Features of the Energy Market Game

Trevor L. Davis *
Program on Energy and Sustainable Development
Department of Economics
Stanford University
Stanford, CA 94305
trevor.l.davis@stanford.edu

July 28, 2020

Abstract

The Program and Energy and Sustainable Development (PESD) at Stanford University has developed the Energy Market Game to help policymakers, regulators, market participants, and students improve their understanding of how energy and environmental markets work. The Energy Market Game simulates wholesale electricity markets and allows players to take on the role of generating companies, retail customers, vertically-integrated utilities, and (financial instrument) traders. The Energy Market Game can incorporate environmental policies that are found in real markets, such as a carbon tax or a cap-and-trade system for greenhouse gas emissions as well as a renewable portfolio standard to incentivize the development of wind and solar facilities. When these additional elements are added to the basic features described above

*PESD gratefully acknowledges funding support from the following organizations:

- William and Flora Hewlett Foundation
- Heising-Simons Foundation
- Western Interstate Energy Board
- FSI: International Policy Implementation Lab
- Stanford Precourt Institute for Energy
- TomKat Center for Sustainable Energy
- Stanford VPTL

the game becomes a sophisticated simulation of an electricity market subject to overlapping environmental regulations. These kinds of complex markets have significant scope for strategic behavior and can be difficult to analyze theoretically. The game has been used in several classes, conferences, and workshops and our experience shows that it allows policymakers, regulators, market participants, and students to attain a higher level of comfort with these markets, as well as an improved sense of how markets may respond to different policies.

1 Introduction

The Energy Market Game (EMG) is a web platform for the education and research of energy markets. The platform can simulate wholesale electricity markets with various agents such as generating companies (gencos), retail customers (retailers), verticaly-integrated utilities (VIUs), and purely financial traders. The electricity grid can have multiple nodes under various transmission constraints. The games supports direct energy trades as well as various financial derivatives such as forward swap contracts, forward cap contracts, forward floor contracts, financial transmission rights (FTRs), power purchase agreements (PPAs), and capacity contracts. The EMG can incorporate environmental policies that are found in real markets: gencos can be subjected to carbon prices either via a carbon tax or a cap-and-trade system with tradable carbon allowances and retailers can be subjected to a Renewable Portfolio Standard (RPS) with tradable Renewable Energy Certificates (RECs). When these additional elements are added to the basic features described above the game becomes a sophisticated simulation of an electricity market subject to overlapping environmental regulations. These kinds of complex markets have significant scope for strategic behavior and can be difficult to analyze theoretically.

The game has been used in several classes, conferences, and workshops around the world and our experience shows that it allows policymakers, regulators, market participants, and students to attain a higher level of comfort with these markets, as well as an improved sense of how markets may respond to different policies – see section B for some of the research papers that have used the EMG. A large number of stylized games are available for anyone to play for free at energymarketgame.org – see the Using the game page for more information about how to play either the single-player or multi-player versions of the stylized games we have made available. Section C describes some of the history of the development of the EMG by The Program on Energy and Sustainable Development at Stanford (PESD) and section D describes the software used to implement the EMG.

2 EMG Game Features

The EMG features a wide variety of possible agents and other game features to provide realistic simulations of wholesale electricity markets and their upstream and downstream effects. Most EMG simulations only take advantage of a small subset of possible agents and other game features supported by the EMG in order to keep the simulation tractable for the players and the researchers running the game. A common practice at PESD is to run several game simulations gradually introducing new feature(s) of the EMG in each game. This description of features supported by the EMG uses a lot of specialized terms – see section E for a glossary.

2.1 Agents

The EMG features a variety of possible agents that can be played by human players or (especially in the case of single-player games) by artificial intelligence (AI) players: genco, retailer, trader, VIU. In multi-player games there is also a human controlled gamemaster

(GM) that manages the game and there is also an independent system operator (ISO) agent that can serve as a counterparty in certain contracts but is not played by a human. *In most EMG simulations the agents will only have enabled a subset of their full capabilities listed below.* All agents can post messages onto the chat page of the EMG.

2.1.1 genco

Gencos hold a portfolio of generation units and sell electricity into a wholesale electricity market (with the electricity being bought by retailers and possibly VIUs). In the EMG gencos have the following capabilities:

- Make price offers on their generation units into a wholesale electricity market. The wholesale electricity price they receive from the ISO can either be determined by a uniform-price auction or a pay-as-bid auction.
- Build new generation units and demolish generation units. See section 2.3 for more details about the generation units held by gencos.
- Can trade any tradable certificate and enter into any financial derivative contract that a trader can. See section 2.1.3 for more details on the type of tradable certificates and derivative contracts.
- Can sell energy to a VIU in an energy trade.
- Can sell all the energy from a particular (renewable) generation unit to a retailer via a PPA.
- Can sell capacity contract contracts to an ISO.

- At the beginning of the game can enter in sell offers in a uniform-price auction to sell capacity contract contracts to the ISO and/or forward swap contract contracts to retailers.
- Under a carbon tax can be taxed a fixed rate per tonne of carbon dioxide (CO_2) emitted by their generation units.
- Under a cap-and-trade must surrender a carbon allowance per tonne of CO_2 emitted by their generation units or face a financial penalty per tonne of excess CO_2 emissions.
- In single-player games the player genco also gets some of the abilities of the GM in order to manage the EMG.

