Features of the Energy Market Game

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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 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 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), vertically-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 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 agents and 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 both educational and research purposes. A common practice at PESD is to run a sequence of game simulations that progressively introduces new feature(s) of the EMG in successive games.

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 a human controlled gamemaster (GM) that manages the game. There also exists 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.*

2.1.1 genco

Gencos hold a portfolio of generation units and sell electricity into a wholesale electricity market. 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 existing generation units. See section 2.3 for more details about the generation units held by gencos.

- Trade any tradable certificate and enter into any financial derivative contract that a trader can. See section 2.1.4 for more details on the types of tradable certificates and derivative contracts that exist.

- Sell energy to a VIU in an energy trade.

- Sell all the energy from a particular renewable generation unit to a retailer via a PPA.

- Sell capacity contract contracts to an ISO.

- At the beginning of a game, submit 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, be assessed a fixed tax per tonne of carbon dioxide (CO_2) emitted by their generation units.

- Under a cap-and-trade, 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 consumers. They have the following capabilities:

- Procure energy to meet a linear demand from consumers. See section 2.2 for more details.
- Trade any tradable certificate and enter into any financial contract that a trader can. See section 2.1.4 for more details.
- At the beginning of a game, submit buy offers in a auction to buy forward swap contract contracts.
- 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 an RPS, surrender a REC quantity equal to the total demand they serve times the renewable energy fraction specified in the RPS, or face a financial penalty per "missing" REC.
- Buy the energy from a particular renewable generation unit from a genco via a PPA.
- Purchase power from a VIU in a energy trade.
- Specify a customer pricing plan by setting the following prices its consumers will pay/receive:
  - A fixed cost the consumer must pay the retailer each period

- A set marginal price that the consumer must pay per MWh consumed
- A multiplier of the *wholesale* electricity price that the consumer must pay per MWh consumed
- The CPR price the consumer will receive from the retailer for each MWh of consumer demand beneath their originally forecasted demand.

2.1.3 consumer

Consumers buy electricity from retailers or VIUs. They have the following capabilities:

- Select which retailer to will buy electricity from.
- If the retailer declares a CPR, the consumer receives a fixed fee per MWh that their demand is below the originally forecasted demand.
- Trade any tradable certificate and enter into any financial contract that a trader can. See section 2.1.4 for more details.
- For each period consumers have a (mostly[1]) linear electricity demand intercept and slope. These intercepts and slopes are affected by the electricity prices set by the retailer they chose to buy electricity from.

2.1.4 trader

- Buy and sell tradable carbon allowances, RECs, and FTR contracts. The EMG can also allow (as well as forbid) traders to *short* these instruments, i.e. sell carbon allowances,

[1]Consumers do not consume negative quantities of electricity. If the demand intercept, slope, and price are such that electricity demand would be negative, they instead choose to purchase zero MWh. However, the typical game has conditions set up so each consumer has positive demand for the electricity prices they will face and hence demand is typically effectively linear.

RECs, or FTR contracts they do not own and make them pay a fixed fine per quantity of any shortfall if they still have a short position at the end of the game.

- Enter into forward swap contracts, forward cap contracts, forward floor contracts, and FTR derivative contracts.
- At the beginning of the game, submit bid offers into a carbon allowance and/or FTR auction.

2.1.5 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.
- Trade any tradable certificate and enter into any financial contract that a trader can. See section 2.1.4 for more details.
- Unlike gencos and retailers, a VIU is not required to be integrated into a wholesale electricity market but may exist alongside it.
- 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 specified transmission lines between the energy buyer and the energy seller.

2.1.6 GM

In multi-player games, GMs manage the EMG. They have the following capabilities:

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

- Toggle on and off the EMG itself. This is useful when you only want gameplay to be available to players at specified times.

- Run initial game auctions and wholesale electricity markets, and at the end of the game, assess any final RPS or cap-and-trade penalties.

- Observe the actions of all other agents in the EMG. The GM also has the ability if desired to log into the pages of any of the other agents.

- Change the cash balances and carbon allowance holdings of all other agents in the EMG. This feature is useful, for example, if portfolios are distributed to teams via an off-line auction and initial cash balances need to reflect the results of these auctions. It can also be used to unwind and/or penalize "illegal" actions or to correct unforeseen problems that cause teams to earn or lose more money than they should.

2.1.7 ISO

The ISO is always played by an AI and its main role is to serve as a counterparty in certain (usually pre-assigned) contracts in lieu of a counterparty that is an active player. In past EMG simulations the ISO has served as the counterparty in forward swap contracts, capacity contracts, and FTRs.

