BLACKOUT: *Teaching Students about the Power Grid through Experiential Workshops and Video Gaming*

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Shifting political landscapes and a drive toward a sustainable future electricity market have motivated the need to educate the public about where their electricity comes from and the feasibilities, effect, and costs associated with energy policy change. For example, the electricity market in Ontario, Canada is comprised mainly of nuclear (59%), hydroelectric (30%), natural gas combustion (10%) and very minor contributions from renewables (wind and solar) and liquid fuels.[1] In contrast, in 2017 the United States produced most of its power from fossil fuels (31.7% natural gas and 30.1% coal), with nuclear (20%), hydropower (7.5%), wind (6.3%) and solar (1.3%) comprising most of the remainder.[2] However, the electricity generation landscape in Ontario is changing as coal plants are decommissioned and their capacities replaced with, largely speaking, natural gas combustion plants and renewables. A similar trend is seen in the United States, where regulations via the Environmental Protection Agency have affected the efficacy and profitability of coal-fired power plants and continue to shift in an unsettled political landscape. The question is: why? What are the driving forces behind these changes, and, more importantly, what are the implications of these changes to the economy, environment, and ultimately the consumer? What sorts of challenges are present to hinder or dissuade us from using a certain technology, whether it be renewables, natural gas or nuclear plants? How does the electricity market in Canada impact the decisions made by providers, and how do these decisions ultimately end up impacting the public? These are questions that must be answered by future generations of engineers and are precisely what *BLACKOUT!* intends to have high school and engineering undergraduate students ponder.

BLACKOUT! is a turn-based online video game and classroom workshop designed to educate secondary school and undergraduate engineering students about the power grid and its market, the different methods of production of electrical power, the ways in which they contribute to the electricity mix, and the trade-offs and limitations of various technologies. The game has a selection of maps (boards) on which the game can be played, each with different characteristics such as the size and distribution of major population centres, and the amounts of water, sunlight, and wind energy available. For the examples shown in this paper, the Ontario map was selected since it relates most directly to the student participants, but all maps are well suited to demonstrate the interactions between energy, the environment, politics, and economics. The key objective of this game is to help students get a better understanding about how the power grid works so that they can make intelligent and informed decisions regarding energy policy in the future. Moreover, the game aims at engaging the interest of students at the high school and undergraduate level to increase awareness and

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raise interest for the discipline of chemical engineering and (more specifically) the design and development of energy systems.

At present, *BLACKOUT!* is used extensively at McMaster University in Hamilton, Ontario, Canada in a variety of venues. The Learning Enrichment Advancement Program (LEAP) engineering academy runs three summer sessions of *BLACKOUT!* to teach grade 9-12 students about the fields of systems engineering, energy systems, and energy policy in Canada. It is worth noting that students elect to participate in this workshop voluntarily and that the participation level in the summer of 2017 resulted in *BLACKOUT!* being one of the most popular elective activities available. Furthermore, undergraduate courses in chemical engineering at McMaster (4A03/6A03: Energy Systems Engineering) play *BLACKOUT!* as a classroom activity to unify the concepts of process design and operation with public policy and economics.

Use of Games in Classroom Settings

Active learning strategies have garnered a lot of attention over the last decade, particularly in the field of chemical engineering.[3,4] It is becoming commonplace for university instructors and secondary teachers to use active learning strategies to maintain the focus and interest of students while simultaneously delivering course content. Video games are one of several media types (much like videos, recordings, or interactive online learning tools) that can be used to enhance learner interaction and interest in an age where media is a huge contributor to student learning. However, video games are also a method of active learning that, when used alongside traditional methods of instruction, allow learners to construct new concepts and ideas based on their individual experiences rather than continuously receiving passive knowledge.[5,6] However, a video game extends beyond the typical paradigm of an interactive learning tool by presenting the learners, or players, with a series of challenges that are meant to convey a sense of accomplishment when they are overcome.[7] The learning experienced in a video game is constructed from the ground-up, and typically includes a cycle of concept recognition, reflecting on choices made, hypothesizing the impacts of future choices, and testing these hypotheses in a simulated setting where the real-world consequences of failure are lower.[7,8] Moreover, games can include competitive elements to keep players invested and engaged. The result is a sense of motivation to improve one's skills and knowledge of the game's world, which in turn can be translated into improved knowledge about the educational material on which the game is based. The actions taken by the player continuously affect how the game unfolds, resulting in an organic and adaptive learning experience that is unique to each student. There have been multiple publications advocating the use of video games to enhance student learning, resulting in the adoption of games at the high school and post-secondary levels.[7-10]

Relation to Chemical Engineering

A prominent facet of chemical engineering is the design, operation, and management of energy systems. Although the focus of these topics is typically restricted to the design and selection of unit operations, it is also critical to keep the policy and economic sides of energy systems in perspective. In typical process design classrooms at the undergraduate levels, rigorous process design is combined with a rudimentary coverage of economics so that the students may perform an objective evaluation of the value of a plant design. *BLACKOUT!* is intended to step back from plant design and focuses rather on the broader impacts of the triple bottom line of sustainability on decision-making for chemical engineers.

Purpose of this Study

The express purpose of this study is to develop, deliver and measure the effectiveness of an educational video game called *BLACKOUT!* that outlines the functions, advantages, and disadvantages of the five major non-hydroelectric power supplies in Canada and the United States. The target audience for this game and workshop are senior high-school students and undergraduate university students with an interest in the fields of process systems, energy systems and chemical engineering. Data have been collected from a number of surveys given to five test groups as recently as August 2017 in order to assess the effectiveness of the game at contributing to students' knowledge of the five power systems presented in the game (coal, natural gas, nuclear, wind and solar), how the bidding and electricity spot-price system works in open power markets (albeit to a simplified extent) and the importance of meeting consumer demand throughout a day in which demand is constantly changing according to typical demand patterns. The following section details the design of the workshop and the specific learning outcomes of this study.

BLACKOUT! WORKSHOP DESIGN

BLACKOUT! is presented to students as a two-part workshop and game simulation (referred to here as "the activity"). The setting of the activity involves at least one game-master or facilitator (typically the class teacher or instructor) that oversees ending turns, providing information and otherwise facilitating the workshop presentation and game. *BLACKOUT!* supports anywhere from two to eight participants (players), but six to eight players is recommended for the best experience, each with their own computer, tablet, or smart phone. If there are more than eight participants, players can form teams so that eight teams are formed in total. BLACKOUT! includes an observer game mode in which anyone not logged in as the team leader can still view useful maps, data and game activity on a separate device while the game is in progress. Thus, teams of more than one student can either cluster around one device, or, each student can use their own depending on available resources.