2.1.2 retailer

Retailers buy electricity from a wholesale electricity market and sell it to downstream electricity consumers at a fixed price.

- Demand from downstream electricity consumers is linear. See 2.2 for more details.
- Can trade any tradable certificate and enter into any financial contract that a trader can. See section 2.1.3 for more details.
- At the beginning of the game can enter in buy offers in a auction to buy forward swap contract contracts.
- May declare a critical peak rebates (CPR) rebate before a given period. This decreases their demand by a random amount. They then pay a fixed fee for each megawatt-hour (MWh) of actual demand that was beneath their originally forecasted demand.

- Under a RPS must surrender a REC per MWh for a fixed fraction of their electricity demand or face a financial penalty per MWh of excess electricity sold not covered by a REC.
- Can buy all the power from a particular (renewable) generation unit from a genco via a PPA.
- Can purchase power from a VIU in a energy trade.

2.1.3 trader

- Can buy and sell tradable carbon allowances, RECs, and FTR contracts. The EMG can also allow (as well as forbid) traders to *short* them i.e. sell carbon allowances, RECs, or FTR contracts they do not own and if they still have a short position at the end of the game make them pay a fixed fine (per quantity of the shortfall).
- Can enter into forward swap contracts, forward cap contracts, forward floor contracts, and FTR derivative contracts.
- At the beginning of the game can enter in bid offers into a carbon allowance and/or a FTR auction.

2.1.4 VIU

- Do anything that a genco can. See section 2.1.1 for more details.
- Do anything that a retailer can. See section 2.1.2 for more details.
- Can trade any tradable certificate and enter into any financial contract that a trader can. See section 2.1.3 for more details.

- Unlike gencos and retailers a VIU may but need not be integrated into a wholesale electricity market but may exist alongside it.

- Can both buy and sell energy in an energy trade. In an energy trade a VIU manually buys a negotiated quantity of power at a negotiated price from another VIU or a genco. This power is "scheduled" on certain transmission lines between the energy buyer and the energy seller.

2.1.5 GM

In multi-player games GMs manage the EMG.

- Can toggle on and off certain features of the EMG: whether gencos can purchase new generation units, whether gencos can decommission generation units, whether agents can trade tradable certificates or enter into new derivative contracts.

- Can toggle on and off the EMG itself. This is useful when you don't want individuals to be distracted from a lecture by the EMG when running long simulations.

- Can click the buttons to run initial game auctions, wholesale electricity markets, and at the end of the game enact any final RPS or cap-and-trade penalties.

- Can observe the actions (and even log into their pages) of all other agents in the EMG.

- Can change the cash balances and carbon allowance holdings of all other agents in the EMG. This is useful if initially distributing teams via an off-line auction to give each team the appropriate handicap as well as useful for unwinding and/or penalizing "illegal" actions.

2.1.6 ISO

The ISO is always played by an AI and their main role is to serve as a counterparty in certain contracts in order to ensure the smooth operation of the electrical grid. In past EMG simulations the ISO has served as counterparties in forward swap contracts, capacity contracts, and FTRs.

2.2 Electricity Markets Dispatch

The EMG dispatches electricity produced by generation units (owned by gencos or VIUs) to downstream electricity consumers (serviced by retailers or VIUs). The electricity markets dispatch part of the EMG has the following features:

Supports arbitrary electrical grids

The EMG can solve for the electricity markets dispatch with an arbitrary number of nodes maintaining any transmission constraints.[1] It also enforces various laws of nature that apply to electricity such as Kirchhoff's laws — in particular the EMG allows for realistic phenomena such as loop flows to occur on the grid.[2] Figure 1 shows the example of the electricity market dispatch for a network involving several gencos and VIUs who have linked together in an integrated wholesale electricity market for a more efficient dispatch plus a lone VIU which for political reasons has elected to stand aloof and remain un-integrated.[3]

[1] This includes completely disconnected nodes (i.e. a transmission constraint of 0 MWh as well as always non-binding transmission constraints (i.e. a transmission constraint of ∞ MWh). These transmission constraints also take into account any energy trades involving a VIU that may have occurred.

[2] The EMG achieves this by solving the optimal pricing in electrical networks problem laid out in Bohn et al. (1984).

[3] This particular scenario was one of several market integration scenarios run in a Western Interstate Energy Board (WIEB) workshop on wholesale electricity market integration.

Random, linear demand at nodes

Demand for electricity at each node is linear. The intercept (the demand when the price of electricity is $0) for the demand each retailer face is a normal random variable – this intercept may be reduced by another normal random variable when the retailers in that node declare CPRs. The slope for each retailer at each node is fixed and can either be vertically sloped (i.e. completely inelastic demand) or negatively sloped (somewhat elastic demand). Hence the demand for electricity at each node is linear – this can allow for realistic phenomena such as (often modest) demand destruction when electricity prices are high.

Evolving demand and supply over different periods within a game

An EMG simulation usually has several periods of a wholesale grid dispatch. Each period can have its own unique demand including realistic cyclic patterns such as low electricity demand at night and high demand during the day – this demand can also be manipulated by retailers who declare CPRs. On the supply side new generation units can be brought online and other generation units can be decommissioned – also for a given period the supply from intermittent renewable generation unit can be random. Hence the demand and supply of a wholesale electricity market can evolve over time in a realistic fashion.

