TransitionZero

Climate Compatible Growth

DARTMOUTH

SFU

Green Grids Initiative

One Sun One World One Grid

Global Interconnected Grid Study

Last update: Nov 11, 2023

Table of contents

Technical Annex

Geographic scope

The Future Energy Outlook (FEO) model has near global coverage, encompassing approximately 99% of the world's population. Figure 1 shows countries that are included within FEO. For the moment, FEO includes 163 countries[1] across 201 nodes. 153 countries are represented at the national level and the remaining 10 at the sub-national level.

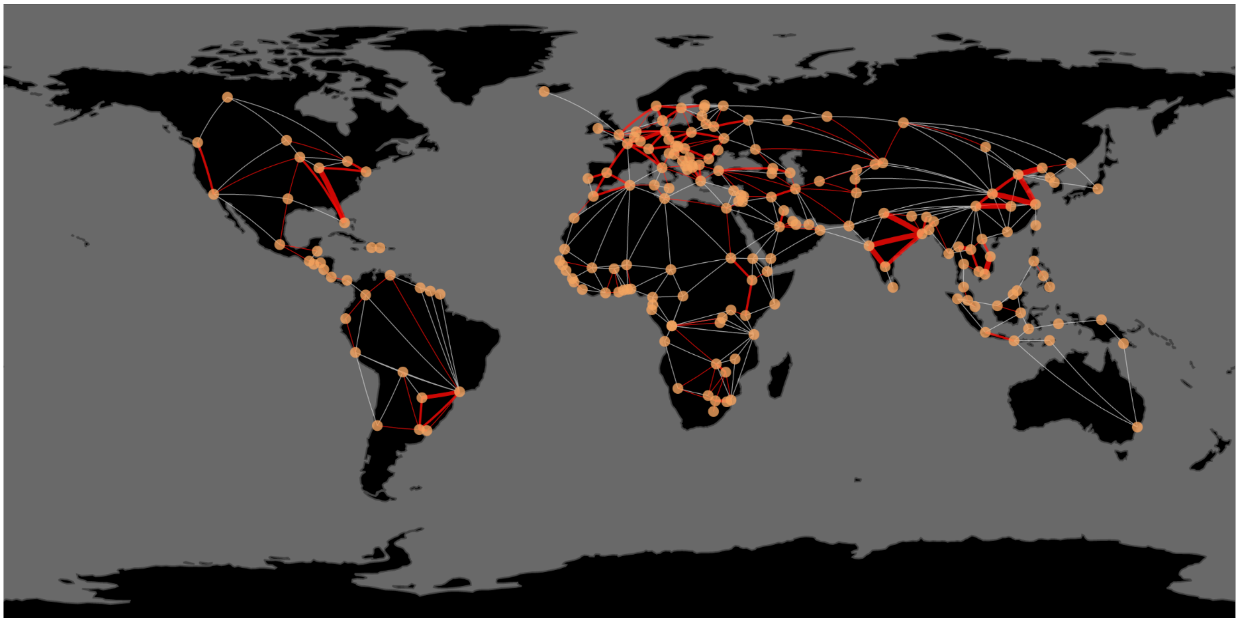


Figure 1: Geographical scope of Future Energy Outlook (FEO).

---

[1] FEO does not model the following regions owing to data and resource limitations. We aim to address these gaps in future releases of FEO:
Aruba, Anguilla, Andorra, American Samoa, French Southern and Antarctic Lands, Antigua and Barbuda, Burundi, The Bahamas, Saint Barthélemy, Belize, Bermuda, Barbados, Cook Islands, Comoros, Curaçao, Cayman Islands, Dominica, Eritrea, Falkland Islands (Malvinas), Faroe Islands, Federated States of Micronesia, Guernsey, Gibraltar, The Gambia, Grenada, Guam, Guyana, Hong Kong, Heard Island and McDonald Islands, Haiti, Isle of Man, British Indian Ocean Territory, Jersey, Kiribati, Saint Kitts and Nevis, Saint Lucia, Liechtenstein, Macao, Saint Martin (French part), Monaco, Maldives, Marshall Islands, Northern Mariana Islands, Montserrat, New Caledonia, Norfolk Island, Niue, Nauru, Pitcairn, Palau, Puerto Rico, State of Palestine, French Polynesia, South Georgia and the South Sandwich Islands, Saint Helena, Ascension and Tristan da Cunha, Solomon Islands, San Marino, Saint Pierre and Miquelon, South Sudan, São Tomé and Príncipe, Sint Maarten (Dutch part), Seychelles, Turks and Caicos Islands, Tonga, Tuvalu, United States Minor Outlying Islands, Vatican City (Holy See), Saint Vincent and the Grenadines, British Virgin Islands, United States Virgin Islands, Vanuatu, Wallis and Futuna, Samoa.