The total activity is intended to be completed in approximately two hours; a summary of each activity component can be seen in Table 1. Before the workshop begins, the survey (discussed in section *BLACKOUT!* workshop design, subsection Participant Survey Design and Delivery) is distributed and the first question is answered. The first 20 minutes of the activity are set aside for the introductory presentation and question/answer period (workshop portion of the activity), which outlines the five power sources available in the game both in the real world (how do we make electricity from coal? What about nuclear fuel sources?) and how these concepts translate to the actual gameplay. The concepts of peaking power, the electricity market (and bidding system) and the overall objectives of the game are introduced. Finally, the graphical user interface (GUI) and methods of control for the players are presented and discussed with a brief example. The next 10-minute period is reserved for the students to log on, create team names and explore the player GUI. Teams may also use this time to discuss their short- and long-term strategies for the game ahead.

Once all players and teams are ready to start, the game portion of the activity begins. It is suggested that 10 minutes are set aside for the first turn of the game as students are still becoming familiarized with the GUI and game mechanics (all game mechanics are discussed in section Playing the Game). It is worth noting here that the instructor has control over when the turns end and thus can confirm with the teams that they are ready to proceed before doing so. The second to fourth turns can take up to 5 minutes as the players continue to gain familiarity with the game. The next eight turns can be estimated to take around 3 minutes each, with the instructor confirming that everyone is ready before proceeding. For the final 12 turns, it is advised that the instructor imposes a 2-minute maximum turn time to introduce a sense of urgency and to ensure that the game is finished within the two-hour allotted time frame. At this point the game dynamics are such that less time is usually required for the later turns anyway. A future point of improvement for *BLACKOUT!* will be the implementation of an automated turn clock with a live countdown on each player's GUI. This will both ensure that the game proceeds at an appropriate pace while eliminating the need for the instructor or game master to intervene. This will also permit students to play the game outside of a classroom setting.

Finally, once the game has been completed and the winners have been announced, the students are asked to complete the remainder of their survey. An open discussion about strategies, learning experiences, what worked or did not work, and what strategies players might use in future games rounds out the remainder of the allotted time. It is up to the instructor to facilitate these discussions by asking questions probing the lessons learned by the students, specifically regarding some of the advantages and disadvantages of certain fuel types. Note that it is important the students complete the survey before the open discussion portion so that their answers are not influenced by the other students.

TABLE 1
Breakdown of typical *BLACKOUT!* workshop and gameplay timeline.

Activity Number	Description	Suggested Time (min)
1	Workshop presentation	20
2	Player login and GUI introduction	10
3	Turn 1	10
4	Turns 2 – 4	15
5	Turns 5 – 12	24
6	Turns 13 – 24	24
7	Debrief and discussion	15
TOTAL	**Total workshop length**	**118**

Intended Learning Outcomes

The intended learning outcomes (ILOs) are as follows: By the end of the workshop, the student should be able to:

1. ***Discuss, compare, and contrast the benefits and drawbacks of renewable power sources and list strategies to overcome these challenges.***

   Renewable electricity is a huge driving force toward a sustainable and economically viable future. One of the outcomes of BLACKOUT! is that students will develop an understanding that the benefits of renewable power sources (low operating costs once constructed, essentially zero carbon emissions) are not without their disadvantages (intermittency, unreliability, low capacity), and that they will likely need to be balanced with more traditional power generation methods in the foreseeable future.

2. ***Acknowledge location restrictions and advantages of certain types of power generation.***

   All nuclear and fossil fuel-based power plants require a significant cooling source, which is usually provided by large bodies of water. BLACKOUT! restricts users to placing any nuclear or fossil fuel plant only adjacent to large bodies of water or major rivers to deliver this message. Moreover, certain locations, based on average annual wind speed and exposure, result in more efficient renewables. BLACKOUT! provides players with average wind speed and solar insolation maps based on real data so that they can apply this concept to planning out their plant locations.

3. ***Compensate for the difficulties of peaking power and non-steady demand through power plant selection and bidding strategies.***

   BLACKOUT! uses a simulated demand profile that includes a typical peak at mid-day and a trough during the night time. This concept, combined with the potential variability of renewable power sources, will drive home the idea that reliable power sources are important to meet a constantly changing demand.

4. **Compare and contrast the relative costs of building and maintaining various types of power plants.**

   The costs of building and operating the various types of power plants in BLACKOUT! are designed to deliver not only a balanced game experience, but to reflect the relative costs of each power system in reality. For example, solar plants have high capital costs but low operating costs while natural gas plants are (historically speaking) just the opposite.

5. **Apply a conceptual understanding of the bidding system for power in open market scenarios.**

   The power grid in most parts of North America is an open and competitive market, which leads to difficulties for the market participants due to constantly changing prices and demand. One of the objectives of BLACKOUT! is to help the students understand how an auction-based system impacts the spot-price of electricity, and therefore potential profits (or losses).