Nodal pricing

The EMG computes a different wholesale electricity price for each node of the electrical grid so that overall supply exceeds demand at the least cost to retailers with the restriction that the electrical grid is subject to the transmission constraints as well as various laws of nature described earlier. Under the assumption that intra-zonal congestion is infrequent and insignificant one can define in the EMG nodes with several generation units and downstream electricity consumers and hence approximate a *zonal* pricing market.

Emergency negawatt production

The EMG can set a maximum price for a given node. If at that price downstream electricity consumer demand at that node exceeds electrical demand at that node demand is automatically reduced to the supply of electricity. This price can be considered the price for outside options for downstream electricity consumers such as diesel generators or the political cost that retailers face for allowing rolling blackouts to occur.

Must-run renewable generation units and possibility for negative electricity prices

In the EMG certain renewable generation units can be configured to always run (they can also be configured to be dispatchable). If the supply from such plants exceeds demand the wholesale electricity market prices (for the relevant nodes) may go negative. At a certain fixed negative price emergency demand kicks in to absorb the remaining excess power – this price can represent the cost to the ISO to pay another grid to take the excess power or to pay certain downstream electricity consumers to wastefully use such excess power.

2.3 Generation units

The generation units owned by gencos (and/or VIUs) have several features supported in the EMG:

Different fixed costs and marginal costs

generation units can have different fixed costs and/or different marginal costs. Fixed costs are incurred every period regardless of whether a generation unit is dispatched.

Marginal costs are incurred per MWh dispatched from the generation unit.

Plants can be built and decommissioned

gencos can build new generation units and decommission generation units.

A variety of abstract generation units types are supported

The EMG has run simulations with battery storage, coal, hydropower, natural gas, nuclear, oil, solar (photovoltaic), solar (CSP), and wind (turbine) generation units.

A variety of CO_2 emissions rates

When a genco is under a carbon-pricing regime (see section 2.6 for more details) a positive emissions rate causes the marginal cost for their generation units to increase when the price of carbon emissions rises. This can lead to real-world phenomenon like merit-order shifts – Figure 2 shows how the merit order for the generation units shifted at selected carbon prices in one of the EMG simulations we ran for the Energy@Stanford & SLAC (E@S&S) conference.

Intermittant renewable generation unit output

The EMG allows for certain renewable generation units for node in each period to have random capacities. This random capacity is modeled to be a normal distribution censored at 0 MWh and at some fixed maximum capacity. All renewable generation units of the same type (i.e. 'solar', 'wind') have perfectly correlated distributions within the same node in the same period. This means there is a non-zero probability that all of generation units of a certain type could not run at all in a given node at a given period. When there is a RPS then some renewable generation units will generate a REC for each MWh of output.

Different capacities

Generation units can have different capacities (MW) from small wind turbines to large nuclear plants.

Battery storage

Battery storage power plants can both buy (charge) electricity from and sell (discharge) electricity to a wholesale electricity market.

2.4 Derivatives

The EMG supports several types of financial contracts (usually some form of derivative contract). For all the following derivative contracts when making an over-the-counter derivative offer the agents can agree to an additional transfer of a negotiated lump-sum of cash:

FTR

In a FTR contract the two agents agree to a quantity of MWh, a given transmission line, direction on that line, and a period. One agent is paid by the other the difference in nodal prices in that period on either end of that transmission line multiplied by the quantity (plus perhaps a lump-sum of cash). If there is no congestion on that transmission line (so that the nodal price on either end is the same) then a FTR contract will pay out nothing – a FTR is a hedge against a particular power line being congested when the difference in nodal prices is high where gencos would like to be able to sell more power to the higher-priced node and retailers would like to buy more power from the lower-priced node.

Forward swap contract

In a forward swap contract the two agents agree to a node, a quantity, a period, and a reference price. One agent is paid by the other the difference between the nodal price and the reference price in that period multiplied by the quantity (plus perhaps a lump-sum of cash). A forward swap contract is a hedge against price risk within a given node where both gencos and retailers would like to lock-in a negotiated price. One common type of forward swap contract is a Day-ahead forward swap contract which is simply a forward swap contract purchased a day ahead of the reference period (often via a centralized auction).

Forward floor contract

A forward floor contract is like a forward swap contract but one agent is only paid by the other the difference between the nodal price and the reference price in that period multiplied by the quantity if the spot price is *higher than* the reference price.

Forward cap contract

A forward floor contract is like a forward swap contract but one agent is only paid by the other the difference between the nodal price and the reference price in that period multiplied by the quantity if the spot price is *lower than* the reference price.

PPA

In a PPA the two agents agree to a generation unit, a period, and a reference price. One agent is paid by the other the difference between the nodal price and the reference price in that period multiplied by all the quantity produced by that generation unit (plus perhaps a lump-sum of cash). A PPA allows a retailer to commit to pre-buying all the power from a genco's new (probably renewable) generation unit.

Capacity contract

In a capacity contract a ISO agrees to purchase a fixed quantity of capacity from a genco at a fixed price for a given set of periods. Once a capacity contract has been sold the genco must maintain enough generation units to match or exceed the MWh of that contract for those periods. The "capacity" of an intermittent renewable generation unit is usually assigned a number in between the generation unit's minimum and maximum capacity.

