Feb 2019
[452] Fingrid (2019). Cross-border transmission capacities – Norway. https://www.fingrid.fi/en/electricity-market/cross-border-transmission/graphs/norway/. Accessed 25 Feb 2019
[453] KOSTT (2011). List of new transmission capacities and interconnection lines (2011-2020). https://dokumen.tips/documents/list-of-new-transmission-capacities-and-interconnection-lines-of-new-transmission.html. Accessed 12 Mar 2019
[454] Neves MM das (2014). Electricity Interconnection and Trade between Norway and Russia. Arctic Review on Law and Politics 5: 177–200.
[455] Huppmann D, Gidden MJ, Nicholls Z, et al (2021). pyam: Analysis and visualisation of integrated assessment and macro-energy scenarios. Open Research Europe 1: 74. doi: 10.12688/openreseurope.13633.1
[456] World development indicators. Washington, D.C. : The World Bank.
[457] 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
[458] 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
[459] 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
[460] 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
[461] 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
[462] 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
[463] Bahrman M, Johnson B (2007). An Overview of High Voltage Direct Current Systems and Applications. IEEE power & energy magazine 32–44.
[464] 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
[465] EIA (2018). Assessing HVDC Transmission for Impacts of Non-Dispatchable Generation. Washington DC
[466] 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
[467] 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

Appendix A: PLEXOS Detailed Equations

A.1 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

A.2 Variables

V_{jt} Integer on/off decision variable for unit j at period t

X_{jt} Integer on/off decision variable for pumped storage pumping unit j at period t

U_{jt} Variable that = 1 at period t if unit j has started in previous period else 0

P_{jt} Power output of unit j (MW)

H_{jt} Pump load for unit j period t (MW)

W_{int} Flow into reservoir at time t (MWh)

W_{outt} Flow out of reservoir at time t (MWh)

W_t Volume of storage at a time t (MWh)

A.3 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

n_{jt} No load cost unit j in period t (€)

c_{jt} Start cost unit j in period t (€)

m_{jt} Production Cost unit j in period t (€)

e_{stor} Efficiency of pumping unit (%)

$pmax_j$ Max power output of a unit j (MW)

$pmin_j$ Mini stable generation of unit j (MW)

$pmpmax_{stor}$ Max pumping capacity of pumping unit

J_j Available units in each generator

J_{stor} Number of pumping units

MRU_j Maximum ramp up rate (MW/min)

MRD_j Maximum ramp down rate (MW/min)

MUT_j Minimum up time (hrs)

A_p Number of hours a unit must initially be online due to its MUT constraint (hrs)

W_{INT} Initial Volume of reservoir (GWh)

W Maximum volume of storage (GWH)

A.4 Objective Function

Eq. A-1 $$OBJ = Min\sum_{t \in T}\sum c_{jt}.U_{jt} + n_{jt}.V_{jt} + m_{jt}.P_{jt} + vl.use_t + vs.usr_t$$

The objective function 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:

A.5 Energy Balance Equation

Eq. A-2 $$\sum_{t \in T}\sum P_{jt} - H_{jt} + use_t = D_t$$

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.

A.6 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.

Eq. A-3 $$-V_{jt} + U_{jt} \geq -1 \quad \forall t = 1$$

Eq. A-4 $$V_{jt} - V_{jt+1} + U_{jt+1} \geq 0$$

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

Eq. A-5 $$P_{jt} - P\max_j .V_{jt} \leq 0$$

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

Eq. A-6 $$P_{jt} - P\min_j .V_{jt} \geq 0$$

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

Eq. A-7 $$H_{jt} - Pmp\max_{Stor} .X_{jt} \leq 0$$

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

Eq. A-8 $$V_{jt} + X_{jt} \leq 1 \quad \text{where} j \in stor$$

Eq. A-9 $$V_j \leq J_j \quad X_j \leq J_{Stor} \quad j \in J$$

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

Eq. A-10 $$A_{p,j} \geq V_{j,t} - V_{j,t-1} \forall t.t - MUT_j - 1$$

Eq. A-11 $$V_{j,t} \geq A_{p,j} - \sum_{t}^{t-MUT_j+1} V_{j,t} / MUT_j \forall t$$

Minimum Up Times[21]: (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,

[21] PLEXOS Help Files

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.

Eq. A-12 $$A_{p,j} \geq V_{j,t-1} - V_{j,t} \forall t.t - MDT_j + 1$$

Eq. A-13 $$V_{j,t} \leq 1 + \sum_{t}^{t-MDT_j+1} V_{j,t} / MDT_j - A_{p,j} \forall t$$

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.

Eq. A-14 $$P_{jt} - P_{j.t-1} - MRU_j.V_{jt} - p_{\min j}.U_j \leq 0$$

Eq. A-15 $$p_{\min j}.P_{jt} + P_{jt} - P_{j.t-1} - P_{jt}.(MRD_j - p_{\min j}) \leq 0$$

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

A.7 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.

Eq. A-16 $$W_{tR} + W_{out.tR} - W_{in.tR} = W_{INT,R} \quad \forall t = 1, R \in RES_{Up}, RES_{low}$$

Eq. A-17 $$W_{t.RES^{up}} + W_{out,RES^{up}} - W_{in,RES^{up}} = 0$$

Eq. A-18 $$e_{stor}.H_{jt.RES^{up}} - W_{in.tRES^{up}} = 0$$

Eq. A-19 $$P_{stor.t} - W_{out.t.RES^{up}} = 0$$

Appendix B: Supplementary Material Chapter 3

Table B-1 Installed capacities and total load for the 2050 EU-NAM reference model. 'Other' nodes are aggregations of the remaining nodes in the respective country or region.

Node	Hydro[1]	Solar[2]	Wind Offshore	Wind Onshore	NG CCGT	NG OCGT	Nuclear	Oil	Coal Fired[4]	Load
	MW	MW	MW	MW	MW	MW	MW	MW	MW	TWh
EU	*189513*	*295194*	*47448*	*319081*	*241726*	*29131*	*96199*	*3367*	*55210*	*4237*
EU-DE	7170	86141	9369	77180	36754	4672	0	674	24057	663
EU-ES	17158	49359	153	46989	12965	1517	0	782	97	333
EU-FR	26559	45200	6056	51513	30812	4112	32276	625	2892	617
EU-IT	19588	56765	644	25314	40549	4513	0	128	1901	438
EU-UK	1818	11255	16533	24935	41457	4645	17302	339	448	502
EU 'Other'	117220	46475	14693	93150	79189	9673	46621	818	25815	1694
CA	*92260*	*7131*	*0*	*27508*	*31345*	*11999*	*9838*	*2485*	*1172*	*705*
CA-AB	913	368	0	7347	16576	6217	0	7	0	107
CA-ON	9978	5916	0	7224	8789	3698	9133	294	0	175
CA-QC	43289	355	0	6781	560	31	0	159	0	251
CA 'Other'	38079	491	0	6156	5420	2052	705	2025	1172	171
US	*80902*	*148026*	*29*	*186296*	*374400*	*213024*	*76500*	*8091*	*159781*	*4669*
US-CAMX	10105	10343	0	21402	16756	12204	0	100	33	295
US-ERCT	457	2031	0	23375	64334	32630	4628	27	9891	280
US-RFCW	1638	7350	0	24587	38811	27592	10568	456	30300	608
US-SRSE	3760	23370	0	15	27627	8919	6942	277	9259	301
US-SRVC	3590	27775	0	1001	31858	11573	14686	685	9440	394
US 'Other'	61353	77156	29	115916	195014	120105	39675	6547	100859	2791

[1] *Includes hydro impoundment and hydro run of river, PSH not incorporated in early-stage simulations.*
[2] *Includes concentrated solar power and solar-PV.*
[3] *Includes biomass and waste, geothermal, tidal and wave-based capacity.*
[4] *Also includes lignite-based capacity.*

Appendix C: Supplementary Material Chapter 4

C.1 Sub-Country Nodes

This section describes the used data and methodologies for the spatial representation, hourly demand profiles and transmission capacities of sub-country nodes within the global model.

C.1.1 Australia

Australia is subdivided into seven nodes, consisting of the six states (New South Wales, Queensland, South Australia, Tasmania, Western Australia and Victoria) plus the Northern Territory as visualized in Figure C-1. The Australian Capital Territory is assumed to be part of the New South Wales node (OC-AUS-SW). The National Electricity Market (NEM) is a wholesale market operated by the Australian Energy Market Operator (AEMO) that covers the grid connected areas of all nodes apart from OC-AUS-WA and OC-AUS-NT [321]. Historical hourly load for the different regions of NEM, which can be directly correlated to the nodes used for this study, can be retrieved through AEMO's data dashboard [322]. Albeit not part of the NEM, OC-AUS-WA has its separate wholesale market also operated by AEMO. Historical hourly load data can be retrieved through [323]. No hourly data for OC-AUS-NT could be found, hence we used the profile shape of OC-AUS-WA and scaled it based on 2015 final electricity demand data from [324]. Aggregated transmission capacities between nodes within the NEM has been determined based on [325]. To-date, no cross-nodal transmission lines exist outside the NEM territory [326].

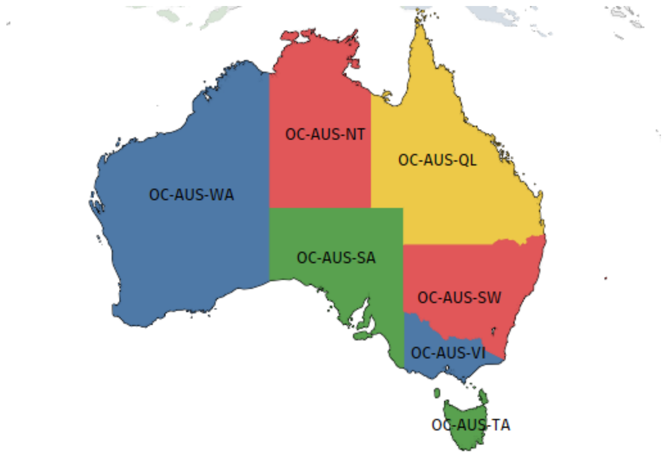


Figure C-1 Nodal representation of Australia in PLEXOS-World. Every copperplated area of an individual colour represents a node with a total of 7 independent nodes.

C.1.2 Brazil

Historically, Brazil's national interconnected electricity system (SIN) consisted of four large grid-connected regions ranging from the South of the country to the North and North-East [327]. In more recent years, several long-distance transmission projects have been implemented which directly interconnect the hydro rich West and North-West of the country with demand centres in central Brazil [328]. We follow Gils and colleagues [329] for the nodal representation of the Brazilian electricity system. Next to the nodes as shown in Figure C-2, this also includes three transmission junction nodes connecting large hydro facilities with demand centers as indicated with an asterisk on the map. We've furthermore used [329] to retrieve the transmission capacities between nodes. The system operator of SIN, 'Operador Nacional do Sistema Eléctrico' (ONS), provides hourly demand data for historical years including 2015 [330]. The profiles for the 'Nordeste' and 'Sul' regions correlate to the nodes SA-BRA-NE and SA-BRA-SO as used for this study, whereas 'Norte' covers SA-BRA-CN, SA-BRA-NW, SA-BRA-WE and 'Sudeste/Centro-Oeste' covers SA-BRA-CW and SA-BRA-SE. For these latter two groups of nodes, we've used the relative population size per node based on [331] as a best estimate to disaggregate the regional demand profiles on a nodal basis.

Figure C-2 Nodal representation of Brazil in PLEXOS-World. Every copperplated area of an individual colour represents a node with a total of 10 independent nodes, consisting of 7 nodes with demand and generation portfolios and 3 transmission junction nodes that represent transmission interconnections connecting large hydro facilities with demand centres (indicated with asterisks on the map).

C.1.3 Canada and the United States

The grid-connected electricity system in Canada and the US spans multiple time zones, stretching from Pacific Standard Time (-8 UTC) on the west coast to Atlantic Standard Time (-4 UTC) in eastern Canada. There are four main interconnected grids; The Eastern, Western, Quebec and ERCOT interconnections [332]. Electricity system integration through transmission interconnection between these independent grids is limited. As of 2015, the reliability of the four interconnections is governed by 16 different North-American Electric Reliability Corporation (NERC) coordinating regions [333]. To add more complexity, there are nine wholesale markets operated by Independent System Operators (ISO) or Regional Transmission Organizations (RTO) [332]. Approximately 70% of demand in the US is supplied through wholesale markets, the remainder through vertically integrated utilities [334]. The US Energy Information Administration (EIA) developed a nodal representation for their National Energy Modelling System (NEMS) with these aspects in mind by disaggregating the country in 22 regions [215]. We follow this approach for the nodal representation of the US, apart from combining the three New York NEMS regions into a singular node. In addition, the insular areas of Alaska, Guam, Hawaii and Puerto Rico are added as seperate nodes. The grid-connected provinces of Canada are represented with eight nodes (New Brunswick, Nova Scotia and Prince Edward Island combined into one node). Furthermore, the isolated systems of The Northwest Territories, Nunavut and Yukon [335] are aggregated into a singular node. Both sets of nodes are visualized in Figure C-3.

All Canadian and US nodes are populated with localized load and transmission data. Hourly load profiles for the Canadian provinces are retrieved from the relevant system operators through online data portals [336–340] and personal communication (L. St-Laurent, Hydro Quebec, 12-02-2018 – B. Owen, Manitoba Hydro, 01-12-2017 – R. Mall, SaskPower, 21-12-2017). Interregional transmission capacities and cross-border capacities towards the US regions are based on reported values [341–347] or derived from maximum reached hourly power exchange values in 2015 as retrieved from [338,348]. We assume that these values equal the NTC between adjacent nodes.

To be able to incorporate accurate data for the US nodes we need to determine which ISO's, RTO's and smaller Balancing Authorities (BA) cover the different NEMS regions. This has been done by comparing the status map on the EIA's US electric system operating data portal [219] with the mapped NEMS regions following [215]. Generally, the different operators clearly fit within a singular node. Yet, in certain situations it is less obvious, requiring additional sources such as market reports of the different BA's to define the correct spatial representation [349–368]. Furthermore, the Southwest Power Pool (SPP), Midcontinent Independent System

Operator (MISO) and the PJM interconnection span a larger area covering multiple NEMS regions. Historically, these larger areas were operated by smaller utilities as shown in [220]. We use these former utilities to disaggregate the load and transmission data of the larger SPP, MISO and PJM regions as explained in more detail below.

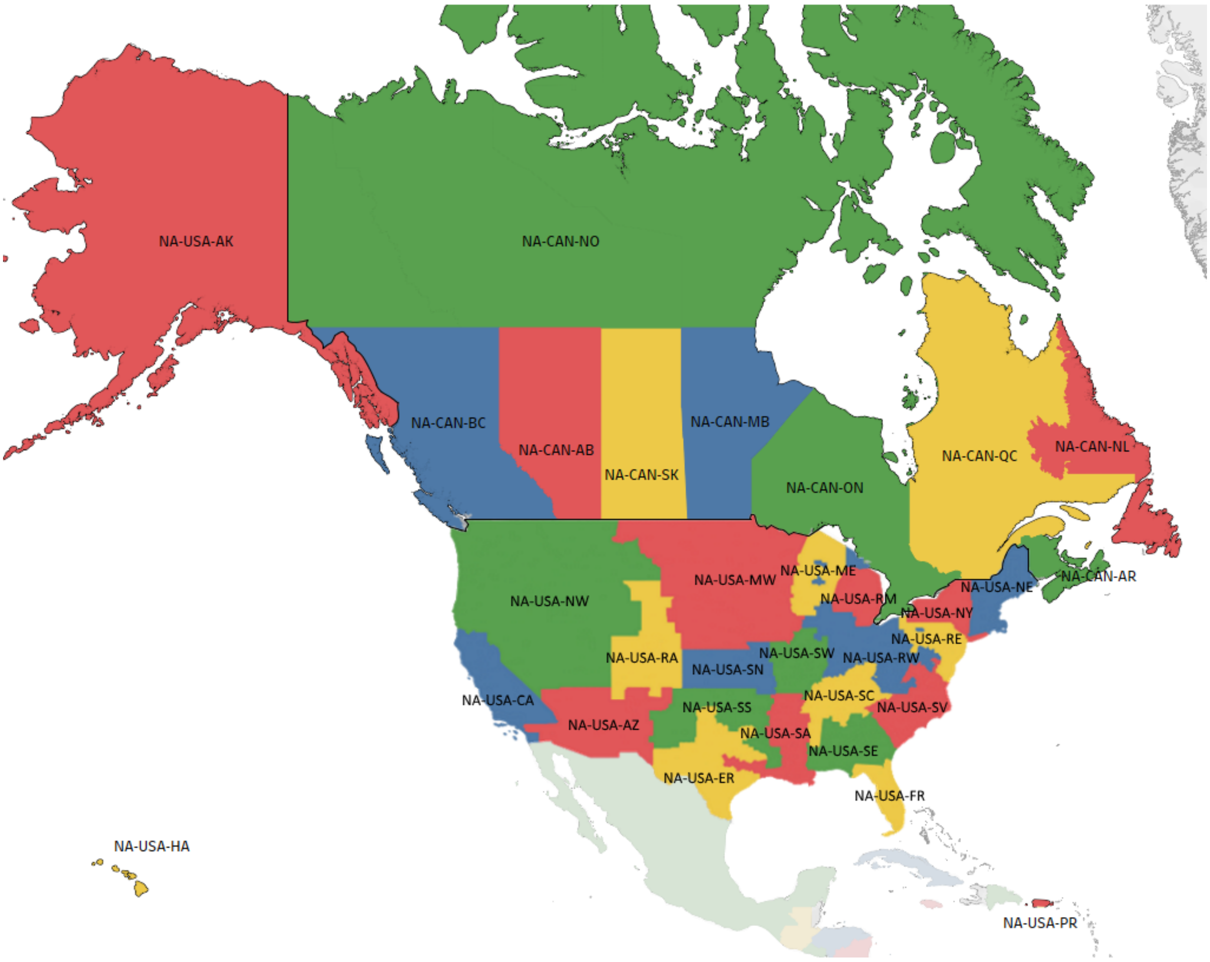


Figure C-3 Nodal representation of Canada and the US in PLEXOS-World. Every copperplated area of an individual colour represents a node with a total of 24 nodes in the US (mainland, in addition to Guam, Hawaii and Puerto Rico) and 9 in Canada. Blue sections in and around NA-USA-ME are part of balancing authorities within NA-USA-RW.

The 2015 hourly load profiles for the US nodes are constructed predominantly based on historically reported data for the different operators as administrated by the Federal Energy Regulatory Commission (FERC) [218]. PJM's data directory [369] is used to retrieve 2015 hourly load data for the sub-regions within PJM. Profiles from the different operators per node, as identified earlier, are aggregated into a single profile. If available, this has been done by utilizing 2015 data, yet in certain cases data from deviating years had to be scaled and shifted to 2015 values by making use of reported yearly demand or sales data from the relevant operators [370–373]. The profile builder tool within PLEXOS has been used to correctly shift profiles from year to year. Rather than using the reported profiles for SPP, MISO and PJM, we used scaled and shifted historical data from the former utilities who compose these larger operators. This approach allows for more accurate spatial representation of load per US node within the model. Finally, the initial aggregated profiles per node are scaled to overall 2015 demand by combining reported final electricity sales to customers per NEMS region in the Annual Energy Outlook (AEO) of the EIA [216,217] with state level T&D losses [374].

Although a dataset exists with all individual power transmission lines in the US [375], this dataset does not incorporate info on potential NTC per line. We therefore use historical hourly exchange data (July 2015-2017) between the different operators [221] as indicator for NTC between US nodes. Data from before July 2015 isn't available. It is assumed that the maximum reached hourly exchange in the period 2015-2017 counts as indicative NTC between two operators. Similar to the approach for hourly demand, we use additional sources to determine transfer capacities to- and within the SPP, MISO and PJM parts of the US nodes for improved spatial representation. Transmission lines and capacities towards sub-areas of SPP can be derived from [376] with help from [332,377] to determine where transmission lines cross bordering nodes. No recent data can be found on transmission capacities within the larger SPP region. Hence, we assume that the maximum external flow from a single pathway coming in to a node covered by SPP can also flow towards adjacent nodes covered by SPP. Looking at the quantity- and voltage of lines running between regions covered by SPP compared to lines to external regions [378] this is a simplified yet best estimate assumption to work with. NTCs to external operators for nodes (partially) covered by MISO are based on hourly exchange data [221], again with additional sources being used to determine where lines cross bordering nodes [379–381]. Flow between the Midwest and South MISO subregions, in essence between the MISO parts of the US-SRDA and US-SRGW nodes, is constrained to 3GW since exchange occurs through infrastructure of other operators [370]. We assume that this flow can be sustained throughout all areas operated by MISO. Finally, maximum interregional and internal 2015 hourly exchange values for the PJM interconnection are retrieved from their data directory [369] and used to determine NTCs. All identified capacities between operators are aggregated into a single bidirectional NTC per transmission pathway between adjacent nodes. These values can be found in Table C-3 in Section C.5.

C.1.4 China

From a data perspective, it is generally difficult to retrieve accurate information on China's electricity system. This is the case for powerplant information as mentioned in the main text of this study, yet also for sub-country demand and transmission data. For this study, China's electricity system is mostly based on received data from the authors of a range of studies by He and colleagues in which they introduce a systems approach to decarbonize China's electricity system [20] and assess China's renewable resource potential [382,383]. We follow the nodes as used for these studies which is on a per state basis as shown in Figure C-4, in addition we include Hong Kong (AS-CHN-HK) and Macau (AS-CHN-MA) as separate nodes within China's larger electricity system. Transmission capacities in between the Chinese nodes as of 2015 are based on the same study of He et al.

Figure C-4 Nodal representation of China and Japan in PLEXOS-World. Every copperplated area of an individual colour represents a node with a total of 34 nodes in China and 6 in Japan.

To-date there's no detailed historical data on hourly demand available for China, not on a regional level nor on an aggregate country level. We therefore developed simplified node specific synthetic hourly demand profiles for the different sub-country Chinese nodes, based on a standard daily shape of hourly demand for China as developed by State Grid [384]. [385]

provides state specific monthly electricity demand data for the period 2007-2008. Using the historical relative share of demand per month per state, combined with the standard hourly shape and with 2015 demand data per state or region [386–388] allows us to develop a hourly demand profile for 2015 that is month and node specific. Albeit its obvious limitations, e.g. every day of a certain month has the exact same hourly values, it is currently the best possible approach based on available open data.

C.1.5 India

India's nodal representation is based on the five main regional grids, integrated since 2014 as a national interconnected grid [389]. The nodal representation is shown in Figure C-5. Internal transmission capacities between the nodes are based on reported values by the Ministry of Power of India [390]. Toktarova et al. [249] has developed synthetic hourly demand profiles for India as a whole. We've used their 2020 profile and scaled and shifted it to 2015 values. Monthly peak demand data per state or regional power grid is provided by the Ministry of Power [391]. Per regional grid, directly correlated to our nodes in this study, we've altered the synthetic profile for India by scaling the hourly values per month based on the historical 2015 monthly peak demand, creating a node specific hourly profile.