2.2 Electricity Market Dispatch

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

Supports arbitrary electrical grids

The EMG can solve for the electricity market dispatch with an arbitrary number of nodes subject to any transmission constraints.[2] It enforces physical laws governing electricity such as Kirchhoff's laws, which allows the EMG to capture realistic phenomena such as loop flows on the grid.[3] Figure 1 shows an example of electricity market dispatch for a network involving several gencos and VIUs that have joined together in an integrated wholesale electricity market for a more efficient dispatch, along with a lone VIU that has chosen to remain un-integrated.[4]

Random, linear demand at nodes

Demand for electricity at each node is (mostly[5]) linear. The intercept (the demand when the price of electricity is $0) for the demand each retailer faces is a normal random variable[6]—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

[2] 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.

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

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

[5] Demand is the aggregate sum of each consumer's demand and the consumers are not able to consume a negative quantity of electricity. See footnote 1. However in most games conditions are set so that consumers' demand at all legal electricity prices will not reach their zero bound and in such cases aggregate demand will be linear.

[6] Technically this random variable is censored at zero but usually means and standard deviations are set such that the probability of this happening is effectively zero.

fixed and can either be vertical (i.e. completely inelastic demand) or negatively sloped (somewhat elastic demand). Hence the demand for electricity at each node is linear, which 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 wholesale market 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. Demand can be influenced by retailers who declare CPRs as well as, when retail competition is active, the parameters of the retail pricing plans chosen by consumers. On the supply side, new generation units can be brought online and other generation units can be decommissioned. The supply from any intermittent renewable generation units can be random. These various features allow the demand and supply of a wholesale electricity market to 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 transmission constraints as well as the physical laws governing electricity. Under the assumption that intra-zonal congestion is infrequent and insignificant, one can define in the EMG nodes with several generation units and consumers in order to represent a *zonal* pricing market.

Emergency negawatt production

The EMG can set a maximum price for a given node. If at that price consumer demand exceeds electrical demand at that node, demand is automatically reduced to the supply of electricity. This price for “emergency negawatts” can be considered to represent the price of outside options for consumers such as diesel generators.

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

In the EMG certain renewable generation units can be configured to always run. 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 consumers to use such excess power on an emergency basis.

Day-ahead “dispatch” takes startup costs into account

The day-ahead forward swap contract auction calculates an optimal least-cost dispatch that not only takes transmission constraints and generation unit bids into account but also factors in generation unit startup costs to determine which generation units are assigned day-ahead forward swap contract contracts.

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 existing generation units.

A variety of generation unit types are supported

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

A variety of CO_2 emissions rates

When a genco is subject to 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 rises. This can lead to real-world phenomenon like merit-order shifts. Figure 2 shows how the merit order for generation units shifted at selected carbon prices in one of the EMG simulations we ran for the Energy@Stanford & SLAC (E@S&S) conference.

Intermittent renewable generation unit output

The EMG allows for renewable generation units to have a random capacity at a given node in a given period. This random capacity is modeled as a normal distribution censored at 0 MWh and at a fixed maximum capacity.[7] All renewable generation units of the same type (e.g. solar or wind) at the same node have perfectly correlated distributions in a given period. This means there is a non-zero probability that all generation units of a certain type will not run at all at that node in that period. When

[7] While the distribution of output of real-world wind and solar units over the 8,760 hours in a year is not well-represented by a normal distribution, a normal distribution functions well as a way to represent renewable output in the 8-20 stylized hours that typically make up an EMG game. The use of these distributions in the EMG allows us to match qualitative characteristics of wind and solar generation—for example, solar output only during the day and wind output that might be greater at night—while also yielding a workable level of overall variation in renewable output over the course of a game's limited number of stylized hours.

there is an RPS, each renewable generation unit generates a REC for each MWh of output.

Different capacities

Generation units can have different capacities (MW), representing anything from small wind turbines, say, 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.

Maintenance

Generation units can be scheduled for maintenance that lasts all periods of the specified "day". A generation unit can also be required to be taken down for maintenance one period each day, where the genco is able to choose which period. Units do not run and do not participate in the wholesale electricity market during any periods in which they are undergoing maintenance.

Startup costs

Generation units can have startup costs. In the EMG this is a set cost charged once a day if the generation unit runs at any point in that day.[8] The day-ahead forward swap contract auctions can take these startup costs into account when optimizing its "dispatch"[9] over the generation unit bids and any transmission constraints.

[8]Assessing startup costs at most once a day makes it much easier to write the mixed integer linear programming problem for optimizing over such startup costs in the day-ahead forward swap contract market.

[9]Technically the day-ahead auctions only assign financial swap contracts, with the physical dispatch occurring in the real-time electricity market.