2.5 Initial Portfolio Auctions

At the beginning of the game the EMG allows certain agents to participate in a uniform-price auction to sell or buy certain allowances or contracts. It is also not uncommon in certain EMG simulations for agents (especially gencos) to be exogenously assigned carbon allowances or forward swap contracts at the beginning of the game without resorting to an auction:

Carbon allowances

In EMG simulations with a cap-and-trade system it is possible for all agents to participate in an auction to buy a fixed number of carbon allowances – the quantity of carbon allowances is equal to the carbon cap.

FTRs

In EMG simulations with a single transmission constraint and FTRs it is possible for all agents to participate in an auction to buy a fixed number of pre-arranged FTRs.

Forward swap contracts (type 1)

Gencos can participate in an auction to sell forward swap contracts to be assigned to the retailers by the ISO – the total MWh quantity of the contracts is equal to expected downstream electricity consumer electricity demand in each period.

Forward swap contracts (type 2)

Gencos and retailers can participate in a two-sided forward swap contracts auction – the gencos selling and retailers buying.

Capacity contracts

In EMG simulations with a capacity contract gencos can participate in an auction to sell capacity contract contracts to the ISO – this quantity is equal to a fixed multiple of peak expected downstream electricity consumer electricity demand.

Support for auctions run outside of the EMG

In EMG it is possible for the GM to change the cash holdings and carbon allowance holdings for all agents. This means it is possible to run certain auctions outside of the EMG and incorporate the results into the final standings within a simulation – a not uncommon one is to run auction before a game to see which team gets the more desirable gencos and/or retailers and then handicap those gencos and retailers cash holdings based on the amount of the winning bids from that auction.

2.6 Environmental policies

The EMG can incorporate several environmental policies that are found in real markets:

RPS

RECs are tradable certificates that represent proof that 1 MWh of electricity was generated from an eligible renewable generation unit. Retailers under a RPS must surrender enough RECs or face a fine. Generally the number of RECs that a retailer must surrender is equal to a certain fraction of the total MWh that they sold to downstream electricity consumers.[4] Gencos receive a REC for each MWh produced by an eligible renewable generation unit that they own – once received they can then sell these RECs. The fine for retailers who failed to acquire enough REC is assessed at the end of the game.

carbon tax

Under a carbon tax gencos must pay a fixed tax for each tonne of CO_2 emitted by one of their generation units.

cap-and-trade

Under a cap-and-trade system each genco must surrender a carbon allowance for each tonne of CO_2 emitted by one of their generation units or face a fixed fine for each excess tonne of CO_2. At the beginning of the simulation a fixed quantity of carbon allowances are distributed to the agents either via a uniform-price auction or by whatever scheme the GM deems appropriate[5]. Once allocated the carbon allowances can be bought and sold. The fine for gencos who failed to acquire enough carbon allowances is assessed at the end of the game.

A Figures

[4] For example in California retailers were required to serve 20% of their retail electricity sales with renewable energy by 2010 and will be required to serve 33% of their retail electricity sales with renewable energy by 2020 and 50% by 2030.

[5] GMs are able to adjust the starting carbon allowances for any agent.

Figure 1: Period 3 electricity dispatch for an EMG integration simulation involving with Californian gencos and several non-Californian VIUs joined together in an integrated wholesale electricity market plus a lone VIU in the Pacific Northwest which has elected to stand aloof.