Below is a table showing the geographic scope of the model by country.

	Country / Region	**Number of nodes**
1	Canada	4 (Regions)
2	USA	6 (NERC regions)
3	Russia	7 (Regions); ‘North Caucasus’ and ‘Southern’ merged into ‘South’
4	India	5 (Grid regions)
5	China	7 (Grid regions)
6	Indonesia	7 (Island groups)
7	Vietnam	3 (Grid regions: North, Central, South)
8	Malaysia	3 (Regions: Peninsular, Sarawak, Sabah)
9	Philippines	3 (Island groups)
10	Thailand	3 (Regions: North, Central, South)
11	*Rest of the world x 1 node each*	153
	TOTAL	**201**

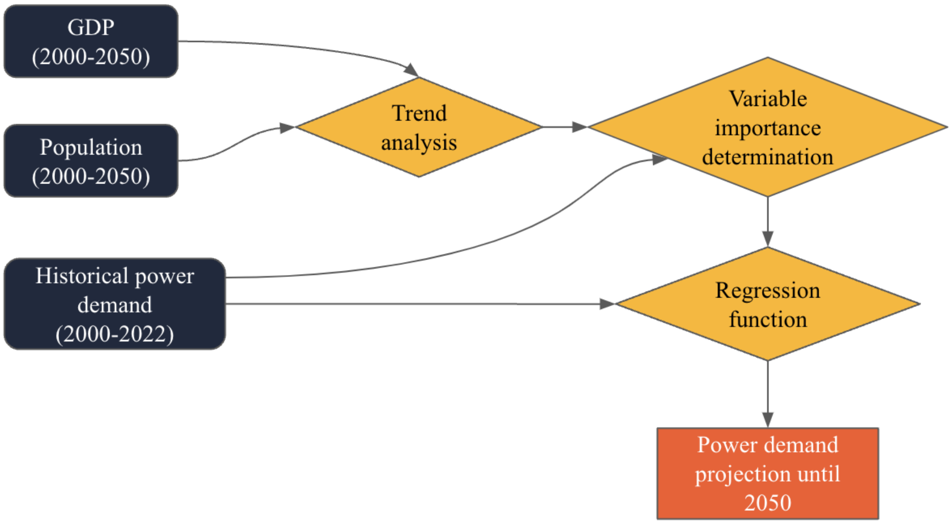
Input Data

Demand Projections

This section delves into the methodology and input data used to build demand projections in this study. The primary focus of our demand projections is power consumption at each designated node. These projections encompass national level data for 153 countries and sub-national data for an additional 10 countries. All data and results in this study are presented on an annual timescale.

For countries represented as national nodes, the methodology begins with a trend analysis of Gross Domestic Product (GDP) growth and population growth data. This analysis determines the growth line's shape whether linear, exponential or polynomial, which is later used for the regression. Subsequently, these same datasets are analysed to quantify their influence on historical demand data. This forms the basis for the assignment of weighting factors to each dataset which are then applied in the regression.

A similar method is applied to countries with subnational zones, where our focus shifts to regional data. Specifically, we consider data such as Gross Regional Domestic Product (GRDP), regional population statistics, and regional electricity demand. In instances where granular power demand data is not available, we adopt a proportional scaling approach based on the ratio of GRDP to GDP within each node. By applying such a method, we individually assess each node, taking into account power usage and characteristics within the context of their unique macroeconomic conditions. It's important to note, however, that the top-down approach utilised in this demand analysis may not capture granular ground-level data with precision. This is due to our constraints in obtaining comprehensive socio-economic data for in-depth behavioural analysis that impacts power utilisation within a given country. Nevertheless, we regard this top-down approach as an effective and straightforward way to illustrate the growth of power demand growth at the national level.



