GLOBAL CCS INSTITUTE

Brief

Global Energy Model Description

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Contents

1. Introduction

The model used for the *Economics of direct air carbon capture and storage* is a bottom-up technology-focused model based on the Open Source Energy Modelling System (OSeMOSYS) framework.[1] OSeMOSYS is similar to MARKAL and TIMES and is used widely in academia and in government for policy analysis and energy system planning (Gardumi et al. 2018; Howells et al. 2011; Löffler et al. 2017; Niet et al. 2021; Welsch et al. 2014).

OSeMOSYS consists of a core set of equations, but a modeller can change or add to these equations to change how the model operates. As a set of equations, OSeMOSYS is not a functioning model until a modeller adds input data that defines the energy system to be modelled, which can range from a model of a small local electricity system to a multi-region multi-sector global energy model. Once the energy system is defined, OSeMOSYS uses a linear program (LP) solver to solve the set of equations to generate results.[2]

The model finds the least-cost mix of technologies and the optimal operation of those technologies that meets future energy demands, taking into account capital, fixed and variable costs, efficiency, fuel cost, resource constraints, and objectives like carbon dioxide (CO_2) reduction pathways.

2. Enhancements to OSeMOSYS

We add equations to the core OSeMOSYS framework to account for different types of carbon capture, including bioenergy with carbon capture and storage (BECCS), fossil fuels with carbon capture and storage (CCS), and direct air carbon capture and storage (DACCS). The model also adds equations to account for where this captured carbon goes, including to geologic storage and synthetic fuels or construction aggregates. We alter core equations in OSeMOSYS and add additional equations to adjust net CO_2 emissions accordingly, given the different types of carbon capture utilization and storage (CCUS) modelled. We also add equations to allow for interregional trade of CO_2 and CO_2 credit banking, though banking is turned off by default

The model finds the direct costs of reaching net zero with rich technological detail. The model has a technology structure that allows for multiple decarbonization pathways (e.g. energy efficiency, renewables, electrification, fuel switching, low-carbon hydrogen, synfuels, biofuels, direct CCS, BECCS, and DACCS). It will always select the least-cost mix of decarbonization options given resource costs, technology costs and characteristics and scenario constraints.

The model data and inputs were originally developed at the King Abdullah Petroleum Studies and Research Center (KAPSARC) as the Model for Optimizing the Circular Carbon Economy (MOCCE). The model used at the Global CCS Institute updates costs and performance characteristics for fossil electricity generating technologies (supercritical coal, oxyfuel coal with CCS, natural gas combined cycle, natural gas combined cycle with CCS, oil-fired combustion turbine), renewable generating technologies (solar PV, onshore wind and offshore wind), hydrogen-producing technologies (natural gas partial oxidation, electrolysis powered by solar or wind or nuclear or grid electricity, oil gasification, and coal gasification) and DACCS technologies (plus a hybrid electricity and thermal solar technology made by Raygen called PV Ultra). This model also adds options not available in MOCCE for CCS retrofits for existing pulverized coal plants and existing natural gas combined cycle plants.

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[1] Specifically the GAMS distribution of OSeMOSYS (https://github.com/OSeMOSYS/OSeMOSYS_GAMS/tree/c732bf7107e852596a821f5767f338b2c2746e53)

[2] The model uses the commercial solver CPLEX.

In MOCCE, the cost of CO_2 compression, transport and storage is a simple USD per tCO2 adder, but in this model, the capital and operating costs, as well as electricity demand, for CO_2 compression are modelled as any other technology, and the cost of pipelines and storage are also updated. Similarly, this model accounts for the cost and energy consumption for compression and transport of hydrogen, whereas MOCCE assumes a simple cost adder per kg of hydrogen output.

The model also replaces the International Energy Agency (IEA) CO_2 trajectory toward net zero from MOCCE with the IPCC SSP1-1.9 scenario as the default CO_2 trajectory to reach net zero.

The current version of the model uses a single annual time segment but adds equations to account for integration costs in the electricity sector as intermittent renewables go beyond specified percentage thresholds of system generation.[3] The model adds equations to the core of OSeMOSYS to keep onshore and offshore wind capacity within assessed wind resource availability by region (Lu, McElroy, and Kiviluoma 2009), while also adding equations to ensure the minimum baseload/dispatchable capacity.

3. Regions

The model currently consists of four regions, or groupings, of countries. Regional results are indicative of the average result among all the countries in that region and may not be applicable to any particular country. The regions enable a richer and more realistic view at the global level and show the importance of emissions trading.

