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

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Section 1 Supplementary Material: Details on spatial and temporal demand downscaling

Section 2 of the main paper describes the different steps of the soft-link framework for connecting global IAMs with global power system models. This section 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[1] 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 [1]. The pyam package is used to extract scenario data from known databases such as the IAMC 1.5°C scenario explorer [2] that among others includes scenario data underpinning chapter 2 of the Special Report on Global Warming of 1.5°C by the IPCC [3].

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 [4] and the World Bank Data python package[2]. 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 (eq1*)* 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.

(eq1) $Y_{pc^h} = a + b_{GDPppp}X_{GDPppp^h} + b_{urb}X_{urb^h} + e$

For country-level projections of the independent variables as well as population projections we used the Shared Socioeconomic Pathways (SSPs) [5] and the accompanying quantifications [6–10], all retrievable through the SSP Public Database[3]. The SSPs are developed based on five different narratives that describe alternative global socio-economic developments. The choice for a specific SSP

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[1] https://github.com/iiasa/IAM-powersystemmodel-linkage
[2] https://github.com/mwouts/world_bank_data
[3] https://tntcat.iiasa.ac.at/SspDb

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 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 (eq2). An example regression is visualized in Figure S1.1 for the Latin America region.

(eq2) $Y_{pc^p} = a + b_{GDPppp}X_{GDPppp^p} + b_{urb}X_{urb^p}$

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 (eq3). 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[4].

(eq3) $Y_p = Y_{pc^p}X_{pop^p}$

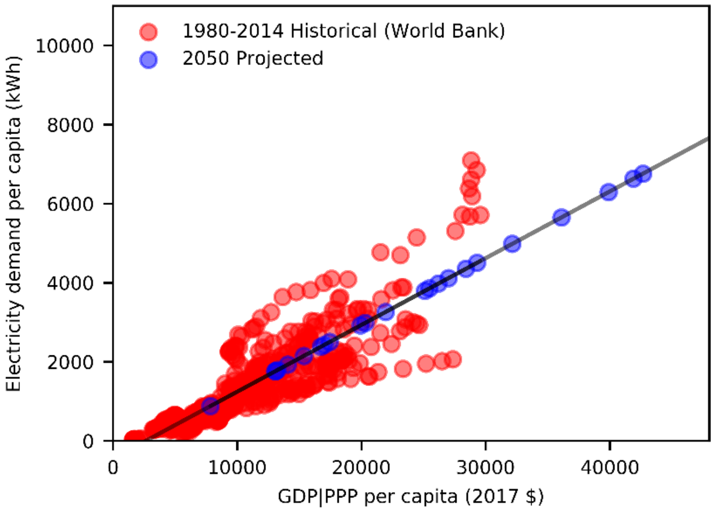
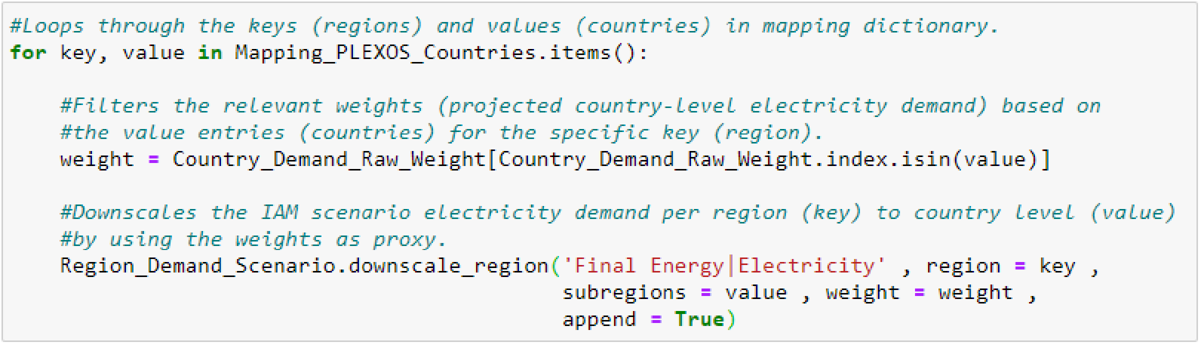


Figure S1.1: Regression example with GDPppp per capita as independent variable (2017 $) and electricity demand per capita (kWh) as dependent variable. Every red dot in the graph represents a single year value for one of the countries in the MESSAGEix-GLOBIOM_R11LAM region for the period 1980-2014. The 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 S1.2. Refer to the GitHub page[1] 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 S1.2: Snapshot of the code for electricity demand spatial downscaling by using the downscale_region function.

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

Figure S1.3 showcases an example comparison of Y_p, Y_s and 2015 country-level historical demand Y_h based on the PLEXOS-World 2015 dataset [11,12] 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 [13]. 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 [3,14].

Explicit modelling of intra-nodal transmission and distribution (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 [15] (eq4).

(eq4) $Y_f = \frac{Y_s TD_p}{100} + Y_s$

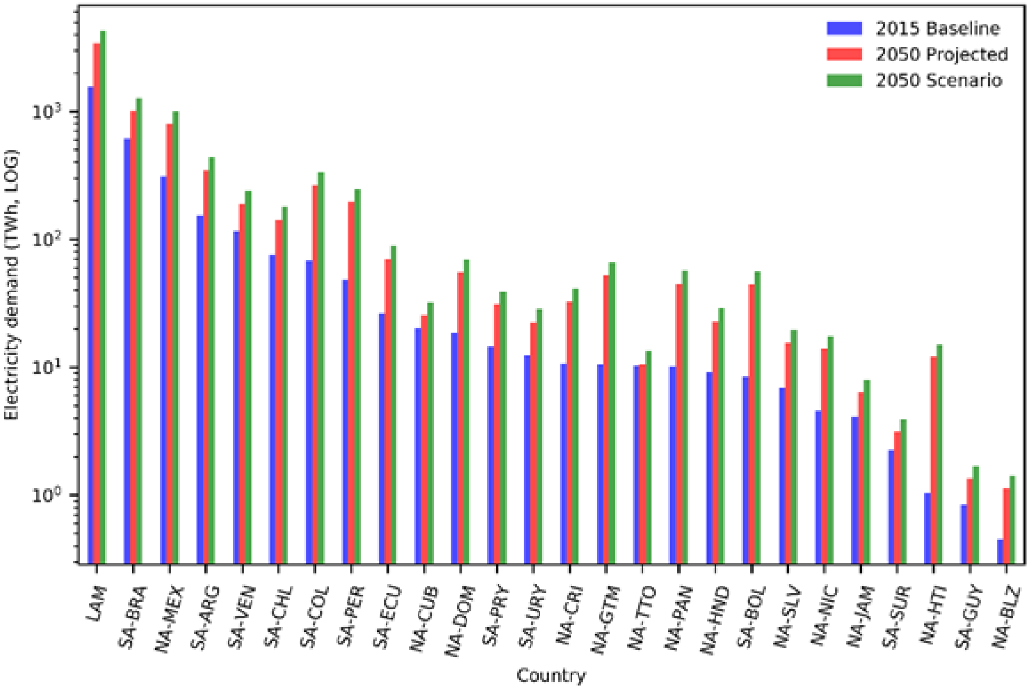

Figure S1.3: Comparison of regional- and country-level projected electricity demand $\boldsymbol{Y_p}$, the downscaled scenario demand $\boldsymbol{Y_s}$ and the 2015 historical demand $\boldsymbol{Y_h}$ for the MESSAGEix-GLOBIOM_R11 LAM region.

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 [11,12], 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 eq5.

(eq5) $Y_{f^i} = \frac{Y_{h^i}}{\sum Y_{h^i}} Y_f$

The upper part of figure S1.4 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 S1.4 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 eq6 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 S1.4.