2.4 Derivatives

The EMG supports several types of financial contracts (usually derivative contracts of different types). For all of the following derivative contracts, agents can agree to an additional lump-sum transfer of cash when making or accepting an over-the-counter derivative offer:

FTR

In an FTR contract the two agents agree to a quantity of MWh, a specified transmission line, a direction on that line, and a period. After the market runs, one agent is paid by the other the difference in nodal prices across the transmission line in that period multiplied by the contracted energy quantity. If there is no congestion on the transmission line, such that the nodal price on either end is the same, then an FTR contract pays out nothing. An FTR acts a hedge against a particular power line being congested. When the difference in nodal prices is high, gencos would like to be able to sell more energy to the higher-priced node and retailers would like to buy more energy from the lower-priced node.

Forward swap contract

In a forward swap contract, also referred to as a fixed-price forward 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 contracted energy quantity. 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. The game allows players to bundle multiple forward swap contracts across multiple periods into a single yes/no offer. In games with day-ahead markets, the day-ahead schedules produced by the day-ahead market are represented as day-ahead forward swap contracts. Standardized Fixed-Price Forward Contracts (SFPFCs) are bundled forward swap contract variants that retroactively adjust contracted energy quantities by period in accordance with the realized load shape over the periods of the game.

Forward floor contract

A forward floor contract is a contract where the contract buyer is paid by the contract seller the difference between the nodal price and the reference price in that period multiplied by the contracted energy quantity only if the spot price is *lower than* the reference price.

Forward cap contract

A forward cap contract is a contract where the contract buyer is paid by the contract seller the difference between the nodal price and the reference price in that period multiplied by the contracted energy quantity only if the spot price is *higher 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 the quantity of energy produced by that generation unit. This PPA contract allows a retailer to commit to pre-buying all the power from a genco's generation unit. Because it simulates the structure of renewable PPAs in real markets, it was designed for use with renewable generation units in the EMG (though it is not restricted to such units).

Capacity contract

In a capacity contract an 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 "firm capacity" (MW) requirement of that contract for those periods. The "firm capacity" of an intermittent renewable generation unit is usually assigned a number between the generation unit's minimum and maximum possible output.

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 the use of an auction. The following products can be auctioned off through initial portfolio auctions or assigned at the start of a game:

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 set number of carbon allowances, with the total quantity of carbon allowances set 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, with the total MWh allotment of contracts matching expected consumer electricity demand in each period. In this scheme the period contract quantities are fixed and known to the gencos immediately after the auction.

Forward swap contracts (type 2)

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

SFPFCs

Gencos can participate in an auction to sell SFPFCs which will then be assigned to retailers. In this scheme the ISO retroactively adjusts period contract quantities in accordance with the realized load shape over the game.

Capacity contracts

In EMG simulations with a capacity contract, gencos can participate in an auction to sell capacity contract contracts to the ISO. The total capacity auctioned off is set equal to a fixed multiple of peak expected consumer electricity demand.

Support for auctions run outside of the EMG

The GM has the ability 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 common use of this functionality is to run an auction before a game to see which teams get which gencos and/or retailers in a case where their portfolios vary in attractiveness, and then to handicap those gencos and retailers cash holdings based on the winning bids from that auction.

2.6 Environmental policies

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

Renewable Portfolio Standard (RPS)

RECs are tradable certificates that represent proof that 1 MWh of electricity was generated from an eligible renewable generation unit. Retailers under an 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.[10] Gencos receive a REC for each MWh produced by an eligible renewable generation unit that they own, and they can sell these RECs in the market. The fine for retailers who fail to acquire enough RECs in the market 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

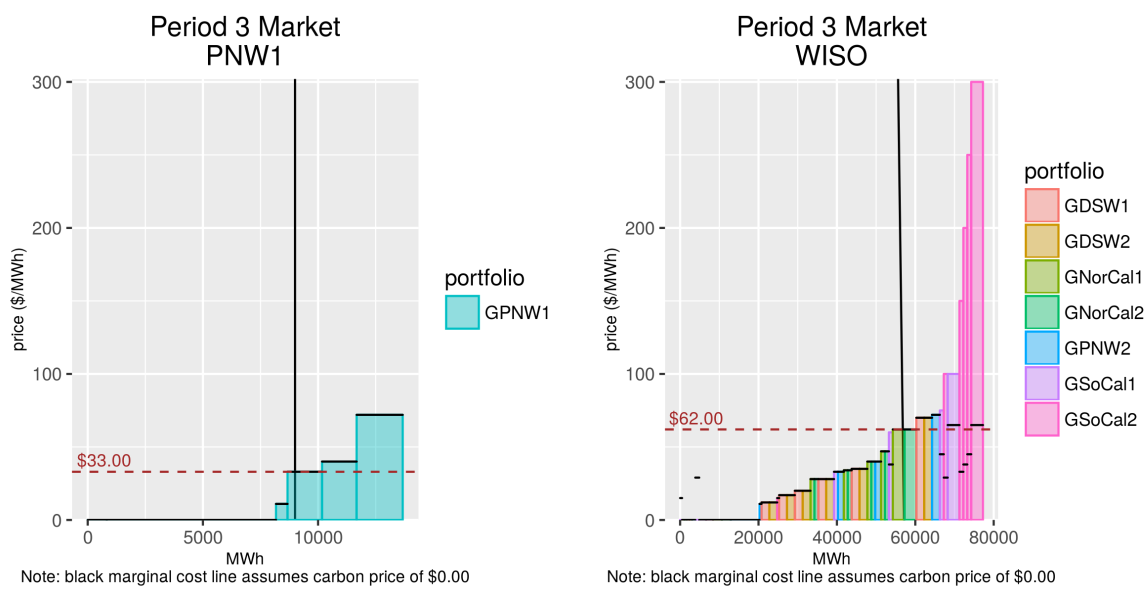
Under a cap-and-trade system each genco must surrender a carbon allowance for each tonne of CO_2 emitted by one of their generation units or face a fixed fine for each excess tonne of CO_2. At the beginning of the simulation a fixed quantity of carbon allowances are distributed to the agents either via a uniform-price auction or by whatever scheme