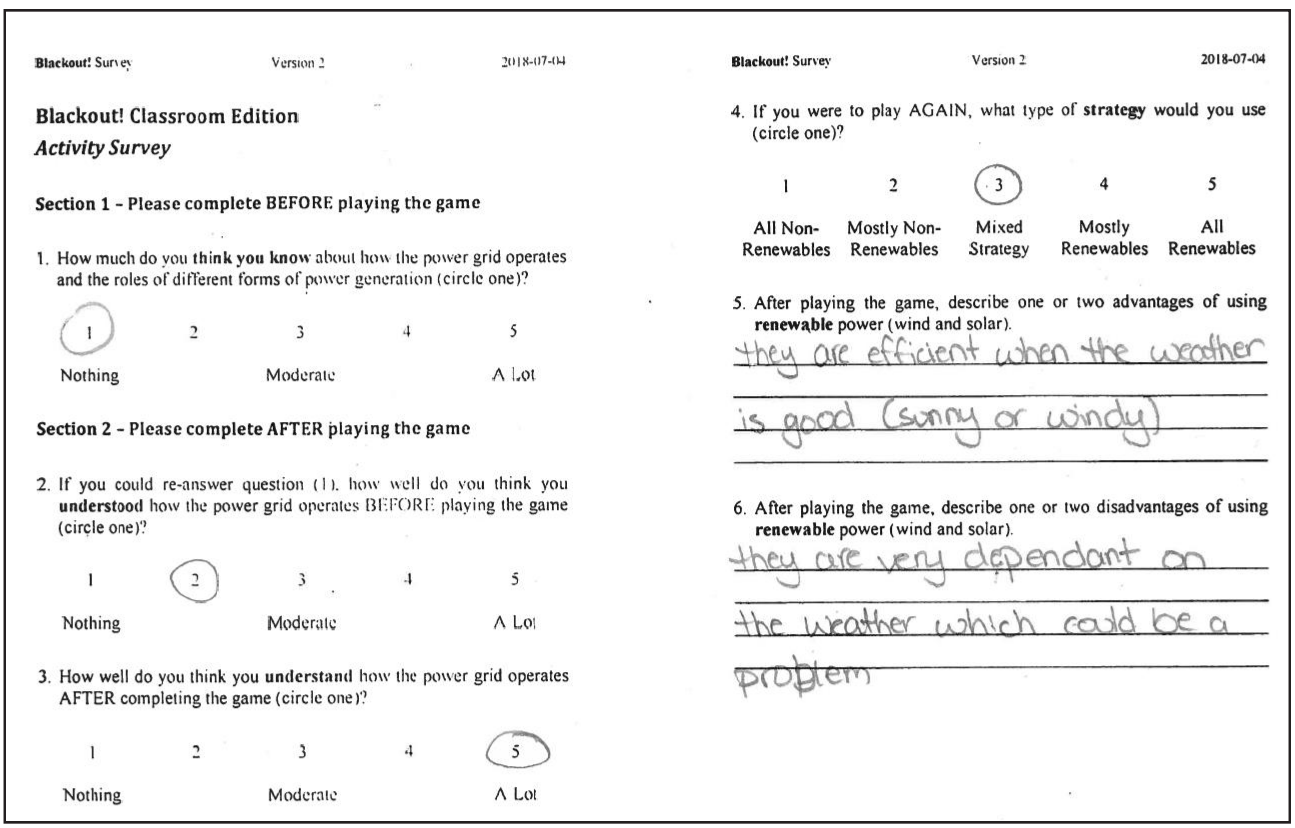
6. **Deliver a summary of the most common CO_2 emission regulations and their potential impacts on economics and future energy strategies for the power industry.**

   This has not yet been added to the current version of BLACKOUT!, but our future work includes developing the ability to play scenarios where CO_2 taxes (the value of which is an option for the instructor to specify) are included and emissions from each plant type are tallied based on real output data for each type of plant. Each fossil-based plant will therefore incur some extra operating cost associated with its CO_2 emissions. The inclusion of CO_2 taxes is intended to allow students to experience how their use will change the electricity generation landscape through economic incentive. Furthermore, provided that the other market conditions are held constant, it will also exhibit the trade-off between reliably meeting demand with renewables and having reliable base-load power at high costs.

Participant Survey Design and Delivery

The participant survey was designed for high school students and to be as short as possible while still obtaining useful information. The critical reason for having a short survey was to obtain truthful and candid data from the workshop participants about their experiences with *BLACKOUT!* without risking resentful or hurried completion. Consequently, six questions were used in the design of this survey. A sample survey given to the students is provided in Figure 1.

The survey includes four questions that utilize Likert scales to judge the relative opinion of each participant. The first question is to be answered at the beginning of the *BLACKOUT!* workshop (before the game is played) to ob-


Blackout! Survey Version 2 2018-07-04

Blackout! Classroom Edition
Activity Survey

Section 1 - Please complete BEFORE playing the game

1. How much do you **think you know** about how the power grid operates and the roles of different forms of power generation (circle one)?

1 2 3 4 5
Nothing Moderate A Lot

Section 2 - Please complete AFTER playing the game

2. If you could re-answer question (1), how well do you think you **understood** how the power grid operates BEFORE playing the game (circle one)?

1 2 3 4 5
Nothing Moderate A Lot

3. How well do you think you **understand** how the power grid operates AFTER completing the game (circle one)?

1 2 3 4 5
Nothing Moderate A Lot

Blackout! Survey Version 2 2018-07-04

4. If you were to play AGAIN, what type of **strategy** would you use (circle one)?

1	2	3	4	5
All Non-Renewables	Mostly Non-Renewables	Mixed Strategy	Mostly Renewables	All Renewables

5. After playing the game, describe one or two advantages of using **renewable** power (wind and solar).

they are efficient when the weather is good (sunny or windy)

6. After playing the game, describe one or two disadvantages of using **renewable** power (wind and solar).

they are very dependant on the weather which could be a problem

Figure 1. *Sample filled-out student survey to be completed as a part of the BLACKOUT! workshop/game activity*

tain a benchmark of what the students think they know about the power grid beforehand. The second question is intended to give the participants a chance to look back at their first answer after completing the activity for them to gauge whether they knew more or less than they originally thought. Any statistically significant change between questions one and two would indicate that the student has self-identified a discrepancy between their original actual and perceived understanding of the power grid. The third question is meant to gauge the opinions of the students regarding the value of the *BLACKOUT!* workshop in improving their understanding of the various sources of electrical power and the intricacies of the power grid. A statistically significant difference between questions one and three indicate that the workshop is perceived by the students to be successful in achieving the ILOs.

The fourth question gives the students an opportunity to reflect on the strategy that they employed throughout the game, and whether they would change that strategy if given a chance to play again. This question is meant to test whether ILO numbers 1, 2 and 4 have been achieved; specifically, that there are advantages and disadvantages of each power source and that a balanced mix of each type is critical for trading off cost, reliability and (when the CO_2 emissions data is added) environmental impact.

The final two questions, rather than using a Likert scale, ask the students to list their thoughts on the advantages and disadvantages of renewable power sources. These questions directly correlate to ILO number 1. Common answers or comments can be extracted from these very short written response questions to identify the most prominent student experiences regarding the use of renewable power sources, both to assess the workshop's ability to deliver on the ILO and to allow for balancing or improvements to the game in future iterations.