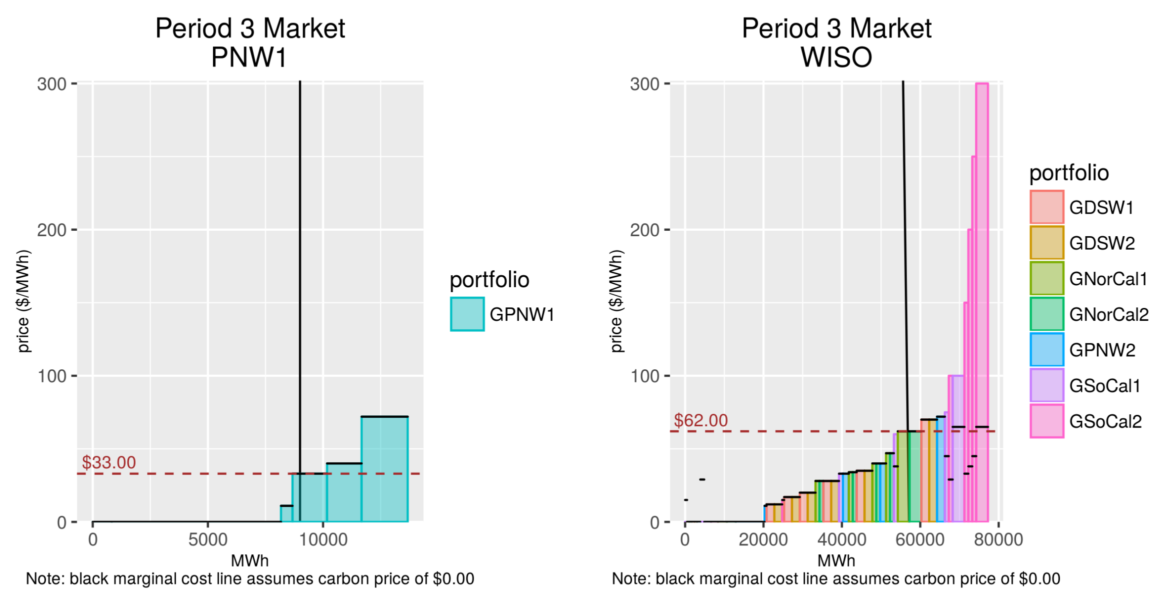
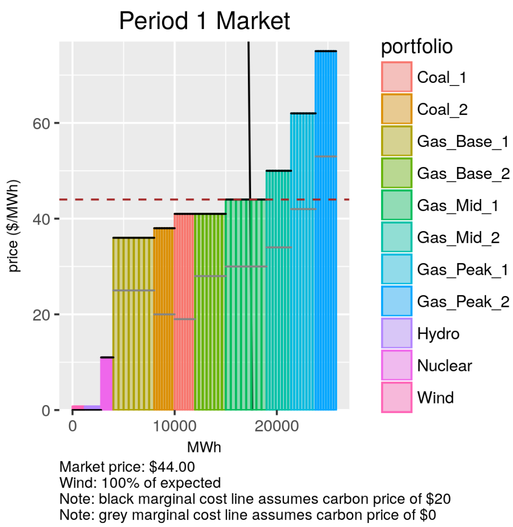
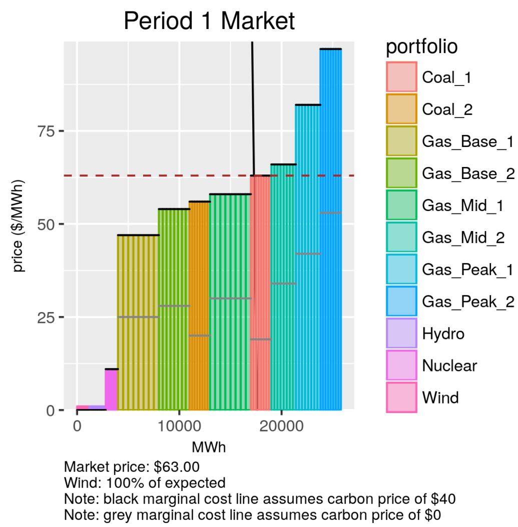


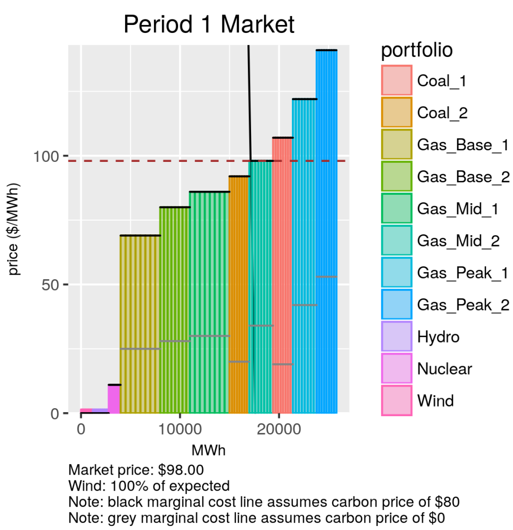
Figure 2: Merit orders induced by select carbon prices in a cap-and-trade simulation



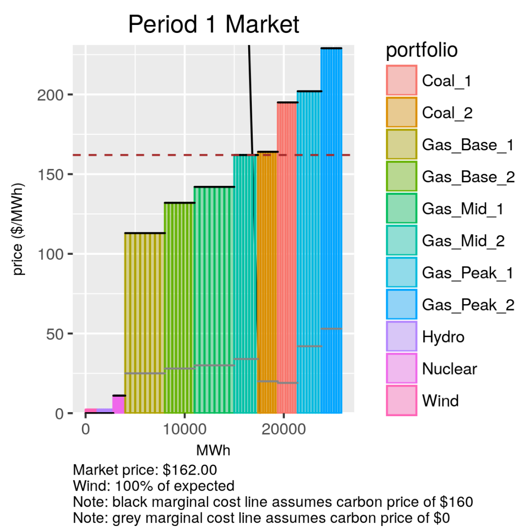
(a) Merit order with carbon price $20



(b) Merit order with carbon price $40



(c) Merit order with carbon price $80



(d) Merit order with carbon price $160

B Research articles that use the EMG

There are several articles that have used the EMG as a economics research tool:

- Carbon in the Classroom: Lessons from a Simulation of Californias Electricity Market Under a Stringent Cap-and- Trade System (Thurber and Wolak, 2013)
- Simulating the Interaction of a Renewable Portfolio Standard with Electricity and Carbon Markets (Thurber et al., 2015)
- Gas-fired generation in a high-renewables world (Thurber, 2018)
- Carbon Allowance Allocation Schemes and Upstream and Downstream Market Outcomes: An Experimental Analysis (Davis, 2019a)
- Wholesale Electricity Market Bid Disclosure and Ease of Collusion: An Experimental Analysis (Davis, 2019b)
- An Experimental Comparison of Carbon Pricing Under Uncertainty in Electricity Markets (Davis et al., 2020)

C History

The EMG has been developed incrementally by PESD since 2013. Here is a timeline of the introduction of major features to the EMG:

2013
- The first version of EMG is used in GSBGEN 336 "Energy Markets and Policy" (GSBGEN 336).
- The EMG allows for gencos to trade carbon allowances.