[10] 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.

the GM deems appropriate[11]. 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.

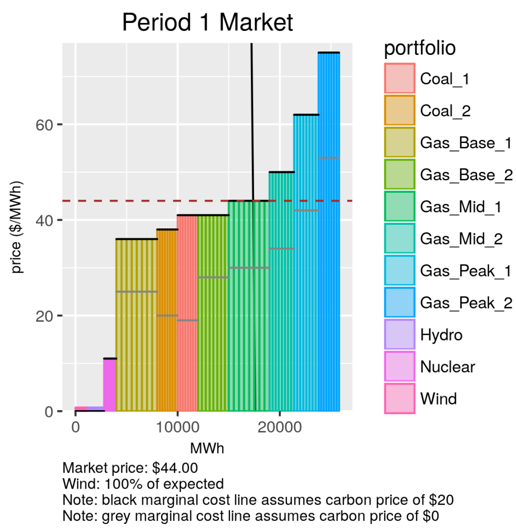
A Figures

Figure 1: Period 3 electricity dispatch for an EMG market integration simulation in which Californian gencos and several non-Californian VIUs have joined together in an integrated wholesale electricity market while a lone VIU in the Pacific Northwest has elected not to join the integrated market.

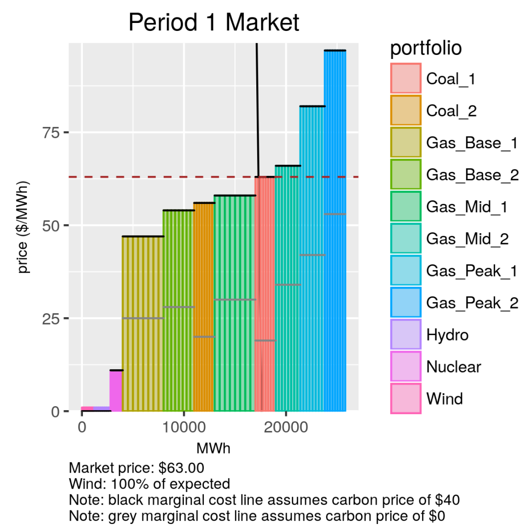


[11] GMs are able to adjust the starting carbon allowances for any agent.

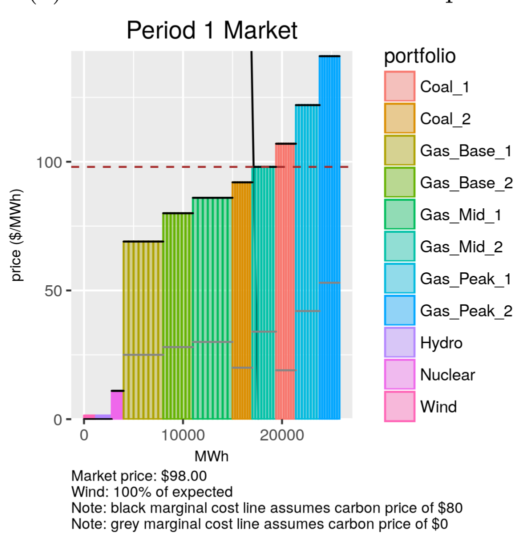
Figure 2: Merit orders induced by select carbon prices in a cap-and-trade simulation