PLAYING THE GAME

Objective of the Game

The scenario of the *BLACKOUT!* game portion is to take the role of an electricity provider participating in the Ontario market. The main objective for each player or team of players is to sell as much power (in units of MW-h; one point is awarded per MW-h provided) to the market as possible (an individual goal), while simultaneously ensuring that the all players collectively meet the changing demand each turn (a cooperative goal). At the end of the game (24 "one-hour" turns), the victor is declared as the player that has provided the most contracted power to the grid in total. One of the most interesting facets of *BLACKOUT!* is that the amount of power sold by each player in a given turn is meaningless until the game is completed; it is therefore up to the players to decide when and why to invest in certain types of power to achieve the most points by the end of the game. Constructing new plants can only be done with available capital (therefore requiring the players to generate revenue each turn), but profitability is ignored when calculating the final score. Players must also be careful not to go bankrupt. Finally, a blackout will occur if players do not meet the cooperative goal of producing enough power to meet demand. After three blackouts, the game ends and everyone loses.

Graphical User Interface and Information Available to Players

BLACKOUT! is provided as a web-based application accessible via any modern web browser with no extra downloads. Students and instructors can play through the web interface on any internet-connected device. The GUI is optimized for computers and tablets (all important information and buttons are seen on one screen, and the screen elements reposition themselves if a tablet is rotated horizontally or vertically), but it will also work on a smart phone. The game has been tested successfully with Internet Explorer 11 and higher, Mozilla Firefox 31.0 and higher, and Google Chrome. All game code is hosted on the process systems engineering education community servers at http://psecom-

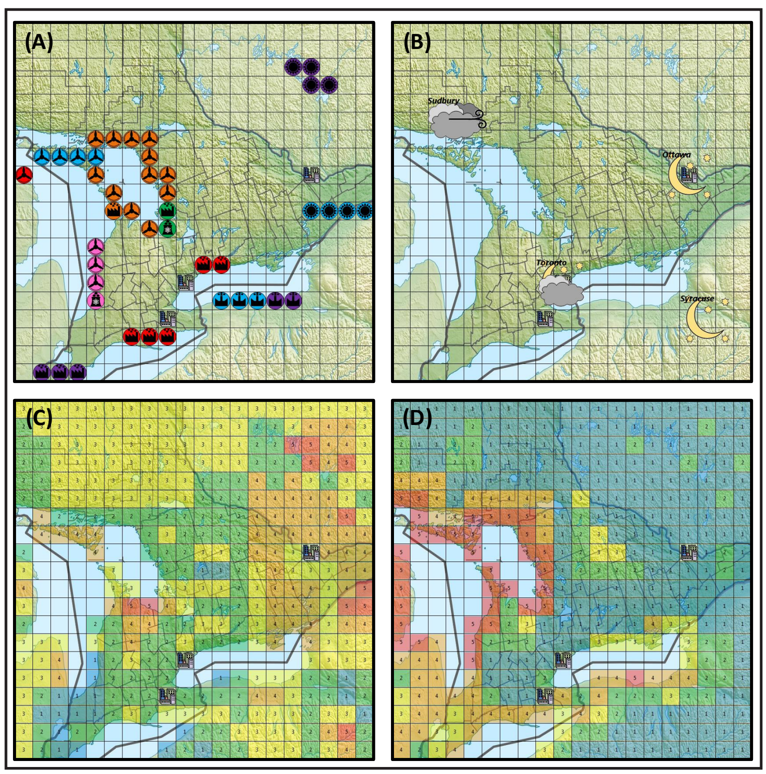


Figure 2. *Sample game board screen shots in the early stages of a 6-player game. Panel (A) shows the current plant locations for every player; Panel (B) shows the current weather forecast for the turn (it is 5am); Panel (C) shows the average annual solar insolation rating for each location on the board; Panel (D) shows the average annual wind exposure for each location on the board.*

munity.org/LAPSE:2018.0136.

BLACKOUT! has been designed to offer a streamlined GUI in which all the available player information is accessible either at once or within one mouse click. The actual game board is a map of the geographical region being simulated in the game (Ontario in the examples provided in the proceeding figures) broken up into a 20 × 20 grid of spaces. Any plants owned by the player or other players are represented by an image depicting the type of plant (symbol) and the owner (image fill colour). Multiple plants cannot occupy the same space on the playing board. Spaces containing only water or those that are pre-occupied with major cities also cannot be built on. Please see section Playing the Game, subsection Power Sources Available for the types of power plants available and their corresponding images. There are four main views of the map available to the user, examples of which can be seen in Figure 2. The *Buildings* view allows the user to see the most current layout of the plants constructed by all players (see Figure 2(A), which contains a sample of buildings constructed at the beginning of a 6-player game). The *Weather* tab provides the current weather forecast information for the main cities for the next turn, which should be used by the player to estimate their potential renewable outputs for the turn (Figure 2(B)). The *Average Sun* and *Average Wind* tabs give the user insight as to what spaces on the board provide the best average wind exposure or solar insolation ratings over the course of a year, from which one can infer the optimal locations for renewables (Figure 2(C) and (D)).

Running along the side of the game map, a panel is displayed that contains all other relevant information to the player. Shown in Figure 3 is a screenshot for the green team at the beginning of round 1. The information panel shows:

A. *The scoreboard and capacity of all players in the game. Capacities with a range indicate that the player has peaking power via natural gas plants or renewable power plants with a range of potential outputs.*

B. *A plot of the forecasted demand for the entire game (24 game-hours or "turns"). The current turn's demand is highlighted in red.*