- For this first version only a separate program – The Electricity Strategy Game (Borenstein and Bushnell, 2011) – is used offline to simulate the wholesale electricity market.

2014

- The EMG is able to simulate two-node wholesale electricity markets.
- The wholesale electricity market can either operate under a uniform-price or pay-as-bid auction.
- Players can also play as the retailers who can engage in demand management via CPR.
- The wholesale electricity market can be subject to a RPS. Retailers must purchase RECs, gencos can buy intermittent solar and wind generation units which generate RECs which can be sold to retailers.
- The wholesale electricity market can be subject to a carbon cap-and-trade system. Gencos can buy and sell carbon carbon allowances. Initial carbon carbon allowances allocation can be determined by either the GM or via a uniform-price auction.
- Agents in the EMG can trade forward derivative contracts.
- Use EMG in a workshop for energy regulators from Ghana and California.

2015

- Use the EMG in a workshop for energy regulators from Nigeria and California.
- Developed stylized games and beta-tested them at a couple of universities.
- Allocation experiment in E@S&S.
- Added support for electricity grids with more than two nodes.
- Add FTR financial contracts.

2016

- Made stylized games available on `www.energymarketgame.org` for the public to play. Hundreds of users have signed up to play these games.
- First round of carbon-pricing experiment in E@S&S. Gencos can be subject to a carbon tax.
- Used in "Regional Integration of Electricity Markets" WIEB workshop. Added VIU agents, energy trades, and support for electricity grids with several nodes some of which may not be integrated with the others.
- Implemented basic AI agents for single-player stylized games.
- Allow gencos to purchase all types of generation units.

2017

- Second round of carbon-pricing experiment in E@S&S.
- Used in WIEB "Western Electricity Market Forum".
- Added ability for renewables to be "must-run" and hence the possibility for "over-generation" and negative electricity market prices.
- Allow gencos to permanently shutter generation units.
- Allow PPA contracts.
- Make public new transmission constraint and carbon-pricing stylized games on `www.energymarketgame.org`.

2018

- Allow a genco to buy multiple generation units at a time.
- Added capacity contracts market which are auctioned at the beginning of the game.
- Added ability for Day-ahead forward swap contracts to be auctioned off at the beginning of the game.

- Used in another WIEB workshop.

2019
- Added battery storage power plants.
- Used again at the E@S&S conferance.
- Added ability for genco to hedge their exposure to volatile natural gas prices. Used in a Stanford Natural Gas Initiative gas and renewable markets workshop.

2020
- With aid from ETH Zurich added a European version of the stylized games to www.energymarketgame.org.
- Added ability for Day-ahead forward swap contracts to be auctioned at any time of the game.

D Software

The EMG is web-program running on an apache (The Apache Software Foundation, 2018) http server that is actually a suite of modular software programs written in Python (Python Software Foundation, 2018) and R (R Core Team, 2020). The EMG contains over 10,000 lines of Python code and 2,000 lines of R code.

Besides the standard library it also takes advantage of the following Python modules:

- scipy (Jones et al., 2018)
- pandas (McKinney, 2010)
- selenium (Selenium Project, 2018)

Besides the standard library it takes advantage of the following R packages:

- dplyr (Wickham et al., 2020)

- ggplot2 (Wickham, 2016)
- gridExtra (Auguie, 2017)
- igraph (Csardi and Nepusz, 2006)
- linprog (Henningsen, 2012)
- png (Urbanek, 2013)
- optparse (Davis, 2020)
- rjson (Couture-Beil, 2018)
- scales (Wickham and Seidel, 2020)
- stringr (Wickham, 2019)
- testthat (Wickham, 2011)
- tidyr (Wickham and Henry, 2020)

E Glossary

Glossary

artificial intelligence (AI)

Some agents in the EMG can be played by machines instead of humans. 3, 7, 21, 27, 29

battery storage power plant

A type of generation unit that uses batteries to store electrical energy. They can both buy (charge) electricity from and sell (discharge) electricity to a wholesale electricity market. 12, 22

cap-and-trade

A carbon-pricing scheme where each genco must play a surrender a carbon allowance for each tonne of CO_2 emitted or face a large financial penalty. 2, 5, 7, 14, 16, 20, 24

capacity contract

In a capacity contract a ISO agrees to purchase a fixed quantity of capacity from a genco at a fixed price. Once a capacity contract has been sold the genco must maintain enough generation units to match or exceed the MWh of that contract. The "capacity" of an intermittant renewable generation unit is usually assigned a number in between the generation unit's minimum and maximum capacity. 2, 4, 7, 13, 15, 21

carbon dioxide (CO_2)

Carbon dioxide is a major greenhouse gas. The EMG supports putting a price on carbon either by a carbon tax or a cap-and-trade. 5, 11, 16, 24

carbon allowance

A tradable certificate representing the right to emit one tonne of CO_2. 2, 5, 6, 7, 14, 15, 16, 19, 20, 24, 30

carbon tax

A carbon-pricing scheme where each genco must play a flat tax for each tonne of CO_2 emitted. 2, 5, 16, 21, 24

critical peak rebates (CPR)