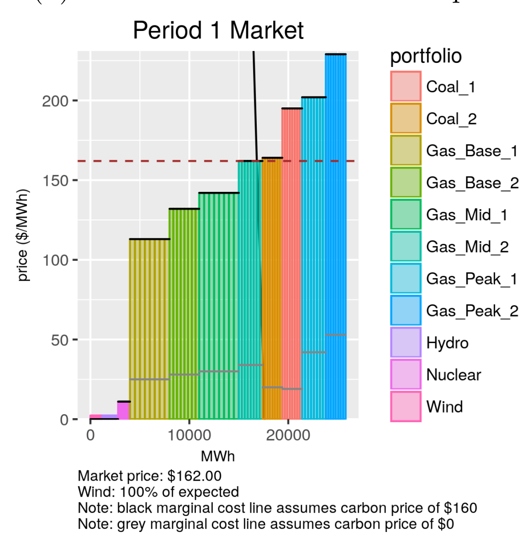
(a) Merit order with $20 carbon price



(b) Merit order with $40 carbon price



(c) Merit order with $80 carbon price



(d) Merit order with $160 carbon price

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 California's 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)
- Game-Based Investigation of Standardized Forward Contracting for Long-Term Resource Adequacy (Thurber et al., 2022)

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 the 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 implemented as a fully web-based, interactive game that can be run in real time in a classroom, workshop, or conference setting.
- The EMG is able to simulate two-node wholesale electricity markets.
- The wholesale electricity market can operate under a uniform-price or pay-as-bid auction.
- Players can take on the roles of retailers who can engage in demand management via CPR.
- The wholesale electricity market can be subject to an RPS, in which retailers must purchase RECs and gencos can buy intermittent solar and wind generation units which generate RECs that 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 allowance allocations can be determined either by the GM or via a uniform-price auction.
- Agents in the EMG can trade forward derivative contracts.
- PESD uses the EMG in a workshop for energy regulators from Ghana and the California Public Utilities Commission (CPUC).

2015

- PESD uses the EMG in a workshop for energy regulators from Nigeria and the CPUC.

- Stylized games are developed and beta-tested at several universities.
- An experiment is run in E@S&S to test the effect of initial carbon allowance allocations on the functioning of a cap-and-trade system.
- Support is added for electricity grids with more than two nodes.
- FTR financial contracts are implemented.

2016
- Stylized games are made available on `www.energymarketgame.org` for the public to play. Hundreds of users have signed up to play these games.
- PESD runs the first round of a carbon-pricing experiment in E@S&S. Gencos can be subject to a carbon tax.
- The EMG is used in a WIEB workshop on "Regional Integration of Electricity Markets". Support is added for VIU agents, energy trades, and electricity grids with nodes that may not be integrated with the others.
- Implemented basic AI agents for single-player stylized games.
- Gencos can purchase all types of generation units.

2017
- The second round of the carbon-pricing experiment is run in E@S&S.
- Used EMG to explore high-renewable scenarios in WIEB's "Western Electricity Market Forum".
- Added ability for renewables to be "must-run" and hence the possibility for "over-generation" and negative electricity market prices.
- Allowed gencos to permanently shutter generation units.
- Allowed PPA contracts.

- Made public new transmission constraint and carbon-pricing stylized games on www.energymarketgame.org.

2018
- Added ability for a genco to buy multiple generation units at a time.
- Implemented an auction of capacity contracts at the beginning of the game.
- Implemented an auction of day-ahead forward swap contracts at the beginning of the game.
- Conducted a WIEB workshop focused on long-term resource adequacy mechanisms in markets with high renewable energy shares.

2019
- Added battery storage power plants.
- Used the EMG to conduct an educational workshop for over 120 incoming Stanford graduate students at the E@S&S conference.
- Added the ability for gencos to hedge their exposure to volatile natural gas prices, and applied this functionality in a workshop on the interaction between gas-fired and renewable generation hosted by the Stanford Natural Gas Initiative (NGI).

2020
- With aid from ETH Zurich, added a European version of the stylized games to www.energymarketgame.org.
- Made further day-ahead forward swap contracts improvements to enable day-ahead markets:
  - Contracts may now be auctioned at any time in the game.
  - Gencos can schedule quantities as well as prices for renewable power plants.
  - The day-ahead market can have different transmission constraints from the real-time market.

  - Contracts can be sold by battery storage power plants.
- Used EMG in workshops hosted by Asian Development Bank Institute (ADBI) and Sim Kee Boon Institute for Financial Economics at Singapore Management University (SKBI).

2021

- Added support for SFPFCs.
- Implemented a basic pay-as-bid AI agent
- Developed new graphics for multiple-node markets.
- Created a game scenario in which gencos place "cost-based" bids for their generation units.
- Allowed gencos to take down their plants for maintenance for a full day.
- Added functionality to mandate that gencos take down their plants for maintenance for at least one period per day.
- Allowed startup costs to be incurred in real-time markets.
- Incorporated multiple-period one-node optimization including startup costs.
- Provided option for "separate" supply and demand equilibrium charts.
- Allowed multi-period forward swap contracts bundles.
- Used EMG in workshops hosted by ADBI, CPUC, Eneva, Universidad Adolfo Ibáñez (UAI), WIEB.

