Teaching the Complex Dynamics of Clean Energy Subsidies With the Help of a Model-as-Game

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ABSTRACT The economic and policy justifications for clean energy subsidies are complex and difficult to internalize. A subsidy induces additional consumers to buy, reducing carbon emissions through reduced fossil fuel consumption. Over the long term, subsidies encourage industry investment and cost reductions. Ideally, subsidies can be removed when the technology is broadly competitive. Deciding on an appropriate level of government subsidy is complex because a decision-maker should balance government expenditures and benefits over both time and space. A subsidy can be excessive when government costs are too high and/or many consumers would have purchased the unsubsidized product, but can also be too low if insufficient to encourage adoption. In order to educate non-experts on these ideas, we created a case study about the topic, consisting of teaching materials and a cooperative multiplayer game that is playable in small groups in 15–30 min. We have used the case study in both university courses and public-facing events and believe that it would be of interest as teaching material for cost-benefit analysis, government subsidy design, clean energy policy, and science and technology policy education or training. After 15 min with the game, players have a basic understanding of all the important factors and dynamics of subsidy design. For the reader, this article offers a specific example of how to translate a sophisticated technoeconomic decision model into an educational game and includes rules and supplementary materials needed to cover the topic of subsidy design and to try the game in courses and general public settings.

KEYWORDS subsidy, cooperative game, clean energy, policy, technological progress

INTRODUCTION

When governments subsidize clean energy technologies, it is common for simple explanations to be offered as justification, often along the lines of “We want to see more wind and solar power, so we should subsidize it.” Other common explanations include the element of competitiveness of the industry: “We need to subsidize electric vehicles so that we can build up a healthy and competitive electric vehicle supply chain.” While these explanations are reasonable one-sentence summaries, they are incomplete and omit much of the complexity behind subsidy design. And while these brief answers do respond to the question “Why subsidize?” they are woefully inadequate for answering the practical questions “How much should we subsidize? And when? And where?”

Even when limited to a qualitative discussion, the question of optimal subsidy engages a wide range of concepts. The most basic is the idea of benefit-cost analysis based on economic principles: attempting to maximize the social benefits minus the government cost of the policy. Benefits include both energy cost savings and reduction in harmful emissions, and those benefits could occur now or in the future. Technological progress should compound those benefits, as an enhancement in early-stage adoption should help to drive improvements in the technology (e.g., more innovations, future cost reductions) and accelerate the competitiveness of the industry. And anticipating the effect of a subsidy requires some understanding of consumer demand or adoption patterns, so we know how subsidy will affect adoption. Adoption can also affect the cost of the policy, due to both the amount of subsidy-induced adoption resulting from the policy and the amount of “free riders” who benefit from the subsidy but would have adopted without it. And a truly exhaustive

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discussion would consider the interaction between policies in different venues, such as differing US/EU/Chinese policies. While this list of concepts may sound exciting for a policy analyst, it is intimidating for those seeking to communicate them to the public.

In this article, we present the development of a cooperative game to educate non-expert participants on the interactions involved in deciding solar subsidies. The motivation and starting point is a technoeconomic systems model that estimates optimal subsidies for the United States, which we developed under a grant from the National Science Foundation. That model and results have been published in peer-reviewed journals (Tibebu et al., 2021, 2022). In translating that work to a simple game, we had three main objectives. The first is to instill understanding of the causal connections between subsidies, adoption, costs, and emissions reductions, including the long-term perspective. Second, players should experience the tension between deriving larger benefits from a higher subsidy and managing total government costs. Third, the players should understand the relevance of heterogeneity among regions, for example, states with dirtier grids get larger emissions benefits from adopting solar, while sunnier, more populous states with high electricity prices see more adoption for the same solar price. While various games or exercise-based methods have been recently introduced in teaching energy or climate change policy (e.g., Asensio et al., 2020; Rooney-Varga et al., 2020), our game is the first teaching case we are aware of that focuses on clean energy subsidies in a cost-benefit framework.

In the game, each player assumes the role of a state policymaker, deciding the amount of subsidy to offer in their state on each turn. The mechanics of the game determine how much solar is adopted in that turn, as well as ensuing emissions reductions and technology cost reductions for the next turn. Each player is instructed to try to encourage solar adoption and carbon emissions while managing government costs. Play is evaluated at the end of the game by comparing carbon reductions, solar price, and cost-effectiveness at state and national levels, comparing with results from previous groups. While this model and game focus on the question of subsidies for rooftop solar, the presence of interacting factors and conflicting goals is common in policymaking settings, so the educational value extends beyond clean energy subsidies.

In this article, we first summarize the policy analysis research that formed the conceptual basis of the game. Then, we discuss the design of a multiplayer game that captures the important qualitative lessons of the research and our experience using that game with students and the general public. We hope that this information can be useful for both researchers interested in new methods of public dissemination for their work and educators or communicators trying to convey the purpose of clean energy subsidies.

CASE EXAMINATION

Policy Analysis Research on Optimal Subsidies

This cooperative game is inspired by our prior research on the optimal subsidy design for clean energy technologies (Tibebu et al., 2021, 2022). We also published an overview of the concept and important results for a general audience (Hittinger et al., 2022). In the research forming the basis of this case study, we proposed a technoeconomic framework that is used to analyze the benefits and costs of clean energy subsidies. This framework is built upon two conceptual justifications for subsidizing clean energy technologies such as residential solar photovoltaic (PV) panels. First, the subsidy reduces the immediate price of clean energy and thus drives consumer adoption of the technology. The induced adoption of clean energy reduces the use of fossil fuels and subsequent carbon emission, thereby producing environmental benefits. The second justification argues that government subsidy plays a role in stimulating the market for immature but socially desirable technologies. As the subsidy increases consumer adoption, it also induces technological progress in the industry. The induced learning or technological progress leads to future cost reduction or performance improvements in the technology, thereby activating broader adoption over time.