C. *An entry form where the player can input their pledged production and bid price.*

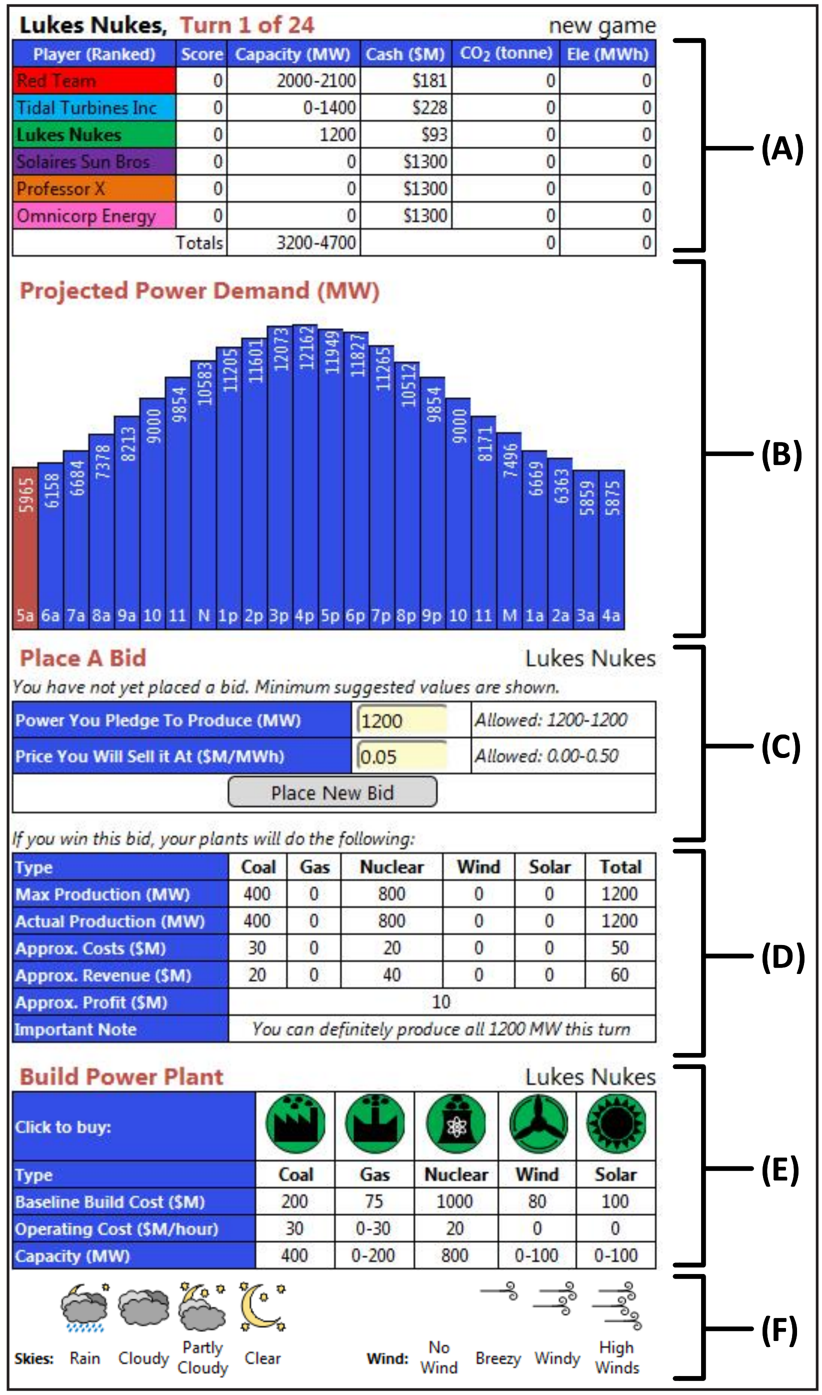


***Figure 3.** Player information panel on the BLACKOUT! game screen. (A): The current score and capacity of each player; (B): The forecasted demand for the game (blue bars) and the demand for the current turn (red bar); (C): Entry form for the player to pledge their power provision for the turn and bid a price to sell at; (D): Breakdown of the power sources owned by the player and the estimated profit for the turn based on their current pledge and bid; (E): The building panel showing the capital cost, operating cost, and capacity of each type of power plant available; (F): Weather symbols so that the forecast may be interpreted*

The minimum allowable pledge is equal to the player's base-load capacity, and a player may not bid higher than their maximum production. The maximum bid price is $0.50 per MW-h produced.

D. *A table that breaks down the player's current capacity by power plant type. This table also shows the anticipated operating cost and revenue contribution of each plant given the current bid and pledge, and projects a range of potential profits. Note that the profit projection does not account for if the player does not sell power due to overbidding.*

E. *A table that shows the characteristics of each power plant. By clicking on an icon, the player may place the given plant on the game board, if they can afford it.*

F. *A summary of the potential weather conditions in the game so that the player may easily interpret the weather forecasts. The skies forecast can be used to estimate solar plant outputs, and the wind forecast may be used to predict wind farm outputs.*

Power Sources Available

There are five different types of power available to the players in *BLACKOUT!*: coal, natural gas, nuclear, wind and solar voltaic. Although hydroelectric power is one of the most efficient and cost-effective methods of power generation (especially in Canada), all worthwhile sources have been essentially utilized already and thus it is assumed for the purposes of the game that no further plants can be built. The workshop portion of the *BLACKOUT!* activity gives a very basic overview of the characteristics of each plant in the real world. Issues such as how energy is converted to electricity in a given plant, the plant's relative popularity on the Canadian and global scale, and other political and environmental considerations are discussed. The workshop then describes how the plants operate in the game itself, giving economic statistics (price, operating cost, capacity etc.) as well as any other ways in which their use impacts the game. A summary of the various plants available is provided in Table 2. It must be noted that the actual costs and capacities of the plants available in *BLACKOUT!* are chosen so that they are relatively similar to reality but also fit within the game's scale. Furthermore, assumptions such as no operating cost for renewable power options and full peaking capabilities of the natural gas plants are acknowledged to be simplifications, but for the sake of gameplay these assumptions are used to improve the game's playability while also conveying general concepts such as low-cost renewables and peaking plants. The advantages and disadvantages of each power plant were chosen specifically to align with the ILOs discussed in section *BLACKOUT* Workshop Design, subsection Intended Learning Outcomes. A more detailed description of each type of power plant offered is provided in an appendix to this paper.

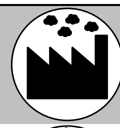
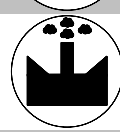
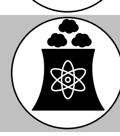
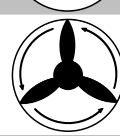
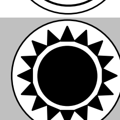
Game Mechanics

BLACKOUT! uses a turn-based gameplay structure in which all the events for the current turn are resolved at the end of the turn, which is controlled by the instructor or game master. The following sections discuss the turn structure and give a basic overview of how the game determines the bidding priority, weather events, and renewable power output for each turn.