2022

- Created new consumer class and flexible retailer pricing plans to enable games with retail competition.
- Developed multiple-period optimization with startup costs over multiple nodes (with optional transmission constraints).

- Used EMG in workshops hosted by ADBI, CPUC, and WIEB.

2023
- Developed basic AI functionality for trading carbon allowances and RECs.
- Used EMG in workshops hosted by ADBI, Energy Leadership Institute, PUC of Texas, and WIEB.

2024
- Used EMG in workshop hosted by CPUC.

Table 1: Electricity market workshops using the EMG

Date	Location	Group	People	Topics
Dec 2013	Stanford, CA	Event: "Regional Carbon Policy"	90	Carbon trading
Apr 2014	Stanford, CA	Ghanaian energy officials	20	High-renewable markets
Nov 2014	Berkeley, CA	UC Berkeley faculty	10	RPS, cap-and-trade
Dec 2014	Stanford, CA	Event: "Financialization"	90	FTRs, RPS
Jul 2015	Stanford, CA	Nigerian energy officials	20	High-renewable markets
Sep 2015	Stanford, CA	Incoming Stanford grad students	120	Allowance allocation in cap-and-trade
Sep 2016	Stanford, CA	Incoming Stanford grad students	120	carbon tax vs. cap-and-trade
Oct 2016	Boise, ID	Western regulators / WIEB	30	Regional market integration
Aug 2017	San Diego, CA	Western regulators / WIEB	30	Supply mix changes with high renewables
Sep 2017	Stanford, CA	Incoming Stanford grad students	120	carbon tax vs. cap-and-trade
Sep 2018	Boise, ID	Western regulators / WIEB	30	Long-term resource adequacy
Dec 2018	Brasilia, Brazil	Brazilian regulators (ANEEL)	30	Long-term resource adequacy
Apr 2019	Oslo, Norway	SSV Conference workshop	20	Offer-based electricity markets
Aug 2019	Stanford, CA	Incoming Stanford grad students	120	carbon tax vs. cap-and-trade
Oct 2019	Stanford, CA	NGI conference	40	Hedging input fuel prices
Sep 2020	Remote	ADBI	30	High-renewables markets
Nov 2020	Remote	SKBI	30	RPS
May 2021	Remote	ADBI	30	High-renewables markets
June 2021	Remote	South American energy experts	30	Cost-based day-ahead markets
Aug 2021	Remote	Western regulators / WIEB	30	Day-ahead markets with congestion and convergence bidding
Oct 2021	Remote	CPUC	30	Long-term resource adequacy
Jun 2022	Salt Lake City, UT	Western regulators / WIEB	30	Day-ahead markets with congestion and convergence bidding
Sep 2022	Remote	ADBI + Singaporean officials	30	Day-ahead markets with renewable energy
Oct 2022	Remote	CPUC	30	Long-term resource adequacy
Apr 2023	Stanford, CA	Energy Leadership Institute	30	High-renewables markets
Aug 2023	Portland, OR	Western regulators / WIEB	30	Day-ahead markets with renewable energy
Oct 2023	Remote	ADBI	30	Offer-based markets (with e-learning)
Oct 2023	Austin, TX	PUC of Texas	30	Long-term resource adequacy
Jan 2024	San Francisco, CA	CPUC	30	Long-term resource adequacy

D Software

The EMG is a web-program running on an apache (The Apache Software Foundation, 2023) http server that is actually a suite of modular software programs written in Python (Python Software Foundation, 2023) and R (R Core Team, 2023). The EMG contains over 10,000 lines of Python code and 2,000 lines of R code.

In addition to the standard library it takes advantage of the following Python modules:

- coverage (Batchelder et al., 2023)
- scipy (Virtanen et al., 2020)
- selenium (Selenium Project, 2023)

It also uses the following R packages:

- dplyr (Wickham et al., 2023a)
- ggplot2 (Wickham, 2016)
- ggpubr (Kassambara, 2023)
- gridExtra (Auguie, 2017)
- igraph (Csardi and Nepusz, 2006)
- lpSolve (Berkelaar et al., 2023)
- png (Urbanek, 2023)
- optparse (Davis, 2022)
- R6 (Chang, 2021)
- rjson (Couture-Beil, 2022)
- scales (Wickham and Seidel, 2022)
- stringr (Wickham, 2022)
- testthat (Wickham, 2011)
- tidyr (Wickham et al., 2023b)

E Glossary

Glossary

artificial intelligence (AI)

Some agents in the EMG can be played by machines instead of humans. 3, 8, 23, 25, 26, 33, 35

Asian Development Bank Institute (ADBI)