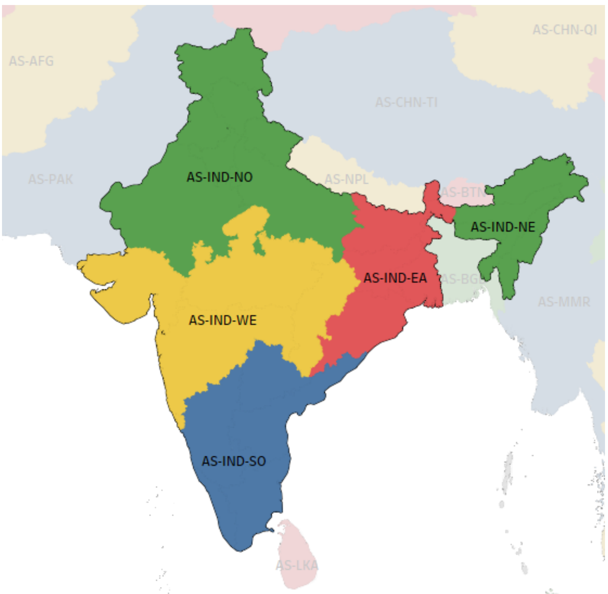


Figure C-5 Nodal representation of India in PLEXOS-World. Every copperplated area of an individual colour represents a node with a total of 5 nodes.

C.1.6 Japan

The electricity system of mainland Japan is divided into two asynchronous grids. Western Japan, including the islands of Kyūshū and Shikoku, runs at 60 Hz and Eastern Japan, including the island of Hokkaido, runs at 50 Hz. To-date, the grids are limitedly interconnected with back to back DC links allowing a maximum flow of 0.9 GW [392]. Supply on the islands of Okinawa is mostly based on decentral diesel-based generation and an increasing integration of renewables [393]. For this study, Honshu is divided into two nodes, with the 50/60 Hz grids as separator. Furthermore, the separate islands (Hokkaido, Kyūshū, Okinawa and Shikoku) are represented by individual nodes. See Figure C-4 in Section C.1.4 for the relative nodal representation. Transmission capacity between the Japanese nodes is based on [392], to-date no cross-border interconnections to the Asian mainland exist. The Japanese ministry of Economy, Trade and Industry has provided hourly demand per system operator for the period April 2010 – March 2011. For simplicity, we've assumed that the shape of the hourly data for January – March 2011, while maintaining a correct representation of weekdays and weekends, can be used as data for January – March 2010 to create an hourly profile for a full calendar year. The hourly values of the different relevant system operators are combined into a singular profile and scaled and shifted to a node-specific 2015 demand profile.

C.1.7 Russia

Russia has the largest landmass around the world and covers 11 time zones from UTC +2 (Kaliningrad) to UTC +12 (Far East). From an electricity system perspective, the country is divided in seven operational territories called 'united energy systems' (UES) [394]. These UES are used for the nodal representation of Russia in the global electricity system model as shown in Figure C-6. Despite the size of the country, only 2% of electricity consumption in Russia is decentralized. The five most western UES are relatively well integrated with significant transmission capacity between regions. Connections towards- and in between AS-RUS-UR and AS-RUS-FE are weak. Interregional transmission capacities between Russian nodes are based on 2010 data from [395]. The System Operator of the UES (SO UES) provides historical hourly demand data per UES per day [396]. By making use of an automated script, we've extracted all data for 2015 and developed node specific hourly profiles for all UES.

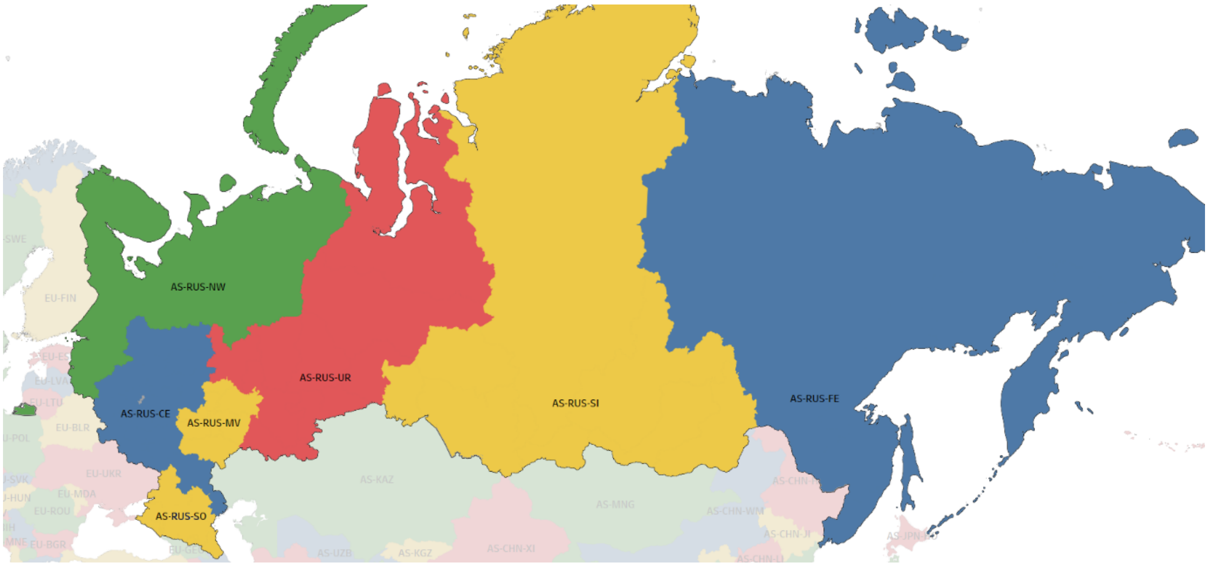
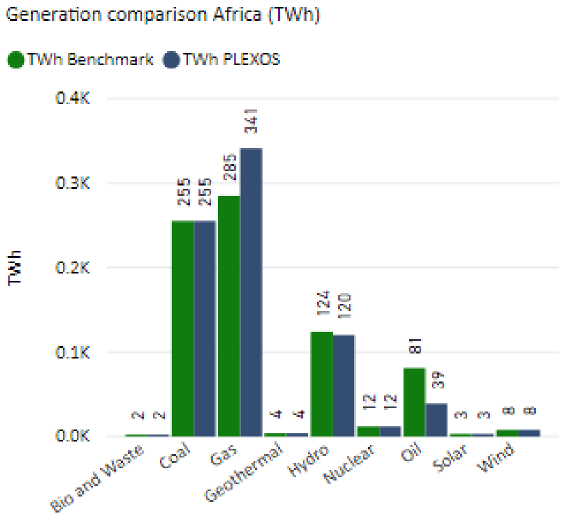
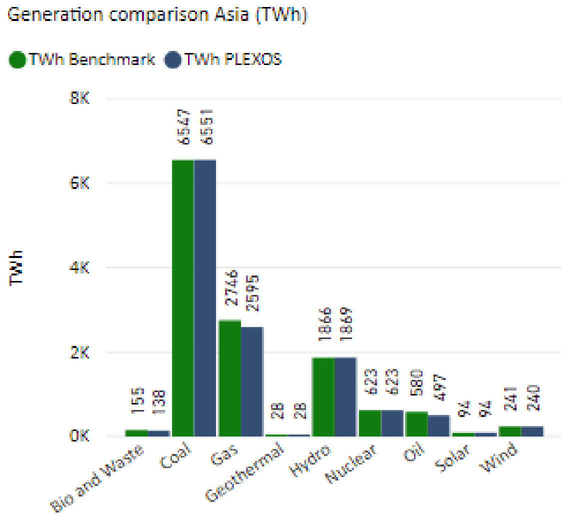
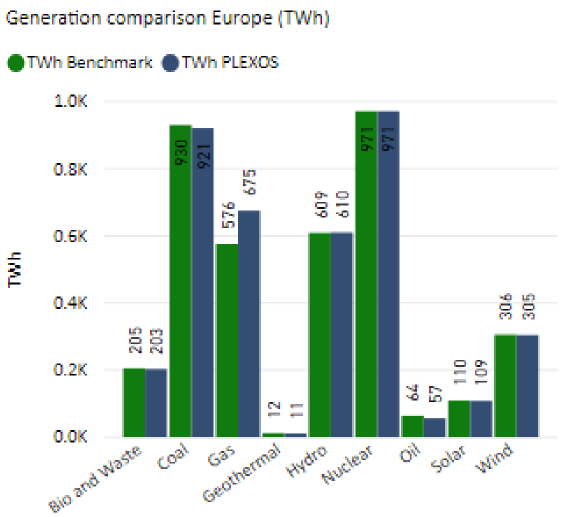


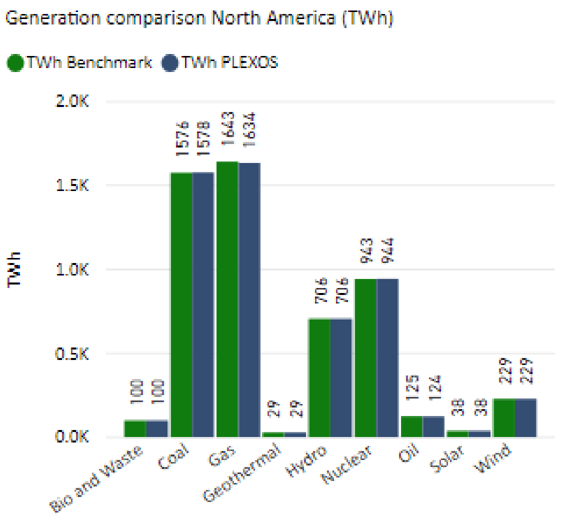
Figure C-6 Nodal representation of Russia in PLEXOS-World. Every copperplated area of an individual colour represents a node with a total of 7 nodes.

C.2 Supplementary graphs model benchmark









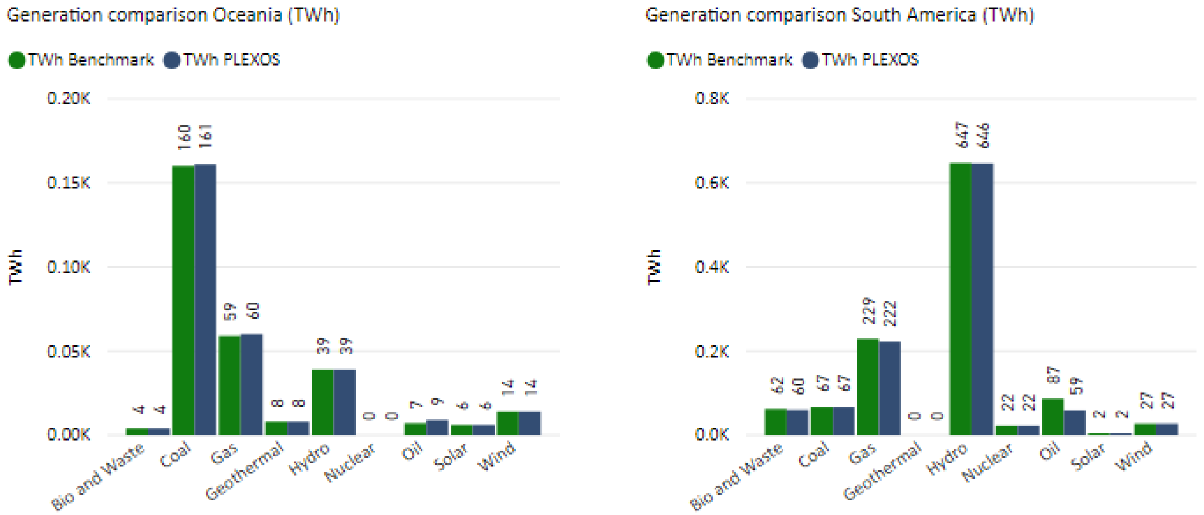
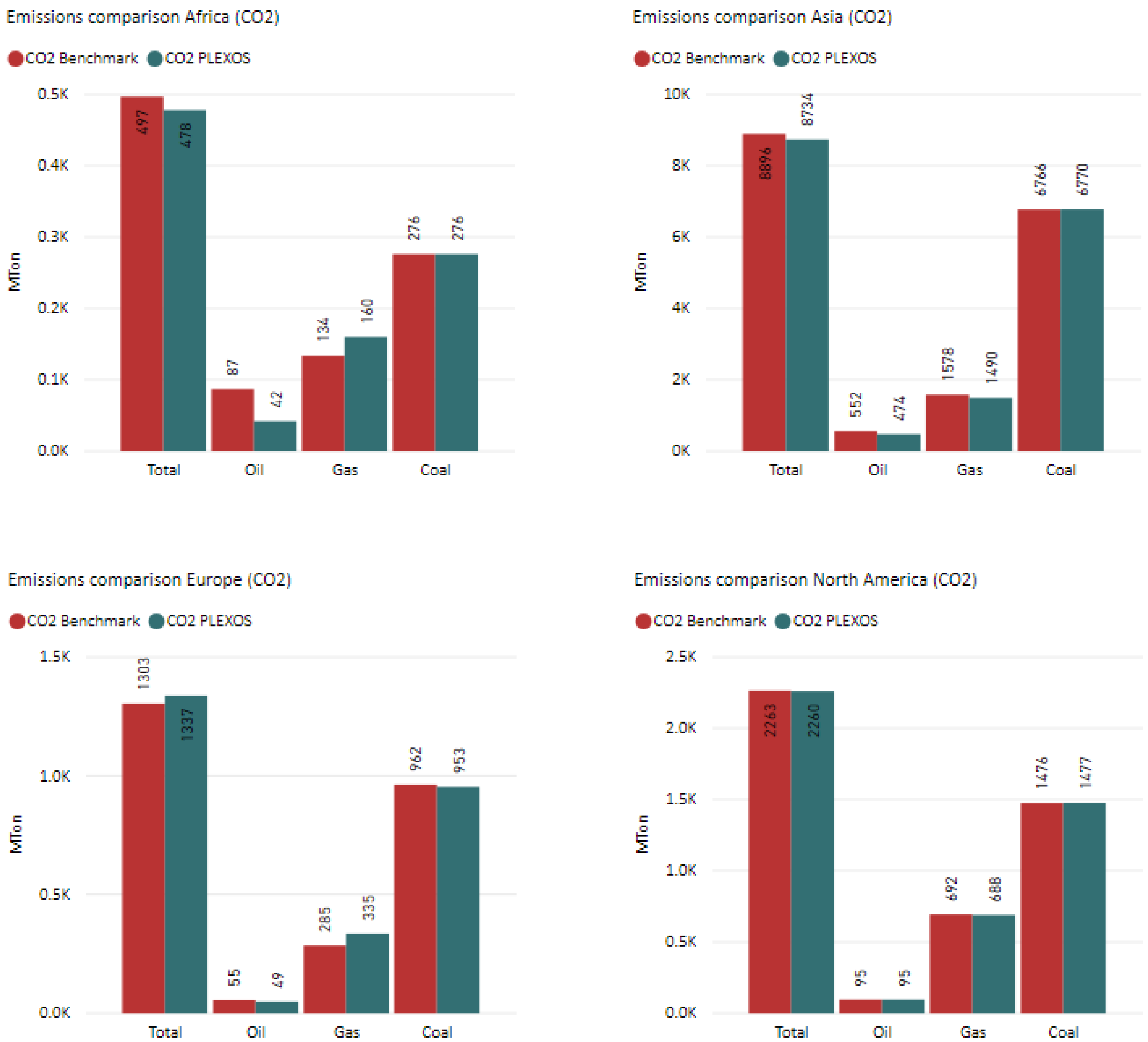
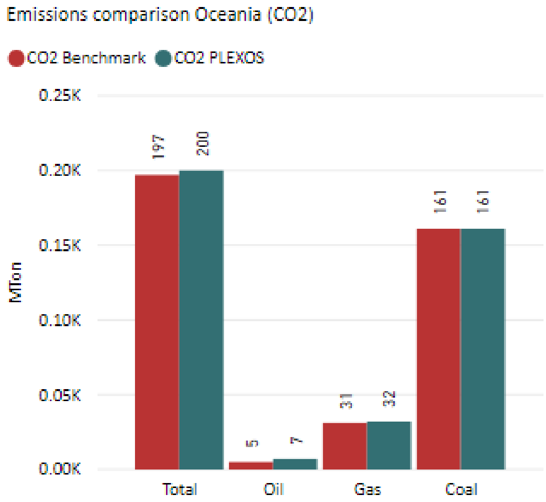


Figure C-7 Comparison of generation values per fuel type from the calibrated PLEXOS-World simulations with historically reported data for 2015.





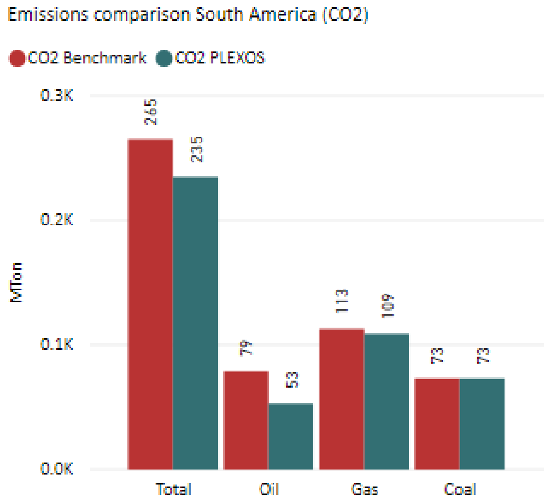


Figure C-8 Comparison of CO2 emissions per fuel type from the calibrated PLEXOS-World simulations with historically reported data for 2015.

C.3 List of Nodes in the PLEXOS-World Model

Table C-1: List of nodes with their geographical representation. Description of the geographical representation of sub-country nodes can be found in Section C.1.

Node	Continent	Country	Geographical region
AF-AGO	Africa	Angola	Angola
AF-BDI	Africa	Burundi	Burundi
AF-BEN	Africa	Benin	Benin
AF-BFA	Africa	Burkina Faso	Burkina Faso
AF-BWA	Africa	Botswana	Botswana
AF-CAF	Africa	Central African Republic	Central African Republic
AF-CIV	Africa	Cote DIvoire	Cote DIvoire
AF-CMR	Africa	Cameroon	Cameroon
AF-COD	Africa	Congo (Kinshasa)	Congo (Kinshasa)
AF-COG	Africa	Congo (Brazzaville)	Congo (Brazzaville)
AF-CPV	Africa	Cape Verde	Cape Verde
AF-DJI	Africa	Djibouti	Djibouti
AF-DZA	Africa	Algeria	Algeria
AF-EGY	Africa	Egypt	Egypt
AF-ERI	Africa	Eritrea	Eritrea
AF-ESH	Africa	Western Sahara	Western Sahara
AF-ETH	Africa	Ethiopia	Ethiopia
AF-GAB	Africa	Gabon	Gabon
AF-GHA	Africa	Ghana	Ghana
AF-GIN	Africa	Guinea	Guinea
AF-GMB	Africa	Gambia	Gambia
AF-GNB	Africa	Guinea-Bissau	Guinea-Bissau
AF-GNQ	Africa	Equatorial Guinea	Equatorial Guinea
AF-KEN	Africa	Kenya	Kenya
AF-LBR	Africa	Liberia	Liberia

AF-LBY	Africa	Libya	Libya
AF-LSO	Africa	Lesotho	Lesotho
AF-MAR	Africa	Morocco	Morocco
AF-MDG	Africa	Madagascar	Madagascar
AF-MLI	Africa	Mali	Mali
AF-MOZ	Africa	Mozambique	Mozambique
AF-MRT	Africa	Mauritania	Mauritania
AF-MUS	Africa	Mauritius	Mauritius
AF-MWI	Africa	Malawi	Malawi
AF-NAM	Africa	Namibia	Namibia
AF-NER	Africa	Niger	Niger
AF-NGA	Africa	Nigeria	Nigeria
AF-RWA	Africa	Rwanda	Rwanda
AF-SDN	Africa	Sudan	Sudan
AF-SEN	Africa	Senegal	Senegal
AF-SLE	Africa	Sierra Leone	Sierra Leone
AF-SWZ	Africa	Swaziland	Swaziland
AF-TGO	Africa	Togo	Togo
AF-TUN	Africa	Tunisia	Tunisia
AF-TZA	Africa	Tanzania	Tanzania
AF-UGA	Africa	Uganda	Uganda
AF-ZAF	Africa	South Africa	South Africa
AF-ZMB	Africa	Zambia	Zambia
AF-ZWE	Africa	Zimbabwe	Zimbabwe
AS-AFG	Asia	Afghanistan	Afghanistan
AS-ARE	Asia	United Arab Emirates	United Arab Emirates
AS-BGD	Asia	Bangladesh	Bangladesh
AS-BHR	Asia	Bahrain	Bahrain
AS-BRN	Asia	Brunei	Brunei
AS-BTN	Asia	Bhutan	Bhutan
AS-CHN-AN	Asia	China	Anhui
AS-CHN-BE	Asia	China	Beijing
AS-CHN-CH	Asia	China	Chongqing
AS-CHN-EM	Asia	China	Inner Mongolia (East)
AS-CHN-FU	Asia	China	Fujian
AS-CHN-GA	Asia	China	Gansu
AS-CHN-GD	Asia	China	Guangdong
AS-CHN-GU	Asia	China	Guizhou
AS-CHN-GX	Asia	China	Guangxi
AS-CHN-HA	Asia	China	Hainan
AS-CHN-HB	Asia	China	Hebei
AS-CHN-HE	Asia	China	Henan
AS-CHN-HJ	Asia	China	Heilongjiang
AS-CHN-HK	Asia	China	Hong Kong

AS-CHN-HN	Asia	China	Hunan
AS-CHN-HU	Asia	China	Hubei
AS-CHN-JI	Asia	China	Jilin
AS-CHN-JS	Asia	China	Jiangsu
AS-CHN-JX	Asia	China	Jiangxi
AS-CHN-LI	Asia	China	Liaoning
AS-CHN-MA	Asia	China	Macau
AS-CHN-NI	Asia	China	Ningxia
AS-CHN-QI	Asia	China	Qinghai
AS-CHN-SC	Asia	China	Sichuan
AS-CHN-SD	Asia	China	Shandong
AS-CHN-SH	Asia	China	Shanghai
AS-CHN-SI	Asia	China	Shaanxi
AS-CHN-SX	Asia	China	Shanxi
AS-CHN-TI	Asia	China	Tibet
AS-CHN-TJ	Asia	China	Tianjin
AS-CHN-WM	Asia	China	Inner Mongolia (West)
AS-CHN-XI	Asia	China	Xinjiang
AS-CHN-YU	Asia	China	Yunnan
AS-CHN-ZH	Asia	China	Zhejiang
AS-IDN	Asia	Indonesia	Indonesia
AS-IND-EA	Asia	India	Eastern Region
AS-IND-NE	Asia	India	North-Eastern Region
AS-IND-NO	Asia	India	Northern Region
AS-IND-SO	Asia	India	Southern Region
AS-IND-WE	Asia	India	Western Region
AS-IRN	Asia	Iran	Iran
AS-IRQ	Asia	Iraq	Iraq
AS-ISR	Asia	Israel & Palestina	Israel & Palestina
AS-JOR	Asia	Jordan	Jordan
AS-JPN-CE	Asia	Japan	Main 60Hz system (Central)
AS-JPN-HO	Asia	Japan	Hokkaido
AS-JPN-KY	Asia	Japan	Kyushu
AS-JPN-OK	Asia	Japan	Okinawa
AS-JPN-SH	Asia	Japan	Shikoku
AS-JPN-TO	Asia	Japan	Main 50Hz system (Tohoku & Tokyo)
AS-KAZ	Asia	Kazakhstan	Kazakhstan
AS-KGZ	Asia	Kyrgyzstan	Kyrgyzstan
AS-KHM	Asia	Cambodia	Cambodia
AS-KOR	Asia	South Korea	South Korea
AS-KWT	Asia	Kuwait	Kuwait
AS-LAO	Asia	Laos	Laos
AS-LBN	Asia	Lebanon	Lebanon
AS-LKA	Asia	Sri Lanka	Sri Lanka