In this study, the projection of power demand relies on three primary input variables: GDP, population and historical electricity demand data. The first two variables are constructed using three distinct sources. Firstly the World Bank provides data spanning from 1990 to 2022 on GDP in the form of Purchasing Power Parity in 2017 international USD. Population data is also provided by the World Bank. For future growth projections, we employ the IIASA's Shared Socioeconomic Pathways (SSP2) dataset, this dataset spans from 2025 to 2100. Finally, to bridge the gap between the World Bank's data and the SSP2 we use the IMF's GDP growth forecast up until 2025. Historical electricity demand data for each country is sourced from EMBER's open dataset and then spot-checked using the IEA's energy statistics data.

Input Variable	**Data Source**	**Data Period**	**Unit of Measurement**
GDP	World Bank	1990 - 2022	PPP in USD 2017
Population	World Bank	1990 - 2022	Total population
Short-term GDP growth projection	IMF	2022 - 2024	Annual percent change
Long-term GDP projection	IIASA SPP2	2025 - 2100	PPP in USD 2017
Historical electricity demand	EMBER	2000-2022	Terawatt hours of electricity demand

For countries that are represented at the sub-national level, data is collected from the official websites and documents of each country as listed below:

Country / Region	Sources
Canada	National Statistical Agency
USA	The Bureau of Economic Analysis, Energy Information Administration
Russia	Federal State Statistic Service
India	Ministry of Statistics and Program Implementation, Central Electricity Authority
China	National Bureau of Statistics of China
Indonesia	RUPTL 2021-2030, Visi Indonesia 2045

Vietnam	Vietnam Statistical Yearbook, Eight National Power Development Plan (PDP8) 2021-2030
Malaysia	The Department of Statistics Malaysia, Malaysia Energy Statistics Handbook
Philippines	Philippine Statistics Authority, Philippine Energy Plan 2020-2040
Thailand	Office of The National Economic and Social Development Council, Electricity Statistic of Energy Policy and Planning Office

Renewable Energy Potentials and Profiles

Potentials

Renewable potentials for solar photovoltaic (PV), onshore wind, and offshore wind were computed across the 201 model nodes. The process involved performing an area analysis for each node N, to ascertain the total area available for the installation of solar PV plants, onshore wind farms, and offshore wind farms. These potentials were then calculated by multiplying these areas by specific installable capacities per unit area associated with each technology.

For solar PV and onshore wind, the area analysis involved excluding unsuitable land types for the given technology, such as protected areas delineated by the WDPA. Following this, assumptions were made regarding the percentage of each land type within the node that could be utilised for installing the technology. For instance, an assumed percentage of 3% of cropland was considered usable for onshore wind. These assumptions were referenced from an area analysis conducted for Europe [Scholz, 2012] , which may not be universally applicable due to varying socio-political factors across different regions.

Data on protected areas were obtained from the WDPA, while information for other land types was sourced from the Copernicus Global Land Service (CGLS), presenting a comprehensive global primary land cover map of 23 discrete classes at a 100m resolution. The table provided lists the CGLS land class codes corresponding to specific land types.

In the case of offshore wind, assumptions were made regarding the permissible installation zones within a node’s exclusive economic zone (EEZ), ensuring turbines are at a distance of at least 5 km from the shoreline and they cannot be built at a depth greater than 300m. Exclusive Economic Zone (EEZ) data was sourced from the Marine Regions World EEZ v12 maritime boundaries dataset, while bathymetry data was acquired from GEBCO.

Installable capacities per area assumptions were derived from Scholz et al (2012)[2]. For onshore and offshore wind, it was assumed that 10.42 MW per km^2 can be installed, while for solar PV the assumption was 141.9 MW per km^2

Table 1: Assumed usable fractions by land type and corresponding Copernicus land classes.

Land Type	**Solar Usable Fraction (%)**	**Onshore Wind Usable Fraction (%)**	**CGLS Land Classes**
Protected Areas	0	0	N/A
Urban	2.4	0[3]	50
Cropland	0.03	3	40
Forest	0	3	111, 112, 113, 114, 115, 116, 121, 122, 124, 125, 126
Shrubs and vegetation	0.03	3	20, 30
Bare	33	33	60
Water, wetland, moss and ice.	0	0	70, 80, 90, 100, 200

Hydropower potentials were obtained from Hoes et al. (2017)[4], an online database providing a collection of potential hydropower locations. This information was aggregated at the node level after excluding any potential locations within protected areas.