The four regional groupings are:

1) **Advanced Economies (AdvEco):**

   OECD grouping: Australia, Austria, Belgium, Canada, Chile, Colombia, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States

   Plus Bulgaria, Croatia, Cyprus, Malta and Romania

2) **Brazil, China, Russia, South Africa (BCRSA)**
3) **Middle East (ME):**

   Bahrain, the Islamic Republic of Iran (Iran), Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, the Syrian Arab Republic (Syria), the United Arab Emirates and Yemen

4) **Rest of the world (ROW):**

   All remaining countries

One of the consequences of having a few large regions is that all the countries in a region can implicitly

[3] Specifically, intermittent renewables fall into three categories: 1) zero added costs for the first tranche of intermittent renewables, 2) added costs for the next tranche of renewables to reflect additional costs to the system to integrate renewables, such as upgraded transmission interconnections, 3) the same added costs as in the second tranche plus added costs to reflect a lower quality resource plus a requirement that battery systems be installed in proportion to the intermittent capacity in this tranche.

trade all energy commodities without restriction and pursue carbon reductions wherever they are available on behalf of all within the region. In this sense, the results underestimate the costs of reaching net zero because countries are unlikely to be as efficient in cooperating to deploy only the lowest-cost carbon reduction options within a larger region.

4. Final demand categories

Final demand (**Table 1**) is exogenous, meaning that the values are entered by the modeler, and the model must satisfy these demands. The model can invest explicitly in energy efficiency in buildings and industry. Demand for transportation is also exogenous, but that demand is for services rather than energy. The model can choose more efficient and/or lower carbon transportation technologies to provide those services, thereby lowering energy consumption and emissions in transportation.

Table 1. Categories of final demand in MOCCE

Exogenous demand	Unit
Industry	
Industrial process and heat demand	EJ
- including separate sub-sector demand for coal, natural gas, and oil in chemicals	EJ
Industrial electricity demand	EJ
Buildings	
Building heat demand	EJ
Building electricity demand	EJ
Transportation	
Light-duty vehicles	billion passengers/km
Aviation	billion passengers/km
Heavy-duty vehicles	billion tonnes/km
Maritime shipping	billion tonnes/km

5. Technologies and cost curves

Table 2 shows the technology categories within the model.

The model uses the same cost and technology characteristics for hydrogen production and renewable generation as the IEA (based on data from IEA [2021], [2019], [2020a], [2020b]) and uses non-renewable electricity generating costs and characteristics from the U.S Energy Information Administration (EIA 2020). Costs and technology characteristics for other technologies are derived from a variety of sources, primarily peer-reviewed journal articles.

Table 2. Technology categories in the model

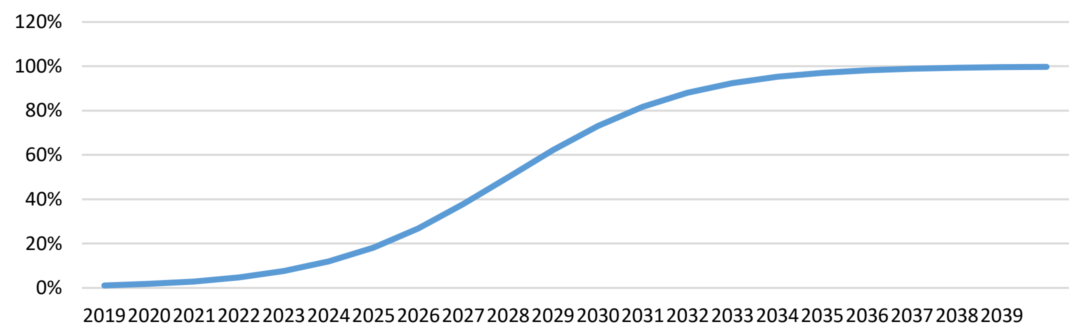
Technology Groups	Number of Technologies
PRIMARY ENERGY	
Oil production	26
Natural gas production	21
Coal production	1
Fossil fuel transport and trade	4
Biomass production	12
SECONDARY ENERGY	
Refining and biofuels	7
Electricity generation	33
Electricity transmission and distribution	2
Hydrogen production	11
Hydrogen transport	4
FINAL ENERGY	
Transportation	
Light-duty transportation	9
Heavy-duty transportation	5
Aviation	2
Maritime shipping	3
Buildings	
Building heat	7
Building electricity and efficiency	11
Industrial	
Industrial electricity	11
Industrial process and Heat	13
CO_2 MANAGEMENT	
Direct air capture	1

5.1 Technology characteristics

Every technology is characterized by capital costs, fixed costs, variable costs, efficiency, capacity factors, availability factors, emission rates, operating lifespans, and existing capacities. The modeler can define a limit on how much new investment or capacity can be deployed annually and over the modeling period by region or at the global level. These limits are in place only to represent a reasonable constraint on how quickly the kinds of infrastructure being modeled can be manufactured and constructed.