AS-MMR	Asia	Myanmar	Myanmar
AS-MNG	Asia	Mongolia	Mongolia
AS-MYS	Asia	Malaysia	Malaysia
AS-NPL	Asia	Nepal	Nepal
AS-OMN	Asia	Oman	Oman
AS-PAK	Asia	Pakistan	Pakistan
AS-PHL	Asia	Philippines	Philippines
AS-PRK	Asia	North Korea	North Korea
AS-QAT	Asia	Qatar	Qatar
AS-RUS-CE	Asia	Russia	UES Center
AS-RUS-FE	Asia	Russia	UES Far East
AS-RUS-MV	Asia	Russia	UES Middle Volga
AS-RUS-NW	Asia	Russia	UES Northwest
AS-RUS-SI	Asia	Russia	UES Siberia
AS-RUS-SO	Asia	Russia	UES South
AS-RUS-UR	Asia	Russia	UES Ural
AS-SAU	Asia	Saudi Arabia	Saudi Arabia
AS-SGP	Asia	Singapore	Singapore
AS-SYR	Asia	Syria	Syria
AS-THA	Asia	Thailand	Thailand
AS-TJK	Asia	Tajikistan	Tajikistan
AS-TKM	Asia	Turkmenistan	Turkmenistan
AS-TUR	Asia	Turkey	Turkey
AS-TWN	Asia	Taiwan	Taiwan
AS-UZB	Asia	Uzbekistan	Uzbekistan
AS-VNM	Asia	Vietnam	Vietnam
AS-YEM	Asia	Yemen	Yemen
EU-ALB	Europe	Albania	Albania
EU-ARM	Europe	Armenia	Armenia
EU-AUT	Europe	Austria	Austria
EU-AZE	Europe	Azerbaijan	Azerbaijan
EU-BEL	Europe	Belgium	Belgium
EU-BGR	Europe	Bulgaria	Bulgaria
EU-BIH	Europe	Bosnia and Herzegovina	Bosnia and Herzegovina
EU-BLR	Europe	Belarus	Belarus
EU-CHE	Europe	Switzerland	Switzerland
EU-CYP	Europe	Cyprus	Cyprus
EU-CZE	Europe	Czech Republic	Czech Republic
EU-DEU	Europe	Germany	Germany
EU-DNK	Europe	Denmark	Denmark
EU-ESP	Europe	Spain	Spain
EU-EST	Europe	Estonia	Estonia
EU-FIN	Europe	Finland	Finland
EU-FRA	Europe	France	France

EU-GBR	Europe	United Kingdom	United Kingdom
EU-GEO	Europe	Georgia	Georgia
EU-GRC	Europe	Greece	Greece
EU-HRV	Europe	Croatia	Croatia
EU-HUN	Europe	Hungary	Hungary
EU-IRL	Europe	Ireland	Ireland
EU-ISL	Europe	Iceland	Iceland
EU-ITA	Europe	Italy	Italy
EU-KOS	Europe	Kosovo	Kosovo
EU-LTU	Europe	Lithuania	Lithuania
EU-LUX	Europe	Luxembourg	Luxembourg
EU-LVA	Europe	Latvia	Latvia
EU-MDA	Europe	Moldova	Moldova
EU-MKD	Europe	Macedonia	Macedonia
EU-MNE	Europe	Montenegro	Montenegro
EU-NLD	Europe	Netherlands	Netherlands
EU-NOR	Europe	Norway	Norway
EU-POL	Europe	Poland	Poland
EU-PRT	Europe	Portugal	Portugal
EU-ROU	Europe	Romania	Romania
EU-SRB	Europe	Serbia	Serbia
EU-SVK	Europe	Slovakia	Slovakia
EU-SVN	Europe	Slovenia	Slovenia
EU-SWE	Europe	Sweden	Sweden
EU-UKR	Europe	Ukraine	Ukraine
NA-CAN-AB	North America	Canada	Alberta
NA-CAN-AR	North America	Canada	Atlantic region
NA-CAN-BC	North America	Canada	British Columbia
NA-CAN-MB	North America	Canada	Manitoba
NA-CAN-NL	North America	Canada	Newfoundland & Labrador
NA-CAN-NO	North America	Canada	Northern Provinces
NA-CAN-ON	North America	Canada	Ontario
NA-CAN-QC	North America	Canada	Quebec
NA-CAN-SK	North America	Canada	Saskatchewan
NA-CRI	North America	Costa Rica	Costa Rica
NA-CUB	North America	Cuba	Cuba
NA-DOM	North America	Dominican Republic	Dominican Republic
NA-GTM	North America	Guatemala	Guatemala
NA-HND	North America	Honduras	Honduras
NA-JAM	North America	Jamaica	Jamaica
NA-MEX	North America	Mexico	Mexico
NA-NIC	North America	Nicaragua	Nicaragua
NA-PAN	North America	Panama	Panama
NA-SLV	North America	El Salvador	El Salvador

NA-TTO	North America	Trinidad and Tobago	Trinidad and Tobago
NA-USA-AK	North America	United States	Alaska
NA-USA-AZ	North America	United States	EIA NEMS Region AZNM
NA-USA-CA	North America	United States	EIA NEMS Region CAMX
NA-USA-ER	North America	United States	EIA NEMS Region ERCT
NA-USA-FR	North America	United States	EIA NEMS Region FRCC
NA-USA-GU	North America	United States	Guam
NA-USA-HA	North America	United States	Hawaii
NA-USA-ME	North America	United States	EIA NEMS Region MROE
NA-USA-MW	North America	United States	EIA NEMS Region MROW
NA-USA-NE	North America	United States	EIA NEMS Region NEWE
NA-USA-NW	North America	United States	EIA NEMS Region NWPP
NA-USA-NY	North America	United States	EIA NEMS Regions NYCW, NYLI & NYUP
NA-USA-PR	North America	United States	Puerto Rico
NA-USA-RA	North America	United States	EIA NEMS Region RMPA
NA-USA-RE	North America	United States	EIA NEMS Region RFCE
NA-USA-RM	North America	United States	EIA NEMS Region RFCM
NA-USA-RW	North America	United States	EIA NEMS Region RFCW
NA-USA-SA	North America	United States	EIA NEMS Region SRDA
NA-USA-SC	North America	United States	EIA NEMS Region SRCE
NA-USA-SE	North America	United States	EIA NEMS Region SRSE
NA-USA-SN	North America	United States	EIA NEMS Region SPNO
NA-USA-SS	North America	United States	EIA NEMS Region SPSO
NA-USA-SV	North America	United States	EIA NEMS Region SRVC
NA-USA-SW	North America	United States	EIA NEMS Region SRGW
OC-ATA	Oceania	Antarctica	Antarctica
OC-AUS-NT	Oceania	Australia	Northern Territory
OC-AUS-QL	Oceania	Australia	Queensland
OC-AUS-SA	Oceania	Australia	South Australia
OC-AUS-SW	Oceania	Australia	New South Wales
OC-AUS-TA	Oceania	Australia	Tasmania
OC-AUS-VI	Oceania	Australia	Victoria
OC-AUS-WA	Oceania	Australia	Western Australia
OC-FJI	Oceania	Fiji	Fiji
OC-NZL	Oceania	New Zealand	New Zealand
OC-PNG	Oceania	Papua New Guinea	Papua New Guinea
SA-ARG	South America	Argentina	Argentina
SA-BOL	South America	Bolivia	Bolivia
SA-BRA-CN	South America	Brazil	Center-Northern Region
SA-BRA-CW	South America	Brazil	Center-Western Region
SA-BRA-J1	South America	Brazil	Transmission Junction J1
SA-BRA-J2	South America	Brazil	Transmission Junction J2
SA-BRA-J3	South America	Brazil	Transmission Junction J3
SA-BRA-NE	South America	Brazil	North-Eastern Region

SA-BRA-NW	South America	Brazil	North-Western Region
SA-BRA-SE	South America	Brazil	South-Eastern Region
SA-BRA-SO	South America	Brazil	Southern Region
SA-BRA-WE	South America	Brazil	Western Region
SA-CHL	South America	Chile	Chile
SA-COL	South America	Colombia	Colombia
SA-ECU	South America	Ecuador	Ecuador
SA-GUF	South America	French Guiana	French Guiana
SA-GUY	South America	Guyana	Guyana
SA-PER	South America	Peru	Peru
SA-PRY	South America	Paraguay	Paraguay
SA-URY	South America	Uruguay	Uruguay
SA-VEN	South America	Venezuela	Venezuela

C.4 List of Publicly Available Hourly Load Data

This Section includes a full overview of publicly available load data with (sub-)hourly time intervals. Furthermore, hourly data retrieved through personal communication (L. St-Laurent, Hydro Quebec, 12-02-2018 – R. Mall, SaskPower, 21-12-2017, Ukrenergo, 29/10/2018) is included as part of the model input. For synthetic hourly load profiles for countries where no data exists in the public domain it is worth highlighting a study by Toktarova and colleagues [249]. The authors constructed a calibrated method to generate demand profiles for future years based on locational economic, technical and climatic characteristics for almost all countries around the world. All load profiles as used for this study can be found in a separate file on the Dataverse [231].

Table C-2: Global list of publicly available load data with (sub-)hourly time intervals.

Area	Years	Coverage of data	Resolution	Source
AF-ETH	2013	Full country	Hourly	[249]
AF-KEN	2010	Full country	Hourly	[249]
AF-MAR	2010	Full country	Hourly	[249]
AF-TUN	2010	Full country	Hourly	[249]
AF-ZAF	2010	Full country	Hourly	[397]
AS-IRN	2015	Full country	Hourly	[249]
AS-ISR	2012	Full country	Hourly	[249]
AS-JPN	2010-2011	Full country or per operating area/ bidding zone	Hourly	[224]
AS-KOR	2015	Full country	Hourly	[398]
AS-LKA	2013	Full country	Hourly	[249]
AS-MYS	2017-2020	Peninsular Malaysia	Hourly	[399]
AS-OMN	2013-2016	Main Interconnected System	Hourly	[400]
AS-PAK	2008	Full country	Hourly	[249]

AS-RUS	2008-2020	Full country or per operating area/ bidding zone	Hourly	[396]
AS-SAU	2013	Full country	Hourly	[249]
AS-SGP	2004-2020	Full country	Half-Hourly	[401]
AS-TUR	2016-2020	Full country	Hourly	[402]
EU-AUT	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-BEL	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-BGR	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-BIH	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-CHE	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-CYP	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-CZE	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-DEU	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-DNK	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-ESP	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-EST	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-FIN	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-FRA	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-GBR	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-GEO	2017-2020	Full country	Hourly	[404]
EU-GRC	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-HRV	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-HUN	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-IRL	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-ISL	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-ITA	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-LTU	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]

EU-LUX	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-LVA	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-MKD	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-MNE	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-NLD	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-NOR	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-POL	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-PRT	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-ROU	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-SRB	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-SVK	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-SVN	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
EU-SWE	2006-2020	Full country or per operating area/ bidding zone	Hourly	[247,403]
NA-CAN-AB	2016	Alberta	Hourly	[339]
NA-CAN-AR	2013-2020	New Brunswick	Hourly	[337]
NA-CAN-AR	2012-2020	Nova Scotia	Hourly	[336]
NA-CAN-BC	2001-2020	British Columbia	Hourly	[340]
NA-CAN-ON	1994-2020	Ontario	Hourly	[338]
NA-CRI	Last 24 hrs	Full country	Per 15 mins	[405]
NA-GTM	2010-2020	Full country	Hourly	[406]
NA-MEX	2016-2018	Full country or per operating area/ bidding zone	Hourly	[407]
NA-NIC	2010-2020	Full country	Hourly	[408]
NA-PAN	2016-2020	Full country	Hourly	[409]
NA-SLV	2018-2020	Full country	Hourly	[410]
NA-USA	2016-2020	Full country or per operating area/ bidding zone	Hourly	[219]
NA-USA	1993-2018	Full country or per operating area/ bidding zone	Hourly	[218]
OC-AUS	2019-2020	Full NEM Territory or per province	Hourly	[322]
OC-AUS-WA	2006-2019	Western Australia	Hourly	[323]
OC-NZL	2010-2020	Full country or per operating area/ bidding zone	Half-Hourly	[411]
SA-ARG	2006-2013	Full country	Hourly	[412]

SA-BRA	1999-2020	Full country or per operating area/ bidding zone	Hourly	[330]
SA-CHL	2005-2018	Central System	Hourly	[413]
SA-COL	2010	Full country	Hourly	[249]
SA-PER	2015-2020	Full country	Half-Hourly	[414]
SA-URY	2015-2020	Full country	Hourly	[415]

C.5 List of Global Cross-Border Transmssion Capacities

Table C-3: Global list of Cross-Border Transmission Capacities. The values represent net transfer capacities between neighbouring nodes as well as capacities for transmission pathways of existing and planned subsea interconnectors. Extensive attempts have been made to base the data on reliable sources with 2015 as base year, yet this data is not always available in the public domain. The 'Data Year' column indicates for which year the data is valid and footnotes are added at the bottom of the table in case additional comments on the data are required. More detailed description regarding transmission capacities between sub-country nodes can be found in Section C.1.

From	To	Max Flow (MW)	Min Flow (MW)	Data Year	Source	Note
AF-AGO	AF-COD	0	0	2015	[252]	
AF-AGO	AF-COG	0	0	2015	[252]	
AF-AGO	AF-NAM	0	0	2015	[252]	
AF-AGO	AF-ZMB	0	0	2015	[252]	
AF-BDI	AF-COD	475	-475	2015	[252]	
AF-BDI	AF-RWA	430	-430	2015	[252]	
AF-BDI	AF-TZA	0	0	2015	[252]	
AF-BEN	AF-BFA	0	0	2015	[252]	
AF-BEN	AF-GHA	936	-936	2015	[252]	
AF-BEN	AF-NER	0	0	2015	[252]	
AF-BEN	AF-NGA	686	-686	2015	[252]	
AF-BEN	AF-TGO	0	0	2015	[252]	
AF-BFA	AF-CIV	327	-327	2015	[252]	
AF-BFA	AF-GHA	0	0	2015	[252]	
AF-BFA	AF-MLI	0	0	2015	[252]	
AF-BFA	AF-NER	0	0	2015	[252]	
AF-BFA	AF-TGO	0	0	2015	[252]	
AF-BWA	AF-NAM	0	0	2015	[252]	
AF-BWA	AF-ZAF	1300	-1300	2015	[252]	
AF-BWA	AF-ZMB	0	0	2015	[252]	
AF-BWA	AF-ZWE	650	-650	2015	[252]	
AF-CAF	AF-CMR	0	0	2015	[252]	
AF-CAF	AF-COD	0	0	2015	[252]	
AF-CAF	AF-COG	0	0	2015	[252]	
AF-CAF	AF-SDN	0	0	2015	[252]	
AF-CIV	AF-GHA	982	-982	2015	[252]	
AF-CIV	AF-GIN	0	0	2015	[252]	

AF-CIV	AF-LBR	338	-338	2015	[252]	
AF-CIV	AF-MLI	0	0	2015	[252]	
AF-CMR	AF-COG	0	0	2015	[252]	
AF-CMR	AF-GAB	0	0	2015	[252]	
AF-CMR	AF-GNQ	0	0	2015	[252]	
AF-CMR	AF-NGA	0	0	2015	[252]	
AF-COD	AF-COG	60	-60	2015	[252]	
AF-COD	AF-RWA	527	-527	2015	[252]	
AF-COD	AF-TZA	0	0	2015	[252]	
AF-COD	AF-UGA	0	0	2015	[252]	
AF-COD	AF-ZMB	310	-310	2015	[252]	
AF-COG	AF-GAB	0	0	2015	[252]	
AF-COG	AF-RWA	0	0	2015	[252]	
AF-COG	AF-TZA	0	0	2015	[252]	
AF-DJI	AF-ERI	0	0	2015	[252]	
AF-DJI	AF-ETH	180	-180	2015	[252]	
AF-DZA	AF-ESH	0	0	2015	[252]	
AF-DZA	AF-LBY	0	0	2015	[252]	
AF-DZA	AF-MAR	400	-400	2013	[254]	
AF-DZA	AF-MLI	0	0	2015	[252]	
AF-DZA	AF-MRT	0	0	2015	[252]	
AF-DZA	AF-NER	0	0	2015	[252]	
AF-DZA	AF-TUN	150	-150	2013	[254]	
AF-EGY	AF-LBY	180	-180	2013	[254]	
AF-EGY	AF-SDN	0	0	2015	[252]	
AF-EGY	AS-ISR	17	0	2015	[252]	
AF-EGY	AS-JOR	450	-200	2013	[254]	Subsea line
AF-ERI	AF-ETH	0	0	2015	[252]	
AF-ERI	AF-SDN	0	0	2015	[252]	
AF-ESH	AF-MAR	0	0	2015	[252]	
AF-ESH	AF-MRT	0	0	2015	[252]	
AF-ETH	AF-KEN	0	0	2015	[252]	
AF-ETH	AF-SDN	200	-200	2015	[252]	
AF-GAB	AF-GNQ	0	0	2015	[252]	
AF-GHA	AF-TGO	963	-963	2015	[252]	
AF-GIN	AF-GNB	0	0	2015	[252]	
AF-GIN	AF-LBR	0	0	2015	[252]	
AF-GIN	AF-MLI	0	0	2015	[252]	
AF-GIN	AF-SEN	0	0	2015	[252]	
AF-GIN	AF-SLE	0	0	2015	[252]	
AF-GMB	AF-SEN	0	0	2015	[252]	
AF-GNB	AF-SEN	0	0	2015	[252]	
AF-KEN	AF-TZA	0	0	2015	[252]	
AF-KEN	AF-UGA	418	-418	2015	[252]	

AF-LBR	AF-SLE	0	0	2015	[252]	
AF-LBY	AF-NER	0	0	2015	[252]	
AF-LBY	AF-SDN	0	0	2015	[252]	
AF-LBY	AF-TUN	200	-200	2015	[252]	
AF-LSO	AF-ZAF	230	-230	2015	[252]	
AF-MLI	AF-MRT	0	0	2015	[252]	
AF-MLI	AF-NER	0	0	2015	[252]	
AF-MLI	AF-SEN	100	-100	2015	[252]	
AF-MOZ	AF-MWI	0	0	2015	[252]	
AF-MOZ	AF-SWZ	1450	-1450	2015	[252]	
AF-MOZ	AF-TZA	0	0	2015	[252]	
AF-MOZ	AF-ZAF	3850	-3850	2015	[252]	
AF-MOZ	AF-ZMB	0	0	2015	[252]	
AF-MOZ	AF-ZWE	700	-700	2015	[252]	
AF-MRT	AF-SEN	0	0	2015	[252]	
AF-MWI	AF-TZA	0	0	2015	[252]	
AF-MWI	AF-ZMB	0	0	2015	[252]	
AF-NAM	AF-ZAF	750	-750	2015	[252]	
AF-NAM	AF-ZMB	200	-200	2015	[252]	
AF-NER	AF-NGA	169	-169	2015	[252]	
AF-NGA	AF-TGO	686	-686	2015	[252]	
AF-RWA	AF-TZA	0	0	2015	[252]	
AF-RWA	AF-UGA	250	-250	2015	[252]	
AF-SWZ	AF-ZAF	1450	-1450	2015	[252]	
AF-TZA	AF-UGA	59	-59	2015	[252]	
AF-TZA	AF-ZMB	0	0	2015	[252]	
AF-ZAF	AF-ZWE	600	-600	2015	[252]	
AF-ZMB	AF-ZWE	700	-700	2015	[252]	
AS-AFG	AS-CHN-XI	0	0	2015	[416]	
AS-AFG	AS-IRN	56	-56	2006	[417]	
AS-AFG	AS-PAK	0	0	2018	[418]	
AS-AFG	AS-TJK	300	-300	2006	[417]	
AS-AFG	AS-TKM	300	-300	2006	[417]	
AS-AFG	AS-UZB	300	-300	2017	[113]	
AS-ARE	AS-OMN	400	-400	2013	[254]	
AS-ARE	AS-SAU	900	-900	2013	[254]	
AS-BGD	AS-IND-EA	500	-500	2018	[419]	
AS-BGD	AS-IND-NE	160	-160	2018	[419]	
AS-BGD	AS-MMR	0	0	2018	[419]	
AS-BHR	AS-SAU	600	-600	2013	[254]	
AS-BRN	AS-MYS	0	0	2015	[255,256]	
AS-BTN	AS-CHN-TI	0	0	2015	[416]	
AS-BTN	AS-IND-EA	1980	0	2014	[420]	
AS-CHN-AN	AS-CHN-HB	4000	-4000	2016	[20,382,383]	