(eq6) $Y_{fsc^i} = \frac{Y_{hsc^i}}{Y_{h^i}} Y_{f^i}$

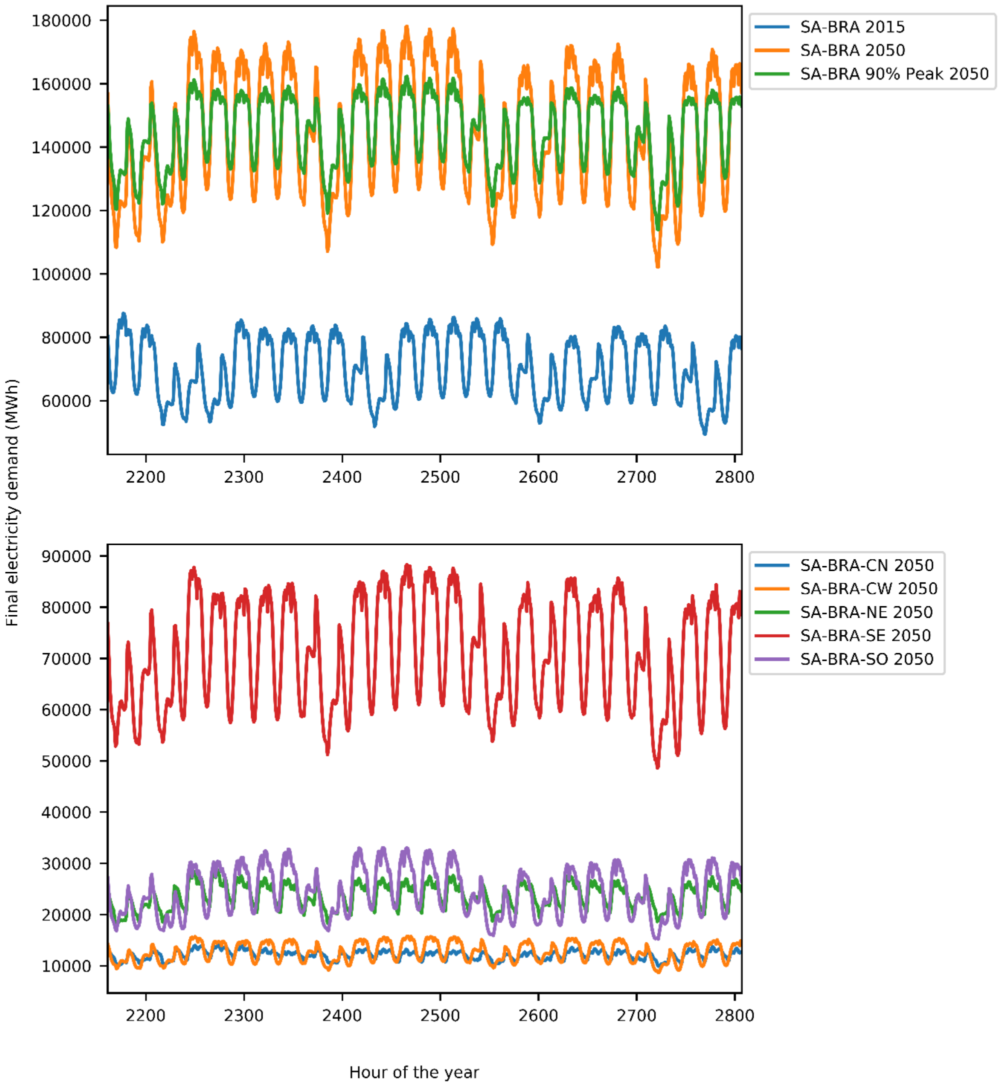

Figure S1.4: Downscaled hourly final electricity demand for South-America - Brazil (SA-BRA). The upper graph showcases the baseline 2050 hourly final demand profile, an exemplary profile with adjusted peak demand at 90% and the 2015 demand profile for reference. The lower graph shows the hourly final demand profiles of the largest sub-country nodes within Brazil (Central North (CN), Central West (CW), North East (NE), South East (SE), South (SO)).

Section 2 Supplementary Material: Details on spatial capacity downscaling

Next to the downscaled demand profiles as described in section 1 of the Supplementary Material, 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 expansion 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 [11]. 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 dynamics 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 eq7 by subtracting the region r and technology t specific capacities Cs retrieved from the IAM scenario output from the baseline powerplant capacities Cb.

(eq7) $Ex_{r}{}_{t} = C_b - C_s$

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 S2.1 shows an example of calculated expansion and retirement constraints for the period 2015-2050 for the MESSAGEix-GLOBIOM_R11LAM region.

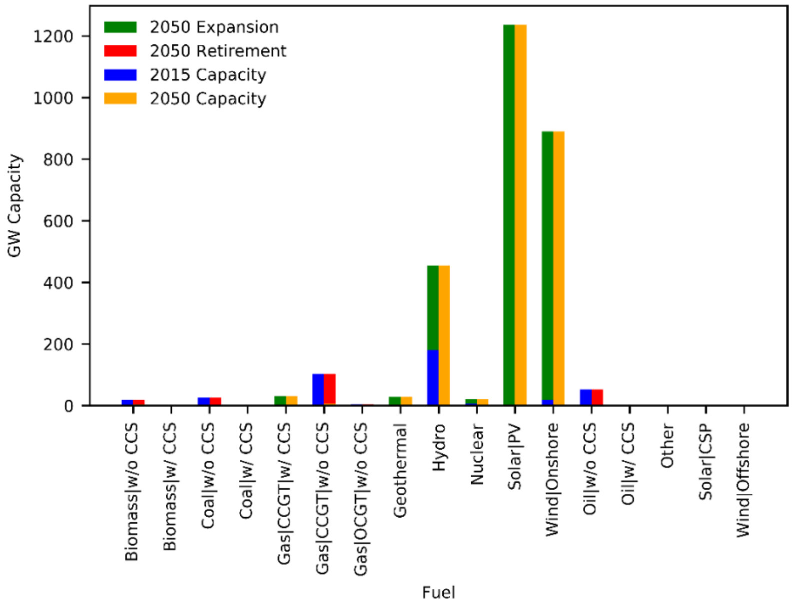

Figure S2.1: Example powerplant expansion and retirement constraints for MESSAGEix-GLOBIOM_R11LAM for the period 2015-2050. Per technology, the left bar indicates the existing baseline capacity in 2015 (blue) and the to be expanded capacity (green). The right bar indicates the required capacity in 2050 (yellow) and the to be retired capacity (red).

Section 3 Supplementary Material: PLEXOS-World and MESSAGEix-GLOBIOM scenario integration

S3.1 PLEXOS long-term capacity expansion

The PLEXOS-World model as applied for this study including all input data and timeseries can be found in [16]. There are two main simulation modules in PLEXOS relevant for this study, the long-term capacity expansion module and the short term UCED module. The objective function of the long-term module in PLEXOS is to minimize the net present value of asset build costs, plus fixed operations- and maintenance costs as well as production costs. As described in Section 2.4 of the main paper, 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 Mixed Integer Linear Programming (MILP) is used in power system expansion planning exercises but the problem size following the global spatial scale of this study merits linearization. Furthermore, whereas in UCED modelling simulations generally occur at (sub-)hourly temporal resolution, for capacity expansion a trade-off has to be made between the temporal detail and the computational complexity. A common method in planning exercises is to use LDC’s to determine the optimal generator portfolio expansion together with an approximation of required system reserves and flexibility, yet with increased variability and uncertainty following the large-scale integration of VRES it becomes critical that the chronology of demand and capacity factor profiles is being kept. Following recommendations in the literature [17,18], 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 S3.1 shows an example of different sampling combinations for demand and VRES series.

For the analysis in this paper we apply a sampling approach using 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 S3.1, generally speaking sampling for demand and solar timeseries can be reasonably accurate due to the relative predictability of diurnal cycles. Picking representative days per month results in a 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.

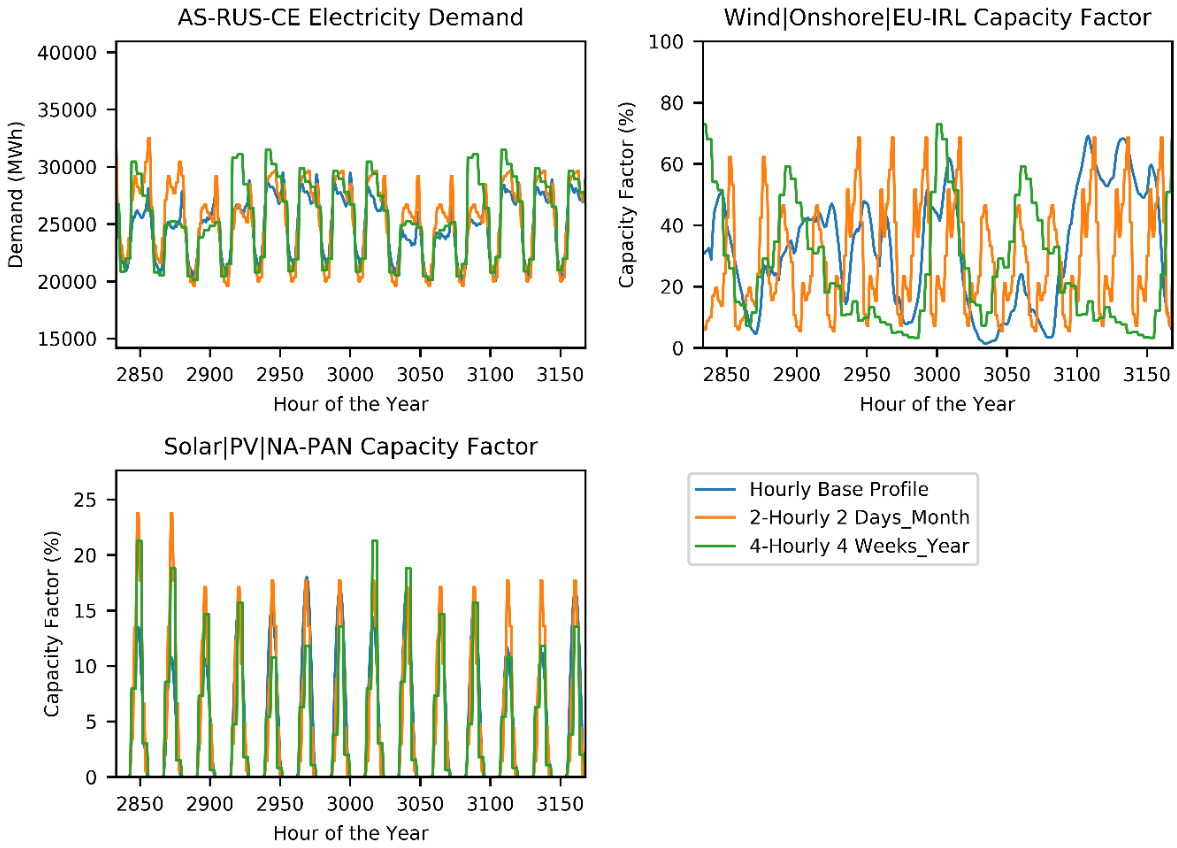

Figure S3.1: Examples of sampling combinations for a variety of demand and VRES series in Asia - Central Russia (AS-RUS-CE), Europe - Ireland (EU-IRL) and North-America - Panama (NA-PAN).