Basic Overview of Turn Structure

- **Game Setup** – At the beginning of the game the instructor/game master can choose which map to play, define whether or not CO_2 taxes will be implemented (and what their value is), select the time of day the game will start at and number of turns (default is 5:00 A.M. with 24 one-hour turns) and decide what the starting cash for each player will be. Recommendations for ideal gameplay conditions are provided on the instructor's GUI.
- **Building/Bidding Phase** – The majority of each turn is open for the players to build new plants, assess the results of the previous turn, and strategize for the current turn. This will likely involve spending money to increase capacity (if desired) and estimating the potential output

TABLE 2
Summary of plants available in *BLACKOUT!*

PLANT TYPE	ICON	Advantages	Disadvantages
Coal **Cost: $200** **Cap: 400 MW** **Turn Cost: $30**		• Moderate purchase cost • Consistent / Predictable • Low operating cost	• Must be built near water • High CO_2 (if applicable)
Natural Gas **Cost: $75** **Cap: 0-200 MW** **Turn Cost: $0-30**		• Controllable output • Low capital cost	• High operating cost • Must be built near water • Low capacity
Nuclear **Cost: $1000** **Cap: 800 MW** **Turn Cost: $20**		• Lowest long-term cost • Low CO_2 emissions • High capacity • Consistent / Predictable	• High initial cost • Must be built near water
Wind **Cost: $80** **Cap: 0-100 MW** **Turn Cost: $0**		• No operating cost • No CO_2 emissions • Medium long-term cost • Can be built anywhere	• Intermittent source • Weather dependent • Low capacity
Solar **Cost: $100** **Cap: 0-100 MW** **Turn Cost: $0**		• No operating cost • No CO_2 emissions • Medium long-term cost • Can be built anywhere	• Intermittent source • Weather dependent • Low capacity • Does not work at night

of any renewable power sources by using the nearest weather forecast.

Players may build a new plant, provided they have the resources, by clicking on one of the plant construction icons in Figure 3(E) and placing it on the board. The cost of construction is equal to the base cost of the plant (Table 2) plus transmission line costs, which increase linearly depending on how far away the plant is from its nearest population center. Furthermore, crossing a provincial or state border (into Quebec for this example) adds a $10M fee to the plant cost, and crossing an international border (into the United States for this example) adds $20M. These fees are meant to emulate the tariffs and administrative costs associated with crossing political boundaries. When a potential plant icon is clicked, the map will change to show all available spaces for construction and the total cost of placing the new plant on a given square, as shown in Figure 4. Shaded spaces (such as those entirely on water or those not close to a large body of water when requesting a fossil fuel plant) are shaded to indicate that it is not possible to build in those locations (see ILO 2).

Once the player constructed any desired plants and estimated the output of their renewable power sources for the turn, they are required to pledge a certain amount of power to provide to the grid and bid a price at which they are willing to sell. The minimum allowable pledge for a given turn is equivalent to their base-load capacity (the sum of all nuclear and coal-fired plants, which are "always on" at a fixed capacity), and the maximum pledge is equal to the maximum possible capacity of all plants they own. It is up to the player to use the information available to them to decide how much they can reliably sell to the grid and what price they should bid to try to both sell as much power as they can and make the most money possible (which are sometimes competing objectives). The bid and pledge results for all players from the previous turn, the capacities and types of power plants owned by all players, and the current weather conditions will always be available to each player to help them make the most informed decision possible. After all players have successfully placed a pledge and bid, the teacher may end the turn, which initiates the renewable production and turn resolution phases.

- **Turn Resolution Phase.** When all of the pledges, bids and supplies for each player have been determined, the game decides which pledges will be bought and how much each of the natural gas plants should produce. The algorithm for handling the bids is complex and is thus omitted for the sake of brevity, but the general idea is that the market buys up bids starting with the least expensive option and then buys more expensive pledges until the total demand has been met. If there is a surplus of supply, it does not buy any extra power produced and those players who have produced it receive no revenue for it (but still may have incurred the costs of production!). If there is inadequate supply, then there is a blackout. Natural gas plants are automatically turned up or down appropriately so that they will always turn up if they are needed for sale or to meet demand, or otherwise they are turned down if the electricity is not purchased. There are penalties associated with not being able to fulfill a pledge that was purchased by the market, and there are rules which cause players to automatically buy surplus power from each other (at higher prices) when this happens to fulfill an unmet pledge. There are other rules for complex but rare events that could occur when pledges do not meet demand, but there is capacity to do so. All of these situations are resolved automatically by the software.

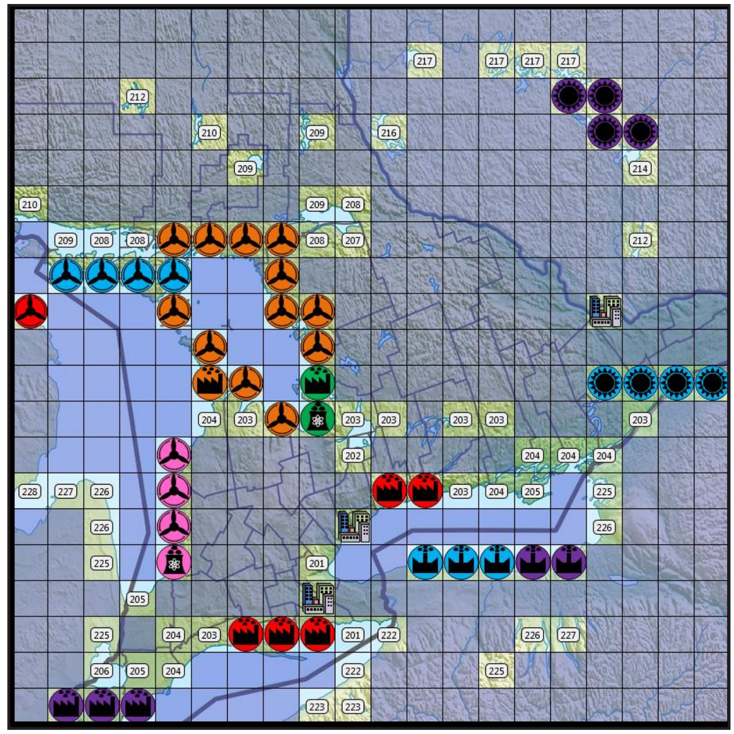


Figure 4. Screenshot of a player requesting the construction of a coal power plant. The numbers indicate the total cost of placing a plant in each location and shaded spaces indicate that the plant may not be placed there.

General Strategy and Game Progression

BLACKOUT! is interesting because it allows for many strategies to be successful at different points throughout the game. Furthermore, the game's technical and social dynamics align well to the ILOs of the game to deliver a truly enriching experience to each student. In our tests, we found that the current leader (the one with the most points at that point in the game) changed rather frequently throughout most games, which makes it very exciting for all players.