AS-CHN-AN	AS-CHN-HE	0	0	2016	[20,382,383]	
AS-CHN-AN	AS-CHN-HU	0	0	2016	[20,382,383]	
AS-CHN-AN	AS-CHN-JS	5000	-5000	2016	[20,382,383]	
AS-CHN-AN	AS-CHN-JX	0	0	2016	[20,382,383]	
AS-CHN-AN	AS-CHN-SD	0	0	2016	[20,382,383]	
AS-CHN-AN	AS-CHN-ZH	0	0	2016	[20,382,383]	
AS-CHN-BE	AS-CHN-EM	5000	-5000	2016	[20,382,383]	
AS-CHN-BE	AS-CHN-HB	4000	-4000	2016	[20,382,383]	
AS-CHN-BE	AS-CHN-TJ	5000	-5000	2016	[20,382,383]	
AS-CHN-CH	AS-CHN-GU	0	0	2016	[20,382,383]	
AS-CHN-CH	AS-CHN-HB	4000	-4000	2016	[20,382,383]	
AS-CHN-CH	AS-CHN-HN	0	0	2016	[20,382,383]	
AS-CHN-CH	AS-CHN-HU	0	0	2016	[20,382,383]	
AS-CHN-CH	AS-CHN-SC	4000	-4000	2016	[20,382,383]	
AS-CHN-CH	AS-CHN-SI	0	0	2016	[20,382,383]	
AS-CHN-CH	AS-CHN-SX	0	0	2016	[20,382,383]	
AS-CHN-EM	AS-CHN-HB	4000	-4000	2016	[20,382,383]	
AS-CHN-EM	AS-CHN-HJ	0	0	2016	[20,382,383]	
AS-CHN-EM	AS-CHN-JI	0	0	2016	[20,382,383]	
AS-CHN-EM	AS-CHN-LI	4000	-4000	2016	[20,382,383]	
AS-CHN-EM	AS-CHN-SD	14400	-14400	2016	[20,382,383]	
AS-CHN-EM	AS-CHN-TJ	4000	-4000	2016	[20,382,383]	
AS-CHN-EM	AS-CHN-WM	0	0	2016	[20,382,383]	
AS-CHN-EM	AS-MNG	0	0	2016	[20,382,383]	
AS-CHN-FU	AS-CHN-GD	0	0	2016	[20,382,383]	
AS-CHN-FU	AS-CHN-JX	0	0	2016	[20,382,383]	
AS-CHN-FU	AS-CHN-ZH	0	0	2016	[20,382,383]	
AS-CHN-GA	AS-CHN-JS	7200	-7200	2016	[20,382,383]	
AS-CHN-GA	AS-CHN-NI	0	0	2016	[20,382,383]	
AS-CHN-GA	AS-CHN-QI	0	0	2016	[20,382,383]	
AS-CHN-GA	AS-CHN-SC	0	0	2016	[20,382,383]	
AS-CHN-GA	AS-CHN-SI	0	0	2016	[20,382,383]	
AS-CHN-GA	AS-CHN-WM	0	0	2016	[20,382,383]	
AS-CHN-GA	AS-CHN-XI	0	0	2016	[20,382,383]	
AS-CHN-GA	AS-MNG	0	0	2015	[416]	
AS-CHN-GD	AS-CHN-GX	0	0	2016	[20,382,383]	
AS-CHN-GD	AS-CHN-HA	600	-600	2015	[421]	
AS-CHN-GD	AS-CHN-HK	1978	-1978	2014-2018	[422]	Estimate[1]
AS-CHN-GD	AS-CHN-HN	0	0	2016	[20,382,383]	
AS-CHN-GD	AS-CHN-JX	0	0	2016	[20,382,383]	
AS-CHN-GD	AS-CHN-MA	1750	-1750	2016	[20,382,383]	
AS-CHN-GD	AS-CHN-SC	6400	-6400	2016	[20,382,383]	
AS-CHN-GD	AS-CHN-YU	5000	-5000	2016	[20,382,383]	
AS-CHN-GU	AS-CHN-GX	0	0	2016	[20,382,383]	

AS-CHN-GU	AS-CHN-HN	0	0	2016	[20,382,383]	
AS-CHN-GU	AS-CHN-JS	7200	-7200	2016	[20,382,383]	
AS-CHN-GU	AS-CHN-SC	0	0	2016	[20,382,383]	
AS-CHN-GU	AS-CHN-YU	0	0	2016	[20,382,383]	
AS-CHN-GX	AS-CHN-HN	0	0	2016	[20,382,383]	
AS-CHN-GX	AS-CHN-XI	0	0	2016	[20,382,383]	
AS-CHN-GX	AS-CHN-YU	0	0	2016	[20,382,383]	
AS-CHN-GX	AS-VNM	0	0	2015	[416]	
AS-CHN-HB	AS-CHN-HE	4000	-4000	2016	[20,382,383]	
AS-CHN-HB	AS-CHN-LI	0	0	2016	[20,382,383]	
AS-CHN-HB	AS-CHN-SD	0	0	2016	[20,382,383]	
AS-CHN-HB	AS-CHN-SX	0	0	2016	[20,382,383]	
AS-CHN-HB	AS-CHN-TJ	0	0	2016	[20,382,383]	
AS-CHN-HB	AS-CHN-WM	0	0	2016	[20,382,383]	
AS-CHN-HE	AS-CHN-HU	4000	-4000	2016	[20,382,383]	
AS-CHN-HE	AS-CHN-JS	0	0	2016	[20,382,383]	
AS-CHN-HE	AS-CHN-SD	0	0	2016	[20,382,383]	
AS-CHN-HE	AS-CHN-SI	0	0	2016	[20,382,383]	
AS-CHN-HE	AS-CHN-SX	0	0	2016	[20,382,383]	
AS-CHN-HE	AS-CHN-XI	14400	-14400	2016	[20,382,383]	
AS-CHN-HJ	AS-CHN-JI	0	0	2016	[20,382,383]	
AS-CHN-HJ	AS-RUS-FE	1000	-1000	2015	[423]	
AS-CHN-HJ	AS-RUS-SI	0	0	2015	[416]	
AS-CHN-HN	AS-CHN-HU	0	0	2016	[20,382,383]	
AS-CHN-HN	AS-CHN-JX	0	0	2016	[20,382,383]	
AS-CHN-HN	AS-CHN-SC	8000	-8000	2016	[20,382,383]	
AS-CHN-HN	AS-CHN-SX	5000	-5000	2016	[20,382,383]	
AS-CHN-HU	AS-CHN-JX	0	0	2016	[20,382,383]	
AS-CHN-HU	AS-CHN-SI	0	0	2016	[20,382,383]	
AS-CHN-JI	AS-CHN-LI	0	0	2016	[20,382,383]	
AS-CHN-JI	AS-PRK	0	0	2015	[416]	
AS-CHN-JS	AS-CHN-SD	5000	-5000	2016	[20,382,383]	
AS-CHN-JS	AS-CHN-SH	5000	-5000	2016	[20,382,383]	
AS-CHN-JS	AS-CHN-SI	4000	-4000	2016	[20,382,383]	
AS-CHN-JS	AS-CHN-SX	5000	-5000	2016	[20,382,383]	
AS-CHN-JS	AS-CHN-ZH	0	0	2016	[20,382,383]	
AS-CHN-JX	AS-CHN-WM	7200	-7200	2016	[20,382,383]	
AS-CHN-JX	AS-CHN-ZH	0	0	2016	[20,382,383]	
AS-CHN-LI	AS-PRK	100	-100	2017	[424]	Estimate[2]
AS-CHN-NI	AS-CHN-SD	4000	-4000	2016	[20,382,383]	
AS-CHN-NI	AS-CHN-SI	0	0	2016	[20,382,383]	
AS-CHN-NI	AS-CHN-WM	0	0	2016	[20,382,383]	
AS-CHN-NI	AS-CHN-ZH	7200	-7200	2016	[20,382,383]	
AS-CHN-QI	AS-CHN-SC	0	0	2016	[20,382,383]	

AS-CHN-QI	AS-CHN-TI	1500	-1500	2016	[20,382,383]	
AS-CHN-QI	AS-CHN-XI	0	0	2016	[20,382,383]	
AS-CHN-SC	AS-CHN-TI	0	0	2016	[20,382,383]	
AS-CHN-SC	AS-CHN-YU	0	0	2016	[20,382,383]	
AS-CHN-SD	AS-CHN-SX	4000	-4000	2016	[20,382,383]	
AS-CHN-SD	AS-CHN-TJ	5000	-5000	2016	[20,382,383]	
AS-CHN-SH	AS-CHN-ZH	5000	-5000	2016	[20,382,383]	
AS-CHN-SI	AS-CHN-SC	0	0	2016	[20,382,383]	
AS-CHN-SI	AS-CHN-SX	0	0	2016	[20,382,383]	
AS-CHN-SI	AS-CHN-WM	0	0	2016	[20,382,383]	
AS-CHN-SX	AS-CHN-WM	9000	-9000	2016	[20,382,383]	
AS-CHN-TI	AS-CHN-XI	0	0	2016	[20,382,383]	
AS-CHN-TI	AS-CHN-YU	0	0	2016	[20,382,383]	
AS-CHN-TI	AS-IND-NE	0	0	2016	[20,382,383]	
AS-CHN-TI	AS-IND-NO	0	0	2016	[20,382,383]	
AS-CHN-TI	AS-MMR	0	0	2016	[20,382,383]	
AS-CHN-TI	AS-NPL	0	0	2015	[416]	
AS-CHN-TI	AS-PAK	0	0	2015	[416]	
AS-CHN-WM	AS-MNG	0	0	2015	[416]	
AS-CHN-WM	AS-RUS-SI	0	0	2016	[20,382,383]	
AS-CHN-XI	AS-IND-NO	0	0	2016	[20,382,383]	
AS-CHN-XI	AS-KAZ	0	0	2015	[416]	
AS-CHN-XI	AS-KGZ	0	0	2015	[416]	
AS-CHN-XI	AS-MNG	0	0	2015	[416]	
AS-CHN-XI	AS-PAK	0	0	2015	[416]	
AS-CHN-XI	AS-RUS-SI	0	0	2015	[416]	
AS-CHN-XI	AS-TJK	0	0	2015	[416]	
AS-CHN-YU	AS-CHN-ZH	7200	-7200	2016	[20,382,383]	
AS-CHN-YU	AS-MMR	600	-600	2015	[416]	
AS-CHN-YU	AS-VNM	500	-500	2015	[416]	
AS-IDN	AS-MYS	0	0	2015	[255,256]	Planned subsea line
AS-IDN	AS-PHL	0	0	2014	[255,256]	Planned subsea line
AS-IDN	AS-SGP	0	0	2015	[255,256]	Planned subsea line
AS-IDN	OC-PNG	0	0	2015	[425]	
AS-IND-EA	AS-IND-NE	2860	-2860	2015	[390]	
AS-IND-EA	AS-IND-NO	14230	-14230	2015	[390]	
AS-IND-EA	AS-IND-SO	3630	-3630	2015	[390]	
AS-IND-EA	AS-IND-WE	10690	-10690	2015	[390]	
AS-IND-EA	AS-NPL	150	-150	2015	[426]	
AS-IND-NE	AS-MMR	3	-3	2018	[419]	
AS-IND-NO	AS-IND-WE	8720	-8720	2015	[390]	
AS-IND-NO	AS-NPL	350	-350	2015	[426]	
AS-IND-NO	AS-PAK	500	-500	2014	[427]	
AS-IND-SO	AS-IND-WE	5720	-5720	2015	[390]	

AS-IND-SO	AS-LKA	0	0	2018	[419]	Planned subsea line
AS-IND-WE	AS-PAK	0	0	2014	[427]	
AS-IRN	AS-IRQ	700	-700	2015	[428]	
AS-IRN	AS-PAK	74	-74	2015	[429]	
AS-IRN	AS-TKM	350	-350	2016	[430]	
AS-IRN	AS-TUR	0	0	2017	[103]	
AS-IRQ	AS-JOR	0	0	2015	[428]	
AS-IRQ	AS-KWT	0	0	2015	[428]	
AS-IRQ	AS-SAU	0	0	2015	[428]	
AS-IRQ	AS-SYR	0	0	2015	[428]	
AS-IRQ	AS-TUR	0	0	2017	[103]	
AS-ISR	AS-JOR	0	-20	2013	[254]	
AS-ISR	AS-LBN	0	0	2018	[431]	
AS-ISR	AS-SYR	0	0	2018	[431]	
AS-JOR	AS-SAU	0	0	2019	[432]	
AS-JOR	AS-SYR	350	-200	2013	[254]	
AS-JPN-CE	AS-JPN-KY	2800	-2800	2015	[392]	
AS-JPN-CE	AS-JPN-SH	2600	-2600	2015	[392]	
AS-JPN-CE	AS-JPN-TO	900	-900	2015	[392]	
AS-JPN-HO	AS-JPN-TO	600	-600	2015	[392]	
AS-KAZ	AS-KGZ	2540	-2540	2016	[433]	
AS-KAZ	AS-RUS-CE	0	0	2016	[433]	
AS-KAZ	AS-RUS-MV	370	-370	2016	[433]	
AS-KAZ	AS-RUS-SI	4200	-4200	2016	[433]	
AS-KAZ	AS-RUS-UR	5860	-5860	2016	[433]	
AS-KAZ	AS-TKM	0	0	2016	[433]	
AS-KAZ	AS-UZB	1900	-1900	2016	[433]	
AS-KGZ	AS-TJK	412	-412	2016	[434]	
AS-KGZ	AS-UZB	1500	-1500	2016	[434]	
AS-KHM	AS-LAO	0	0	2015	[255,256]	
AS-KHM	AS-THA	100	-100	2015	[255,256]	
AS-KHM	AS-VNM	200	-200	2015	[255,256]	
AS-KOR	AS-PRK	0	0	2015	[435]	
AS-KWT	AS-SAU	1200	-1200	2013	[254]	
AS-LAO	AS-MMR	5	-5	2018	[436]	
AS-LAO	AS-THA	2111	-2111	2015	[255,256]	
AS-LAO	AS-VNM	248	-248	2015	[255,256]	
AS-LBN	AS-SYR	160	-50	2013	[254]	
AS-MMR	AS-THA	0	0	2015	[255,256]	
AS-MNG	AS-RUS-SI	100	-100	2017	[113]	
AS-MYS	AS-PHL	0	0	2015	[255,256]	Planned subsea line
AS-MYS	AS-THA	380	-380	2015	[255,256]	
AS-OMN	AS-SAU	0	0	2013	[254]	
AS-OMN	AS-YEM	0	0	2018	[437]	

AS-PRK	AS-RUS-FE	0	0	2015	[435]	
AS-QAT	AS-SAU	750	-750	2013	[254]	
AS-RUS-CE	AS-RUS-MV	3500	-3500	2010	[395]	
AS-RUS-CE	AS-RUS-NW	1500	-1500	2010	[395]	
AS-RUS-CE	AS-RUS-SO	2400	-2400	2010	[395]	
AS-RUS-CE	EU-UKR	1800	-1800	2019	[438]	
AS-RUS-FE	AS-RUS-SI	0	0	2010	[395]	
AS-RUS-MV	AS-RUS-UR	3000	-3000	2010	[395]	
AS-RUS-NW	AS-RUS-UR	0	0	2010	[395]	
AS-RUS-SI	AS-RUS-UR	3300	-3300	2010	[395]	
AS-RUS-SO	EU-UKR	1200	-1200	2019	[438]	
AS-SAU	AS-YEM	0	0	2018	[437]	
AS-SYR	AS-TUR	250	-250	2013	[254]	
AS-TJK	AS-UZB	5445	-5445	2016	[434]	
AS-TKM	AS-UZB	0	0	2018	[439]	
EU-ALB	EU-GRC	250	-250	2015	[260]	Estimate[3]
EU-ALB	EU-KOS	210	-210	2012	[440]	
EU-ALB	EU-MKD	0	0	2012	[440]	
EU-ARM	AS-IRN	300	-300	2016	[441]	
EU-ARM	AS-TUR	0	0	2015	[442]	
EU-ARM	EU-AZE	0	0	2016	[441]	
EU-ARM	EU-GEO	150	-150	2015	[443]	
EU-AUT	EU-CHE	1700	-1700	2015	[47]	UCC EU model
EU-AUT	EU-CZE	1000	-1200	2015	[47]	UCC EU model
EU-AUT	EU-DEU	2100	-2100	2015	[47]	UCC EU model
EU-AUT	EU-HUN	1200	-800	2015	[47]	UCC EU model
EU-AUT	EU-ITA	405	-235	2015	[47]	UCC EU model
EU-AUT	EU-SVK	0	0	2015	[47]	UCC EU model
EU-AUT	EU-SVN	1200	-1200	2015	[47]	UCC EU model
EU-AZE	AS-IRN	800	-800	2015	[444]	
EU-AZE	AS-RUS-SO	500	-850	2015	[444]	
EU-AZE	AS-TUR	100	-100	2015	[444]	
EU-AZE	EU-GEO	1020	-1020	2015	[443]	
EU-BEL	EU-DEU	0	0	2015	[47]	UCC EU model
EU-BEL	EU-FRA	1800	-3300	2015	[47]	UCC EU model
EU-BEL	EU-GBR	0	0	2015	[53]	Planned subsea line
EU-BEL	EU-LUX	180	0	2015	[47]	UCC EU model
EU-BEL	EU-NLD	400	-400	2015	[47]	UCC EU model
EU-BGR	AS-TUR	650	-500	2017	[445]	
EU-BGR	EU-GRC	1728	-1032	2015	[47]	UCC EU model
EU-BGR	EU-MKD	400	-200	2011	[446]	
EU-BGR	EU-ROU	400	-300	2015	[47]	UCC EU model
EU-BGR	EU-SRB	600	-300	2015	[259]	Estimate[3]
EU-BIH	EU-HRV	800	-800	2015	[259]	Estimate[3]

EU-BIH	EU-MNE	725	-725	2015	[261]	Estimate[4]
EU-BIH	EU-SRB	600	-600	2015	[259]	Estimate[3]
EU-BLR	AS-RUS-CE	859	-1117	2006	[447]	
EU-BLR	AS-RUS-NW	141	-183	2006	[447]	
EU-BLR	EU-LTU	1300	-1350	2014	[448]	
EU-BLR	EU-LVA	0	0	2015	[449]	
EU-BLR	EU-POL	0	0	2013	[450]	
EU-BLR	EU-UKR	900	-900	2018	[438]	
EU-CHE	EU-DEU	4700	-3286	2015	[47]	UCC EU model
EU-CHE	EU-FRA	1300	-3200	2015	[47]	UCC EU model
EU-CHE	EU-ITA	4090	-3260	2015	[47]	UCC EU model
EU-CYP	AF-EGY	0	0	2018	[99]	Planned subsea line
EU-CYP	AS-ISR	0	0	2015	[53]	Planned subsea line
EU-CYP	EU-GRC	0	0	2015	[53]	Planned subsea line
EU-CZE	EU-DEU	300	0	2015	[47]	UCC EU model
EU-CZE	EU-POL	500	-600	2015	[47]	UCC EU model
EU-CZE	EU-SVK	2100	-1100	2015	[47]	UCC EU model
EU-DEU	EU-DNK	2350	-2380	2015	[47]	UCC EU model
EU-DEU	EU-FRA	3000	-3000	2015	[47]	UCC EU model
EU-DEU	EU-LUX	2300	-2300	2015	[47]	UCC EU model
EU-DEU	EU-NLD	3100	-3300	2015	[47]	UCC EU model
EU-DEU	EU-NOR	0	0	2015	[53]	Planned subsea line
EU-DEU	EU-POL	0	-1500	2015	[47]	UCC EU model
EU-DEU	EU-SWE	600	-600	2015	[47]	Subsea, UCC EU model
EU-DNK	EU-GBR	0	0	2015	[258]	Planned subsea line
EU-DNK	EU-NLD	0	0	2015	[258]	Planned subsea line
EU-DNK	EU-NOR	1640	-1640	2015	[47]	Subsea, UCC EU model
EU-DNK	EU-SWE	2440	-1980	2015	[47]	Subsea, UCC EU model
EU-ESP	AF-MAR	700	-700	2015	[47]	Subsea, UCC EU model
EU-ESP	EU-FRA	1900	-2700	2015	[47]	UCC EU model
EU-ESP	EU-PRT	2600	-2150	2015	[47]	UCC EU model
EU-EST	AS-RUS-NW	850	-1000	2014	[448]	
EU-EST	EU-FIN	1016	-1000	2015	[47]	UCC EU model
EU-EST	EU-LVA	1100	-1100	2015	[47]	UCC EU model
EU-FIN	AS-RUS-NW	320	-1300	2016	[451]	
EU-FIN	EU-NOR	126	-126	2015	[452]	
EU-FIN	EU-SWE	1500	-1900	2015	[47]	UCC EU model
EU-FRA	EU-GBR	2000	-2000	2015	[47]	Subsea, UCC EU model
EU-FRA	EU-IRL	0	0	2015	[258]	Planned subsea line
EU-FRA	EU-ITA	4350	-2160	2015	[47]	UCC EU model
EU-FRA	EU-LUX	380	0	2015	[47]	UCC EU model
EU-GBR	EU-IRL	800	-800	2015	[47]	Subsea, UCC EU model
EU-GBR	EU-ISL	0	0	2015	[53]	Planned subsea line
EU-GBR	EU-NLD	1000	-1000	2015	[47]	Subsea, UCC EU model

EU-GBR	EU-NOR	0	0	2015	[53]	Planned subsea line
EU-GEO	AS-RUS-SO	750	-850	2015	[443]	
EU-GEO	AS-TUR	850	-850	2015	[443]	
EU-GRC	AS-TUR	650	-500	2017	[445]	
EU-GRC	EU-ITA	500	-500	2015	[47]	Subsea, UCC EU model
EU-GRC	EU-MKD	350	-450	2015	[259]	Estimate[3]
EU-HRV	EU-HUN	2000	-2000	2015	[47]	UCC EU model
EU-HRV	EU-MNE	0	0	2015	[449]	
EU-HRV	EU-SRB	600	-600	2015	[259]	Estimate[3]
EU-HRV	EU-SVN	2000	-2000	2015	[259]	Estimate[3]
EU-HUN	EU-ROU	1300	-1400	2015	[47]	UCC EU model
EU-HUN	EU-SRB	700	-800	2015	[259]	Estimate[3]
EU-HUN	EU-SVK	1800	-450	2015	[47]	UCC EU model
EU-HUN	EU-SVN	1700	-2000	2015	[47]	UCC EU model
EU-HUN	EU-UKR	650	-650	2018	[438]	
EU-ITA	AF-TUN	0	0	2016	[74]	Planned subsea line
EU-ITA	EU-SVN	580	-530	2015	[47]	
EU-KOS	EU-MKD	400	-400	2011	[453]	
EU-KOS	EU-MNE	400	-400	2011	[453]	
EU-KOS	EU-SRB	600	-600	2011	[453]	
EU-LTU	AS-RUS-NW	680	-600	2014	[448]	
EU-LTU	EU-LVA	1500	-1200	2015	[47]	UCC EU model
EU-LTU	EU-POL	500	0	2015	[47]	UCC EU model
EU-LTU	EU-SWE	700	-700	2015	[47]	Subsea, UCC EU model
EU-LVA	AS-RUS-NW	1200	-1500	2006	[447]	
EU-MDA	EU-ROU	0	0	2015	[259]	Estimate[3]
EU-MDA	EU-UKR	700	-700	2018	[438]	
EU-MKD	EU-SRB	300	-700	2015	[259]	Estimate[3]
EU-MNE	EU-SRB	700	-700	2015	[259]	Estimate[3]
EU-NLD	EU-NOR	700	-700	2015	[47]	Subsea, UCC EU model
EU-NOR	AS-RUS-NW	50	-50	2013	[454]	
EU-NOR	EU-SWE	3695	-3995	2015	[47]	UCC EU model
EU-POL	EU-SVK	990	-990	2015	[47]	UCC EU model
EU-POL	EU-SWE	600	-600	2015	[47]	Subsea, UCC EU model
EU-POL	EU-UKR	235	-235	2018	[438]	
EU-ROU	EU-SRB	700	-800	2015	[259]	
EU-ROU	EU-UKR	650	-650	2018	[438]	
EU-SVK	EU-UKR	650	-650	2018	[438]	
NA-CAN-AB	NA-CAN-BC	1000	-1200	2015	[345]	
NA-CAN-AB	NA-CAN-NO	0	0	2015	[345]	
NA-CAN-AB	NA-CAN-SK	150	-150	2015	[345]	
NA-CAN-AB	NA-USA-NW	325	-300	2015	[345]	
NA-CAN-AR	NA-CAN-QC	785	-1029	2015	[347]	
NA-CAN-AR	NA-USA-NE	1120	-750	2015	[326]	