Next to the expansion- and retirement constraints and the load profiles developed based on the MESSAGEix-GLOBIOM scenario data, input data for PLEXOS based on MESSAGEix-GLOBIOM for this exercise consists of regional specific carbon- and fuel prices, generator heat rates and storage capacities- and characteristics. All data input is integrated by making use of a python script that converts and directs IAM scenario output. The expansion of storage in PLEXOS follows the representation of MESSAGEix-GLOBIOM where storage is modelled as a single generic technology with a cycle efficiency of 80%, storage capacity of 24 hours and a capital cost of \$800/kW [19]. 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. [20], 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 (eq8) that considers the radius of the earth.

$$\text{(EQ8) } ACOS(COS(RADIANS(90-Lat1)) * COS(RADIANS(90-Lat2)) + SIN(RADIANS(90-Lat1)) * SIN(RADIANS(90-Lat2)) * COS(RADIANS(Long1-Long2))) * 6371$$

Similar to powerplant capacities, baseline transmission capacities are retrieved from the PLEXOS-World dataset [11,12]. 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 [21]. An overview of the techno-economic parameters as used for the transmission capacity expansion can be seen in Table S3.1.

Table S3.1: Assumed techno-economic parameters for transmission infrastructure capacity expansion. All parameters are based on [20] with the exception of CAPEX line costs for land-based HVDC which is based on [22].

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 are generally used with High Voltage Alternating Current (HVAC) lines for shorter transmission distances and High Voltage Direct Current (HVDC) lines for longer distances. HVDC becomes only efficient at longer distances ratings 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 [23–26]. 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 S3.1, 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 [21]. 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 S3.2.

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. [27] and country-level potential for onshore- and offshore wind based on a global assessment by Eurek and colleagues [28]. 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 [29]. 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 [30] 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 transportability of biomass between regions.

Table S3.2: 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 [11,12] 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	Operational Life	Wheeling Charge
	KM		k$2010/MW	k$2010/MW/yr	%	yr	$/MW
AFG-CHN-XI	1682	HVDC	558	33.5	7.2	40	4
AFG-IRN	1664	HVDC	554	33.3	7.1	40	4
AFG-PAK	1354	HVDC	497	29.8	6	40	4
AFG-TJK	223	HVAC	221	13.3	1.5	40	4
AFG-TKM	1030	HVDC	436	26.2	4.9	40	4
AFG-UZB	507	HVDC	339	20.3	3.1	40	4
AGO-COD	551	HVDC	347	20.8	3.2	40	4
AGO-COG	557	HVDC	348	20.9	3.2	40	4
AGO-NAM	1581	HVDC	539	32.4	6.8	40	4
AGO-ZMB	1791	HVDC	578	34.7	7.6	40	4
ALB-GRC	500	HVDC	337	20.3	3.1	40	4
ALB-KOS	186	HVAC	197	11.8	1.3	40	4
ALB-MKD	154	HVAC	177	10.6	1	40	4
ALB-MNE	132	HVAC	163	9.8	0.9	40	4
ARE-IRN	1218	Subsea - HVDC	539	32.3	5.6	40	4
ARE-OMN	381	HVDC	315	18.9	2.6	40	4
ARE-SAU	860	HVDC	404	24.3	4.3	40	4
ARG-BOL	1934	HVDC	605	36.3	8.1	40	4
ARG-BRA-SO	1343	HVDC	495	29.7	6	40	4
ARG-CHL	1137	HVDC	456	27.4	5.3	40	4
ARG-PRY	1037	HVDC	438	26.3	4.9	40	4
ARG-URY	205	HVAC	209	12.6	1.4	40	4
ARM-AZE	454	HVDC	329	19.7	2.9	40	4
ARM-GEO	173	HVAC	189	11.3	1.2	40	4
ARM-IRN	786	HVDC	391	23.5	4.1	40	4
ARM-TUR	1310	HVDC	488	29.3	5.9	40	4
AUS-NT-AUS-QL	2849	HVDC	776	46.5	11.3	40	4
AUS-NT-AUS-SA	2622	HVDC	733	44	10.5	40	4
AUS-NT-AUS-WA	2658	HVDC	740	44.4	10.6	40	4
AUS-QL-AUS-SA	1603	HVDC	543	32.6	6.9	40	4
AUS-QL-AUS-SW	740	HVDC	382	22.9	3.9	40	4
AUS-QL-PNG	2092	Subsea - HVDC	750	45	8.6	40	4
AUS-SA-AUS-SW	1159	HVDC	460	27.6	5.4	40	4
AUS-SA-AUS-VI	654	HVDC	366	22	3.6	40	4
AUS-SA-AUS-WA	2133	HVDC	642	38.5	8.8	40	4
AUS-SW-AUS-VI	708	HVDC	376	22.6	3.8	40	4
AUS-TA-AUS-VI	593	Subsea - HVDC	388	23.3	3.4	40	4
AUS-WA-IDN	3016	Subsea - HVDC	974	58.5	11.9	40	4
AUS-WA-TLS	2789	Subsea - HVDC	919	55.2	11.1	40	4
AUT-CHE	591	HVDC	354	21.3	3.4	40	4
AUT-CZE	251	HVAC	239	14.3	1.7	40	4
AUT-DEU	524	HVDC	342	20.5	3.1	40	4

AUT-HUN	217	HVAC	217	13	1.5	40	4
AUT-ITA	764	HVDC	387	23.2	4	40	4
AUT-SVK	56	HVAC	114	6.9	0.4	40	4
AUT-SVN	277	HVAC	255	15.3	1.9	40	4
AZE-GEO	450	HVDC	328	19.7	2.9	40	4
AZE-IRN	543	HVDC	345	20.7	3.2	40	4
AZE-RUS-SO	1113	HVDC	452	27.1	5.2	40	4
AZE-TUR	1754	HVDC	571	34.3	7.4	40	4
BDI-COD	1562	HVDC	535	32.1	6.8	40	4
BDI-RWA	176	HVAC	191	11.5	1.2	40	4
BDI-TZA	1161	HVDC	461	27.7	5.4	40	4
BEL-DEU	652	HVDC	366	22	3.6	40	4
BEL-FRA	261	HVAC	245	14.7	1.8	40	4
BEL-GBR	319	Subsea - HVDC	321	19.3	2.4	40	4
BEL-LUX	187	HVAC	198	11.9	1.3	40	4
BEL-NLD	173	HVAC	189	11.3	1.2	40	4
BEN-BFA	693	HVDC	373	22.4	3.7	40	4
BEN-GHA	403	HVDC	319	19.2	2.7	40	4
BEN-NER	704	HVDC	375	22.5	3.8	40	4
BEN-NGA	176	HVAC	191	11.5	1.2	40	4
BEN-TGO	145	HVAC	171	10.3	1	40	4
BFA-CIV	831	HVDC	399	24	4.2	40	4
BFA-GHA	632	HVDC	362	21.7	3.5	40	4
BFA-MLI	704	HVDC	375	22.5	3.8	40	4
BFA-NER	415	HVDC	321	19.3	2.8	40	4
BFA-TGO	756	HVDC	385	23.1	3.9	40	4
BGD-IND-EA	253	HVAC	240	14.4	1.7	40	4
BGD-IND-NE	304	HVAC	273	16.4	2.1	40	4
BGD-MMR	972	HVDC	425	25.5	4.7	40	4
BGR-GRC	524	HVDC	342	20.5	3.1	40	4
BGR-MKD	172	HVAC	188	11.3	1.2	40	4
BGR-ROU	297	HVAC	268	16.1	2	40	4
BGR-SRB	330	HVAC	289	17.4	2.2	40	4
BGR-TUR	503	HVDC	338	20.3	3.1	40	4
BHR-SAU	422	HVDC	323	19.4	2.8	40	4
BIH-HRV	287	HVAC	262	15.7	1.9	40	4
BIH-MNE	172	HVAC	188	11.3	1.2	40	4
BIH-SRB	198	HVAC	205	12.3	1.3	40	4
BLR-LTU	170	HVAC	187	11.2	1.1	40	4
BLR-LVA	403	HVDC	319	19.2	2.7	40	4
BLR-POL	475	HVDC	333	20	3	40	4
BLR-RUS-CE	675	HVDC	370	22.2	3.7	40	4
BLR-RUS-NW	692	HVDC	373	22.4	3.7	40	4
BLR-UKR	435	HVDC	325	19.5	2.8	40	4