Profiles

Profiles for onshore wind, offshore wind, and solar PV were extracted from renewables ninja. This platform utilises the VWF model to convert wind speed data from NASA MERRA reanalysis data into power output and computes solar profiles using the GSEE model (Global Solar Energy Estimator). The wind profile references[5],

---

[2] Scholz, Yvonne. "Renewable energy based electricity supply at low costs: development of the REMix model and application for Europe." (2012).

[3] Onshore wind was forbidden within 1km of urban areas.

[4] Hoes, Olivier AC, Lourens JJ Meijer, Ruud J. Van Der Ent, and Nick C. Van De Giesen. "Systematic high-resolution assessment of global hydropower potential." PloS one 12, no. 2 (2017): e0171844.

[5] Staffell, Iain, and Stefan Pfenninger. "Using bias-corrected reanalysis to simulate current and future wind power output." Energy 114 (2016): 1224-1239.

leveraging NASA MERRA reanalysis data[6], while the solar profile references[7] and utilises solar radiation data from[8]. For each node, a representative latitude and longitude were selected, and the 2013 profile at this point was employed as the node's profile.

Hydropower profiles were obtained from the PLEXOS World model data[9]. This in turn consolidated location-specific monthly capacity factors for every hydro power plant (7155 in total) from the Global Reservoir and Dam Database (GRAND)[10] and a study by Gernaat and colleagues[11]. 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.

Scenario design

The main goal of this study is to assess the potential techno-economic advantages of increased interconnection and transmission for the transition to net zero global power system. This study sets out two scenarios: the first assumes constraints on transmission and interconnector deployment while targeting net-zero emissions by 2040. The second assumes that existing interconnectors can be expanded as much as is economically efficient, whilst aiming for net-zero emissions within the same timeframe.

Both scenarios depict viable strategies for the global electricity sector to become net-zero by 2040. Choices regarding technology use are influenced by factors such as cost, how advanced the technology is, market conditions, existing infrastructure, and policy priorities. Both scenarios also emphasise an orderly transition. They focus on maintaining security of supply with well-planned and synchronised policies. These policies and incentives are designed to help everyone prepare for the swift changes ahead, and to reduce unexpected market shifts and stranded assets.

Understanding that reaching a net-zero electricity sector by 2040 requires genuine and effective global cooperation is essential. The path to achieving net-zero

---

[6] Rienecker, Michele M., Max J. Suarez, Ronald Gelaro, Ricardo Todling, Julio Bacmeister, Emily Liu, Michael G. Bosilovich et al. "MERRA: NASA's modern-era retrospective analysis for research and applications." Journal of climate 24, no. 14 (2011): 3624-3648.

[7] Pfenninger, Stefan, and Iain Staffell. "Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data." Energy 114 (2016): 1251-1265.

[8] Müller, Richard, Uwe Pfeifroth, Christine Träger-Chatterjee, Jörg Trentmann, and Roswitha Cremer. "Digging the METEOSAT treasure—3 decades of solar surface radiation." Remote Sensing 7, no. 6 (2015): 8067-8101.

[9] https://dataverse.harvard.edu/dataverse/PLEXOS-World

[10] B. Lehner, C.R. Liermann, C. Revenga, et al., High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management, Front. Ecol. Environ. 9 (2011) 494–502, https://doi.org/10.1890/100125.