Critical peak rebates is a form of demand reduction where retailers declare a critical event for a given period and downstream electricity consumers are then paid a fixed rate for any reduction in consumption beneath their originally forecasted consumption. 5, 8, 9, 20

Day-ahead forward swap contract

Day-ahead forward forward swap contract contracts are forward swap contract contracts purchased one day ahead. 12, 21, 22

derivative

Derivatives are purely financial contracts. 2, 4, 6, 7, 12, 20, 25, 26, 30

downstream electricity consumer

Downstream electricity consumers purchase electricity from retailers (or VIUs). In the EMG they purchase from their retailer electricity at a fixed price. 5, 8, 9, 10, 14, 15, 24

Energy@Stanford & SLAC (E@S&S)

Energy@Stanford & SLAC is a large annual conference multi-day conference for Stanford graduate students interested in energy. There is more information available at `https://energy.stanford.edu/energystanford-slac`. 11, 20, 21, 22

energy trade

In an energy trade a VIU manually buys a negotiated quantity of energy at a negotiated price from another VIU or a genco. This energy is "scheduled" on certain transmission lines. See section 2.1.4 for more details. Contrast with a forward swap contract which is a derivative contract used by retailers in a wholesale electricity market to hedge the same risk. 2, 4, 6, 7, 8, 21

Energy Market Game (EMG)

Energy Market Game is an energy markets simulator developed by PESD. 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 14, 15, 16, 19, 20, 22, 23, 24, 25, 26, 29

financial transmission right (FTR)

A financial transmissions-right contract is a type of derivative contract, see 2.4 for more details. 2, 6, 7, 12, 14, 20

forward

Forward contracts are a type of derivative contract. The EMG supports forward swap contract, forward cap contract, and forward floor contract forward contracts. 25, 26

forward floor contract

A forward floor contract is a type of forward derivative contract, see 2.4 for more details. 2, 6, 13, 26

forward cap contract

A forward cap contract is a type of forward derivative contract, see 2.4 for more details. 2, 6, 13, 26

forward swap contract

A forward swap contract is a type of forward derivative contract, see 2.4 for more details. 2, 4, 5, 6, 7, 12, 13, 14, 25, 26

gamemaster (GM)

A gamemaster sets up and runs a EMG simulation. single-player games the player acts as their own gamemaster. See section 2.1.5 for more details. 3, 5, 7, 15, 16, 20

generating company (genco)

Gencos hold a portfolio of generation units and sell electricity into a wholesale electricity market (with the electricity being bought by retailers and possibly VIUs). See section 2.1.1 for more information. 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16, 19, 20, 21, 24, 25, 27, 28, 31

generation unit

Generation units are power plants help by a genco or VIU that produce electrical power. 4, 5, 6, 7, 8, 9, 10, 11, 13, 15, 16, 20, 21, 23, 24, 27, 28, 30

GSBGEN 336 "Energy Markets and Policy" (GSBGEN 336)

GSBGEN 336 "Energy Markets and Policy" is a graduate level course on energy and environmental markets taught at the Stanford Graduate School of Business taught by PESD researchers. 19

independent system operator (ISO)

An independent system operator coordinates, controls, and monitors an electric grid. Very similar to a regional transmission organization (RTO). See section 2.1.6 for more details. 3, 4, 7, 10, 13, 14, 15, 24, 28

megawatt-hour (MWh)

1 MWh is equivalent to 1 megawatt of power sustained for one hour. 5, 8, 10, 11, 12, 13, 14, 15, 27, 28

multi-player

Multi-player games have several players playing agent(s) in the game. It is still possible that some agents in the game are played by AIs (i.e. humans may play the gencos while an AI plays the retailers). 2, 3, 7

negawatt

A negawatt is a theoretical unit of power representing the amount of electrical power saved by reduced energy demand. 10

node

An electrical grid network is made up of nodes – points where power can be added and/or taken away from the network. 2, 8, 10, 12, 20, 21

pay-as-bid

In a pay-as-bid auction every bidder pays/receives the price they bid in. 4, 20

power purchase agreement (PPA)

In a power purchase agreement a retailer agrees to buy all the generation output from a given (usually renewable) generation unit (owned by a genco) at a negotiated price. See section 2.4 for more details. 2, 4, 6, 13, 21

regional transmission organization (RTO)

A regional transmission organization coordinates, controls, and monitors a multi-state electric grid. Very similar to a ISO. 27

renewable

renewable energy comes from renewable resources as opposed to non-renewable resources like fossil fuels and uranium. Under a RPS non-hydropower renewable energy provides RECs. 4, 6, 9, 10, 11, 13, 15, 21, 24, 28

Renewable Energy Certificate (REC)

Renewable Energy Certificates are tradable certificates that represent proof that 1 MWh of electricity was generated from an eligible renewable generating unit. retailers under a RPS must purchase enough of them or face a fine. See section 2.6 for more details. 2, 5, 6, 11, 15, 20, 28, 29, 30

Renewable Portfolio Standard (RPS)

retailers under a RPS must surrender enough RECs or face a fine. See section 2.6 for more details. 2, 5, 7, 11, 15, 20, 28, 29

retail customer (retailer)

Retail customers buy electricity from a wholesale electricity market and sell it to downstream electricity consumers. See section 2.1.2 for more details. 2, 3, 4, 5, 6, 8, 9, 10, 12, 13, 14, 15, 20, 24, 25, 27, 28, 29, 31

single-player

Single-player games have only one player playing as an agent in the game. All other agents in the game are played by AIs. 2, 3, 5, 21, 26