BLZ-GTM	406	HVDC	320	19.2	2.7	40	4
BLZ-MEX	1174	HVDC	463	27.8	5.4	40	4
BOL-BRA-CW	1644	HVDC	551	33.1	7.1	40	4
BOL-BRA-WE	1004	HVDC	431	25.9	4.8	40	4
BOL-CHL	1897	HVDC	598	35.9	7.9	40	4
BOL-PER	1614	HVDC	545	32.7	6.9	40	4
BOL-PRY	1018	HVDC	434	26.1	4.9	40	4
BRA-CN-BRA-CW	1595	HVDC	542	32.5	6.9	40	4
BRA-CN-BRA-J2	826	HVDC	398	23.9	4.2	40	4
BRA-CN-BRA-J3	1126	HVDC	454	27.3	5.2	40	4
BRA-CN-BRA-NE	1689	HVDC	559	33.6	7.2	40	4
BRA-CN-BRA-NW	1293	HVDC	485	29.1	5.8	40	4
BRA-CN-GUY	1413	HVDC	508	30.5	6.2	40	4
BRA-CN-SUR	1099	HVDC	449	27	5.1	40	4
BRA-CW-BRA-J2	872	HVDC	407	24.4	4.4	40	4
BRA-CW-BRA-NE	1063	HVDC	442	26.6	5	40	4
BRA-CW-BRA-NW	1933	HVDC	605	36.3	8.1	40	4
BRA-CW-BRA-SE	872	HVDC	407	24.4	4.4	40	4
BRA-CW-BRA-SO	1081	HVDC	446	26.8	5.1	40	4
BRA-CW-BRA-WE	1903	HVDC	599	36	8	40	4
BRA-CW-PRY	1463	HVDC	517	31	6.4	40	4
BRA-J1-BRA-SE	290	HVAC	264	15.8	2	40	4
BRA-J1-BRA-SO	94	HVAC	138	8.3	0.6	40	4
BRA-J2-BRA-J3	1380	HVDC	501	30.1	6.1	40	4
BRA-J2-BRA-NE	932	HVDC	418	25.1	4.6	40	4
BRA-J3-BRA-NW	371	HVDC	313	18.8	2.6	40	4
BRA-J3-BRA-SE	2326	HVDC	678	40.7	9.4	40	4
BRA-NE-BRA-SE	1455	HVDC	515	30.9	6.4	40	4
BRA-NW-BRA-WE	762	HVDC	386	23.2	4	40	4
BRA-NW-COL	1783	HVDC	577	34.6	7.5	40	4
BRA-NW-GUF	1235	HVDC	474	28.5	5.6	40	4
BRA-NW-GUY	1120	HVDC	453	27.2	5.2	40	4
BRA-NW-PER	2125	HVDC	640	38.4	8.7	40	4
BRA-NW-SUR	1129	HVDC	455	27.3	5.3	40	4
BRA-NW-VEN	1695	HVDC	560	33.6	7.2	40	4
BRA-SE-BRA-SO	344	HVAC	298	17.9	2.3	40	4
BRA-SO-PRY	836	HVDC	400	24	4.2	40	4
BRA-SO-URY	1238	HVDC	475	28.5	5.6	40	4
BRA-WE-PER	1484	HVDC	521	31.3	6.5	40	4
BRN-MYS	1480	HVDC	520	31.2	6.5	40	4
BTN-CHN-TI	281	HVAC	258	15.5	1.9	40	4
BTN-IND-EA	569	HVDC	350	21	3.3	40	4
BWA-NAM	928	HVDC	417	25	4.5	40	4
BWA-ZAF	272	HVAC	252	15.1	1.8	40	4

BWA-ZMB	1056	HVDC	441	26.5	5	40	4
BWA-ZWE	927	HVDC	417	25	4.5	40	4
CAF-CMR	783	HVDC	390	23.4	4	40	4
CAF-COD	1032	HVDC	437	26.2	4.9	40	4
CAF-COG	1026	HVDC	435	26.1	4.9	40	4
CAF-SDN	1973	HVDC	612	36.7	8.2	40	4
CAF-TCD	944	HVDC	420	25.2	4.6	40	4
CAN-AB-CAN-BC	674	HVDC	370	22.2	3.7	40	4
CAN-AB-CAN-NO	1263	HVDC	480	28.8	5.7	40	4
CAN-AB-CAN-SK	525	HVDC	342	20.5	3.1	40	4
CAN-AB-USA-NW	710	HVDC	376	22.6	3.8	40	4
CAN-AR-CAN-QC	789	HVDC	391	23.5	4.1	40	4
CAN-AR-USA-NE	657	HVDC	367	22	3.6	40	4
CAN-BC-CAN-NO	1559	HVDC	535	32.1	6.8	40	4
CAN-BC-USA-AK	2088	HVDC	634	38	8.6	40	4
CAN-BC-USA-NW	193	HVAC	202	12.1	1.3	40	4
CAN-MB-CAN-NO	1746	HVDC	570	34.2	7.4	40	4
CAN-MB-CAN-ON	1511	HVDC	526	31.6	6.6	40	4
CAN-MB-CAN-SK	711	HVDC	377	22.6	3.8	40	4
CAN-MB-USA-MW	620	HVDC	360	21.6	3.5	40	4
CAN-NL-CAN-QC	1608	HVDC	544	32.7	6.9	40	4
CAN-NL-GRL	1505	Subsea - HVDC	608	36.5	6.6	40	4
CAN-NO-CAN-SK	1231	HVDC	474	28.4	5.6	40	4
CAN-NO-USA-AK	1808	HVDC	581	34.9	7.6	40	4
CAN-ON-CAN-QC	503	HVDC	338	20.3	3.1	40	4
CAN-ON-USA-MW	1109	HVDC	451	27.1	5.2	40	4
CAN-ON-USA-NY	562	HVDC	349	20.9	3.3	40	4
CAN-ON-USA-RM	333	HVAC	291	17.5	2.2	40	4
CAN-QC-USA-NE	406	HVDC	320	19.2	2.7	40	4
CAN-QC-USA-NY	535	HVDC	344	20.6	3.2	40	4
CAN-SK-USA-MW	1267	HVDC	480	28.8	5.7	40	4
CAN-SK-USA-NW	1227	HVDC	473	28.4	5.6	40	4
CHE-DEU	669	HVDC	369	22.1	3.6	40	4
CHE-FRA	490	HVDC	335	20.1	3	40	4
CHE-ITA	684	HVDC	372	22.3	3.7	40	4
CHL-PER	2467	HVDC	704	42.3	9.9	40	4
CHN-AN-CHN-HB	735	HVDC	381	22.9	3.9	40	4
CHN-AN-CHN-HE	466	HVDC	331	19.9	2.9	40	4
CHN-AN-CHN-HU	319	HVAC	282	16.9	2.2	40	4
CHN-AN-CHN-JS	143	HVAC	170	10.2	1	40	4
CHN-AN-CHN-JX	377	HVDC	314	18.9	2.6	40	4
CHN-AN-CHN-SD	549	HVDC	346	20.8	3.2	40	4
CHN-AN-CHN-ZH	328	HVAC	288	17.3	2.2	40	4
CHN-BE-CHN-EM	337	HVAC	294	17.6	2.3	40	4

CHN-BE-CHN-HB	266	HVAC	248	14.9	1.8	40	4
CHN-BE-CHN-TJ	113	HVAC	151	9	0.8	40	4
CHN-CH-CHN-GU	332	HVAC	291	17.4	2.2	40	4
CHN-CH-CHN-HB	1191	HVDC	466	28	5.5	40	4
CHN-CH-CHN-HN	639	HVDC	363	21.8	3.5	40	4
CHN-CH-CHN-HU	747	HVDC	383	23	3.9	40	4
CHN-CH-CHN-SC	272	HVAC	252	15.1	1.8	40	4
CHN-CH-CHN-SI	567	HVDC	350	21	3.3	40	4
CHN-CH-CHN-SX	1075	HVDC	445	26.7	5.1	40	4
CHN-EM-CHN-HB	604	HVDC	357	21.4	3.4	40	4
CHN-EM-CHN-HJ	727	HVDC	380	22.8	3.8	40	4
CHN-EM-CHN-JI	548	HVDC	346	20.8	3.2	40	4
CHN-EM-CHN-LI	375	HVDC	314	18.9	2.6	40	4
CHN-EM-CHN-SD	697	HVDC	374	22.5	3.7	40	4
CHN-EM-CHN-TJ	379	HVDC	315	18.9	2.6	40	4
CHN-EM-CHN-WM	781	HVDC	390	23.4	4	40	4
CHN-EM-MNG	1132	HVDC	455	27.3	5.3	40	4
CHN-FU-CHN-GD	505	HVDC	338	20.3	3.1	40	4
CHN-FU-CHN-JX	519	HVDC	341	20.5	3.1	40	4
CHN-FU-CHN-ZH	677	HVDC	370	22.2	3.7	40	4
CHN-FU-TWN	358	Subsea - HVDC	331	19.9	2.6	40	4
CHN-GA-CHN-JS	1449	HVDC	514	30.9	6.4	40	4
CHN-GA-CHN-NI	347	HVAC	300	18	2.3	40	4
CHN-GA-CHN-QI	192	HVAC	201	12.1	1.3	40	4
CHN-GA-CHN-SC	599	HVDC	356	21.4	3.4	40	4
CHN-GA-CHN-SI	504	HVDC	338	20.3	3.1	40	4
CHN-GA-CHN-WM	733	HVDC	381	22.9	3.9	40	4
CHN-GA-CHN-XI	1625	HVDC	547	32.8	7	40	4
CHN-GA-MNG	1344	HVDC	495	29.7	6	40	4
CHN-GD-CHN-GX	514	HVDC	340	20.4	3.1	40	4
CHN-GD-CHN-HA	464	HVDC	331	19.8	2.9	40	4
CHN-GD-CHN-HK	128	HVAC	160	9.6	0.9	40	4
CHN-GD-CHN-HN	563	HVDC	349	21	3.3	40	4
CHN-GD-CHN-JX	666	HVDC	368	22.1	3.6	40	4
CHN-GD-CHN-MA	107	HVAC	147	8.8	0.7	40	4
CHN-GD-CHN-SC	1241	HVDC	476	28.5	5.6	40	4
CHN-GD-CHN-YU	1101	HVDC	449	27	5.2	40	4
CHN-GU-CHN-GX	448	HVDC	328	19.7	2.9	40	4
CHN-GU-CHN-HN	643	HVDC	364	21.9	3.6	40	4
CHN-GU-CHN-JS	1317	HVDC	490	29.4	5.9	40	4
CHN-GU-CHN-SC	523	HVDC	342	20.5	3.1	40	4
CHN-GU-CHN-YU	438	HVDC	326	19.6	2.8	40	4
CHN-GX-CHN-HN	759	HVDC	386	23.2	4	40	4
CHN-GX-CHN-XI	3009	HVDC	805	48.3	11.8	40	4