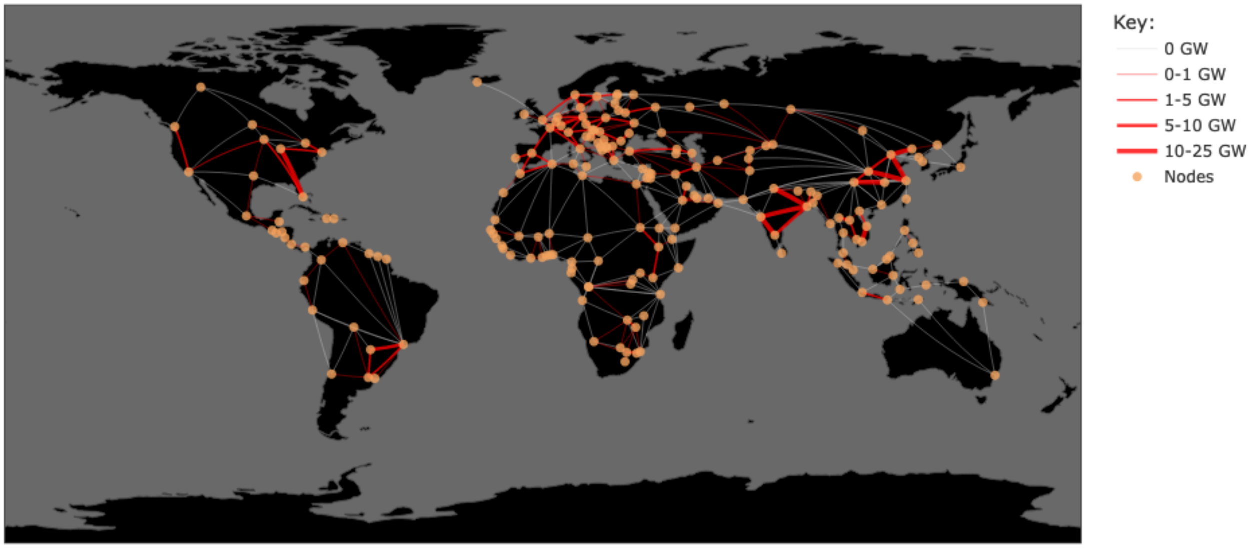
[11] D.E.H.J. Gernaat, P.W. Bogaart, D.P.V. Vuuren, et al., High-resolution assessment of global technical and economic hydropower potential, Nature Energy 2 (2017) 821–828, https://doi.org/10.1038/s41560-017-0006-y.

emissions by 2040 is challenging. Specifics on both scenarios are detailed in the table below.

Table 2. Scenario description between net-zero electricity by 2040 with and without new interconnection and transmission

Scenario	Description
Net-zero by 2040 with new interconnection and transmission	● Net zero electricity generation by 2040 globally, consistent with the IEA's Net Zero Scenario (NZS)
Net-zero by 2040 with no new interconnection and transmission	● Net zero electricity generation by 2040 globally, consistent with the IEA's Net Zero Scenario (NZS)

Interconnectors



Interconnector candidates

Within the applied modelling framework, it is assumed that investments in new interconnector capacities can occur between any countries and regions that are geographically adjacent as well as between countries and regions that are already connected by means of subsea interconnectors (e.g. France and the United Kingdom). In addition to this, specific interconnector expansion candidates that are of interest from a Global Interconnected Grid perspective are introduced (e.g. Australia - Indonesia) whereas certain pathways with existing interconnectors yet with a low likelihood of further expansion are excluded (e.g. Ukraine and the Russian Federation). An overview of allowed interconnector candidates are visualised in Figure X.

Interconnector database

For the data inputs for the modelling of electricity interconnectors between countries and regions, we make use of the Global Transmission Database[12] that has been developed in parallel to this study. The database includes existing- and planned interconnector capacities between all countries globally as well as inter-regional capacities for a sample of larger countries (Australia, Brazil, Canada, China, India, Indonesia, Japan, Philippines, Russian Federation, Thailand, United States, Vietnam). For this study, we only integrate existing interconnector capacities given that the database is still in development when it comes to planned interconnector capacities. Capacities from interconnectors with higher spatial detail as provided in the database are aggregated to match the spatial representation as used for this study. Existing global interconnector capacities as retrieved from the database can be seen in Figure X.

---

[12] Brinkerink, M., Sherman, G., Osei-Owusu, S., Mohanty, R., Majid, A., Barnes, T., Niet, T., Shivakumar, A., & Mayfield, E. (2023). Global Transmission Database (0.1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.10063446

Interconnector centre-points

There are many ways to model the trade of electricity between regions, where among others the assumptions on start- and end points of potential interconnectors can have a large impact on its overall financial and operational feasibility. For the modelling of transmission interconnectors within this study, we follow an approach as developed by Zappa et al.[13] which consists of a 'centre-of-gravity' approach to model electricity trade, with the to-be expanded transmission interconnectors assumed to be located between the main population-weighted demand centres in neighbouring regions. To limit the computational complexity of model simulations, it is assumed that all capacity can be standardised as a combined interface rather than individual transmission lines. The straight-line distance between the centre-points based on longitudes and latitudes can be calculated with an excel formula that considers the radius of the earth.

```
ACOS(COS(RADIANS(90 - Lat1)) * COS(RADIANS(90 - Lat2)) + SIN(RADIANS(90 - Lat1))
* SIN(RADIANS(90 - Lat2)) * COS(RADIANS(Long1 - Long2))) * 6371
```