The Program on Energy and Sustainable Development at Stanford (PESD)

The Program on Energy and Sustainable Development at Stanford is a research prorgam advancing policy-relevant research, teaching, and outreach on global energy markets and their impact on society and the environment. PESD is the developer of the EMG and is part of the Freeman Spogli Institute for International Studies. 2, 3, 19, 26, 27, 29

tonne

A tonne is 1,000 kg or approximately 2,204.6 lb. Also known as the *metric ton*. 5, 16

trader

Traders do not directly participate in wholesale electricity markets but do participate in related markets such as those for financial derivatives, carbon allowances, and RECs. See section 2.1.3 for more details. 2, 3, 4, 5, 6

transmission constraint

Power lines on an electrical grid network are constrained by the maximum amount of power that can flow over them at a time – this constraint is called a "transmission constraint". 2, 8, 9, 14, 21

uniform-price

In an uniform-price auction every bidder pays/receives the same price. 4, 14, 16, 20

vertically integrated utility (VIU)

Vertically-integrated utilities own a portfolio of generation units which they use to provide electricity to their electricity consumers. They may also buy/sell electricity from/to a wholesale electricity market or other VIUs. See section 2.1.4 for more details. 2, 3, 4, 6, 7, 8, 10, 16, 21, 25, 27, 30, 31

Western Interstate Energy Board (WIEB)

The Western Interstate Energy Board is an organization of 11 Western States and three western Canadian Provinces. The Western Interstate Energy Board promotes energy policy that is developed cooperatively among member states and provinces and with the federal government in order to "enhance the economy of the West and contribute to the well-being of the regions people". See https://westernenergyboard.org/ for more information. 8, 21

wholesale electricity market

A wholesale electricity market is where gencos sell electricity and retailers buy electricity (and where VIUs can do both). 2, 4, 5, 6, 7, 8, 9, 10, 12, 16, 19, 20, 23, 25, 27, 29, 30

References

Auguie, B. (2017). *gridExtra: Miscellaneous Functions for "Grid" Graphics*. R package version 2.3.

Bohn, R. E., Caramanis, M. C., and Schweppe, F. C. (1984). Optimal pricing in electrical networks over space and time. *Rand Journal of Economics*, 15(3):360–376.

Borenstein, S. and Bushnell, J. (2011). *Operating Instructions for the Electricity Strategy Game Version 1.00*.

Couture-Beil, A. (2018). *rjson: JSON for R*. R package version 0.2.20.

Csardi, G. and Nepusz, T. (2006). The igraph software package for complex network research. *InterJournal*, Complex Systems:1695.

Davis, T. L. (2019a). Carbon allowance allocation schemes and upstream and downstream market outcomes: An experimental analysis. Working paper.

Davis, T. L. (2019b). Wholesale electricity market bid disclosure and ease of collusion: An experimental analysis. Working paper.

Davis, T. L. (2020). *optparse: Command Line Option Parser*. R package version 1.6.6.

Davis, T. L., Thurber, M. C., and Wolak, F. A. (2020). An experimental comparison of carbon pricing under uncertainty in electricity markets. Working Paper 27260, National Bureau of Economic Research.

Henningsen, A. (2012). *linprog: Linear Programming / Optimization*. R package version 0.9-2.

Jones, E., Oliphant, T., Peterson, P., et al. (2001–2018). SciPy: Open source scientific tools for Python. [Online; accessed 2018-12-31].

McKinney, W. (2010). Data structures for statistical computing in python. In van der Walt, S. and Millman, J., editors, *Proceedings of the 9th Python in Science Conference*, pages 51 – 56.

Python Software Foundation (2001–2018). Python. [Online; accessed 2018-12-31].

R Core Team (2020). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.

Selenium Project (2008–2018). Selenium: Browser automation. [Online; accessed 2018-12-31].

The Apache Software Foundation (1997–2018). Apache: http server project. [Online; accessed 2018-12-31].

Thurber, M. C. (2018). Gas-fired generation in a high-renewables world. Natural gas brief, Stanford Natural Gas Initiative.

Thurber, M. C., Davis, T. L., and Wolak, F. A. (2015). Simulating the interaction of a renewable portfolio standard with electricity and carbon markets. *Electricity Journal*.

Thurber, M. C. and Wolak, F. A. (2013). Carbon in the classroom: Lessons from a simulation of californias electricity market under a stringent cap and trade system. *The Electricity Journal*, 26:8–21.

Urbanek, S. (2013). *png: Read and write PNG images*. R package version 0.1-7.

Wickham, H. (2011). testthat: Get started with testing. *The R Journal*, 3:5–10.

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York.

Wickham, H. (2019). *stringr: Simple, Consistent Wrappers for Common String Operations*. R package version 1.4.0.

Wickham, H., Franois, R., Henry, L., and Mller, K. (2020). *dplyr: A Grammar of Data Manipulation*. R package version 1.0.0.

Wickham, H. and Henry, L. (2020). *tidyr: Tidy Messy Data*. R package version 1.1.0.

Wickham, H. and Seidel, D. (2020). *scales: Scale Functions for Visualization*. R package version 1.1.1.