CHN-GX-CHN-YU	625	HVDC	361	21.7	3.5	40	4
CHN-GX-VNM	1346	HVDC	495	29.7	6	40	4
CHN-HB-CHN-HE	374	HVDC	314	18.8	2.6	40	4
CHN-HB-CHN-LI	871	HVDC	407	24.4	4.3	40	4
CHN-HB-CHN-SD	563	HVDC	349	21	3.3	40	4
CHN-HB-CHN-SX	171	HVAC	188	11.3	1.2	40	4
CHN-HB-CHN-TJ	265	HVAC	248	14.9	1.8	40	4
CHN-HB-CHN-WM	494	HVDC	336	20.2	3	40	4
CHN-HE-CHN-HU	468	HVDC	331	19.9	2.9	40	4
CHN-HE-CHN-JS	562	HVDC	349	20.9	3.3	40	4
CHN-HE-CHN-SD	622	HVDC	360	21.6	3.5	40	4
CHN-HE-CHN-SI	440	HVDC	326	19.6	2.8	40	4
CHN-HE-CHN-SX	361	HVAC	309	18.6	2.4	40	4
CHN-HE-CHN-XI	2447	HVDC	701	42	9.9	40	4
CHN-HJ-CHN-JI	234	HVAC	228	13.7	1.6	40	4
CHN-HJ-RUS-FE	509	HVDC	339	20.4	3.1	40	4
CHN-HJ-RUS-SI	3204	HVDC	842	50.5	12.5	40	4
CHN-HN-CHN-HU	293	HVAC	266	15.9	2	40	4
CHN-HN-CHN-JX	289	HVAC	263	15.8	2	40	4
CHN-HN-CHN-SC	904	HVDC	413	24.8	4.5	40	4
CHN-HN-CHN-SX	1077	HVDC	445	26.7	5.1	40	4
CHN-HU-CHN-JX	262	HVAC	246	14.8	1.8	40	4
CHN-HU-CHN-SI	650	HVDC	365	21.9	3.6	40	4
CHN-JI-CHN-LI	276	HVAC	255	15.3	1.9	40	4
CHN-JI-PRK	540	HVDC	345	20.7	3.2	40	4
CHN-JS-CHN-SD	471	HVDC	332	19.9	2.9	40	4
CHN-JS-CHN-SH	268	HVAC	250	15	1.8	40	4
CHN-JS-CHN-SI	952	HVDC	422	25.3	4.6	40	4
CHN-JS-CHN-SX	861	HVDC	405	24.3	4.3	40	4
CHN-JS-CHN-ZH	240	HVAC	232	13.9	1.6	40	4
CHN-JX-CHN-WM	1441	HVDC	513	30.8	6.3	40	4
CHN-JX-CHN-ZH	450	HVDC	328	19.7	2.9	40	4
CHN-LI-PRK	366	HVAC	312	18.7	2.5	40	4
CHN-NI-CHN-SD	1270	HVDC	481	28.9	5.7	40	4
CHN-NI-CHN-SI	522	HVDC	341	20.5	3.1	40	4
CHN-NI-CHN-WM	389	HVDC	317	19	2.7	40	4
CHN-NI-CHN-ZH	1566	HVDC	536	32.2	6.8	40	4
CHN-QI-CHN-SC	695	HVDC	374	22.4	3.7	40	4
CHN-QI-CHN-TI	1259	HVDC	479	28.7	5.7	40	4
CHN-QI-CHN-XI	1443	HVDC	513	30.8	6.4	40	4
CHN-SC-CHN-SI	604	HVDC	357	21.4	3.4	40	4
CHN-SC-CHN-TI	1251	HVDC	477	28.7	5.7	40	4
CHN-SC-CHN-YU	637	HVDC	363	21.8	3.5	40	4
CHN-SD-CHN-SX	719	HVDC	378	22.7	3.8	40	4

CHN-SD-CHN-TJ	436	HVDC	325	19.5	2.8	40	4
CHN-SD-KOR	616	Subsea - HVDC	393	23.6	3.5	40	4
CHN-SD-PRK	578	Subsea - HVDC	384	23	3.3	40	4
CHN-SH-CHN-ZH	162	HVAC	182	10.9	1.1	40	4
CHN-SI-CHN-SX	517	HVDC	340	20.4	3.1	40	4
CHN-SI-CHN-WM	714	HVDC	377	22.6	3.8	40	4
CHN-SX-CHN-WM	388	HVDC	316	19	2.7	40	4
CHN-TI-CHN-XI	1605	HVDC	543	32.6	6.9	40	4
CHN-TI-CHN-YU	1251	HVDC	477	28.7	5.7	40	4
CHN-TI-IND-NE	393	HVDC	317	19.1	2.7	40	4
CHN-TI-IND-NO	1350	HVDC	496	29.8	6	40	4
CHN-TI-MMR	1512	HVDC	526	31.6	6.6	40	4
CHN-TI-NPL	603	HVDC	357	21.4	3.4	40	4
CHN-TI-PAK	2437	HVDC	699	41.9	9.8	40	4
CHN-WM-MNG	840	HVDC	401	24.1	4.2	40	4
CHN-WM-RUS-SI	2537	HVDC	717	43.1	10.2	40	4
CHN-XI-IND-NO	1918	HVDC	602	36.1	8	40	4
CHN-XI-KAZ	860	HVDC	404	24.3	4.3	40	4
CHN-XI-KGZ	1055	HVDC	441	26.5	5	40	4
CHN-XI-MNG	1561	HVDC	535	32.1	6.8	40	4
CHN-XI-PAK	2813	HVDC	769	46.1	11.1	40	4
CHN-XI-RUS-SI	1291	HVDC	485	29.1	5.8	40	4
CHN-XI-TJK	1673	HVDC	556	33.4	7.2	40	4
CHN-YU-CHN-ZH	1814	HVDC	582	35	7.6	40	4
CHN-YU-LAO	790	HVDC	391	23.5	4.1	40	4
CHN-YU-MMR	1133	HVDC	455	27.3	5.3	40	4
CHN-YU-VNM	1641	HVDC	550	33	7	40	4
CIV-GHA	307	HVAC	275	16.5	2.1	40	4
CIV-GIN	1161	HVDC	461	27.7	5.4	40	4
CIV-LBR	756	HVDC	385	23.1	3.9	40	4
CIV-MLI	924	HVDC	416	25	4.5	40	4
CMR-COG	996	HVDC	430	25.8	4.8	40	4
CMR-GAB	450	HVDC	328	19.7	2.9	40	4
CMR-GNQ	295	HVAC	267	16	2	40	4
CMR-NGA	944	HVDC	420	25.2	4.6	40	4
CMR-TCD	996	HVDC	430	25.8	4.8	40	4
COD-COG	9	HVAC	84	5.1	0.1	40	4
COD-RWA	1658	HVDC	553	33.2	7.1	40	4
COD-TZA	2665	HVDC	741	44.5	10.6	40	4
COD-UGA	1987	HVDC	615	36.9	8.3	40	4
COD-ZMB	1879	HVDC	595	35.7	7.9	40	4
COG-GAB	828	HVDC	399	23.9	4.2	40	4
COG-RWA	1660	HVDC	554	33.2	7.1	40	4
COG-TZA	2669	HVDC	742	44.5	10.6	40	4