NA-CAN-BC	NA-CAN-NO	0	0	2015	[348]	Estimate[4]
NA-CAN-BC	NA-USA-AK	0	0	2015	[348]	Estimate[4]
NA-CAN-BC	NA-USA-NW	2364	-2364	2015	[348]	Estimate[4]
NA-CAN-MB	NA-CAN-NO	0	0	2015	[346]	
NA-CAN-MB	NA-CAN-ON	234	-234	2015	[346]	
NA-CAN-MB	NA-CAN-SK	220	-175	2015	[346]	
NA-CAN-MB	NA-USA-MW	2100	-2100	2015	[346]	
NA-CAN-NL	NA-CAN-QC	5150	0	2012	[344]	
NA-CAN-NO	NA-CAN-SK	0	0	2015	[343]	
NA-CAN-ON	NA-CAN-QC	1970	-2705	2015	[326]	
NA-CAN-ON	NA-USA-MW	132	-132	2015	[338]	Estimate[4]
NA-CAN-ON	NA-USA-NY	1949	-1949	2015	[338]	Estimate[4]
NA-CAN-ON	NA-USA-RM	1747	-1747	2015	[338]	Estimate[4]
NA-CAN-QC	NA-USA-NE	2275	-2170	2015	[326]	
NA-CAN-QC	NA-USA-NY	1999	-1100	2015	[326]	
NA-CAN-SK	NA-USA-MW	100	-50	2015	[343]	
NA-CRI	NA-NIC	300	-300	2015	[253]	
NA-CRI	NA-PAN	300	-300	2015	[253]	
NA-GTM	NA-HND	300	-300	2015	[253]	
NA-GTM	NA-MEX	200	-200	2015	[253]	
NA-GTM	NA-SLV	300	-300	2015	[253]	
NA-HND	NA-NIC	300	-300	2015	[253]	
NA-HND	NA-SLV	300	-300	2015	[253]	
NA-USA-AZ	NA-MEX	0	0	2015-2017	[221]	Estimate[4]
NA-USA-AZ	NA-USA-CA	7247	-7247	2015-2017	[221]	Estimate[4]
NA-USA-AZ	NA-USA-ER	0	0	2015-2017	[221]	Estimate[4]
NA-USA-AZ	NA-USA-NW	2067	-2067	2015-2017	[221]	Estimate[4]
NA-USA-AZ	NA-USA-RA	1960	-1960	2015-2017	[221]	Estimate[4]
NA-USA-AZ	NA-USA-SS	400	-400	2015-2017	[376]	
NA-USA-CA	NA-MEX	408	-408	2015-2017	[221]	Estimate[4]
NA-USA-CA	NA-USA-NW	10211	-10211	2015-2017	[221]	Estimate[4]
NA-USA-ER	NA-MEX	431	-431	2015-2017	[221]	Estimate[4]
NA-USA-ER	NA-USA-SA	0	0	2015-2017	[221]	Estimate[4]
NA-USA-ER	NA-USA-SS	834	-834	2015-2017	[221]	Estimate[4]
NA-USA-FR	NA-USA-SE	3897	-3897	2015-2017	[221]	Estimate[4]
NA-USA-ME	NA-USA-MW	3000	-3000	2015-2017	[221]	Estimate[6]
NA-USA-NW	NA-CAN-SK	0	0	2015-2017	[221]	Estimate[4]
NA-USA-NW	NA-USA-MW	187	-187	2015-2017	[221]	Estimate[4]
NA-USA-NW	NA-USA-RA	1827	-1827	2015-2017	[221]	Estimate[4]
NA-USA-NY	NA-USA-NE	1764	-1764	2015-2017	[221]	Estimate[4]
NA-USA-RA	NA-USA-MW	432	-432	2015-2017	[221]	Estimate[4]
NA-USA-RA	NA-USA-SN	210	-210	2015-2017	[376]	
NA-USA-RA	NA-USA-SS	0	0	2015-2017	[221]	Estimate[4]
NA-USA-RE	NA-USA-NY	4086	-4086	2015-2017	[369]	

NA-USA-RE	NA-USA-SV	4529	-4529	2015-2017	[369]	
NA-USA-RW	NA-USA-ME	1456	-1456	2015-2017	[369]	
NA-USA-RW	NA-USA-MW	2196	-2196	2015-2017	[369]	
NA-USA-RW	NA-USA-RE	6793	-6793	2015-2017	[369]	
NA-USA-RW	NA-USA-RM	5320	-5320	2015-2017	[369]	
NA-USA-RW	NA-USA-SV	7342	-7342	2015-2017	[369]	
NA-USA-SA	NA-USA-SN	0	0	2015-2017	[221]	Estimate[4]
NA-USA-SA	NA-USA-SW	3000	-3000	2015-2017	[221]	Estimate[6]
NA-USA-SC	NA-USA-RW	4859	-4859	2015-2017	[221]	Estimate[4]
NA-USA-SC	NA-USA-SA	2371	-2371	2015-2017	[221]	Estimate[4]
NA-USA-SC	NA-USA-SV	592	-592	2015-2017	[221]	Estimate[4]
NA-USA-SE	NA-USA-SA	2032	-2032	2015-2017	[221]	Estimate[4]
NA-USA-SE	NA-USA-SC	4405	-4405	2015-2017	[221]	Estimate[4]
NA-USA-SE	NA-USA-SV	4896	-4896	2015-2017	[221]	Estimate[4]
NA-USA-SN	NA-USA-MW	2668	-2668	2015-2017	[376]	Estimate[5]
NA-USA-SN	NA-USA-SW	6978	-6978	2015-2017	[376]	
NA-USA-SS	NA-USA-SA	6889	-6889	2015-2017	[221]	Estimate[4]
NA-USA-SS	NA-USA-SN	6889	-6889	2015-2017	[221]	Estimate[5]
NA-USA-SW	NA-USA-MW	3000	-3000	2015-2017	[221]	Estimate[6]
NA-USA-SW	NA-USA-RW	6295	-6295	2015-2017	[221]	Estimate[6]
NA-USA-SW	NA-USA-SC	2970	-2970	2015-2017	[221]	Estimate[4]
OC-AUS-NT	OC-AUS-QL	0	0	2019	[326]	
OC-AUS-NT	OC-AUS-SA	0	0	2019	[326]	
OC-AUS-NT	OC-AUS-WA	0	0	2019	[326]	
OC-AUS-QL	OC-AUS-SA	0	0	2019	[326]	
OC-AUS-QL	OC-AUS-SW	1288	-707	2017	[325]	
OC-AUS-SA	OC-AUS-SW	0	0	2019	[326]	
OC-AUS-SA	OC-AUS-VI	660	-680	2017	[325]	
OC-AUS-SA	OC-AUS-WA	0	0	2019	[326]	
OC-AUS-SW	OC-AUS-VI	1350	-1600	2017	[325]	
OC-AUS-TA	OC-AUS-VI	594	-478	2017	[325]	
SA-ARG	SA-BOL	0	0	2015	[253]	
SA-ARG	SA-BRA-SO	2250	-2250	2015	[253]	
SA-ARG	SA-CHL	633	-633	2015	[253]	
SA-ARG	SA-PRY	3320	-3320	2015	[253]	
SA-ARG	SA-URY	3276	-3276	2015	[253]	
SA-BOL	SA-BRA-CW	0	0	2015	[253]	
SA-BOL	SA-BRA-WE	0	0	2015	[253]	
SA-BOL	SA-CHL	0	0	2015	[253]	
SA-BOL	SA-PER	0	0	2015	[253]	
SA-BOL	SA-PRY	0	0	2015	[253]	
SA-BRA-CN	SA-BRA-CW	0	0	2017	[329]	
SA-BRA-CN	SA-BRA-J2	8518	-8518	2017	[329]	
SA-BRA-CN	SA-BRA-J3	13700	-13700	2017	[329]	

SA-BRA-CN	SA-BRA-NE	0	0	2017	[329]	
SA-BRA-CN	SA-BRA-NW	0	0	2017	[329]	
SA-BRA-CN	SA-GUY	0	0	2015	[253]	
SA-BRA-CW	SA-BRA-J2	5598	-5380	2017	[329]	
SA-BRA-CW	SA-BRA-NE	0	0	2017	[329]	
SA-BRA-CW	SA-BRA-NW	0	0	2017	[329]	
SA-BRA-CW	SA-BRA-SE	15000	-15000	2017	[329]	
SA-BRA-CW	SA-BRA-SO	0	0	2017	[329]	
SA-BRA-CW	SA-BRA-WE	7092	-7092	2017	[329]	
SA-BRA-CW	SA-PRY	0	0	2015	[253]	
SA-BRA-J1	SA-BRA-SE	6800	-6800	2017	[329]	
SA-BRA-J1	SA-BRA-SO	8726	-8617	2017	[329]	
SA-BRA-J2	SA-BRA-J3	4115	-4115	2017	[329]	
SA-BRA-J2	SA-BRA-NE	8200	-4849	2017	[329]	
SA-BRA-J3	SA-BRA-NW	2700	-2700	2017	[329]	
SA-BRA-J3	SA-BRA-SE	8000	-8000	2017	[329]	
SA-BRA-NE	SA-BRA-SE	6936	-6500	2017	[329]	
SA-BRA-NW	SA-BRA-WE	0	0	2017	[329]	
SA-BRA-NW	SA-COL	0	0	2015	[253]	
SA-BRA-NW	SA-GUF	0	0	2015	[253]	
SA-BRA-NW	SA-GUY	0	0	2015	[253]	
SA-BRA-NW	SA-PER	0	0	2015	[253]	
SA-BRA-NW	SA-VEN	200	-200	2015	[253]	
SA-BRA-SE	SA-BRA-SO	14920	-14608	2017	[329]	
SA-BRA-SO	SA-PRY	7000	-7000	2015	[253]	
SA-BRA-SO	SA-URY	570	-570	2015	[253]	
SA-BRA-WE	SA-PER	0	0	2015	[253]	
SA-CHL	SA-PER	0	0	2015	[253]	
SA-COL	NA-PAN	0	0	2015	[253]	
SA-COL	SA-ECU	613	-613	2015	[253]	
SA-COL	SA-PER	0	0	2015	[253]	
SA-COL	SA-VEN	394	-394	2015	[253]	
SA-ECU	SA-PER	110	-110	2015	[253]	
SA-GUY	SA-VEN	0	0	2015	[253]	

[1] *Estimate based on contracted supply from Guangdong to Hong Kong.*

[2] *Estimate based on mentioned yearly export values.*

[3] *Estimate based on forecasted month/year ahead values.*

[4] *Estimate based on the assumption that the maximum hourly exchange value in the specified period represents the NTC.*

[5] *Estimate based on the assumption that maximum external flow from a single pathway coming into a node covered by SPP can also flow towards adjacent nodes covered by SPP (See Section S2 underneath Canada and the United States for further explanation).*

[6] *Estimate based on the assumption that maximum external flow from a single pathway coming into a node covered by MISO can also flow towards adjacent nodes covered by MISO (See Section S2 underneath Canada and the United States for further explanation).*

Appendix D: Supplementary Material Chapter 5

D.1 Details on Spatial and Temporal Electricity Demand Downscaling

Section 5.3 describes the different steps of the soft-link framework for connecting global IAMs with global power system models. This Supplementary Material provides enhanced details on the required spatial and temporal demand downscaling and conversion steps within the framework including provided examples based on the ENGAGE SSP2 NPI2020 500 scenario of the global IAM MESSAGEix-GLOBIOM. The accompanying python script[22] that can be used to coordinate a soft-link between IAM and power system model uses pyam, an open source python package for analysis and visualization of IAM scenario data [455]. The pyam package is used to extract scenario data from known databases such as the IAMC 1.5°C scenario explorer [312] that among others includes scenario data underpinning chapter 2 of the Special Report on Global Warming of 1.5°C by the IPCC [7].

Although any downscaling approach can be applied for downscaling of IAM scenario regional electricity demand in the proposed soft-link framework, within the accompanying python script of the main paper we apply a forecasting methodology for country-level electricity demand based on multivariate linear regression with GDP at purchasing power parity X_{GDPppp} per capita and urbanization share X_{urb} as independent variables and electricity consumption per capita Y_{pc} as dependent variable. Historical country level values h for the above variables have been retrieved by means of the World Banks World Development Indicators [456] and the World Bank Data python package[23]. Country level values are grouped per region according to the spatial representation of the specific scenario followed by the derivation of the regional regression equations (Eq. D-1) for the period 1980-2014 with a being the intercept and b_{GDPppp} and b_{urb} the respective slopes and e the residual. More recent data years for electricity consumption per capita are not available within the World Bank World Development Indicators hence 2014 as most recent year. The regression has been applied per region and not per country because historical data is not available for all countries globally.

Eq. D-1 $$Y_{pc^h} = a + b_{GDPppp}X_{GDPppp^h} + b_{urb}X_{urb^h} + e$$

For country-level projections of the independent variables as well as population projections we used the Shared Socioeconomic Pathways (SSPs) [265] and the accompanying

[22] https://github.com/iiasa/IAM-powersystemmodel-linkage
[23] https://github.com/mwouts/world_bank_data

quantifications [457–461], all retrievable through the SSP Public Database[24]. 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 country-level projections p for GDP at Purchasing Power Parity (PPP) X_{GDPppp^p} and urbanization share X_{urb^p}, per capita electricity demand at country-level Y_{pc^p} can be projected specific per SSP (Eq. D-2). An example regression is visualized in Figure D-1 for the Latin America region.

Eq. D-2 $$Y_{pc^p} = a + b_{GDPppp}X_{GDPppp^p} + b_{urb}X_{urb^p}$$

By multiplying Y_{pc^p} with country-level population projections for the corresponding SSP X_{pop^p}, aggregate projected country-level electricity demand Y_p can be calculated (Eq. D-3). The regression can be applied manually as shown in this section, yet in the python script we use the linear regression module of the sklearn python package[25].

Eq. D-3 $$Y_p = Y_{pc^p}X_{pop^p}$$

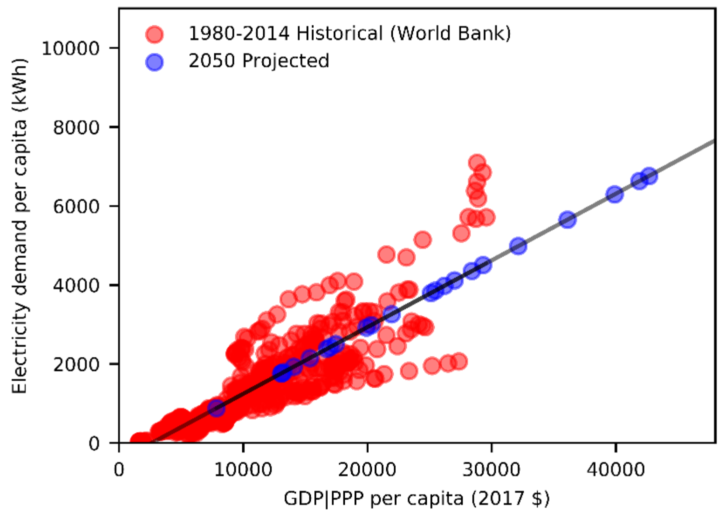


Figure D-1 Regression example with GDPppp per capita as independent variable (2017 $) and electricity demand per capita (kWh) as dependent variable. Every red dot in the graph represents a single year value for one of the countries in the MESSAGEix-GLOBIOM_R11LAM region for the period 1980-2014. The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

Y_p is used as a proxy to downscale IAM scenario regional demand values to country-level scenario demand values (Y_s). Within the python script this occurs by making use of downscaling functionalities within pyam, example code shown in Figure D-2. Refer to the

[24] https://tntcat.iiasa.ac.at/SspDb
[25] https://scikit-learn.org/stable/modules/generated/sklearn.linear_model.LinearRegression.html

GitHub page[22] for the full code as used for the different steps in the spatial demand downscaling.

```
#Loops through the keys (regions) and values (countries) in mapping dictionary.
for key, value in Mapping_PLEXOS_Countries.items():

    #Filters the relevant weights (projected country-level electricity demand) based on
    #the value entries (countries) for the specific key (region).
    weight = Country_Demand_Raw_Weight[Country_Demand_Raw_Weight.index.isin(value)]

    #Downscales the IAM scenario electricity demand per region (key) to country level (value)
    #by using the weights as proxy.
    Region_Demand_Scenario.downscale_region('Final Energy|Electricity' , region = key ,
                                            subregions = value , weight = weight ,
                                            append = True)
```

Figure D-2 Snapshot of the code for electricity demand spatial downscaling by using the downscale_region function.

Figure D-3 showcases an example comparison of Y_p, Y_s and 2015 country-level historical demand Y_h based on the PLEXOS-World 2015 dataset [231,287] for contextual purposes. Compared to the historical 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 [462]. 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 [6,7].

Explicit modelling of intra-nodal T&D is not incorporated in PLEXOS-World. Hence, country-level final electricity demand Y_f includes projected T&D losses specific per country TD_p based on [298] (Eq. D-4).

Eq. D-4 $$Y_f = \frac{Y_s TD_p}{100} + Y_s$$

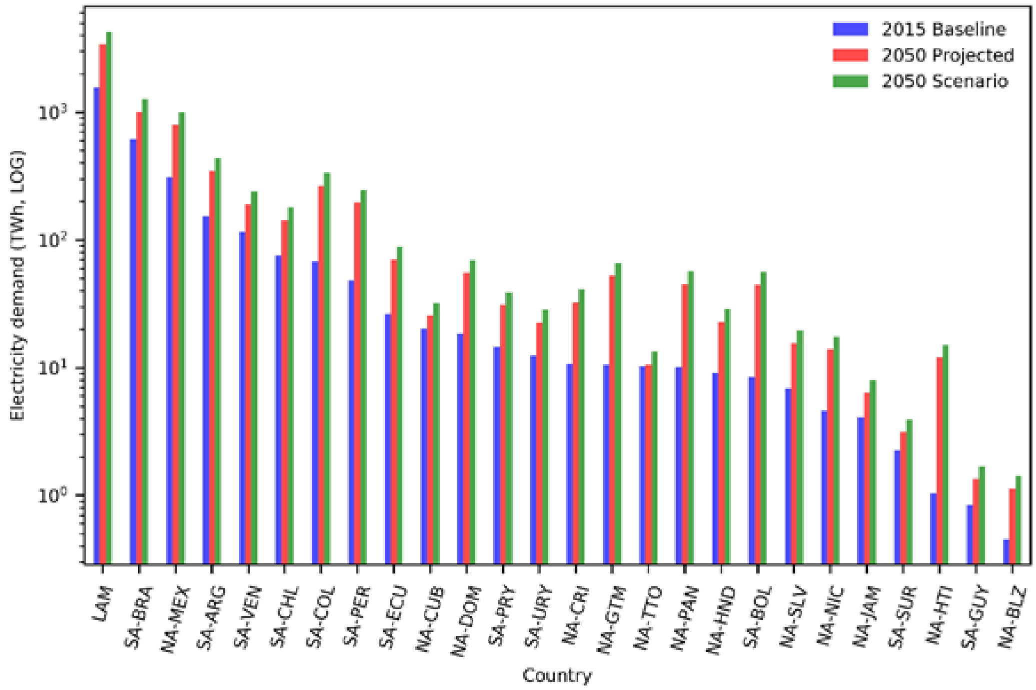


Figure D-3 Comparison of regional- and country-level projected electricity demand Y_p, the downscaled scenario demand Y_s and the 2015 historical demand Y_h for the MESSAGEix-GLOBIOM_R11 LAM region.

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 [231,287], which includes hourly demand data for all countries globally and a wide range of sub-country regions based on the 2015 calendar year. Approximately 50% of profiles in the dataset are based on actual historical operational power system data. The country-level final electricity demand per hourly interval i can be calculated with Eq. D-5.

Eq. D-5 $$Y_f{}^i = \frac{Y_h{}^i}{\sum Y_h{}^i} Y_f$$

The upper part of Figure D-4 shows an example of the temporally downscaled final electricity demand for Brazil for the specific scenario. Note that the occurance of periods with relative lower demand - i.e. weekends - does not coincide in both calendar years. Scaling of demand profiles for this study occurs with a profile builder module within PLEXOS which has the ability to shift profiles based on a given calendar year. The relative peak demand 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 D-4 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 Y_{fsc^i} with Eq. D-6 by using historical relative demand shares for sub-country nodes per interval Y_{hsc^i} as proxy. This is visualized in the lower part of Figure D-4.

Eq. D-6 $$Y_{fsc^i} = \frac{Y_{hsc^i}}{Y_{h^i}} Y_{f^i}$$

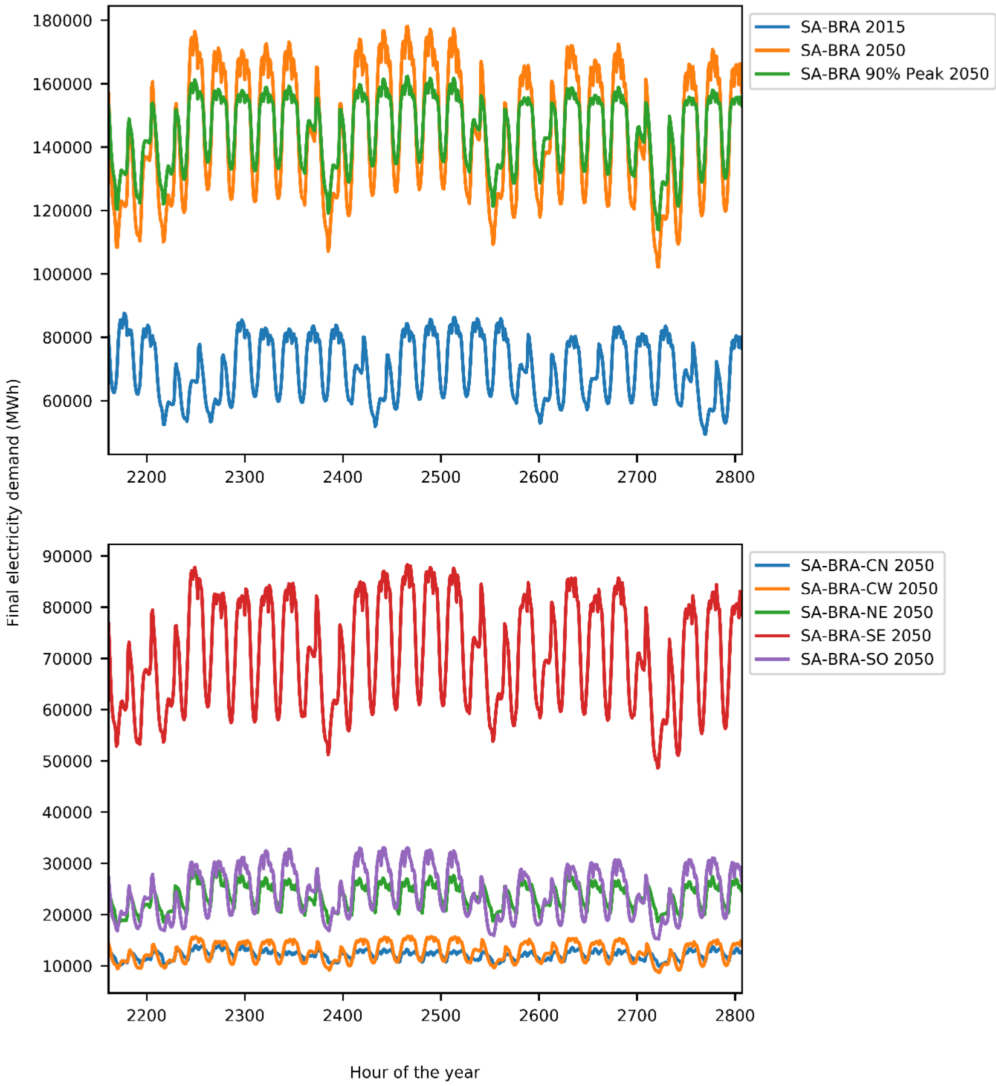


Figure D-4 Downscaled hourly final electricity demand for South America - Brazil (SA-BRA). The upper graph showcases the baseline 2050 hourly final demand profile, an exemplary profile with adjusted peak demand at 90% and the 2015 demand profile for reference. The lower graph shows the hourly final demand profiles of the largest sub-country nodes within Brazil (Central North (CN), Central West (CW), North East (NE), South East (SE), South (SO)).