The Asian Development Bank Institute is the Tokyo-based think tank of the Asian Development Bank. ADBI provides demand-driven policy research, capacity building and training, and outreach to help developing countries in Asia and the Pacific "practically address sustainability challenges, accelerate socioeconomic change, and realize more robust, inclusive, and sustainable growth". See https://www.adb.org/adbi/main for more information.. 25, 26

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. 13, 24, 25

California Public Utilities Commission (CPUC)

The California Public Utilities Commission regulates privately owned electric, natural gas, telecommunications, water, railroad, rail transit, and passenger transportation companies, in addition to authorizing video franchises. See https://www.cpuc.ca.gov/about-cpuc for more information.. 22, 25, 26

cap-and-trade

A carbon-pricing scheme where each genco must a surrender a tradable carbon allowance for each tonne of CO_2 emitted or face a financial penalty. 2, 4, 8, 16, 18, 20, 22, 23, 26, 29

capacity contract

In a capacity contract an 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 MW of that contract. The "capacity" of an intermittent renewable generation unit is usually assigned a number between the generation unit's minimum and maximum capacity. 2, 4, 8, 16, 17, 24

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. 4, 12, 18, 29

carbon allowance

A tradable certificate representing the right to emit one tonne of CO_2. 2, 4, 6, 7, 8, 16, 17, 18, 19, 22, 23, 26, 29, 36

carbon tax

A carbon-pricing scheme where each genco must play a flat tax for each tonne of CO_2 emitted. 2, 4, 18, 23, 26, 29

consumer

Downstream electricity consumers purchase electricity from retailers (or VIUs). See section 2.1.3 for more details.. 5, 6, 9, 10, 11, 17, 25, 30

critical peak rebates (CPR)

Critical peak rebates is a form of demand reduction where retailers declare a critical event for a given period and consumers are then paid a fixed rate for any reduction in consumption beneath their originally forecasted consumption.. 5, 6, 9, 10, 22

day-ahead forward swap contract

Day-ahead forward swap contract contracts are forward swap contract contracts purchased one day ahead, generally via the day-ahead market. 11, 13, 15, 24

derivative

Derivatives are purely financial contracts whose value is a function of a market-determined quantity (such as, for example, the spot price of electricity). 2, 4, 7, 8, 14, 22, 31, 32, 36

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

Energy@Stanford & SLAC is an annual multi-day conference for Stanford graduate students interested in energy. More information is available at `https://energy.stanford.edu/energystanford-slac`. 12, 23, 24

energy trade

In the context of the EMG, an energy trade is when a VIU manually buys a negotiated quantity of energy at a negotiated price from another VIU or a genco, with the energy "scheduled" on a specified transmission line. This functionality was developed to allow the EMG to explore market integration scenarios. See section 2.1.5 for more details.. 2, 4, 5, 7, 9, 23

Energy Market Game (EMG)

The Energy Market Game is an energy market simulator developed by PESD. 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 21, 22, 23, 24, 25, 26, 28, 29, 30, 31, 32, 36

Eneva

Eneva is one of the largest integrated energy generators in Brazil. See `https://eneva.com.br/en/` for more information. 25

financial transmission right (FTR)

A financial transmission right contract is a type of derivative contract that allows parties to hedge against the risk that transmission congestion will lower (for gencos) or increase (for retailers) the price at which energy is sold or bought. See 2.4 for more details. 2, 6, 7, 8, 14, 16, 23, 26

forward

Forward contracts are a type of derivative contract. The EMG supports forward swap contracts, forward cap contracts, and forward floor contracts.. 31, 32

forward floor contract

A forward floor contract is a type of forward derivative contract that hedges against the risk of low electricity prices. See 2.4 for more details. 2, 7, 15, 31

forward cap contract

A forward cap contract is a type of forward derivative contract that hedges against the risk of high electricity prices. See 2.4 for more details. 2, 7, 15, 31

forward swap contract

A forward swap contract, also known as a fixed-price forward contract, is a type of forward derivative contract that allows parties to hedge against price risk. See 2.4 for more details. 2, 4, 5, 7, 8, 14, 15, 16, 17, 25, 30, 31, 32

gamemaster (GM)

A gamemaster sets up and runs an EMG simulation. In single-player games the player acts as their own gamemaster. See section 2.1.6 for more details. 3, 4, 7, 8, 17, 19, 22

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, 7, 8, 9, 11, 12, 13, 14, 15, 16, 17, 18, 19, 22, 23, 24, 25, 29, 30, 32, 33, 37

generation unit

Generation units are power plants held by a genco or VIU that produce electrical power. 3, 4, 5, 8, 9, 10, 11, 12, 13, 15, 16, 18, 22, 23, 24, 25, 28, 29, 32, 33, 34, 37

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 by PESD researchers. 21

independent system operator (ISO)

An independent system operator coordinates, controls, and monitors an electric grid.