COL-ECU	998	HVDC	430	25.8	4.8	40	4
COL-PAN	773	HVDC	388	23.3	4	40	4
COL-PER	1880	HVDC	595	35.7	7.9	40	4
COL-VEN	1027	HVDC	436	26.2	4.9	40	4
CRI-NIC	343	HVAC	298	17.9	2.3	40	4
CRI-PAN	511	HVDC	339	20.4	3.1	40	4
CYP-EGY	602	Subsea - HVDC	390	23.4	3.4	40	4
CYP-GRC	915	Subsea - HVDC	465	27.9	4.5	40	4
CYP-ISR	367	Subsea - HVDC	333	20	2.6	40	4
CYP-LBN	243	Subsea - HVDC	303	18.2	2.2	40	4
CYP-SYR	327	Subsea - HVDC	323	19.4	2.4	40	4
CYP-TUR	762	Subsea - HVDC	428	25.7	4	40	4
CZE-DEU	281	HVAC	258	15.5	1.9	40	4
CZE-POL	515	HVDC	340	20.4	3.1	40	4
CZE-SVK	289	HVAC	263	15.8	2	40	4
DEU-DNK	355	HVAC	305	18.3	2.4	40	4
DEU-FRA	878	HVDC	408	24.5	4.4	40	4
DEU-LUX	602	HVDC	356	21.4	3.4	40	4
DEU-NLD	575	HVDC	351	21.1	3.3	40	4
DEU-NOR	838	Subsea - HVDC	447	26.8	4.2	40	4
DEU-POL	516	HVDC	340	20.4	3.1	40	4
DEU-SWE	813	Subsea - HVDC	441	26.5	4.1	40	4
DJI-ERI	617	HVDC	359	21.6	3.5	40	4
DJI-ETH	452	HVDC	328	19.7	2.9	40	4
DJI-SOM	1087	HVDC	447	26.8	5.1	40	4
DJI-YEM	433	Subsea - HVDC	349	20.9	2.8	40	4
DNK-GBR	955	Subsea - HVDC	475	28.5	4.6	40	4
DNK-NLD	621	Subsea - HVDC	394	23.7	3.5	40	4
DNK-NOR	483	Subsea - HVDC	361	21.7	3	40	4
DNK-SWE	525	Subsea - HVDC	371	22.3	3.1	40	4
DOM-HTI	257	HVAC	243	14.6	1.7	40	4
DZA-ESH	1865	HVDC	592	35.5	7.8	40	4
DZA-ESP	711	Subsea - HVDC	416	25	3.8	40	4
DZA-FRA	1347	Subsea - HVDC	570	34.2	6	40	4
DZA-ITA	991	Subsea - HVDC	484	29	4.8	40	4
DZA-LBY	1019	HVDC	434	26.1	4.9	40	4
DZA-MAR	1031	HVDC	436	26.2	4.9	40	4
DZA-MLI	2899	HVDC	785	47.1	11.4	40	4
DZA-MRT	2788	HVDC	764	45.9	11.1	40	4
DZA-NER	2587	HVDC	727	43.6	10.4	40	4
DZA-TUN	635	HVDC	363	21.8	3.5	40	4
ECU-PER	1138	HVDC	456	27.4	5.3	40	4
EGY-ISR	404	HVDC	319	19.2	2.7	40	4
EGY-JOR	494	Subsea - HVDC	364	21.8	3	40	4

EGY-LBY	1740	HVDC	569	34.1	7.4	40	4
EGY-SAU	1645	Subsea - HVDC	642	38.5	7.1	40	4
EGY-SDN	1613	HVDC	545	32.7	6.9	40	4
ERI-ETH	212	HVAC	214	12.8	1.4	40	4
ERI-SAU	1319	Subsea - HVDC	563	33.8	5.9	40	4
ERI-SDN	686	HVDC	372	22.3	3.7	40	4
ERI-SOM	1635	HVDC	549	33	7	40	4
ERI-YEM	565	Subsea - HVDC	381	22.9	3.3	40	4
ESH-MAR	895	HVDC	411	24.7	4.4	40	4
ESH-MRT	1047	HVDC	439	26.4	5	40	4
ESP-FRA	1054	HVDC	441	26.5	5	40	4
ESP-MAR	833	Subsea - HVDC	446	26.8	4.2	40	4
ESP-PRT	504	HVDC	338	20.3	3.1	40	4
EST-FIN	83	Subsea - HVDC	264	15.9	1.6	40	4
EST-LVA	279	HVAC	257	15.4	1.9	40	4
EST-RUS-NW	317	HVAC	281	16.9	2.1	40	4
ETH-KEN	1670	HVDC	556	33.3	7.1	40	4
ETH-SDN	782	HVDC	390	23.4	4	40	4
FIN-NOR	787	HVDC	391	23.5	4.1	40	4
FIN-RUS-NW	300	HVAC	270	16.2	2	40	4
FIN-SWE	393	HVDC	317	19.1	2.7	40	4
FRA-GBR	341	Subsea - HVDC	327	19.6	2.5	40	4
FRA-IRL	777	Subsea - HVDC	432	25.9	4	40	4
FRA-ITA	1107	HVDC	451	27	5.2	40	4
FRA-LUX	288	HVAC	262	15.8	1.9	40	4
GAB-GNQ	169	HVAC	186	11.2	1.1	40	4
GBR-IRL	463	HVDC	330	19.8	2.9	40	4
GBR-ISL	1891	Subsea - HVDC	702	42.1	7.9	40	4
GBR-NLD	358	Subsea - HVDC	331	19.9	2.6	40	4
GBR-NOR	1154	Subsea - HVDC	523	31.4	5.3	40	4
GEO-RUS-SO	733	HVDC	381	22.9	3.9	40	4
GEO-TUR	1316	HVDC	490	29.4	5.9	40	4
GHA-TGO	321	HVAC	283	17	2.2	40	4
GIN-GNB	334	HVAC	292	17.5	2.3	40	4
GIN-LBR	478	HVDC	333	20	3	40	4
GIN-MLI	710	HVDC	376	22.6	3.8	40	4
GIN-SEN	709	HVDC	376	22.6	3.8	40	4
GIN-SLE	128	HVAC	160	9.6	0.9	40	4
GMB-SEN	165	HVAC	184	11	1.1	40	4
GNB-SEN	376	HVDC	314	18.9	2.6	40	4
GRC-ITA	1052	Subsea - HVDC	499	29.9	5	40	4
GRC-LBY	1110	Subsea - HVDC	513	30.8	5.2	40	4
GRC-MKD	488	HVDC	335	20.1	3	40	4
GRC-TUR	570	HVDC	350	21	3.3	40	4

GRL-ISL	1249	Subsea - HVDC	546	32.8	5.7	40	4
GTM-HND	361	HVAC	309	18.6	2.4	40	4
GTM-MEX	1060	HVDC	442	26.5	5	40	4
GTM-SLV	175	HVAC	190	11.4	1.2	40	4
GUY-SUR	349	HVAC	301	18.1	2.4	40	4
GUY-VEN	1046	HVDC	439	26.4	5	40	4
HND-NIC	240	HVAC	232	13.9	1.6	40	4
HND-SLV	219	HVAC	218	13.1	1.5	40	4
HRV-HUN	302	HVAC	271	16.3	2	40	4
HRV-MNE	455	HVDC	329	19.7	2.9	40	4
HRV-SRB	366	HVAC	312	18.7	2.5	40	4
HRV-SVN	118	HVAC	154	9.2	0.8	40	4
HUN-ROU	640	HVDC	363	21.8	3.5	40	4
HUN-SRB	317	HVAC	281	16.9	2.1	40	4
HUN-SVK	164	HVAC	183	11	1.1	40	4
HUN-SVN	383	HVDC	315	18.9	2.6	40	4
HUN-UKR	896	HVDC	411	24.7	4.4	40	4
IDN-MYS	1185	Subsea - HVDC	531	31.9	5.4	40	4
IDN-PHL	2788	Subsea - HVDC	919	55.1	11.1	40	4
IDN-PNG	4459	HVDC	1076	64.6	16.9	40	4
IDN-SGP	894	Subsea - HVDC	460	27.6	4.4	40	4
IDN-TLS	2084	HVDC	633	38	8.6	40	4
IND-EA-IND-NE	537	HVDC	344	20.7	3.2	40	4
IND-EA-IND-NO	1306	HVDC	488	29.3	5.9	40	4
IND-EA-IND-SO	1553	HVDC	534	32	6.7	40	4
IND-EA-IND-WE	1653	HVDC	552	33.2	7.1	40	4
IND-EA-NPL	655	HVDC	366	22	3.6	40	4
IND-NE-MMR	1130	HVDC	455	27.3	5.3	40	4
IND-NO-IND-WE	1162	HVDC	461	27.7	5.4	40	4
IND-NO-NPL	799	HVDC	393	23.6	4.1	40	4
IND-NO-PAK	1100	HVDC	449	27	5.2	40	4
IND-SO-IND-WE	840	HVDC	401	24.1	4.2	40	4
IND-SO-LKA	716	Subsea - HVDC	417	25.1	3.8	40	4
IND-WE-PAK	888	HVDC	410	24.6	4.4	40	4
IRN-IRQ	694	HVDC	374	22.4	3.7	40	4
IRN-PAK	1913	HVDC	601	36.1	8	40	4
IRN-TKM	669	HVDC	369	22.1	3.6	40	4
IRN-TUR	2038	HVDC	624	37.5	8.4	40	4
IRQ-JOR	807	HVDC	395	23.7	4.1	40	4
IRQ-KWT	557	HVDC	348	20.9	3.2	40	4
IRQ-SAU	994	HVDC	429	25.8	4.8	40	4
IRQ-SYR	751	HVDC	384	23.1	3.9	40	4
IRQ-TUR	1609	HVDC	544	32.7	6.9	40	4
ISR-JOR	111	HVAC	149	9	0.7	40	4