D.2 Details on spatial capacity downscaling

Next to the downscaled demand profiles as described in Section D.1, other main input data for the power system model that requires spatial downscaling based on the IAM scenario output are regional powerplant expansion and retirement constraints. These determine per 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. The constraints are used as basis for the capacity allocation exercise within the power system model 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. This paper and the accompanying script uses the PLEXOS-World 2015 dataset [231]. The dataset includes global powerplant-, storage- and transmission capacities as of 2015 separated by 258 nodes.

Given the high temporal resolution of power system models, UCED exercises are usually restricted to a year at maximum per model simulation as a snapshot analysis of the operations of a given power system. Taking 2050 as an example as intended simulation year for the UCED, scenario specific expansion and retirement constraints Ex for the period up to 2050 can be calculated with Eq. D-7 by subtracting the region r and technology t specific capacities Cs retrieved from the IAM scenario output from the baseline powerplant capacities Cb.

Eq. D-7 $$Ex_{r^,t} = C_s - C_b$$

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 to make the capacity expansion exercise computationally less intensive. The latter approach is used for this proof of concept study as automated in the python script. Figure D-5 shows an example of calculated expansion and retirement constraints for the period 2015-2050 for the MESSAGEix-GLOBIOM_R11LAM region.

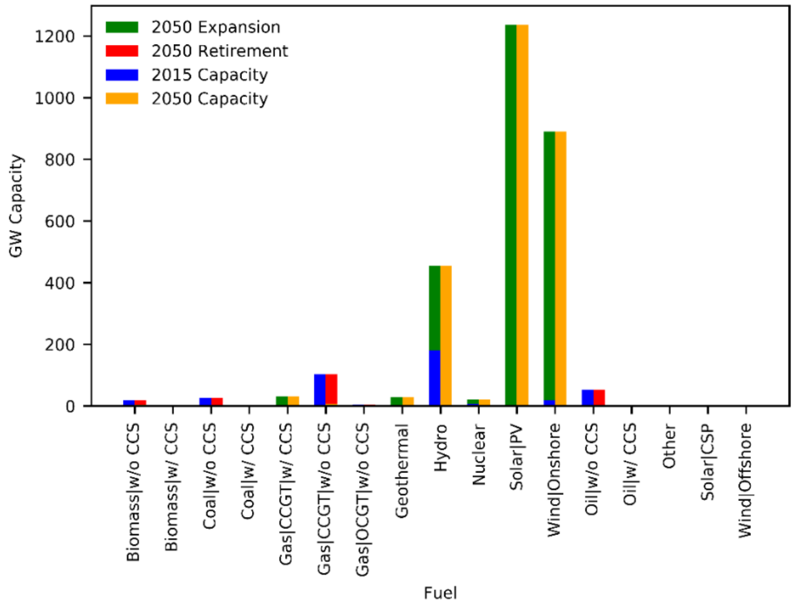


Figure D-5 Example powerplant expansion and retirement constraints for MESSAGEix-GLOBIOM_R11LAM for the period 2015-2050. Per technology, the left bar indicates the existing baseline capacity in 2015 (blue) and the to be expanded capacity (green). The right bar indicates the required capacity in 2050 (yellow) and the to be retired capacity (red).

D.3 PLEXOS-World and MESSAGEix-GLOBIOM scenario integration

D.3.1 PLEXOS long-term capacity expansion

The PLEXOS-World model as applied for this study including all input data and timeseries can be found in [307]. 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 5.3.4, in context of the soft-link framework, the capacity expansion module is used to downscale given regional powerplant capacities 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 MIP 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 LDCs 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 [318,319], 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 D-6 shows an example of different sampling combinations for demand and VRES series.

For the analysis in this paper we apply a sampling approach using 3-weeks per year at 4-hourly time resolution (total of 126 4-hourly timeslices) for the different profiles in the expansion exercise. In essence, this means that PLEXOS selects 3 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 D-6, 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 slightly 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 solely short-term storage.

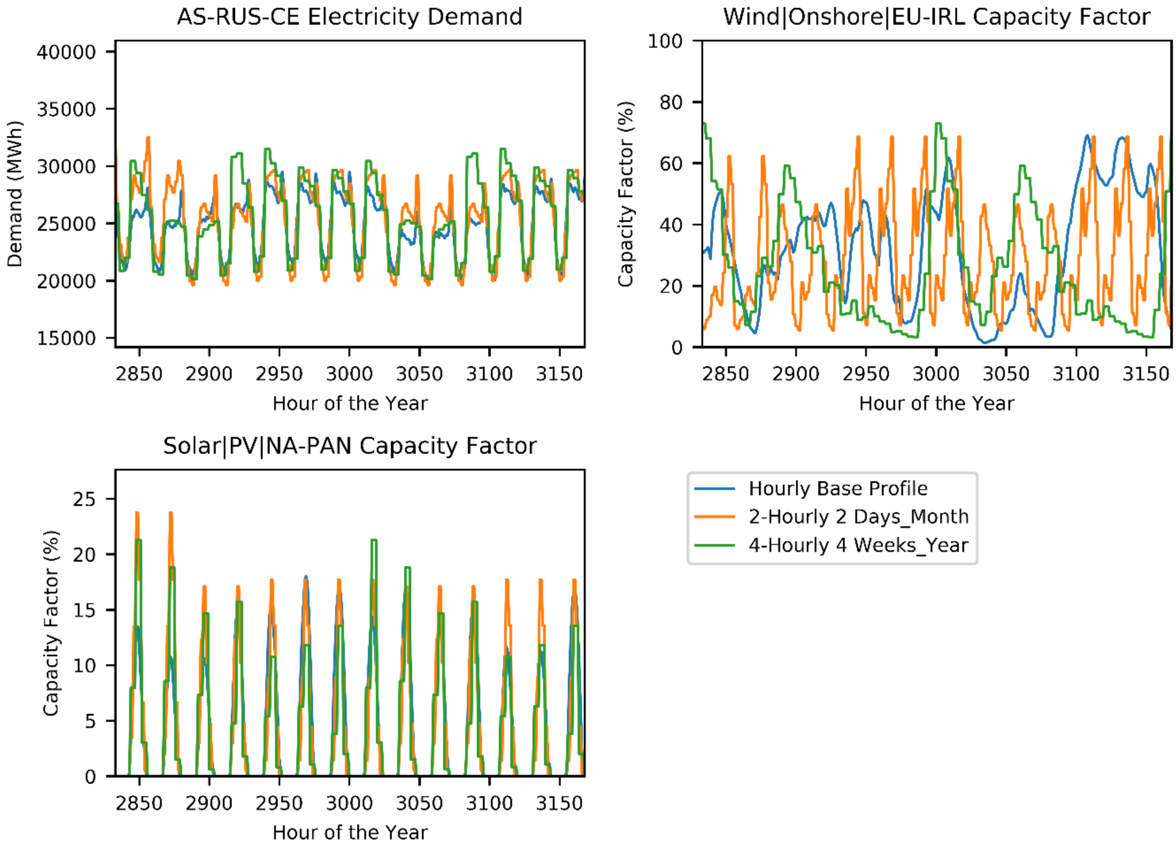


Figure D-6 Examples of sampling combinations for a variety of demand and VRES series. Examples are given for Asia - Central Russia (AS-RUS-CE), Europe - Ireland (EU-IRL) and North America - Panama (NA-PAN).

Next to the expansion- and retirement constraints and the load profiles developed based on the MESSAGEix-GLOBIOM scenario data, input data for PLEXOS-World 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 IAM scenario output. The expansion of storage in PLEXOS-World 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 [276]. 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.

Expansion of transmission infrastructure requires additional sources and assumptions. Following Zappa et al. [17], 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. All capacity is standardized as a combined interface rather than individual lines. The distance between demand centers based on longitudes and latitudes has been calculated with an excel formula (Eq. D-8) that considers the radius of the earth.

Eq. D-8 $$ACOS(COS(RADIANS(90 - Lat1)) * COS(RADIANS(90 - Lat2)) + SIN(RADIANS(90 - Lat1)) * SIN(RADIANS(90 - Lat2)) * COS(RADIANS(Long1 - Long2))) * 6371$$

Similar to powerplant capacities, baseline transmission capacities are retrieved from the PLEXOS-World dataset [231,287]. Expansion candidates in PLEXOS-World exist for all land-based adjacent nodes, for interfaces with existing subsea transmission capacity as well as for interfaces with potential for subsea transmission capacity following an earlier review on the concept of a globally interconnected power grid [227]. An overview of the techno-economic parameters as used for the transmission capacity expansion can be seen in Table D-1.

Table D-1 Assumed techno-economic parameters for transmission infrastructure capacity expansion. All parameters are based on [17] with the exception of CAPEX line costs for land-based HVDC which is based on [458].

Parameter	HVAC	HVDC	HVDC Subsea
CAPEX Line ($2010/MW/KM)	639	187	242
CAPEX Substations/Converter pair ($2010/MW)	78542	244042	244042
Fixed Operation & Maintenance cost (% of CAPEX/year)	3.5	3.5	3.5
Line losses (%/1000 km)	6.75	3.5	3.5
AC/DC Converter pair losses (%)	0	1.3	1.3

For bulk power flow, high voltage transmission lines with voltages of 110 kV and above are generally used with HVAC lines for shorter transmission distances and HVDC lines for longer distances. HVDC becomes only efficient at longer distances due to its initially high base costs for AC/DC converters compensated by significantly lower transmission losses and costs. 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 [77,463–465]. This break-even distance not only includes 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 potential transmission lines are not known before model simulation we calculate the break-even distance solely based on CAPEX costs and fixed operation and maintenance costs. Based on the parameters in Table D-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 [227]. Following this approach, every transmission pathway has personalized associated costs and transmission losses. A full overview of characteristics, costs and losses per transmission pathway as included in the PLEXOS-World modelling can be found in Table D-2.

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. [466] and country-level potential for onshore- and offshore wind based on a global assessment by Eurek and colleagues [280]. 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 [242]. 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 [467] 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 assumed unconstrained transportability of biomass within IAM regions.

Table D-2 Transmission pathway specific techno-economic parameters as used for the modelling in PLEXOS-World. Naming conventions as used for the Interfaces are based on ISO 3 codes for countries. Refer to Appendix C for details on naming conventions for the two letter codes for sub-country nodes in PLEXOS-World as well as for baseline 2015 capacities per pathway.

Interface	Distance	Type	Build Cost	FOM	Losses	Wheeling Charge
	KM		k$2010/MW	k$2010/MW/yr	%	$/MW
AFG-CHN-XI	1682	HVDC	558	33.5	7.2	4
AFG-IRN	1664	HVDC	554	33.3	7.1	4
AFG-PAK	1354	HVDC	497	29.8	6	4

AFG-TJK	223	HVAC	221	13.3	1.5	4
AFG-TKM	1030	HVDC	436	26.2	4.9	4
AFG-UZB	507	HVDC	339	20.3	3.1	4
AGO-COD	551	HVDC	347	20.8	3.2	4
AGO-COG	557	HVDC	348	20.9	3.2	4
AGO-NAM	1581	HVDC	539	32.4	6.8	4
AGO-ZMB	1791	HVDC	578	34.7	7.6	4
ALB-GRC	500	HVDC	337	20.3	3.1	4
ALB-KOS	186	HVAC	197	11.8	1.3	4
ALB-MKD	154	HVAC	177	10.6	1	4
ALB-MNE	132	HVAC	163	9.8	0.9	4
ARE-IRN	1218	Subsea - HVDC	539	32.3	5.6	4
ARE-OMN	381	HVDC	315	18.9	2.6	4
ARE-SAU	860	HVDC	404	24.3	4.3	4
ARG-BOL	1934	HVDC	605	36.3	8.1	4
ARG-BRA-SO	1343	HVDC	495	29.7	6	4
ARG-CHL	1137	HVDC	456	27.4	5.3	4
ARG-PRY	1037	HVDC	438	26.3	4.9	4
ARG-URY	205	HVAC	209	12.6	1.4	4
ARM-AZE	454	HVDC	329	19.7	2.9	4
ARM-GEO	173	HVAC	189	11.3	1.2	4
ARM-IRN	786	HVDC	391	23.5	4.1	4
ARM-TUR	1310	HVDC	488	29.3	5.9	4
AUS-NT-AUS-QL	2849	HVDC	776	46.5	11.3	4
AUS-NT-AUS-SA	2622	HVDC	733	44	10.5	4
AUS-NT-AUS-WA	2658	HVDC	740	44.4	10.6	4
AUS-QL-AUS-SA	1603	HVDC	543	32.6	6.9	4
AUS-QL-AUS-SW	740	HVDC	382	22.9	3.9	4
AUS-QL-PNG	2092	Subsea - HVDC	750	45	8.6	4
AUS-SA-AUS-SW	1159	HVDC	460	27.6	5.4	4
AUS-SA-AUS-VI	654	HVDC	366	22	3.6	4
AUS-SA-AUS-WA	2133	HVDC	642	38.5	8.8	4
AUS-SW-AUS-VI	708	HVDC	376	22.6	3.8	4
AUS-TA-AUS-VI	593	Subsea - HVDC	388	23.3	3.4	4
AUS-WA-IDN	3016	Subsea - HVDC	974	58.5	11.9	4
AUS-WA-TLS	2789	Subsea - HVDC	919	55.2	11.1	4
AUT-CHE	591	HVDC	354	21.3	3.4	4
AUT-CZE	251	HVAC	239	14.3	1.7	4
AUT-DEU	524	HVDC	342	20.5	3.1	4
AUT-HUN	217	HVAC	217	13	1.5	4
AUT-ITA	764	HVDC	387	23.2	4	4
AUT-SVK	56	HVAC	114	6.9	0.4	4
AUT-SVN	277	HVAC	255	15.3	1.9	4
AZE-GEO	450	HVDC	328	19.7	2.9	4

AZE-IRN	543	HVDC	345	20.7	3.2	4
AZE-RUS-SO	1113	HVDC	452	27.1	5.2	4
AZE-TUR	1754	HVDC	571	34.3	7.4	4
BDI-COD	1562	HVDC	535	32.1	6.8	4
BDI-RWA	176	HVAC	191	11.5	1.2	4
BDI-TZA	1161	HVDC	461	27.7	5.4	4
BEL-DEU	652	HVDC	366	22	3.6	4
BEL-FRA	261	HVAC	245	14.7	1.8	4
BEL-GBR	319	Subsea - HVDC	321	19.3	2.4	4
BEL-LUX	187	HVAC	198	11.9	1.3	4
BEL-NLD	173	HVAC	189	11.3	1.2	4
BEN-BFA	693	HVDC	373	22.4	3.7	4
BEN-GHA	403	HVDC	319	19.2	2.7	4
BEN-NER	704	HVDC	375	22.5	3.8	4
BEN-NGA	176	HVAC	191	11.5	1.2	4
BEN-TGO	145	HVAC	171	10.3	1	4
BFA-CIV	831	HVDC	399	24	4.2	4
BFA-GHA	632	HVDC	362	21.7	3.5	4
BFA-MLI	704	HVDC	375	22.5	3.8	4
BFA-NER	415	HVDC	321	19.3	2.8	4
BFA-TGO	756	HVDC	385	23.1	3.9	4
BGD-IND-EA	253	HVAC	240	14.4	1.7	4
BGD-IND-NE	304	HVAC	273	16.4	2.1	4
BGD-MMR	972	HVDC	425	25.5	4.7	4
BGR-GRC	524	HVDC	342	20.5	3.1	4
BGR-MKD	172	HVAC	188	11.3	1.2	4
BGR-ROU	297	HVAC	268	16.1	2	4
BGR-SRB	330	HVAC	289	17.4	2.2	4
BGR-TUR	503	HVDC	338	20.3	3.1	4
BHR-SAU	422	HVDC	323	19.4	2.8	4
BIH-HRV	287	HVAC	262	15.7	1.9	4
BIH-MNE	172	HVAC	188	11.3	1.2	4
BIH-SRB	198	HVAC	205	12.3	1.3	4
BLR-LTU	170	HVAC	187	11.2	1.1	4
BLR-LVA	403	HVDC	319	19.2	2.7	4
BLR-POL	475	HVDC	333	20	3	4
BLR-RUS-CE	675	HVDC	370	22.2	3.7	4
BLR-RUS-NW	692	HVDC	373	22.4	3.7	4
BLR-UKR	435	HVDC	325	19.5	2.8	4
BLZ-GTM	406	HVDC	320	19.2	2.7	4
BLZ-MEX	1174	HVDC	463	27.8	5.4	4
BOL-BRA-CW	1644	HVDC	551	33.1	7.1	4
BOL-BRA-WE	1004	HVDC	431	25.9	4.8	4
BOL-CHL	1897	HVDC	598	35.9	7.9	4

BOL-PER	1614	HVDC	545	32.7	6.9	4
BOL-PRY	1018	HVDC	434	26.1	4.9	4
BRA-CN-BRA-CW	1595	HVDC	542	32.5	6.9	4
BRA-CN-BRA-J2	826	HVDC	398	23.9	4.2	4
BRA-CN-BRA-J3	1126	HVDC	454	27.3	5.2	4
BRA-CN-BRA-NE	1689	HVDC	559	33.6	7.2	4
BRA-CN-BRA-NW	1293	HVDC	485	29.1	5.8	4
BRA-CN-GUY	1413	HVDC	508	30.5	6.2	4
BRA-CN-SUR	1099	HVDC	449	27	5.1	4
BRA-CW-BRA-J2	872	HVDC	407	24.4	4.4	4
BRA-CW-BRA-NE	1063	HVDC	442	26.6	5	4
BRA-CW-BRA-NW	1933	HVDC	605	36.3	8.1	4
BRA-CW-BRA-SE	872	HVDC	407	24.4	4.4	4
BRA-CW-BRA-SO	1081	HVDC	446	26.8	5.1	4
BRA-CW-BRA-WE	1903	HVDC	599	36	8	4
BRA-CW-PRY	1463	HVDC	517	31	6.4	4
BRA-J1-BRA-SE	290	HVAC	264	15.8	2	4
BRA-J1-BRA-SO	94	HVAC	138	8.3	0.6	4
BRA-J2-BRA-J3	1380	HVDC	501	30.1	6.1	4
BRA-J2-BRA-NE	932	HVDC	418	25.1	4.6	4
BRA-J3-BRA-NW	371	HVDC	313	18.8	2.6	4
BRA-J3-BRA-SE	2326	HVDC	678	40.7	9.4	4
BRA-NE-BRA-SE	1455	HVDC	515	30.9	6.4	4
BRA-NW-BRA-WE	762	HVDC	386	23.2	4	4
BRA-NW-COL	1783	HVDC	577	34.6	7.5	4
BRA-NW-GUF	1235	HVDC	474	28.5	5.6	4
BRA-NW-GUY	1120	HVDC	453	27.2	5.2	4
BRA-NW-PER	2125	HVDC	640	38.4	8.7	4
BRA-NW-SUR	1129	HVDC	455	27.3	5.3	4
BRA-NW-VEN	1695	HVDC	560	33.6	7.2	4
BRA-SE-BRA-SO	344	HVAC	298	17.9	2.3	4
BRA-SO-PRY	836	HVDC	400	24	4.2	4
BRA-SO-URY	1238	HVDC	475	28.5	5.6	4
BRA-WE-PER	1484	HVDC	521	31.3	6.5	4
BRN-MYS	1480	HVDC	520	31.2	6.5	4
BTN-CHN-TI	281	HVAC	258	15.5	1.9	4
BTN-IND-EA	569	HVDC	350	21	3.3	4
BWA-NAM	928	HVDC	417	25	4.5	4
BWA-ZAF	272	HVAC	252	15.1	1.8	4
BWA-ZMB	1056	HVDC	441	26.5	5	4
BWA-ZWE	927	HVDC	417	25	4.5	4
CAF-CMR	783	HVDC	390	23.4	4	4
CAF-COD	1032	HVDC	437	26.2	4.9	4
CAF-COG	1026	HVDC	435	26.1	4.9	4

CAF-SDN	1973	HVDC	612	36.7	8.2	4
CAF-TCD	944	HVDC	420	25.2	4.6	4
CAN-AB-CAN-BC	674	HVDC	370	22.2	3.7	4
CAN-AB-CAN-NO	1263	HVDC	480	28.8	5.7	4
CAN-AB-CAN-SK	525	HVDC	342	20.5	3.1	4
CAN-AB-USA-NW	710	HVDC	376	22.6	3.8	4
CAN-AR-CAN-QC	789	HVDC	391	23.5	4.1	4
CAN-AR-USA-NE	657	HVDC	367	22	3.6	4
CAN-BC-CAN-NO	1559	HVDC	535	32.1	6.8	4
CAN-BC-USA-AK	2088	HVDC	634	38	8.6	4
CAN-BC-USA-NW	193	HVAC	202	12.1	1.3	4
CAN-MB-CAN-NO	1746	HVDC	570	34.2	7.4	4
CAN-MB-CAN-ON	1511	HVDC	526	31.6	6.6	4
CAN-MB-CAN-SK	711	HVDC	377	22.6	3.8	4
CAN-MB-USA-MW	620	HVDC	360	21.6	3.5	4
CAN-NL-CAN-QC	1608	HVDC	544	32.7	6.9	4
CAN-NL-GRL	1505	Subsea - HVDC	608	36.5	6.6	4
CAN-NO-CAN-SK	1231	HVDC	474	28.4	5.6	4
CAN-NO-USA-AK	1808	HVDC	581	34.9	7.6	4
CAN-ON-CAN-QC	503	HVDC	338	20.3	3.1	4
CAN-ON-USA-MW	1109	HVDC	451	27.1	5.2	4
CAN-ON-USA-NY	562	HVDC	349	20.9	3.3	4
CAN-ON-USA-RM	333	HVAC	291	17.5	2.2	4
CAN-QC-USA-NE	406	HVDC	320	19.2	2.7	4
CAN-QC-USA-NY	535	HVDC	344	20.6	3.2	4
CAN-SK-USA-MW	1267	HVDC	480	28.8	5.7	4
CAN-SK-USA-NW	1227	HVDC	473	28.4	5.6	4
CHE-DEU	669	HVDC	369	22.1	3.6	4
CHE-FRA	490	HVDC	335	20.1	3	4
CHE-ITA	684	HVDC	372	22.3	3.7	4
CHL-PER	2467	HVDC	704	42.3	9.9	4
CHN-AN-CHN-HB	735	HVDC	381	22.9	3.9	4
CHN-AN-CHN-HE	466	HVDC	331	19.9	2.9	4
CHN-AN-CHN-HU	319	HVAC	282	16.9	2.2	4
CHN-AN-CHN-JS	143	HVAC	170	10.2	1	4
CHN-AN-CHN-JX	377	HVDC	314	18.9	2.6	4
CHN-AN-CHN-SD	549	HVDC	346	20.8	3.2	4
CHN-AN-CHN-ZH	328	HVAC	288	17.3	2.2	4
CHN-BE-CHN-EM	337	HVAC	294	17.6	2.3	4
CHN-BE-CHN-HB	266	HVAC	248	14.9	1.8	4
CHN-BE-CHN-TJ	113	HVAC	151	9	0.8	4
CHN-CH-CHN-GU	332	HVAC	291	17.4	2.2	4
CHN-CH-CHN-HB	1191	HVDC	466	28	5.5	4
CHN-CH-CHN-HN	639	HVDC	363	21.8	3.5	4