Provided that the recommended 5:00 A.M. starting point is used, the early rounds of *BLACKOUT!* will be focused on the players working together to meet the increasing demand of the market every turn (hence avoiding blackouts and therefore allowing the game to continue). It should quickly become evident that, although they are inexpensive and environmentally friendly, renewable power sources will typically fail to ensure that demand is met at every turn due to their low capacity and unreliability within the framework of the game. Moreover, the players are usually not given enough money collectively to satisfy the early-round demands with renewables alone. It therefore becomes evident in the early rounds that reliable, high-capacity power such as that provided by the base-load plants is important to meeting demand, especially as the demand begins to rise. These early-game dynamics correlate nicely to ILOs 3 and 4. With regards to bidding tactics, the generally low amount of available supply will usually result in very high bidding prices early on since the probability of having a bid sold is very high. These high prices are necessary while power demand is on the rise in order for the players to build additional plants and meet demand at later turns. The higher prices charged by each player while moving toward the peak of the day correlates nicely to ILOs 3 and 5, while by utilizing high prices to earn an income the players will be forced to relate their success to ILO 4 and simultaneously plan for lower prices in the future (should they anticipate such an event). It is also important to note that while demand is rising (the first 12 turns), it is possible for a player to come back from bankruptcy due to the generally high bids. Consequently, any player that runs out of money and declares bankruptcy in the first 12 turns will have their score cut in half but will be allowed to continue playing.

Once the peak demand for the day has passed, the overall game strategy, tactics and advantages of certain power plants change dramatically. As the demand begins to decline, the collective capacity of the players will begin to be far too much (the market will become saturated). It is not uncommon for the collective base-load capacity of the players to be sufficient to meet demand during the last 6 turns without the use of renewables or gas plants at all. Consequently, the later turns of the game produce a bidding war between players who are trying to sell as much power as possible. Renewable power sources are very valuable at these stages due to their low operating costs, which allow for players to bid lower prices than competitors with large amounts of fossil fuels. This rapid decrease in prices, the resulting price advantages for certain types of power, and the corresponding bidding war between players correlate to ILOs 1, 3, 4 and 5. If certain players decided to invest heavily in non-renewable power options there is a strong chance that they were successful early due to their high capacity and capability of selling at high prices; however, toward these later stages of the game, their obligation to pay the operating cost for non-renewable plants will make it very difficult to avoid losing money *and* capacity to players with a more renewable-focused capacity. As a result, without proper planning it is very possible that many players with high non-renewable capacities will go bankrupt during the later stages of the game. After the 12th turn, if a player goes bankrupt their score is immediately set to zero and they (and their existing plants) are removed from the game.

Due to this general trend moving from high prices to a bidding war, it is possible to win with any combination of power plants. However, to do so the players are required to critically identify and assess the limitations and advantages of each type of plant so that they may be used in a winning strategy.

CLASSROOM IMPLEMENTATION AND RESULTS

Eight games of *BLACKOUT!* have been tested at the time of writing this manuscript with high school senior students attending the engineering and science camp at McMaster University during the summers of 2014-2017. Each game had a full eight teams, with teams ranging from one to four players each, depending on attendance. In total, roughly 150 students were given the full workshop/game experience, and five of the eight games played resulted in the collection of user survey data for a total of 78 survey entries.

Quantitative Survey Results and Discussion

As mentioned in the survey and workshop design section, several Likert scales were used to obtain some quantitative evidence of the effectiveness of *BLACKOUT!* at achieving the intended ILOs. The first and third questions on the survey essentially asked the same thing: what is the perceived knowledge of the student regarding the types of power available and the electricity grid and market in Ontario? The first question was asked before participating in the workshop and game activity, and the third question was filled out after the activity was completed. Perceived knowledge had to be tested since it would not have been reasonable to test the true knowledge of each student during the two-hour workshop. The comparative results for questions 1 and 3 are shown in

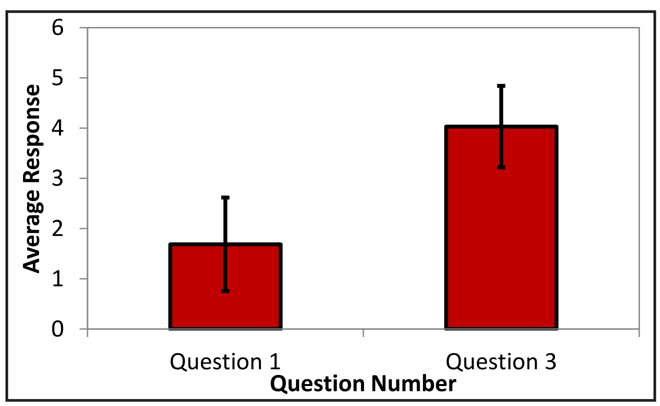


Figure 5. *Numerical results for questions 1 and 3 on the BLACKOUT! survey. The error bars represent the sample standard deviations of the results.*

Figure 5. There is a significant difference between the perceived knowledge before (mean of 2.2, standard deviation of 1.0) and after (mean of 4.1, standard deviation of 0.7) the workshop and game activity. This indicates that the students are significantly more confident in their knowledge of how power is produced, the trade-offs between certain power sources, and how the spot-market and power grid in the Ontario market work. These questions are meant to provide insight into the effectiveness of *BLACKOUT!* at achieving ILOs 1-5, and it is clear from the data collected that *BLACKOUT!* is succeeding in this regard.

The fourth question is intended to relate to ILOs 1 and 2, particularly to assess whether the workshop participants understand that a balanced power mix is the best way to ensure reliable supply for the market while also trading off costs (and, in the future iterations of the game, CO_2 emissions). The average response to question 4 is 3.1 with a standard deviation of 0.6, which strongly suggests that the workshop participants acknowledge this concept. One of the key takeaways for the *BLACKOUT!* activity is for students to understand that there is no simple fix to achieving a reliable, sustainable future, but rather a balanced mix will yield the best result for producers (the players) and consumers (the simulated market) alike.

Qualitative Survey Results and Discussion

Along with the quantitative questions posed in the student survey, brief open-ended questions were used to allow for the students to make their own observations about the use of renewable power sources. Specifically, these questions were meant to provide more detailed information on the effectiveness of *BLACKOUT!* at addressing ILOs 1 and 4. It is important to note that these questions require written responses and thus responses mentioning these ILOs are entirely unsolicited and therefore (hopefully) unbiased.