The open-source basic package of the World Cities Database[14] (last updated on March 31, 2023) was used to retrieve latitude, longitude, and population values for the 43,000 largest cities in the world. Per model region, the largest city as identified in the database was assumed to be the respective demand centre-point. Determination of the largest city for the country-level regions in the model was automated by filtering on ISO code, yet matching demand centre-point to the sub-country regions in the model had to be done manually. This is relevant for sub-country regions based on distinct administrative boundaries (e.g. provinces in China) as well as for custom regions (e.g. combination of balancing authorities in the U.S.).

Interconnector costs- and losses

Baseline values for interconnector costs- and losses can be found in Table X. These values are derived from studies by Zappa et al.[15] and Droste-Franke et al.[16] while accounting for inflation and conversion into $2020. For this study, in line with Brinkerink et al.[17], the assumed interconnectors costs- and associated operational

---

[13] 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.

[14] Pareto Software, LLC (2023), World Cities Database, https://simplemaps.com/data/world-cities, accessed 11/01/2023.

[15] 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.

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

[17] Brinkerink, M. et al (2022). Assessing global climate change mitigation scenarios from a power system perspective using a novel multi-model framework. Environmental Modelling & Software 150, 105336.

losses per interconnector pathway are distance and technology specific. We consider High-Voltage Alternating Current (HVAC) for shorter transmission distances and High-Voltage Direct Current (HVDC) for longer transmission distances with the straight-line distance calculated with the earlier introduced formula. Subsea pathways are assumed to solely use HVDC yet with higher associated costs per unit of distance. With the indicated CAPEX and Fixed O&M costs, the break-even distance at which land-based HVDC becomes more cost-efficient compared to HVAC is determined to be 374 km (not accounting for transmission losses, variable costs or wheeling charges). Within the model, it is assumed that any land-based transmission pathway with a straight-line distance above the break-even distance is HVDC and vice versa HVAC.

Parameter	**Unit**	**HVAC**	**HVDC**	**HVDC Subsea**
CAPEX Line	$2020/MW/km	779.4	237.8	295.1
CAPEX Converter Pair	$2020/MW	47,699.8	148,754.5	148,754.5
Fixed O&M Costs	% of CAPEX/yr	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
Technical Life	yr	40	40	40

Power plant Data Collection and Standardisation

In this section we provide an account of our data collection and standardisation process for the power plants that were included in our model.Powerplant data was obtained from the Global Energy Monitor's (GEM) power plant trackers. These trackers provide detailed information about power plants, including their capacity, location, and start date. This information was consolidated and standardised to ensure consistency.

Matching Power Plants to Study Nodes

Subsequently, we harmonised this data with the specific nodes employed in the model. This matching process was facilitated by employing latitude and longitude coordinates, enabling us to compute the total power capacity associated with each node.

Inclusion Criteria

Our dataset encompasses power plants that meet the following statuses as labelled by GEM.

1. **Operating:** These are plants that have been successfully commissioned and are now operating commercially.

2. **Under Construction:** These are plants in which equipment installation is actively underway.
.
3. **Permitted:** This category comprises power plants that have obtained all the necessary environmental approvals, even if physical construction has not yet commenced.

Data Sources and Releases

Our dataset is sourced from the following specific releases of GEM's tracker:

Tracker	**Release Date**
Global Coal Plant Tracker	July 2023
Global Oil and Gas Plant Tracker	August 2023
Global Solar Power Tracker	May 2023
Global Wind Power Tracker	May 2023
Global Hydropower Tracker	May 2023
Global Geothermal Power Tracker	July 2023
Global Bioenergy Power Tracker	January 2023
Global Nuclear Power Tracker	January 2023

Technology costs

Technology capital and fixed operating costs were sourced from the IEA's 2022 World Energy Outlook Report, and extracted from the IEA's 2050 Stated Policies scenarios for Europe, United States, Japan, Russia, China, India, Middle East, Africa and Brazil.