CHN-CH-CHN-HU	747	HVDC	383	23	3.9	4
CHN-CH-CHN-SC	272	HVAC	252	15.1	1.8	4
CHN-CH-CHN-SI	567	HVDC	350	21	3.3	4
CHN-CH-CHN-SX	1075	HVDC	445	26.7	5.1	4
CHN-EM-CHN-HB	604	HVDC	357	21.4	3.4	4
CHN-EM-CHN-HJ	727	HVDC	380	22.8	3.8	4
CHN-EM-CHN-JI	548	HVDC	346	20.8	3.2	4
CHN-EM-CHN-LI	375	HVDC	314	18.9	2.6	4
CHN-EM-CHN-SD	697	HVDC	374	22.5	3.7	4
CHN-EM-CHN-TJ	379	HVDC	315	18.9	2.6	4
CHN-EM-CHN-WM	781	HVDC	390	23.4	4	4
CHN-EM-MNG	1132	HVDC	455	27.3	5.3	4
CHN-FU-CHN-GD	505	HVDC	338	20.3	3.1	4
CHN-FU-CHN-JX	519	HVDC	341	20.5	3.1	4
CHN-FU-CHN-ZH	677	HVDC	370	22.2	3.7	4
CHN-FU-TWN	358	Subsea - HVDC	331	19.9	2.6	4
CHN-GA-CHN-JS	1449	HVDC	514	30.9	6.4	4
CHN-GA-CHN-NI	347	HVAC	300	18	2.3	4
CHN-GA-CHN-QI	192	HVAC	201	12.1	1.3	4
CHN-GA-CHN-SC	599	HVDC	356	21.4	3.4	4
CHN-GA-CHN-SI	504	HVDC	338	20.3	3.1	4
CHN-GA-CHN-WM	733	HVDC	381	22.9	3.9	4
CHN-GA-CHN-XI	1625	HVDC	547	32.8	7	4
CHN-GA-MNG	1344	HVDC	495	29.7	6	4
CHN-GD-CHN-GX	514	HVDC	340	20.4	3.1	4
CHN-GD-CHN-HA	464	HVDC	331	19.8	2.9	4
CHN-GD-CHN-HK	128	HVAC	160	9.6	0.9	4
CHN-GD-CHN-HN	563	HVDC	349	21	3.3	4
CHN-GD-CHN-JX	666	HVDC	368	22.1	3.6	4
CHN-GD-CHN-MA	107	HVAC	147	8.8	0.7	4
CHN-GD-CHN-SC	1241	HVDC	476	28.5	5.6	4
CHN-GD-CHN-YU	1101	HVDC	449	27	5.2	4
CHN-GU-CHN-GX	448	HVDC	328	19.7	2.9	4
CHN-GU-CHN-HN	643	HVDC	364	21.9	3.6	4
CHN-GU-CHN-JS	1317	HVDC	490	29.4	5.9	4
CHN-GU-CHN-SC	523	HVDC	342	20.5	3.1	4
CHN-GU-CHN-YU	438	HVDC	326	19.6	2.8	4
CHN-GX-CHN-HN	759	HVDC	386	23.2	4	4
CHN-GX-CHN-XI	3009	HVDC	805	48.3	11.8	4
CHN-GX-CHN-YU	625	HVDC	361	21.7	3.5	4
CHN-GX-VNM	1346	HVDC	495	29.7	6	4
CHN-HB-CHN-HE	374	HVDC	314	18.8	2.6	4
CHN-HB-CHN-LI	871	HVDC	407	24.4	4.3	4
CHN-HB-CHN-SD	563	HVDC	349	21	3.3	4

CHN-HB-CHN-SX	171	HVAC	188	11.3	1.2	4
CHN-HB-CHN-TJ	265	HVAC	248	14.9	1.8	4
CHN-HB-CHN-WM	494	HVDC	336	20.2	3	4
CHN-HE-CHN-HU	468	HVDC	331	19.9	2.9	4
CHN-HE-CHN-JS	562	HVDC	349	20.9	3.3	4
CHN-HE-CHN-SD	622	HVDC	360	21.6	3.5	4
CHN-HE-CHN-SI	440	HVDC	326	19.6	2.8	4
CHN-HE-CHN-SX	361	HVAC	309	18.6	2.4	4
CHN-HE-CHN-XI	2447	HVDC	701	42	9.9	4
CHN-HJ-CHN-JI	234	HVAC	228	13.7	1.6	4
CHN-HJ-RUS-FE	509	HVDC	339	20.4	3.1	4
CHN-HJ-RUS-SI	3204	HVDC	842	50.5	12.5	4
CHN-HN-CHN-HU	293	HVAC	266	15.9	2	4
CHN-HN-CHN-JX	289	HVAC	263	15.8	2	4
CHN-HN-CHN-SC	904	HVDC	413	24.8	4.5	4
CHN-HN-CHN-SX	1077	HVDC	445	26.7	5.1	4
CHN-HU-CHN-JX	262	HVAC	246	14.8	1.8	4
CHN-HU-CHN-SI	650	HVDC	365	21.9	3.6	4
CHN-JI-CHN-LI	276	HVAC	255	15.3	1.9	4
CHN-JI-PRK	540	HVDC	345	20.7	3.2	4
CHN-JS-CHN-SD	471	HVDC	332	19.9	2.9	4
CHN-JS-CHN-SH	268	HVAC	250	15	1.8	4
CHN-JS-CHN-SI	952	HVDC	422	25.3	4.6	4
CHN-JS-CHN-SX	861	HVDC	405	24.3	4.3	4
CHN-JS-CHN-ZH	240	HVAC	232	13.9	1.6	4
CHN-JX-CHN-WM	1441	HVDC	513	30.8	6.3	4
CHN-JX-CHN-ZH	450	HVDC	328	19.7	2.9	4
CHN-LI-PRK	366	HVAC	312	18.7	2.5	4
CHN-NI-CHN-SD	1270	HVDC	481	28.9	5.7	4
CHN-NI-CHN-SI	522	HVDC	341	20.5	3.1	4
CHN-NI-CHN-WM	389	HVDC	317	19	2.7	4
CHN-NI-CHN-ZH	1566	HVDC	536	32.2	6.8	4
CHN-QI-CHN-SC	695	HVDC	374	22.4	3.7	4
CHN-QI-CHN-TI	1259	HVDC	479	28.7	5.7	4
CHN-QI-CHN-XI	1443	HVDC	513	30.8	6.4	4
CHN-SC-CHN-SI	604	HVDC	357	21.4	3.4	4
CHN-SC-CHN-TI	1251	HVDC	477	28.7	5.7	4
CHN-SC-CHN-YU	637	HVDC	363	21.8	3.5	4
CHN-SD-CHN-SX	719	HVDC	378	22.7	3.8	4
CHN-SD-CHN-TJ	436	HVDC	325	19.5	2.8	4
CHN-SD-KOR	616	Subsea - HVDC	393	23.6	3.5	4
CHN-SD-PRK	578	Subsea - HVDC	384	23	3.3	4
CHN-SH-CHN-ZH	162	HVAC	182	10.9	1.1	4
CHN-SI-CHN-SX	517	HVDC	340	20.4	3.1	4

CHN-SI-CHN-WM	714	HVDC	377	22.6	3.8	4
CHN-SX-CHN-WM	388	HVDC	316	19	2.7	4
CHN-TI-CHN-XI	1605	HVDC	543	32.6	6.9	4
CHN-TI-CHN-YU	1251	HVDC	477	28.7	5.7	4
CHN-TI-IND-NE	393	HVDC	317	19.1	2.7	4
CHN-TI-IND-NO	1350	HVDC	496	29.8	6	4
CHN-TI-MMR	1512	HVDC	526	31.6	6.6	4
CHN-TI-NPL	603	HVDC	357	21.4	3.4	4
CHN-TI-PAK	2437	HVDC	699	41.9	9.8	4
CHN-WM-MNG	840	HVDC	401	24.1	4.2	4
CHN-WM-RUS-SI	2537	HVDC	717	43.1	10.2	4
CHN-XI-IND-NO	1918	HVDC	602	36.1	8	4
CHN-XI-KAZ	860	HVDC	404	24.3	4.3	4
CHN-XI-KGZ	1055	HVDC	441	26.5	5	4
CHN-XI-MNG	1561	HVDC	535	32.1	6.8	4
CHN-XI-PAK	2813	HVDC	769	46.1	11.1	4
CHN-XI-RUS-SI	1291	HVDC	485	29.1	5.8	4
CHN-XI-TJK	1673	HVDC	556	33.4	7.2	4
CHN-YU-CHN-ZH	1814	HVDC	582	35	7.6	4
CHN-YU-LAO	790	HVDC	391	23.5	4.1	4
CHN-YU-MMR	1133	HVDC	455	27.3	5.3	4
CHN-YU-VNM	1641	HVDC	550	33	7	4
CIV-GHA	307	HVAC	275	16.5	2.1	4
CIV-GIN	1161	HVDC	461	27.7	5.4	4
CIV-LBR	756	HVDC	385	23.1	3.9	4
CIV-MLI	924	HVDC	416	25	4.5	4
CMR-COG	996	HVDC	430	25.8	4.8	4
CMR-GAB	450	HVDC	328	19.7	2.9	4
CMR-GNQ	295	HVAC	267	16	2	4
CMR-NGA	944	HVDC	420	25.2	4.6	4
CMR-TCD	996	HVDC	430	25.8	4.8	4
COD-COG	9	HVAC	84	5.1	0.1	4
COD-RWA	1658	HVDC	553	33.2	7.1	4
COD-TZA	2665	HVDC	741	44.5	10.6	4
COD-UGA	1987	HVDC	615	36.9	8.3	4
COD-ZMB	1879	HVDC	595	35.7	7.9	4
COG-GAB	828	HVDC	399	23.9	4.2	4
COG-RWA	1660	HVDC	554	33.2	7.1	4
COG-TZA	2669	HVDC	742	44.5	10.6	4
COL-ECU	998	HVDC	430	25.8	4.8	4
COL-PAN	773	HVDC	388	23.3	4	4
COL-PER	1880	HVDC	595	35.7	7.9	4
COL-VEN	1027	HVDC	436	26.2	4.9	4
CRI-NIC	343	HVAC	298	17.9	2.3	4

CRI-PAN	511	HVDC	339	20.4	3.1	4
CYP-EGY	602	Subsea - HVDC	390	23.4	3.4	4
CYP-GRC	915	Subsea - HVDC	465	27.9	4.5	4
CYP-ISR	367	Subsea - HVDC	333	20	2.6	4
CYP-LBN	243	Subsea - HVDC	303	18.2	2.2	4
CYP-SYR	327	Subsea - HVDC	323	19.4	2.4	4
CYP-TUR	762	Subsea - HVDC	428	25.7	4	4
CZE-DEU	281	HVAC	258	15.5	1.9	4
CZE-POL	515	HVDC	340	20.4	3.1	4
CZE-SVK	289	HVAC	263	15.8	2	4
DEU-DNK	355	HVAC	305	18.3	2.4	4
DEU-FRA	878	HVDC	408	24.5	4.4	4
DEU-LUX	602	HVDC	356	21.4	3.4	4
DEU-NLD	575	HVDC	351	21.1	3.3	4
DEU-NOR	838	Subsea - HVDC	447	26.8	4.2	4
DEU-POL	516	HVDC	340	20.4	3.1	4
DEU-SWE	813	Subsea - HVDC	441	26.5	4.1	4
DJI-ERI	617	HVDC	359	21.6	3.5	4
DJI-ETH	452	HVDC	328	19.7	2.9	4
DJI-SOM	1087	HVDC	447	26.8	5.1	4
DJI-YEM	433	Subsea - HVDC	349	20.9	2.8	4
DNK-GBR	955	Subsea - HVDC	475	28.5	4.6	4
DNK-NLD	621	Subsea - HVDC	394	23.7	3.5	4
DNK-NOR	483	Subsea - HVDC	361	21.7	3	4
DNK-SWE	525	Subsea - HVDC	371	22.3	3.1	4
DOM-HTI	257	HVAC	243	14.6	1.7	4
DZA-ESH	1865	HVDC	592	35.5	7.8	4
DZA-ESP	711	Subsea - HVDC	416	25	3.8	4
DZA-FRA	1347	Subsea - HVDC	570	34.2	6	4
DZA-ITA	991	Subsea - HVDC	484	29	4.8	4
DZA-LBY	1019	HVDC	434	26.1	4.9	4
DZA-MAR	1031	HVDC	436	26.2	4.9	4
DZA-MLI	2899	HVDC	785	47.1	11.4	4
DZA-MRT	2788	HVDC	764	45.9	11.1	4
DZA-NER	2587	HVDC	727	43.6	10.4	4
DZA-TUN	635	HVDC	363	21.8	3.5	4
ECU-PER	1138	HVDC	456	27.4	5.3	4
EGY-ISR	404	HVDC	319	19.2	2.7	4
EGY-JOR	494	Subsea - HVDC	364	21.8	3	4
EGY-LBY	1740	HVDC	569	34.1	7.4	4
EGY-SAU	1645	Subsea - HVDC	642	38.5	7.1	4
EGY-SDN	1613	HVDC	545	32.7	6.9	4
ERI-ETH	212	HVAC	214	12.8	1.4	4
ERI-SAU	1319	Subsea - HVDC	563	33.8	5.9	4

ERI-SDN	686	HVDC	372	22.3	3.7	4
ERI-SOM	1635	HVDC	549	33	7	4
ERI-YEM	565	Subsea - HVDC	381	22.9	3.3	4
ESH-MAR	895	HVDC	411	24.7	4.4	4
ESH-MRT	1047	HVDC	439	26.4	5	4
ESP-FRA	1054	HVDC	441	26.5	5	4
ESP-MAR	833	Subsea - HVDC	446	26.8	4.2	4
ESP-PRT	504	HVDC	338	20.3	3.1	4
EST-FIN	83	Subsea - HVDC	264	15.9	1.6	4
EST-LVA	279	HVAC	257	15.4	1.9	4
EST-RUS-NW	317	HVAC	281	16.9	2.1	4
ETH-KEN	1670	HVDC	556	33.3	7.1	4
ETH-SDN	782	HVDC	390	23.4	4	4
FIN-NOR	787	HVDC	391	23.5	4.1	4
FIN-RUS-NW	300	HVAC	270	16.2	2	4
FIN-SWE	393	HVDC	317	19.1	2.7	4
FRA-GBR	341	Subsea - HVDC	327	19.6	2.5	4
FRA-IRL	777	Subsea - HVDC	432	25.9	4	4
FRA-ITA	1107	HVDC	451	27	5.2	4
FRA-LUX	288	HVAC	262	15.8	1.9	4
GAB-GNQ	169	HVAC	186	11.2	1.1	4
GBR-IRL	463	HVDC	330	19.8	2.9	4
GBR-ISL	1891	Subsea - HVDC	702	42.1	7.9	4
GBR-NLD	358	Subsea - HVDC	331	19.9	2.6	4
GBR-NOR	1154	Subsea - HVDC	523	31.4	5.3	4
GEO-RUS-SO	733	HVDC	381	22.9	3.9	4
GEO-TUR	1316	HVDC	490	29.4	5.9	4
GHA-TGO	321	HVAC	283	17	2.2	4
GIN-GNB	334	HVAC	292	17.5	2.3	4
GIN-LBR	478	HVDC	333	20	3	4
GIN-MLI	710	HVDC	376	22.6	3.8	4
GIN-SEN	709	HVDC	376	22.6	3.8	4
GIN-SLE	128	HVAC	160	9.6	0.9	4
GMB-SEN	165	HVAC	184	11	1.1	4
GNB-SEN	376	HVDC	314	18.9	2.6	4
GRC-ITA	1052	Subsea - HVDC	499	29.9	5	4
GRC-LBY	1110	Subsea - HVDC	513	30.8	5.2	4
GRC-MKD	488	HVDC	335	20.1	3	4
GRC-TUR	570	HVDC	350	21	3.3	4
GRL-ISL	1249	Subsea - HVDC	546	32.8	5.7	4
GTM-HND	361	HVAC	309	18.6	2.4	4
GTM-MEX	1060	HVDC	442	26.5	5	4
GTM-SLV	175	HVAC	190	11.4	1.2	4
GUY-SUR	349	HVAC	301	18.1	2.4	4

GUY-VEN	1046	HVDC	439	26.4	5	4
HND-NIC	240	HVAC	232	13.9	1.6	4
HND-SLV	219	HVAC	218	13.1	1.5	4
HRV-HUN	302	HVAC	271	16.3	2	4
HRV-MNE	455	HVDC	329	19.7	2.9	4
HRV-SRB	366	HVAC	312	18.7	2.5	4
HRV-SVN	118	HVAC	154	9.2	0.8	4
HUN-ROU	640	HVDC	363	21.8	3.5	4
HUN-SRB	317	HVAC	281	16.9	2.1	4
HUN-SVK	164	HVAC	183	11	1.1	4
HUN-SVN	383	HVDC	315	18.9	2.6	4
HUN-UKR	896	HVDC	411	24.7	4.4	4
IDN-MYS	1185	Subsea - HVDC	531	31.9	5.4	4
IDN-PHL	2788	Subsea - HVDC	919	55.1	11.1	4
IDN-PNG	4459	HVDC	1076	64.6	16.9	4
IDN-SGP	894	Subsea - HVDC	460	27.6	4.4	4
IDN-TLS	2084	HVDC	633	38	8.6	4
IND-EA-IND-NE	537	HVDC	344	20.7	3.2	4
IND-EA-IND-NO	1306	HVDC	488	29.3	5.9	4
IND-EA-IND-SO	1553	HVDC	534	32	6.7	4
IND-EA-IND-WE	1653	HVDC	552	33.2	7.1	4
IND-EA-NPL	655	HVDC	366	22	3.6	4
IND-NE-MMR	1130	HVDC	455	27.3	5.3	4
IND-NO-IND-WE	1162	HVDC	461	27.7	5.4	4
IND-NO-NPL	799	HVDC	393	23.6	4.1	4
IND-NO-PAK	1100	HVDC	449	27	5.2	4
IND-SO-IND-WE	840	HVDC	401	24.1	4.2	4
IND-SO-LKA	716	Subsea - HVDC	417	25.1	3.8	4
IND-WE-PAK	888	HVDC	410	24.6	4.4	4
IRN-IRQ	694	HVDC	374	22.4	3.7	4
IRN-PAK	1913	HVDC	601	36.1	8	4
IRN-TKM	669	HVDC	369	22.1	3.6	4
IRN-TUR	2038	HVDC	624	37.5	8.4	4
IRQ-JOR	807	HVDC	395	23.7	4.1	4
IRQ-KWT	557	HVDC	348	20.9	3.2	4
IRQ-SAU	994	HVDC	429	25.8	4.8	4
IRQ-SYR	751	HVDC	384	23.1	3.9	4
IRQ-TUR	1609	HVDC	544	32.7	6.9	4
ISR-JOR	111	HVAC	149	9	0.7	4
ISR-LBN	211	HVAC	213	12.8	1.4	4
ISR-SYR	213	HVAC	214	12.9	1.4	4
ITA-MLT	689	HVDC	373	22.4	3.7	4
ITA-SVN	490	HVDC	335	20.1	3	4
ITA-TUN	600	Subsea - HVDC	389	23.4	3.4	4

JOR-SAU	1335	HVDC	493	29.6	6	4
JOR-SYR	176	HVAC	191	11.5	1.2	4
JPN-CE-JPN-KY	482	HVDC	334	20.1	3	4
JPN-CE-JPN-SH	267	HVAC	249	15	1.8	4
JPN-CE-JPN-TO	403	HVDC	319	19.2	2.7	4
JPN-CE-KOR	821	Subsea - HVDC	443	26.6	4.2	4
JPN-HO-JPN-TO	833	HVDC	399	24	4.2	4
JPN-HO-RUS-FE	765	Subsea - HVDC	429	25.8	4	4
JPN-KY-KOR	539	Subsea - HVDC	374	22.5	3.2	4
KAZ-KGZ	196	HVAC	204	12.2	1.3	4
KAZ-RUS-CE	3099	HVDC	822	49.3	12.1	4
KAZ-RUS-MV	2409	HVDC	693	41.6	9.7	4
KAZ-RUS-SI	1372	HVDC	500	30	6.1	4
KAZ-RUS-UR	1892	HVDC	597	35.8	7.9	4
KAZ-TKM	1670	HVDC	556	33.3	7.1	4
KAZ-UZB	665	HVDC	368	22.1	3.6	4
KEN-SOM	1021	HVDC	435	26.1	4.9	4
KEN-TZA	671	HVDC	369	22.2	3.6	4
KEN-UGA	503	HVDC	338	20.3	3.1	4
KGZ-TJK	685	HVDC	372	22.3	3.7	4
KGZ-UZB	470	HVDC	332	19.9	2.9	4
KHM-LAO	756	HVDC	385	23.1	3.9	4
KHM-THA	536	HVDC	344	20.7	3.2	4
KHM-VNM	212	HVAC	214	12.8	1.4	4
KOR-PRK	195	HVAC	203	12.2	1.3	4
KOS-MKD	77	HVAC	127	7.7	0.5	4
KOS-MNE	157	HVAC	179	10.7	1.1	4
KOS-SRB	246	HVAC	236	14.1	1.7	4
KWT-SAU	539	HVDC	345	20.7	3.2	4
LAO-MMR	690	HVDC	373	22.4	3.7	4
LAO-THA	519	HVDC	341	20.5	3.1	4
LAO-VNM	910	HVDC	414	24.8	4.5	4
LBN-SYR	84	HVAC	132	7.9	0.6	4
LBR-SLE	360	HVAC	308	18.5	2.4	4
LBY-MLT	356	Subsea - HVDC	330	19.8	2.5	4
LBY-NER	2429	HVDC	697	41.8	9.8	4
LBY-SDN	2739	HVDC	755	45.3	10.9	4
LBY-TCD	2318	HVDC	676	40.6	9.4	4
LBY-TUN	514	HVDC	340	20.4	3.1	4
LSO-ZAF	354	HVAC	305	18.3	2.4	4
LTU-LVA	263	HVAC	246	14.8	1.8	4
LTU-POL	393	HVDC	317	19.1	2.7	4
LTU-RUS-NW	657	HVDC	367	22	3.6	4
LTU-SWE	678	Subsea - HVDC	408	24.5	3.7	4