An ISO is very similar to a regional transmission organization (RTO). See section 2.1.7 for more details. 3, 4, 8, 11, 16, 17, 29, 34

maintenance

Generation units can be periodically taken out of service for maintenance purposes. 13, 25

megawatt-hour (MWh)

1 MWh is a unit of energy equal to 1 megawatt of power sustained for one hour. 5, 6, 9, 11, 12, 13, 14, 17, 18, 33, 34

multi-player

Multi-player games have several players playing agents in the game. Some agents in multi-player games may be played by AIs (for example, 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 to and/or taken away from the network. 2, 9, 10, 11, 12, 14, 22, 23, 25

pay-as-bid

In a pay-as-bid auction every winning bidder pays/receives the price they bid in. 4, 22, 25

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 at a negotiated price. See section 2.4 for more details.. 2, 4, 5, 15, 23

regional transmission organization (RTO)

A regional transmission organization coordinates, controls, and monitors a multi-state electric grid. Very similar to an ISO. 33

renewable

Renewable energy comes from renewable resources like wind or solar as opposed to non-renewable resources like fossil fuels or uranium. Under an RPS, non-hydropower renewable energy generates RECs. 4, 5, 10, 11, 12, 13, 15, 16, 18, 23, 24, 29, 34

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 an RPS must purchase enough RECs or face a fine. See section 2.6 for more details. 2, 5, 6, 7, 13, 18, 22, 26, 34, 36

Renewable Portfolio Standard (RPS)

A Renewable Portfolio Standard sets a target fraction of energy to be generated with renewable sources, and retailers must surrender a quantity of RECs equal to this fraction times their total served demand or face a fine for every REC they are short. See section 2.6 for more details. 2, 5, 8, 13, 18, 22, 26, 34

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, 7, 9, 10, 14, 15, 17, 18, 22, 25, 29, 30, 32, 33, 34, 37

Sim Kee Boon Institute for Financial Economics at Singapore Management University (SKBI)

The Sim Kee Boon Institute for Financial Economics at Singapore Management University (SMU). The Sim Kee Boon Institute generates financial economic research through multidisciplinary collaborations involving not only the SMU community, but also research talent from around the world as well as industry and public-sector partners. See `https://skbi.smu.edu.sg/about-skbi/vision-and-mission` for more information.. 25, 26

single-player

Single-player games have only one player participating as an agent in the game. All other agents in the game are played by AIs. 2, 3, 4, 23, 32

Standardized Fixed-Price Forward Contract (SFPFC)

Standardized Fixed-Price Forward Contracts are standardized forward contract products sold through a standardized procurement process in which a high percentage of expected demand is auctioned off several years ahead of energy delivery, and forward contract quantities in each hour retroactively adjust to match the actual load shape of energy delivered over all the hours in the compliance period. See Thurber et al. (2022) for more details.. 15, 17, 25

Stanford Natural Gas Initiative (NGI)

The Stanford Natural Gas Initiative is a collaboration of more than 40 research groups at Stanford University drawn from engineering, science, policy, geopolitical, and business disciplines that works with a consortium of industry partners and other external stakeholders to generate the knowledge needed to use natural gas to its greatest social, economic, and environmental benefit. See `https://ngi.stanford.edu/` for more information.. 24, 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. 3, 21, 22, 23, 31, 32, 36

tonne

A tonne is 1,000 kg or approximately 2,204.6 lb. Also known as a *metric ton*. 4, 18

trader

Traders do not participate operationally in wholesale electricity markets but can participate in associated markets such as those for financial derivatives, carbon allowances, and RECs. See section 2.1.4 for more details.. 2, 3, 4, 5, 6, 7

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, which is called a "transmission constraint". 2, 9, 10, 11, 13, 16, 24, 25

uniform-price

In a uniform-price auction, every winning bidder pays/receives the price that was required to clear the market. 4, 16, 18, 22

Universidad Adolfo Ibáñez (UAI)

The Universidad Adolfo Ibáñez is a private research university in Santiago, Chile. 25

vertically integrated utility (VIU)

Vertically-integrated utilities own a portfolio of generation units which they use to provide electricity to their own electricity consumers; in other words, they combine the functions of gencos and retailers. They may also buy/sell electricity from/to a wholesale electricity market or other VIUs. See section 2.1.5 for more details.. 2, 3, 4, 5, 6, 7, 9, 11, 19, 23, 29, 30, 32, 37

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 region's people". See https://westernenergyboard.org/ for more information.. 9, 23, 24, 25, 26

wholesale electricity market

A wholesale electricity market is a market in which gencos sell electricity and retailers buy electricity (and VIUs can do both). 2, 3, 5, 7, 8, 9, 10, 11, 13, 19, 22, 28, 32, 34, 36, 37

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