Electric vehicles (EVs) in the light-duty vehicle segment are a challenge to model from an economic perspective. EVs are soon expected to be cost-effective compared to conventional vehicles in many markets, and unconstrained, the model would switch to EVs from conventional vehicles quicker than is realistic under the most optimistic scenarios because this shift to EVs relies on charging infrastructure in order to be deployed at scale, and people often factor in considerations other than economic when making vehicle purchasing decisions. The process of technology adoption can be quick, but it does not happen within a year or two. A well-established literature on technology diffusion and adoption suggests that EVs, like every major new technology adopted by the public, follows an S-shaped adoption curve (Bass, 1969, 1980; Griliches, 1957; Mansfield, 1961). The upper limit on EVs in the model in 2025 is 18%, by 2030 is 73% and by 2039 and beyond is 100% (**Figure 1**), based on an EV diffusion curve developed for this study informed by Virta (2021), US EIA (2021) and International Energy Agency (2021). The model can opt for a lower penetration of EVs if a lower penetration is least-cost, but the model cannot transition to EVs faster than allowed by this limit.

Figure 1. Maximum penetration of EVs allowed in the model



Heavy-duty vehicle technology assumptions are based on Moultak (2017) and Gray, McDonagh, O'Shea, Smyth, and Murphy (2021). Maritime shipping technology is also based on Gray et al. (2021), as well as UNCTAD (2020). The only low-carbon options in aviation in the model are synthetic fuels that can be used by existing airplane technology, so alternative airplane technology characteristics are not needed. The approach to modeling transportation in an OSeMOSYS model is based on Lavigne (2017).

The technology characteristics for hydrogen-based synthetic fuels and direct air capture were derived from several sources (Fasihi, Bogdanov, and Breyer 2016; Realmonte et al. 2019; Schmidt, Weindorf, Roth, Batteiger, and Riegel 2016; Socolow et al. 2011; Viebahn, Scholz, & Zelt 2019). Bio-synthetic fuels, biomethane, and bioethanol technology characteristics are based on Brown (2020).

5.2 Oil and natural gas supply curves

The model is strictly linear, meaning that non-linear relationships are not allowed in the model. For this reason, the model cannot model demand or supply elasticities, nor model any process that is defined by a non-linear equation. One way around this limitation is to use a stepwise linear curve in order to provide an endogenous supply price response within a linear optimization model. Oil and natural gas production are each represented by up to 26 different supply curve segments that are modelled as separate technologies that produce the relevant fuel at prices and quantities corresponding to the segment in the supply curve, for each of the four regions. These "curves" are derived from multiple sources (Rioux et al. 2020; IEA 2020b; Wood Mackenzie 2016). Each technology represents a linear segment of a supply curve that, when taken together, mimic the shape of a curve (**Figure 2** and **Figure 3**).

Figure 2. Global oil supply curve aggregated from the 4 regional oil supply curves.