When asked to identify one or two of the advantages of using renewable power, 90% (70 out of 78) of students identified that renewable power plants have a relatively low operating cost when compared to traditional fossil fuel-based options. This indicates that *BLACKOUT!* does an excellent job of demonstrating the inexpensive nature of renewable energy sources by directly comparing these options with fossil fueled plants in the same game setting. Furthermore, 40% (31 of 78) of students identified that renewable power sources have a relatively low initial capital investment (on a per-plant basis) than coal or nuclear plants.

When asked to identify some of the potential disadvantages of renewable power sources, 72% (56 of 78) of students identified that renewable power sources are intermittent and that this was a problem when trying to achieve high or predictable capacities. Furthermore, 73% (57 of 78) of students mentioned that due to the intermittency, time-of-day and weather-dependency of renewable power options, the abilities of renewable sources to meet demand at any given time was very low. Finally, 28% (22 of 78) of students indicated that renewables have a relatively low capacity, and therefore result in much more distributed systems. Consequently, obtaining a high capacity using renewables required many smaller plants to be built, which increased their capital expenditures due to transmission line costs (incurred as additional land costs while building a plant). This data demonstrates that *BLACKOUT!* was effective in achieving ILOs 1 and 4 by making the advantages and disadvantages of real-world renewable power sources clear to the players.

CONCLUSIONS AND NEXT STEPS

A workshop and video game hybrid activity called *BLACKOUT!* has been designed, tested, and implemented with high school students. The gameplay, workshop focus and theme of *BLACKOUT!* were designed with the six independent learning outcomes related to how power is produced, bought, and sold. A brief survey was also designed to be completed by the students before and after taking part in the hybrid workshop activity. Survey results from eight workshops (five with survey data) with high school senior students at the McMaster engineering summer camp indicate that *BLACKOUT!* is effective at achieving the first five targeted ILOs by providing a fair, fun and educational experience.

Future work will involve the inclusion of ILO 6 by giving the game master an option to include CO_2 taxes in the game's framework. Each plant will have a certain amount of CO_2 emitted per turn, and the CO_2 tax chosen by the game master will dictate any increases in operating costs for a given plant. It is anticipated that the change in costs will result in both increased prices to consumers and the increased use of renewables. In addition, we are expanding the maps that can be chosen such as for a very sunny location (Mexico), one for a very windy location in Central Europe, and one in a very population-dense location (Eastern United States).

Moreover, future work via funding from the Ontario Research Fund will involve several improvements to the game's code, interface, and optimization. This will include updated visuals to help streamline the student's information gathering activities, automated turn clocks, and personalized player logins. Finally, as mentioned *BLACKOUT!* and all its relevant documentation and workshop material will be hosted on psecommunity.org and will be free to all interested faculty members worldwide. An online forum will also serve as a platform for continuous improvement. *BLACKOUT!* is free for all users and will remain this way as an educational tool through the process systems education community.

ACKNOWLEDGEMENTS

Support for this project was provided by an Ontario Research Fund Research Excellence grant.

TRYING THE GAME FOR YOURSELF

The authors are happy to share the host locations and all associated files with interested readers of CEE. Please contact the corresponding author for this information or to set up a demonstration. The source code and files for *BLACKOUT!* are also available as a free download from the Live Archive for Process Systems Engineering via:

http://psecommunity.org/LAPSE:2018.0136.

APPENDIX

Within the realm of the game, **coal** power plants are meant to be the bread-and-butter base-load option. As such, coal plants have a relatively low building cost ($0.5/MW of capacity) and a reasonable operating cost ($0.075/MW-h). However, coal is a base-load plant, which means that it produces its maximum capacity of 400 MW-h every turn without any ability to change it. This also means that the player incurs the full operating cost of $30 per turn for each coal plant in their network. Once CO_2 emissions and carbon taxes are implemented into the game's framework, the long-term economic sustainability of coal plants will be diminished.

Natural gas plants are unique in *BLACKOUT!* since they are the only option which allow the power produced to be turned up or down as needed. For the purposes of the game it is assumed that it can output anywhere from 0-100% of its maximum capacity (200 MW) at any given time (real plants have restrictions as to the amount and rate of change, but are still rather flexible). Natural gas plants are very inexpensive to build ($0.375/MW of capacity), but due to its peaking capabilities it is the most expensive to operate ($0.15/MW-h). Since natural gas plants are variable, the game will automatically use them to compensate for over-predicted renewable production in order to meet pledges, or to provide extra power to the grid at a competitive price if there is a risk of a blackout during any given turn. Please see section Playing the Game, subsection Game Mechanics for details on how the output of natural gas plants is determined.

Nuclear plants have the highest initial investment of any option available ($1.25/MW). However, nuclear plants have the highest capacity (800 MW) and have the lowest operating cost of any non-renewable possibility ($0.025/MW-h). The high capital cost of a nuclear plant reflects the emphasis placed on the extremely high safety standards and high material costs for nuclear reactors. As with the coal plant, a nuclear plant provides a base-load output that is produced in the same amount every turn. The player is therefore obligated to pay the full operating cost for the nuclear plant at all times.

Wind farm power plants are the more economically favourable of the two renewable power options in the game setting. For the sake of simplicity, the operating cost of wind farms in the game is zero. Wind farms have a relatively high capital cost ($0.8/MW) when compared to traditional fossil fuel plants, but may have the lowest long-term cost in-game due to their negligible per-turn cost, making them the least expensive option if sufficiently windy weather is experienced during the game. The amount of wind is dependent on the weather forecast as well as the annual average wind exposure rating of its location (see Figure 2(D)). Wind farms, unlike fossil fuel plants, may be placed anywhere (except on open water) since they do not require a large body of water nearby for cooling or safety reasons.

Solar farms behave in manner very similar to the wind farms in that they have a relatively high building cost (slightly higher than wind at $1/MW) and a negligible operating cost. Their output may be anywhere from 0 to 100 MW-h per turn, depending on the solar radiation received, which is influenced both by the weather and the average annual solar insolation (see Figure 2C). However, the time of day also matters, since solar plants never produce during the night. The weather forecast symbols (see Figure 3(F)) will change between night and day according to the game time for a given turn. As with wind farms, a solar plant may be placed anywhere on the game map except for open water.

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