ISR-LBN	211	HVAC	213	12.8	1.4	40	4
ISR-SYR	213	HVAC	214	12.9	1.4	40	4
ITA-MLT	689	HVDC	373	22.4	3.7	40	4
ITA-SVN	490	HVDC	335	20.1	3	40	4
ITA-TUN	600	Subsea - HVDC	389	23.4	3.4	40	4
JOR-SAU	1335	HVDC	493	29.6	6	40	4
JOR-SYR	176	HVAC	191	11.5	1.2	40	4
JPN-CE-JPN-KY	482	HVDC	334	20.1	3	40	4
JPN-CE-JPN-SH	267	HVAC	249	15	1.8	40	4
JPN-CE-JPN-TO	403	HVDC	319	19.2	2.7	40	4
JPN-CE-KOR	821	Subsea - HVDC	443	26.6	4.2	40	4
JPN-HO-JPN-TO	833	HVDC	399	24	4.2	40	4
JPN-HO-RUS-FE	765	Subsea - HVDC	429	25.8	4	40	4
JPN-KY-KOR	539	Subsea - HVDC	374	22.5	3.2	40	4
KAZ-KGZ	196	HVAC	204	12.2	1.3	40	4
KAZ-RUS-CE	3099	HVDC	822	49.3	12.1	40	4
KAZ-RUS-MV	2409	HVDC	693	41.6	9.7	40	4
KAZ-RUS-SI	1372	HVDC	500	30	6.1	40	4
KAZ-RUS-UR	1892	HVDC	597	35.8	7.9	40	4
KAZ-TKM	1670	HVDC	556	33.3	7.1	40	4
KAZ-UZB	665	HVDC	368	22.1	3.6	40	4
KEN-SOM	1021	HVDC	435	26.1	4.9	40	4
KEN-TZA	671	HVDC	369	22.2	3.6	40	4
KEN-UGA	503	HVDC	338	20.3	3.1	40	4
KGZ-TJK	685	HVDC	372	22.3	3.7	40	4
KGZ-UZB	470	HVDC	332	19.9	2.9	40	4
KHM-LAO	756	HVDC	385	23.1	3.9	40	4
KHM-THA	536	HVDC	344	20.7	3.2	40	4
KHM-VNM	212	HVAC	214	12.8	1.4	40	4
KOR-PRK	195	HVAC	203	12.2	1.3	40	4
KOS-MKD	77	HVAC	127	7.7	0.5	40	4
KOS-MNE	157	HVAC	179	10.7	1.1	40	4
KOS-SRB	246	HVAC	236	14.1	1.7	40	4
KWT-SAU	539	HVDC	345	20.7	3.2	40	4
LAO-MMR	690	HVDC	373	22.4	3.7	40	4
LAO-THA	519	HVDC	341	20.5	3.1	40	4
LAO-VNM	910	HVDC	414	24.8	4.5	40	4
LBN-SYR	84	HVAC	132	7.9	0.6	40	4
LBR-SLE	360	HVAC	308	18.5	2.4	40	4
LBY-MLT	356	Subsea - HVDC	330	19.8	2.5	40	4
LBY-NER	2429	HVDC	697	41.8	9.8	40	4
LBY-SDN	2739	HVDC	755	45.3	10.9	40	4
LBY-TCD	2318	HVDC	676	40.6	9.4	40	4
LBY-TUN	514	HVDC	340	20.4	3.1	40	4

LSO-ZAF	354	HVAC	305	18.3	2.4	40	4
LTU-LVA	263	HVAC	246	14.8	1.8	40	4
LTU-POL	393	HVDC	317	19.1	2.7	40	4
LTU-RUS-NW	657	HVDC	367	22	3.6	40	4
LTU-SWE	678	Subsea - HVDC	408	24.5	3.7	40	4
LVA-RUS-NW	491	HVDC	336	20.2	3	40	4
MAR-PRT	586	Subsea - HVDC	386	23.2	3.4	40	4
MDA-ROU	357	HVAC	307	18.4	2.4	40	4
MDA-UKR	400	HVDC	319	19.1	2.7	40	4
MEX-USA-AZ	2029	HVDC	623	37.4	8.4	40	4
MEX-USA-CA	2506	HVDC	712	42.7	10.1	40	4
MEX-USA-ER	1211	HVDC	470	28.2	5.5	40	4
MKD-SRB	323	HVAC	285	17.1	2.2	40	4
MLI-MRT	1047	HVDC	439	26.4	5	40	4
MLI-NER	1100	HVDC	449	27	5.2	40	4
MLI-SEN	1049	HVDC	440	26.4	5	40	4
MLT-TUN	401	Subsea - HVDC	341	20.5	2.7	40	4
MMR-THA	579	HVDC	352	21.1	3.3	40	4
MNE-SRB	281	HVAC	258	15.5	1.9	40	4
MNG-RUS-SI	1826	HVDC	585	35.1	7.7	40	4
MOZ-MWI	1340	HVDC	494	29.7	6	40	4
MOZ-SWZ	122	HVAC	156	9.4	0.8	40	4
MOZ-TZA	2251	HVDC	664	39.9	9.2	40	4
MOZ-ZAF	443	HVDC	327	19.6	2.9	40	4
MOZ-ZMB	1251	HVDC	477	28.7	5.7	40	4
MOZ-ZWE	918	HVDC	415	24.9	4.5	40	4
MRT-SEN	407	HVDC	320	19.2	2.7	40	4
MWI-TZA	999	HVDC	430	25.8	4.8	40	4
MWI-ZMB	613	HVDC	358	21.5	3.4	40	4
MYS-PHL	2467	Subsea - HVDC	841	50.5	9.9	40	4
MYS-THA	1184	HVDC	465	27.9	5.4	40	4
NAM-ZAF	1178	HVDC	464	27.8	5.4	40	4
NAM-ZMB	1420	HVDC	509	30.5	6.3	40	4
NER-NGA	799	HVDC	393	23.6	4.1	40	4
NER-TCD	1411	HVDC	507	30.4	6.2	40	4
NGA-TCD	1426	HVDC	510	30.6	6.3	40	4
NGA-TGO	242	HVAC	233	14	1.6	40	4
NLD-NOR	915	Subsea - HVDC	465	27.9	4.5	40	4
NOR-RUS-NW	1086	HVDC	447	26.8	5.1	40	4
NOR-SWE	418	HVDC	322	19.3	2.8	40	4
OMN-IND-WE	1562	Subsea - HVDC	622	37.3	6.8	40	4
OMN-IRN	1508	Subsea - HVDC	609	36.6	6.6	40	4
OMN-PAK	863	Subsea - HVDC	453	27.2	4.3	40	4
OMN-SAU	1205	HVDC	469	28.1	5.5	40	4

OMN-YEM	1764	HVDC	573	34.4	7.5	40	4
POL-SVK	533	HVDC	343	20.6	3.2	40	4
POL-SWE	810	Subsea - HVDC	440	26.4	4.1	40	4
POL-UKR	691	HVDC	373	22.4	3.7	40	4
PRK-RUS-FE	689	HVDC	373	22.4	3.7	40	4
QAT-SAU	474	HVDC	332	20	3	40	4
ROU-SRB	448	HVDC	328	19.7	2.9	40	4
ROU-UKR	745	HVDC	383	23	3.9	40	4
RUS-CE-RUS-MV	720	HVDC	378	22.7	3.8	40	4
RUS-CE-RUS-NW	634	HVDC	362	21.8	3.5	40	4
RUS-CE-RUS-SO	958	HVDC	423	25.4	4.7	40	4
RUS-CE-UKR	757	HVDC	385	23.1	3.9	40	4
RUS-FE-RUS-SI	3713	HVDC	937	56.2	14.3	40	4
RUS-MV-RUS-UR	717	HVDC	378	22.7	3.8	40	4
RUS-NW-RUS-UR	1781	HVDC	576	34.6	7.5	40	4
RUS-SI-RUS-UR	1401	HVDC	505	30.3	6.2	40	4
RUS-SO-UKR	760	HVDC	386	23.2	4	40	4
RWA-TZA	1154	HVDC	459	27.6	5.3	40	4
RWA-UGA	377	HVDC	314	18.9	2.6	40	4
SAU-YEM	1067	HVDC	443	26.6	5	40	4
SDN-SAU	1793	Subsea - HVDC	678	40.7	7.6	40	4
SDN-TCD	1926	HVDC	603	36.2	8	40	4
SOM-YEM	1483	Subsea - HVDC	603	36.2	6.5	40	4
SVK-UKR	1000	HVDC	431	25.8	4.8	40	4
SWZ-ZAF	337	HVAC	294	17.6	2.3	40	4
SYR-TUR	1063	HVDC	442	26.6	5	40	4
TJK-UZB	309	HVAC	276	16.6	2.1	40	4
TKM-UZB	1006	HVDC	432	25.9	4.8	40	4
TZA-UGA	1085	HVDC	446	26.8	5.1	40	4
TZA-ZMB	1533	HVDC	530	31.8	6.7	40	4
USA-AZ-USA-CA	586	HVDC	353	21.2	3.4	40	4
USA-AZ-USA-ER	1633	HVDC	549	32.9	7	40	4
USA-AZ-USA-NW	1782	HVDC	576	34.6	7.5	40	4
USA-AZ-USA-RA	941	HVDC	420	25.2	4.6	40	4
USA-AZ-USA-SS	1351	HVDC	496	29.8	6	40	4
USA-CA-USA-NW	1537	HVDC	531	31.9	6.7	40	4
USA-ER-USA-SA	527	HVDC	342	20.6	3.1	40	4
USA-ER-USA-SS	662	HVDC	368	22.1	3.6	40	4
USA-FR-USA-SE	461	HVDC	330	19.8	2.9	40	4
USA-ME-USA-MW	473	HVDC	332	19.9	3	40	4
USA-ME-USA-RW	538	HVDC	344	20.7	3.2	40	4
USA-MW-USA-NW	2239	HVDC	662	39.7	9.1	40	4
USA-MW-USA-RA	1114	HVDC	452	27.1	5.2	40	4
USA-MW-USA-RW	1008	HVDC	432	25.9	4.8	40	4