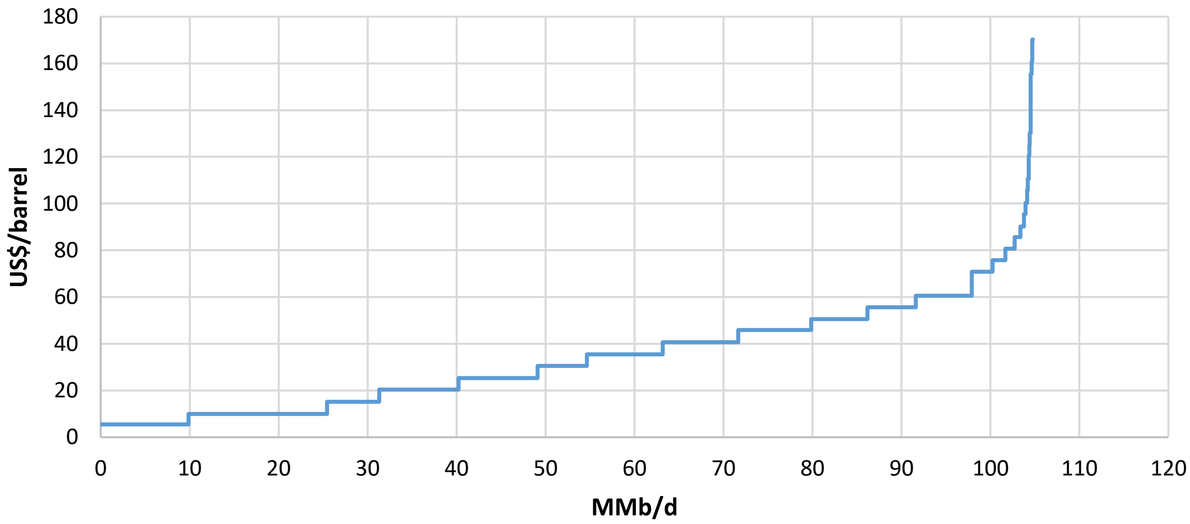
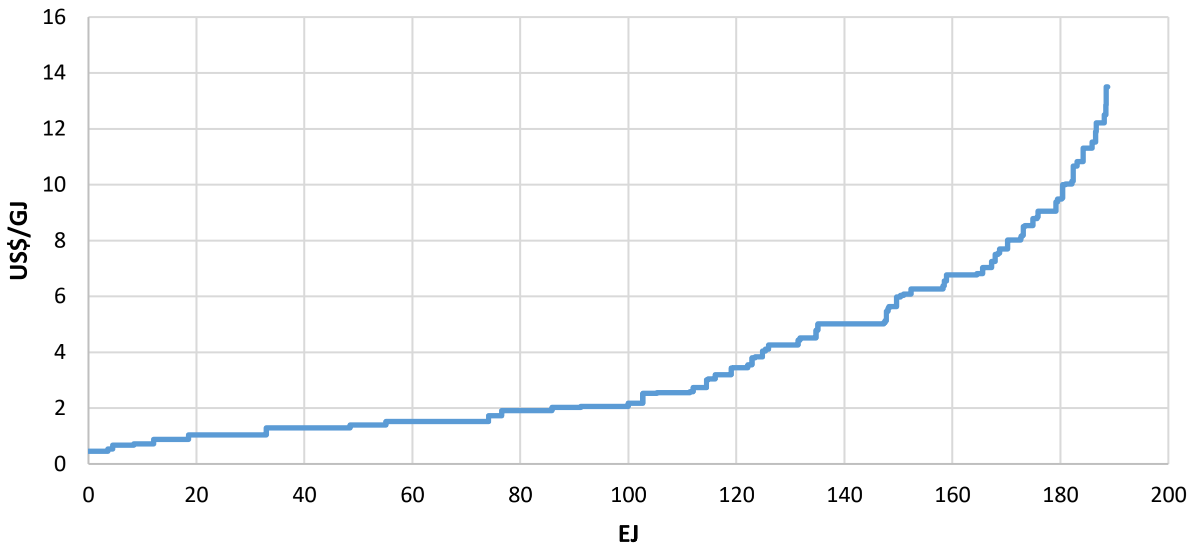


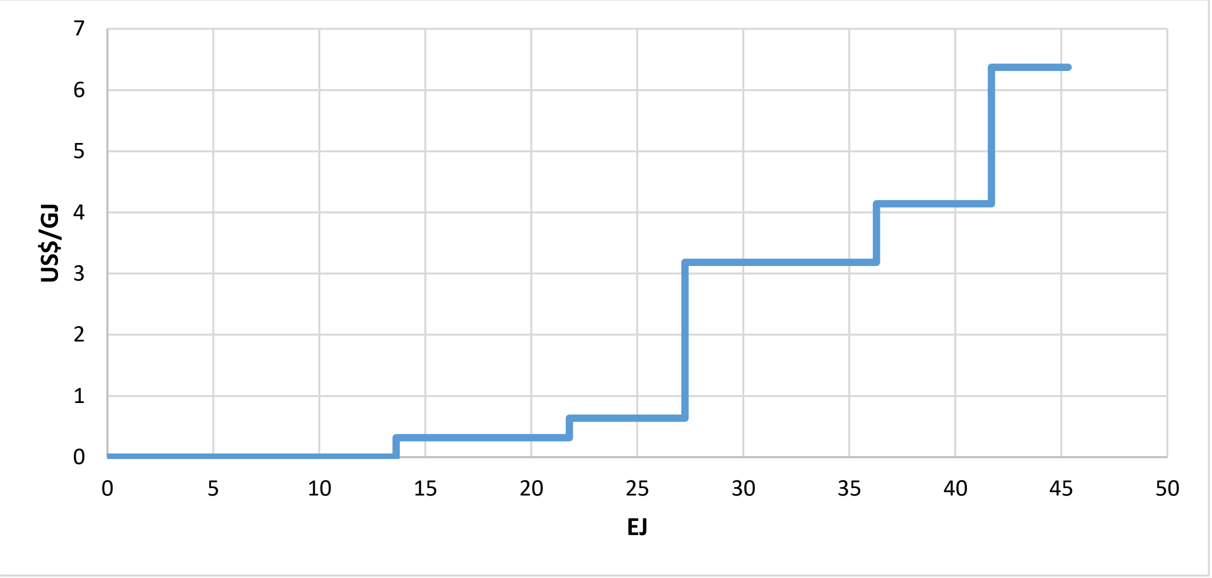
Figure 3. Global natural gas supply curve aggregated from the 4 regional natural gas supply curves.