LVA-RUS-NW	491	HVDC	336	20.2	3	4
MAR-PRT	586	Subsea - HVDC	386	23.2	3.4	4
MDA-ROU	357	HVAC	307	18.4	2.4	4
MDA-UKR	400	HVDC	319	19.1	2.7	4
MEX-USA-AZ	2029	HVDC	623	37.4	8.4	4
MEX-USA-CA	2506	HVDC	712	42.7	10.1	4
MEX-USA-ER	1211	HVDC	470	28.2	5.5	4
MKD-SRB	323	HVAC	285	17.1	2.2	4
MLI-MRT	1047	HVDC	439	26.4	5	4
MLI-NER	1100	HVDC	449	27	5.2	4
MLI-SEN	1049	HVDC	440	26.4	5	4
MLT-TUN	401	Subsea - HVDC	341	20.5	2.7	4
MMR-THA	579	HVDC	352	21.1	3.3	4
MNE-SRB	281	HVAC	258	15.5	1.9	4
MNG-RUS-SI	1826	HVDC	585	35.1	7.7	4
MOZ-MWI	1340	HVDC	494	29.7	6	4
MOZ-SWZ	122	HVAC	156	9.4	0.8	4
MOZ-TZA	2251	HVDC	664	39.9	9.2	4
MOZ-ZAF	443	HVDC	327	19.6	2.9	4
MOZ-ZMB	1251	HVDC	477	28.7	5.7	4
MOZ-ZWE	918	HVDC	415	24.9	4.5	4
MRT-SEN	407	HVDC	320	19.2	2.7	4
MWI-TZA	999	HVDC	430	25.8	4.8	4
MWI-ZMB	613	HVDC	358	21.5	3.4	4
MYS-PHL	2467	Subsea - HVDC	841	50.5	9.9	4
MYS-THA	1184	HVDC	465	27.9	5.4	4
NAM-ZAF	1178	HVDC	464	27.8	5.4	4
NAM-ZMB	1420	HVDC	509	30.5	6.3	4
NER-NGA	799	HVDC	393	23.6	4.1	4
NER-TCD	1411	HVDC	507	30.4	6.2	4
NGA-TCD	1426	HVDC	510	30.6	6.3	4
NGA-TGO	242	HVAC	233	14	1.6	4
NLD-NOR	915	Subsea - HVDC	465	27.9	4.5	4
NOR-RUS-NW	1086	HVDC	447	26.8	5.1	4
NOR-SWE	418	HVDC	322	19.3	2.8	4
OMN-IND-WE	1562	Subsea - HVDC	622	37.3	6.8	4
OMN-IRN	1508	Subsea - HVDC	609	36.6	6.6	4
OMN-PAK	863	Subsea - HVDC	453	27.2	4.3	4
OMN-SAU	1205	HVDC	469	28.1	5.5	4
OMN-YEM	1764	HVDC	573	34.4	7.5	4
POL-SVK	533	HVDC	343	20.6	3.2	4
POL-SWE	810	Subsea - HVDC	440	26.4	4.1	4
POL-UKR	691	HVDC	373	22.4	3.7	4
PRK-RUS-FE	689	HVDC	373	22.4	3.7	4

QAT-SAU	474	HVDC	332	20	3	4
ROU-SRB	448	HVDC	328	19.7	2.9	4
ROU-UKR	745	HVDC	383	23	3.9	4
RUS-CE-RUS-MV	720	HVDC	378	22.7	3.8	4
RUS-CE-RUS-NW	634	HVDC	362	21.8	3.5	4
RUS-CE-RUS-SO	958	HVDC	423	25.4	4.7	4
RUS-CE-UKR	757	HVDC	385	23.1	3.9	4
RUS-FE-RUS-SI	3713	HVDC	937	56.2	14.3	4
RUS-MV-RUS-UR	717	HVDC	378	22.7	3.8	4
RUS-NW-RUS-UR	1781	HVDC	576	34.6	7.5	4
RUS-SI-RUS-UR	1401	HVDC	505	30.3	6.2	4
RUS-SO-UKR	760	HVDC	386	23.2	4	4
RWA-TZA	1154	HVDC	459	27.6	5.3	4
RWA-UGA	377	HVDC	314	18.9	2.6	4
SAU-YEM	1067	HVDC	443	26.6	5	4
SDN-SAU	1793	Subsea - HVDC	678	40.7	7.6	4
SDN-TCD	1926	HVDC	603	36.2	8	4
SOM-YEM	1483	Subsea - HVDC	603	36.2	6.5	4
SVK-UKR	1000	HVDC	431	25.8	4.8	4
SWZ-ZAF	337	HVAC	294	17.6	2.3	4
SYR-TUR	1063	HVDC	442	26.6	5	4
TJK-UZB	309	HVAC	276	16.6	2.1	4
TKM-UZB	1006	HVDC	432	25.9	4.8	4
TZA-UGA	1085	HVDC	446	26.8	5.1	4
TZA-ZMB	1533	HVDC	530	31.8	6.7	4
USA-AZ-USA-CA	586	HVDC	353	21.2	3.4	4
USA-AZ-USA-ER	1633	HVDC	549	32.9	7	4
USA-AZ-USA-NW	1782	HVDC	576	34.6	7.5	4
USA-AZ-USA-RA	941	HVDC	420	25.2	4.6	4
USA-AZ-USA-SS	1351	HVDC	496	29.8	6	4
USA-CA-USA-NW	1537	HVDC	531	31.9	6.7	4
USA-ER-USA-SA	527	HVDC	342	20.6	3.1	4
USA-ER-USA-SS	662	HVDC	368	22.1	3.6	4
USA-FR-USA-SE	461	HVDC	330	19.8	2.9	4
USA-ME-USA-MW	473	HVDC	332	19.9	3	4
USA-ME-USA-RW	538	HVDC	344	20.7	3.2	4
USA-MW-USA-NW	2239	HVDC	662	39.7	9.1	4
USA-MW-USA-RA	1114	HVDC	452	27.1	5.2	4
USA-MW-USA-RW	1008	HVDC	432	25.9	4.8	4
USA-MW-USA-SN	658	HVDC	367	22	3.6	4
USA-MW-USA-SW	747	HVDC	383	23	3.9	4
USA-NE-USA-NY	298	HVAC	269	16.1	2	4
USA-NW-USA-RA	1647	HVDC	551	33.1	7.1	4
USA-NY-USA-RE	128	HVAC	160	9.6	0.9	4

USA-RA-USA-SN	889	HVDC	410	24.6	4.4	4
USA-RA-USA-SS	805	HVDC	394	23.7	4.1	4
USA-RE-USA-RW	669	HVDC	369	22.1	3.6	4
USA-RE-USA-SV	732	HVDC	381	22.8	3.9	4
USA-RM-USA-RW	267	HVAC	249	15	1.8	4
USA-RW-USA-SC	539	HVDC	345	20.7	3.2	4
USA-RW-USA-SV	564	HVDC	349	21	3.3	4
USA-RW-USA-SW	642	HVDC	364	21.8	3.5	4
USA-SA-USA-SC	739	HVDC	382	22.9	3.9	4
USA-SA-USA-SE	662	HVDC	368	22.1	3.6	4
USA-SA-USA-SN	1092	HVDC	448	26.9	5.1	4
USA-SA-USA-SS	929	HVDC	417	25.1	4.6	4
USA-SA-USA-SW	953	HVDC	422	25.3	4.6	4
USA-SC-USA-SE	344	HVAC	298	17.9	2.3	4
USA-SC-USA-SV	548	HVDC	346	20.8	3.2	4
USA-SC-USA-SW	410	HVDC	321	19.2	2.7	4
USA-SE-USA-SV	366	HVAC	312	18.7	2.5	4
USA-SN-USA-SS	483	HVDC	334	20.1	3	4
USA-SN-USA-SW	377	HVDC	314	18.9	2.6	4
ZAF-ZWE	979	HVDC	427	25.6	4.7	4
ZMB-ZWE	397	HVDC	318	19.1	2.7	4

D.3.2 PLEXOS Unit Commitment and Economic Dispatch

The UCED simulations in PLEXOS-World 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 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 medium term 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 medium term schedule and PASA the UCED simulation can be applied. The detailed objective function of the UCED simulations in PLEXOS-World can be found in Appendix A. For the UCED we use MIP at hourly resolution. Optimization steps for the full year 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. Powerplants in the PLEXOS-World model are disaggregated per turbine unit to be able to incorporate technological generator characteristics relevant for (sub-)hourly power system modelling. This is done by utilizing a standard unit size methodology per fuel type as applied in previous studies [47,195,237]. Table D-3 shows an overview of some of the generator characteristics per technology as applied in PLEXOS-World for this study.

Table D-3 Sample of standardized generator characteristics and variables as applied for this study.

Fuel Type	**Standard Unit Size**	**Minimum Stable Factor**[1]	**Start Cost**	**Maintenance Rate**[2]	**Forced Outage Rate**[3]	**Mean Time to Repair**[4]
	MW	**%**	**$**	**%**	**%**	**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	-	0	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.

D.3.3 MESSAGEix-GLOBIOM integration of inter-regional trade

In previous versions of MESSAGEix-GLOBIOM, inter-regional trade of electricity occurred as any other commodity based on a global market. In essence this meant that regions had the ability to either supply to- or import electricity from the global market, without consideration of the spatial feasibility of exchange between regions. However, as part of the modelling effort in parallel to this study, the representation in MESSAGEix-GLOBIOM has been adapted to only allow for inter-regional exchange bilaterally by means of investments in transmission grid infrastructure. Input variable values for the initial setup of bilateral trade as applied in MESSAGEix-GLOBIOM can be seen in Table D-4 in the 'First Iteration' columns. The input variables for this initial setup are mostly generically applied for all inter-regional transmission pathways and without baseline transmission capacities. This has limitations from two perspectives. First, as argued in Section 5.4.6, the costs and losses for electricity transmission are dependent among others on the transmission distance which is not taken into account for inter-regional trade in the initial setup within MESSAGEix-GLOBIOM. Second, to date cross-border transmission capacities between countries in adjacent MESSAGEix regions – for example between Western Europe (WEU) and Eastern Europe (EEU) – are significant and need to be taken into account as baseline values.

The results from the 'No Storage Constraints' PLEXOS-World simulation regarding interconnector CFs for the year 2050 are used as input for a second iteration in MESSAGEix-GLOBIOM to optimize its representation of inter-regional electricity trade. Furthermore, interconnector CFs for the year 2015 as well as reference 2015 inter-regional import and export capacities are extracted from the 2015 PLEXOS-World model [231,287] and integrated as baseline for MESSAGEix-GLOBIOM. Interconnector CFs in 2050 are significantly higher compared to 2015 mostly due to its important role of balancing demand and supply in power systems with high VRES integration. Region specific investment costs and efficiencies are based on input data from the PLEXOS-World model. Per inter-regional transmission pathway, average values for costs and efficiencies are calculated based on Table D-2 weighted by the existing 2015 capacities for cross-border transmission interfaces existing between two adjacent regions (refer to Appendix C for the full global dataset of 2015 cross-border transmission capacities). If no capacity exists as of 2015 for a specific inter-regional transmission pathway, a normal average is taken based on all identified potential cross-border transmission interfaces per inter-regional transmission pathway. Operational costs are standardized based on values as used in the PLEXOS-World model.

Table D-4 Inter-regional transmission pathway specific input variables for both iterations of MESSAGEix-GLOBIOM as applied for the modelling in this study. Values for the second iteration of MESSAGEix-GLOBIOM are based on PLEXOS-World data.

Pathway	Variable	Unit	2015	2015	2050	2050
			First Itera-tion	Second Itera-tion	First Itera-tion	Second Itera-tion
AFR-MEA	Capacity Factor|Electricity|Transmission	%	55	14.4	55	62.6
CPA-FSU	Capacity Factor|Electricity|Transmission	%	55	13.8	55	61.8
CPA-PAS	Capacity Factor|Electricity|Transmission	%	55	13.8	55	51.8
CPA-SAS	Capacity Factor|Electricity|Transmission	%	55	0	55	67.5
EEU-FSU	Capacity Factor|Electricity|Transmission	%	55	14.1	55	59.1
EEU-WEU	Capacity Factor|Electricity|Transmission	%	55	12.6	55	58.5
FSU-MEA	Capacity Factor|Electricity|Transmission	%	55	14.9	55	55.4
FSU-PAO	Capacity Factor|Electricity|Transmission	%	0	0	0	61.6
FSU-SAS	Capacity Factor|Electricity|Transmission	%	55	13.2	55	56.8
FSU-WEU	Capacity Factor|Electricity|Transmission	%	55	13.9	55	61.9
LAM-NAM	Capacity Factor|Electricity|Transmission	%	55	0	55	47.6
MEA-SAS	Capacity Factor|Electricity|Transmission	%	55	15.2	55	59.2
MEA-WEU	Capacity Factor|Electricity|Transmission	%	55	12.9	55	56.8
NAM-WEU	Capacity Factor|Electricity|Transmission	%	0	0	0	0
PAO-PAS	Capacity Factor|Electricity|Transmission	%	0	0	0	61.6
PAS-SAS	Capacity Factor|Electricity|Transmission	%	55	15.8	55	60.1
AFR-MEA	Capacity|Electricity|Transmission|Export	MW	0	200	-	-
CPA-FSU	Capacity|Electricity|Transmission|Export	MW	0	1100	-	-
CPA-PAS	Capacity|Electricity|Transmission|Export	MW	0	2816	-	-
CPA-SAS	Capacity|Electricity|Transmission|Export	MW	0	0	-	-
EEU-FSU	Capacity|Electricity|Transmission|Export	MW	0	6215	-	-
EEU-WEU	Capacity|Electricity|Transmission|Export	MW	0	9558	-	-
FSU-MEA	Capacity|Electricity|Transmission|Export	MW	0	1450	-	-
FSU-PAO	Capacity|Electricity|Transmission|Export	MW	0	0	-	-
FSU-SAS	Capacity|Electricity|Transmission|Export	MW	0	900	-	-
FSU-WEU	Capacity|Electricity|Transmission|Export	MW	0	1320	-	-
LAM-NAM	Capacity|Electricity|Transmission|Export	MW	0	839	-	-
MEA-SAS	Capacity|Electricity|Transmission|Export	MW	0	130	-	-
MEA-WEU	Capacity|Electricity|Transmission|Export	MW	0	950	-	-
NAM-WEU	Capacity|Electricity|Transmission|Export	MW	0	0	-	-
PAO-PAS	Capacity|Electricity|Transmission|Export	MW	0	0	-	-
PAS-SAS	Capacity|Electricity|Transmission|Export	MW	0	3	-	-
AFR-MEA	Capacity|Electricity|Transmission|Import	MW	0	200	-	-
CPA-FSU	Capacity|Electricity|Transmission|Import	MW	0	1100	-	-
CPA-PAS	Capacity|Electricity|Transmission|Import	MW	0	2816	-	-
CPA-SAS	Capacity|Electricity|Transmission|Import	MW	0	0	-	-

EEU-FSU	Capacity|Electricity|Transmission|Import	MW	0	6635	-	-
EEU-WEU	Capacity|Electricity|Transmission|Import	MW	0	9762	-	-
FSU-MEA	Capacity|Electricity|Transmission|Import	MW	0	1450	-	-
FSU-PAO	Capacity|Electricity|Transmission|Import	MW	0	0	-	-
FSU-SAS	Capacity|Electricity|Transmission|Import	MW	0	900	-	-
FSU-WEU	Capacity|Electricity|Transmission|Import	MW	0	2300	-	-
LAM-NAM	Capacity|Electricity|Transmission|Import	MW	0	839	-	-
MEA-SAS	Capacity|Electricity|Transmission|Import	MW	0	130	-	-
MEA-WEU	Capacity|Electricity|Transmission|Import	MW	0	950	-	-
NAM-WEU	Capacity|Electricity|Transmission|Import	MW	0	0	-	-
PAO-PAS	Capacity|Electricity|Transmission|Import	MW	0	0	-	-
PAS-SAS	Capacity|Electricity|Transmission|Import	MW	0	3	-	-
AFR-MEA	Capital Cost|Electricity|Transmission	US$2010/kW	1120	390	1120	390
CPA-FSU	Capital Cost|Electricity|Transmission	US$2010/kW	1120	361	1120	361
CPA-PAS	Capital Cost|Electricity|Transmission	US$2010/kW	1120	365	1120	365
CPA-SAS	Capital Cost|Electricity|Transmission	US$2010/kW	1120	507	1120	507
EEU-FSU	Capital Cost|Electricity|Transmission	US$2010/kW	1120	324	1120	324
EEU-WEU	Capital Cost|Electricity|Transmission	US$2010/kW	1120	307	1120	307
FSU-MEA	Capital Cost|Electricity|Transmission	US$2010/kW	1120	360	1120	360
FSU-PAO	Capital Cost|Electricity|Transmission	US$2010/kW	0	429	0	429
FSU-SAS	Capital Cost|Electricity|Transmission	US$2010/kW	1120	332	1120	332
FSU-WEU	Capital Cost|Electricity|Transmission	US$2010/kW	1120	395	1120	395
LAM-NAM	Capital Cost|Electricity|Transmission	US$2010/kW	1120	587	1120	587
MEA-SAS	Capital Cost|Electricity|Transmission	US$2010/kW	1120	581	1120	581
MEA-WEU	Capital Cost|Electricity|Transmission	US$2010/kW	1120	445	1120	445
NAM-WEU	Capital Cost|Electricity|Transmission	US$2010/kW	0	1368	0	1368
PAO-PAS	Capital Cost|Electricity|Transmission	US$2010/kW	0	737	0	737
PAS-SAS	Capital Cost|Electricity|Transmission	US$2010/kW	1120	455	1120	455
AFR-MEA	Efficiency|Electricity|Transmisssion	%	86.0	96.0	89.0	96.0
CPA-FSU	Efficiency|Electricity|Transmisssion	%	87.0	96.5	90.1	96.5
CPA-PAS	Efficiency|Electricity|Transmisssion	%	87.0	96.4	90.1	96.4
CPA-SAS	Efficiency|Electricity|Transmisssion	%	87.0	93.7	90.1	93.7
EEU-FSU	Efficiency|Electricity|Transmisssion	%	85.0	97.0	90.1	97.0
EEU-WEU	Efficiency|Electricity|Transmisssion	%	85.0	97.5	90.1	97.5
FSU-MEA	Efficiency|Electricity|Transmisssion	%	80.0	96.5	90.1	96.5
FSU-PAO	Efficiency|Electricity|Transmisssion	%	0.0	96.0	0.0	96.0
FSU-SAS	Efficiency|Electricity|Transmisssion	%	80.0	96.8	90.1	96.8
FSU-WEU	Efficiency|Electricity|Transmisssion	%	80.0	95.8	90.1	95.8
LAM-NAM	Efficiency|Electricity|Transmisssion	%	85.5	92.3	90.1	92.3
MEA-SAS	Efficiency|Electricity|Transmisssion	%	83.0	92.4	88.3	92.4
MEA-WEU	Efficiency|Electricity|Transmisssion	%	83.0	95.6	88.3	95.6
NAM-WEU	Efficiency|Electricity|Transmisssion	%	0.0	82.4	0.0	82.4

PAO-PAS	Efficiency|Electricity|Transmisssion	%	0.0	91.5	0.0	91.5
PAS-SAS	Efficiency|Electricity|Transmisssion	%	90.0	94.7	90.1	94.7
AFR-MEA	OM Cost|Fixed|Electricity|Transmission	US$2010/kW/yr	0.7	2.1	0.7	2.1
CPA-FSU	OM Cost|Fixed|Electricity|Transmission	US$2010/kW/yr	0.7	2.1	0.7	2.1
CPA-PAS	OM Cost|Fixed|Electricity|Transmission	US$2010/kW/yr	0.7	2.1	0.7	2.1
CPA-SAS	OM Cost|Fixed|Electricity|Transmission	US$2010/kW/yr	0.7	2.1	0.7	2.1
EEU-FSU	OM Cost|Fixed|Electricity|Transmission	US$2010/kW/yr	0.7	2.1	0.7	2.1
EEU-WEU	OM Cost|Fixed|Electricity|Transmission	US$2010/kW/yr	0.7	2.1	0.7	2.1
FSU-MEA	OM Cost|Fixed|Electricity|Transmission	US$2010/kW/yr	0.7	2.1	0.7	2.1
FSU-PAO	OM Cost|Fixed|Electricity|Transmission	US$2010/kW/yr	0	2.1	0	2.1
FSU-SAS	OM Cost|Fixed|Electricity|Transmission	US$2010/kW/yr	0.7	2.1	0.7	2.1
FSU-WEU	OM Cost|Fixed|Electricity|Transmission	US$2010/kW/yr	0.7	2.1	0.7	2.1
LAM-NAM	OM Cost|Fixed|Electricity|Transmission	US$2010/kW/yr	0.7	2.1	0.7	2.1
MEA-SAS	OM Cost|Fixed|Electricity|Transmission	US$2010/kW/yr	0.7	2.1	0.7	2.1
MEA-WEU	OM Cost|Fixed|Electricity|Transmission	US$2010/kW/yr	0.7	2.1	0.7	2.1
NAM-WEU	OM Cost|Fixed|Electricity|Transmission	US$2010/kW/yr	0	2.1	0	2.1
PAO-PAS	OM Cost|Fixed|Electricity|Transmission	US$2010/kW/yr	0	2.1	0	2.1
PAS-SAS	OM Cost|Fixed|Electricity|Transmission	US$2010/kW/yr	0.7	2.1	0.7	2.1
AFR-MEA	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.004	0.00286	0.004
CPA-FSU	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.004	0.00286	0.004
CPA-PAS	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.004	0.00286	0.004
CPA-SAS	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.004	0.00286	0.004
EEU-FSU	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.004	0.00286	0.004
EEU-WEU	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.004	0.00286	0.004
FSU-MEA	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.004	0.00286	0.004
FSU-PAO	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00000	0.004	0.00000	0.004
FSU-SAS	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.004	0.00286	0.004
FSU-WEU	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.004	0.00286	0.004
LAM-NAM	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00000	0.004	0.00000	0.004
MEA-SAS	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00000	0.004	0.00000	0.004
MEA-WEU	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.004	0.00286	0.004
NAM-WEU	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.004	0.00286	0.004
PAO-PAS	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.004	0.00286	0.004
PAS-SAS	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.004	0.00286	0.004