USA-MW-USA-SN	658	HVDC	367	22	3.6	40	4
USA-MW-USA-SW	747	HVDC	383	23	3.9	40	4
USA-NE-USA-NY	298	HVAC	269	16.1	2	40	4
USA-NW-USA-RA	1647	HVDC	551	33.1	7.1	40	4
USA-NY-USA-RE	128	HVAC	160	9.6	0.9	40	4
USA-RA-USA-SN	889	HVDC	410	24.6	4.4	40	4
USA-RA-USA-SS	805	HVDC	394	23.7	4.1	40	4
USA-RE-USA-RW	669	HVDC	369	22.1	3.6	40	4
USA-RE-USA-SV	732	HVDC	381	22.8	3.9	40	4
USA-RM-USA-RW	267	HVAC	249	15	1.8	40	4
USA-RW-USA-SC	539	HVDC	345	20.7	3.2	40	4
USA-RW-USA-SV	564	HVDC	349	21	3.3	40	4
USA-RW-USA-SW	642	HVDC	364	21.8	3.5	40	4
USA-SA-USA-SC	739	HVDC	382	22.9	3.9	40	4
USA-SA-USA-SE	662	HVDC	368	22.1	3.6	40	4
USA-SA-USA-SN	1092	HVDC	448	26.9	5.1	40	4
USA-SA-USA-SS	929	HVDC	417	25.1	4.6	40	4
USA-SA-USA-SW	953	HVDC	422	25.3	4.6	40	4
USA-SC-USA-SE	344	HVAC	298	17.9	2.3	40	4
USA-SC-USA-SV	548	HVDC	346	20.8	3.2	40	4
USA-SC-USA-SW	410	HVDC	321	19.2	2.7	40	4
USA-SE-USA-SV	366	HVAC	312	18.7	2.5	40	4
USA-SN-USA-SS	483	HVDC	334	20.1	3	40	4
USA-SN-USA-SW	377	HVDC	314	18.9	2.6	40	4
ZAF-ZWE	979	HVDC	427	25.6	4.7	40	4
ZMB-ZWE	397	HVDC	318	19.1	2.7	40	4

S3.2 PLEXOS Unit Commitment and Economic Dispatch

The Unit Commitment and Economic Dispatch (UCED) simulations in PLEXOS use the results from the long-term capacity expansion exercise in an automated fashion after the long-term simulation finishes. Yet, before this occurs two separate modelling phases are applied as preparation for the UCED. First, a Medium Term (MT) schedule decomposes constraints with time horizons longer than the intended UCED horizon. For example, within PLEXOS-World we use monthly CF profiles for hydropower plants based on the seasonal availability of water resources specified per node. The MT schedule decomposes these constraints to a horizon that is computationally manageable for the UCED, for example to daily constraints. Furthermore, a Projected Assessment of System Adequacy (PASA) phase is applied that among others optimizes scheduled maintenance events while retaining system reliability. The PASA also provides reliability indicators as output that can be used to assess the feasibility of reserve assumptions following the MESSAGEix-GLOBIOM scenario. After the MT and PASA the UCED simulation can be applied. The detailed objective function of the UCED simulations in PLEXOS can be found in section 4 of the Supplementary Material. For the UCED we use MILP 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 [31–33]. Table S3.3 shows an overview of some of the generator characteristics per technology as applied in PLEXOS-World for this study.

Table S3.3: Sample of standardized generator characteristics and variables as applied for this study.

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

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

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

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

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

S3.3 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 S3.4 in the 'MESSAGEix 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 3.6 in the main body of the text, 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 [11,12] 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 S3.2

weighted by the existing 2015 capacities for cross-border transmission interfaces existing between two adjacent regions (refer to [11,12] 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 S3.4: 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.

Inter-Regional Transmission Pathway	Variable	Unit	2015	2015	2050	2050
			MESSAGEix First Iteration	MESSAGEix Second Iteration	MESSAGEix First Iteration	MESSAGEix Second Iteration
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	0.00400	0.00286	0.00400
CPA-FSU	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.00400	0.00286	0.00400
CPA-PAS	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.00400	0.00286	0.00400
CPA-SAS	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.00400	0.00286	0.00400
EEU-FSU	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.00400	0.00286	0.00400
EEU-WEU	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.00400	0.00286	0.00400
FSU-MEA	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.00400	0.00286	0.00400
FSU-PAO	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00000	0.00400	0.00000	0.00400
FSU-SAS	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.00400	0.00286	0.00400
FSU-WEU	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.00400	0.00286	0.00400
LAM-NAM	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00000	0.00400	0.00000	0.00400
MEA-SAS	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00000	0.00400	0.00000	0.00400
MEA-WEU	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.00400	0.00286	0.00400
NAM-WEU	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.00400	0.00286	0.00400
PAO-PAS	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.00400	0.00286	0.00400
PAS-SAS	OM Cost|Variable|Electricity|Transmission	US$2010/kWh	0.00286	0.00400	0.00286	0.00400

Section 4 Supplementary Material: PLEXOS UCED Detailed Equations

Indices

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

Variables

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

Parameters

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

Objective Function:

$$\text{(eq9)} \quad OBJ = Min \sum \sum_{t \in T} c_{jt}.U_{jt} + n_{jt}.V_{jt} + m_{jt}.P_{jt} + vl.use_t + vs.usr_t$$

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

Energy Balance Equation:

(eq10) $\sum_{t \in T}\sum P_{jt} - H_{jt} + use_t = D_t$

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.

Operation Constraints on Units:

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

(eq11) $-V_{jt} + U_{jt} \geq -1 \quad \forall t = 1$

(eq12) $V_{jt} - V_{jt+1} + U_{jt+1} \geq 0$

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

(eq13) $P_{jt} - P\max_j . V_{jt} \leq 0$

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

(eq14) $P_{jt} - P\min_j . V_{jt} \geq 0$

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

(eq15) $H_{jt} - Pmp\max_{Stor} . X_{jt} \leq 0$

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

(eq16) $V_{jt} + X_{jt} \leq 1 \quad \text{where } j \in stor$

(eq17) $V_j \leq J_j \quad X_j \leq J_{Stor} \quad j \in J$

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

(eq18) $A_{p,j} \geq V_{j,t} - V_{j,t-1} \forall t..t - MUT_j - 1$

(eq19) $V_{j,t} \geq A_{p,j} - \sum_{t}^{t-MUT_j+1} V_{j,t} / MUT_j \forall t$

Minimum Up Times[5]: (Note the following text is directly from the PLEXOS Help files). The variable A_p tracks if any starts have occurred on the unit inside the periods preceding p with a window equal to MUT. *i.e.* if no starts happen in the last MUT periods then A_p will be zero, but if one (or more) starts have occurred then A_p will equal unity. The MUT constraints then set a lower bound on the unit commitment that is normally below zero, but when a unit is started, the bound rises above zero until the minimum up time has expired. This fractional lower bound when considered in an integer program forces the unit to stay on for its minimum up time.

(eq20) $A_{p,j} \geq V_{j,t-1} - V_{j,t} \forall t.t - MDT_j + 1$

(eq21) $V_{j,t} \leq 1 + \sum_{t}^{t-MDT_j+1} V_{j,t} / MDT_j - A_{p,j} \forall t$

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.

(eq22) $P_{jt} - P_{j.t-1} - MRU_j.V_{jt} - p_{\min j}.U_j \leq 0$

(eq23) $p_{\min j}.P_{jt} + P_{jt} - P_{j.t-1} - P_{jt}.(MRD_j - p_{\min j}) \leq 0$

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

Water Balance Equations:

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

(eq24) $W_{tR} + W_{out.tR} - W_{in.tR} = W_{INT,R} \quad \forall t = 1, R \in RES_{Up}, RES_{low}$

(eq25) $W_{t.RES^{up}} + W_{out,RES^{up}} - W_{in,RES^{up}} = 0$

(eq26) $e_{stor}.H_{jt.RES^{up}} - W_{in.tRES^{up}} = 0$

(eq27) $P_{stor.t} - W_{out.t.RES^{up}} = 0$

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[5] PLEXOS Help Files

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