Key assumptions include capital costs sourced were considered on a weighted average basis, with costs associated with renewable energy technologies and CCS-equipped power plants based on below assumed learning rates sourced from IEA (IEA, 2022).

Renewables Category	**Plant Specification**	**Technological rate of learning**
Bioenergy	Large-scale unit	5%
	Medium-scale CHP	5%
	Small-scale CHP	5%
	Biogas	5%
	Waste incineration	5%
	Cofiring	5%
Geothermal	Geothermal electricity only	5%
	Geothermal CHP	5%
Hydropower	Large-scale unit	1%
	Small-scale unit	1%
Solar Photovoltaic	Large-scale	20%
	Buildings	20%
Concentrated Solar Power		10%
Marine		14%
Wind Energy	Onshore	5%
	Offshore	14%

Fuel prices

Fuel Price Data

The fuel price data utilised in this study is sourced from the Climate Compatible Growth (CCG) data repository available on the CCG Energy and Transport Starter Data Kit website. The dataset encompasses various fuel types, including Crude Oil, Heavy Oil, Light Oil, Biomass and Coal. This data is projected up to the year 2050, captured at 5-year intervals. The base year for calculating fuel prices is referenced as USD 2020.

References for Base Year and Fuel Price Projection Calculation

- IRENA, Planning and prospects for renewable power: West Africa, International Renewable Energy Agency, Abu Dhabi, 2018.
- IRENA, Planning and Prospects for Renewable Power: Eastern and Southern Africa, The International Renewable Energy Agency, Abu Dhabi, 2021
- World Energy outlook 2016
- Annual Energy Outlook 2020

Model framework

This study is built in TransitionZero's Future Energy Outlook (FEO) platform. FEO is a fully open-source energy system data platform. It provides a transparent alternative to closed-source energy outlooks, such as the IEA and consultants, with a much higher spatial granularity. FEO helps users to answer difficult questions around the energy transition, including trade-offs with land use, climate mitigation, and other policy priorities, all in an entirely shareable and reproducible framework. Importantly, non-technical users, such as policymakers and investors with no coding experience, can generate their own scenarios for resource planning decisions.

For this study, we utilised the FEO-OSeMOSYS model, a capacity expansion model grounded in the OSeMOSYS Global framework. Capacity expansion models are designed to simulate investments in generation and transmission capacity. They base these simulations on various factors, including predictions about future electricity demand, fuel prices, technological costs and performance, as well as policies and regulations. The model aims to represent the electricity system as accurately as possible, subject to constraints on data and computation time. The main aspects that improve the accuracy of the model's representation are its spatial and temporal resolution. FEO-OSeMOSYS spatially covers 163 countries and 201 nodes. Regarding temporal resolution, each year is divided into two seasons, with each season being further subdivided into 4 daily time slices. Together, there are 8 representative time slices in the model. The temporal resolution is the same for the entire model period.

Our study relies on a set of assumptions that forecast techno-economic trends on a global scale. General assumptions used across both scenarios are available in the table below. Since FEO is an open source platform, all data points and associated code are available on the platform or via our Github repository.

Reference documents

CIGRE, 'Global electricity network Feasibility study', (2019). https://drive.google.com/file/d/1zFiWw7YBH0SHy08QnMCa2PZdJlD8R3CD/view?usp=sharing

Guo, F., van Ruijven, B.J., Zakeri, B. et al. 'Implications of intercontinental renewable electricity trade for energy systems and emissions', Nature Energy 7, 1144–1156 (2022). https://doi.org/10.1038/s41560-022-01136-0

FAQ

1. How do you define a globally-interconnected power grid?

2. When is net-zero? Is this just electricity (i.e. net-zero electricity by 2050 ≠ net-zero energy by 2050)?
   We are only modelling the electricity system for this study.

3. Is there a gold-standard for interconnector and transmission data globally?

4. What is the difference between interconnection and transmission?
   Interconnectors are defined as cross-border while transmission is within national borders

5. Does it include transmission within countries (i.e. for those with multiple nodes)?
   Yes. It includes transmission within countries (within and between each sub-national node)

6. How do you define planned or conceptual interconnection?

7. Are there any constraints (e.g. geo-politics) placed on the model?

8. How do you create a short-list of projects (that will ‘change the world’)?