5.3 Bioenergy supply curves

The model incorporates four different biomass sources (waste from agriculture, waste from forestry, municipal solid waste (MSW), and dedicated agricultural crops). Each source is modeled as a three-segment piecewise, linear supply curve in each region in the model, derived from an assessment of sustainable biomass supply and an evaluation of biomass costs (Brown 2020; Haberl, Beringer, Bhattacharya, Erb, and Hoogwijk 2010). **Figure 4** shows the four supply curves aggregated as a single curve for the Advanced Economies region, though the model treats each supply curve separately because some bio-energy applications can use certain resources and not others. Some portions of the individual supply curves have the same cost, so the aggregated curve shows six segments, as opposed to the 12 segments that the model uses for each region (three segments for four biomass curves).

Figure 4. Biomass supply curve aggregated from separate supply curves in the model for dedicated crops, agricultural waste, forestry waste, and MSW, in the Advanced Economies region as representative of other regions.



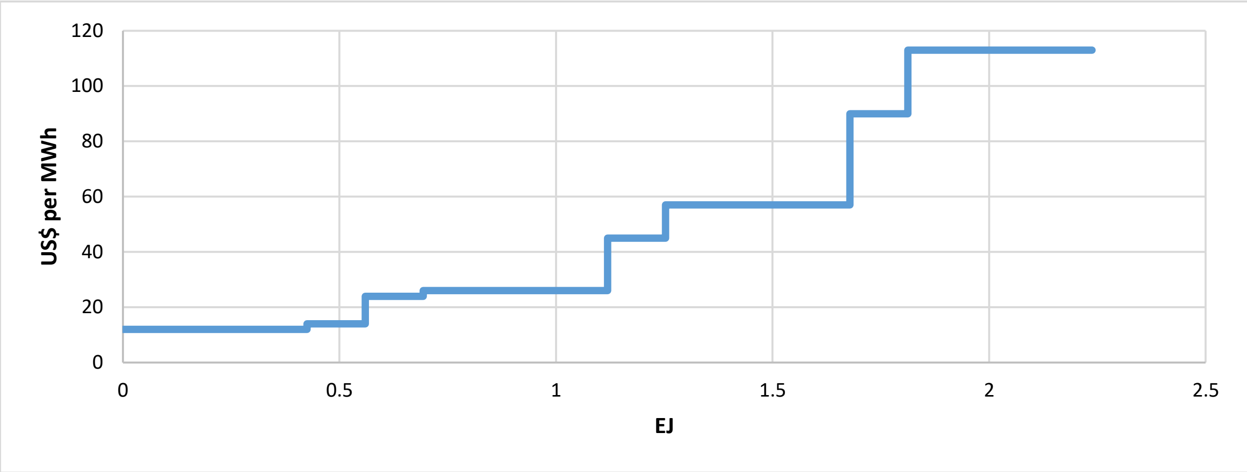
5.4 Energy trade

Trade in oil and natural gas is allowed between regions, though natural gas trade is restricted based on current natural gas trade between regions, with a modest annual expansion in natural gas trade allowed over time. Trade in synthetic fuel, bioethanol, and hydrogen are also allowed, but the supply of these fuels is determined entirely endogenously within the model based on investments in technologies that produce these fuels, the resource availability of the inputs needed to produce them, and the relative costs and regional demand for these fuels.

5.5 Energy efficiency cost curves

Energy efficiency curves are modeled as stepwise linear supply curves for the same reasons that oil and natural gas supply curves are. Together, two sets of eight technologies form stepwise linear cost curves that provide an endogenous demand/energy efficiency response within the model for buildings and for industry in each region (Gumerman and Vegh 2019). The curves are based on a United States (U.S.) database of the costs and outcomes of utility and government energy efficiency (EE) programs. Even if an EE option saves money and has a negative cost, there is a positive cost after factoring in program costs to motivate/facilitate EE investments. Therefore, the low end of the EE supply curve in the model has low but positive costs.

Figure 5. Electricity efficiency supply curve for buildings in the Advanced Economies region, which is indicative of building and industry electricity efficiency supply curves across the regions.



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