We operationalized this proposed technoeconomic framework in the model illustrated in figure 1. The basic logic of this model is that a clean energy subsidy (using residential solar PV as an example) will immediately increase consumer adoption of solar PV, which then drives technological learning in the PV industry and leads to cost reductions of the technology. The reduced cost of solar will in turn increase adoption in the following years. Hence, the benefits of a subsidy should incorporate both the direct environmental benefits (i.e., reduced emissions) and indirect technological progress benefits (i.e., cost reductions of the technology). In our model, all benefits are quantified as monetized emission reductions from

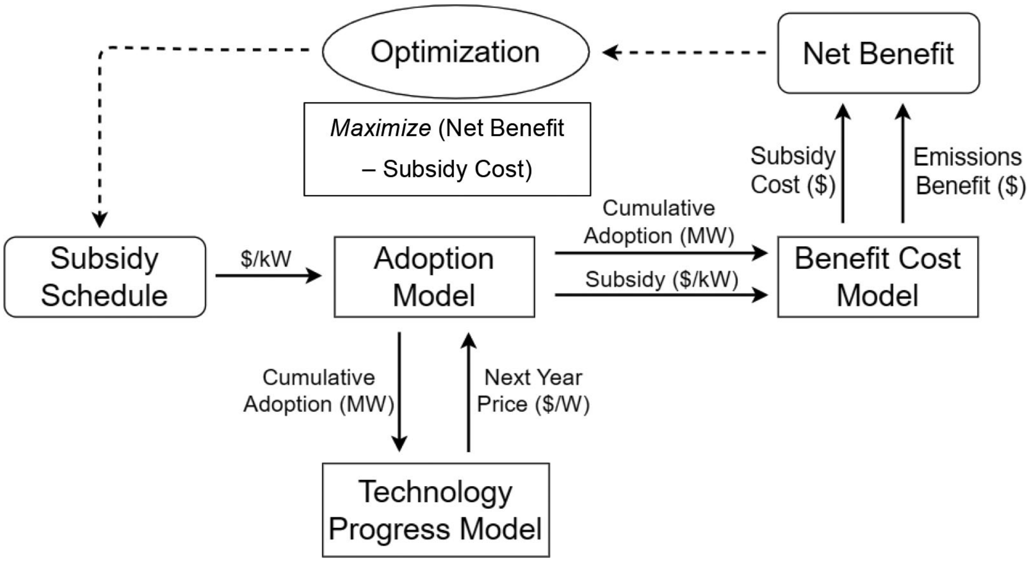


FIGURE 1. Framework for determining an optimal subsidy for clean energy technologies used in our research that forms the basis for the solar subsidy game.

total induced technology adoption (including those directly induced by the subsidy and the follow-on adoption driven by price reductions). We further quantify the net benefits as the total social benefits of the subsidy minus government expenditure on subsidies (i.e., subsidy costs) and use an iterative process to identify the optimal energy subsidy schedule (with varying subsidy levels over an extended period of time).

As shown in figure 1, this technoeconomic model integrates three submodules: adoption, technology progress, and benefit-cost analysis to calculate the net social benefits of the clean energy subsidy. In Tibebu et al. (2021), the adoption model predicts state-level residential solar purchases as a function of the net present value of adopting solar (with the latter being determined by the subsidy level, electricity price, and solar resources in that state) that is discounted over a 20-year period. The technological progress model treats the cost of solar PV as a function of prior consumer adoption using an experience curve model. Using emission factors (Azevedo et al., 2019), the benefit-cost model estimates emission reductions in CO_2 and criteria pollutants (PM, SO_x, and NO_x) attributable to solar adoption and then uses a social cost of carbon and the EASIUR model (Heo & Adams, 2015) to monetize health benefits of emission reductions. We used empirical data (e.g., historical costs, adoption, and emission data) to estimate the regression parameters for each submodule and then integrated all three into a system of equations to calculate the resulting adoption, price reductions, and monetized emission benefits (from 2018 to 2030) using a trial schedule of solar subsidies as an input. Optimization is then done to find the subsidy schedule that minimizes total emission benefits less government subsidy costs. In Tibebu et al. (2021), we find that the optimal federal subsidy would begin at US$585/kW and declines to zero in 14 years. This pattern is largely due to the benefits from early cost reductions and the need to reduce subsidies as a technology becomes cheaper. That work also looked at state-differentiated subsidies, which can achieve greater emissions benefits at lower costs. In another related study (Tibebu et al., 2022), we applied the same framework to estimate the optimal subsidy schedule for utility wind. Unlike the subsidy for residential solar, we show that the optimal subsidy for wind would depend on the region and be roughly constant over time, since the wind subsidy is primarily justified through the direct environmental benefits.

As professors in Public Policy and Sustainability programs, we found that this research offered a useful case study for students. Thinking about optimal subsidy requires students to engage with several different concepts that are important in clean technology policy (adoption rates and technology progress) and consider tradeoffs between several relevant factors (government cost and emissions benefits). It is a sufficiently complex topic that even the general form of the optimal solution is not obvious, but the elements of the problem are accessible even to a general audience. As a result, we created both a cooperative game that illustrates the most essential features of the topic along with a set of teaching materials used to convey the relevant lessons about cost-benefit analysis and clean energy policy design.

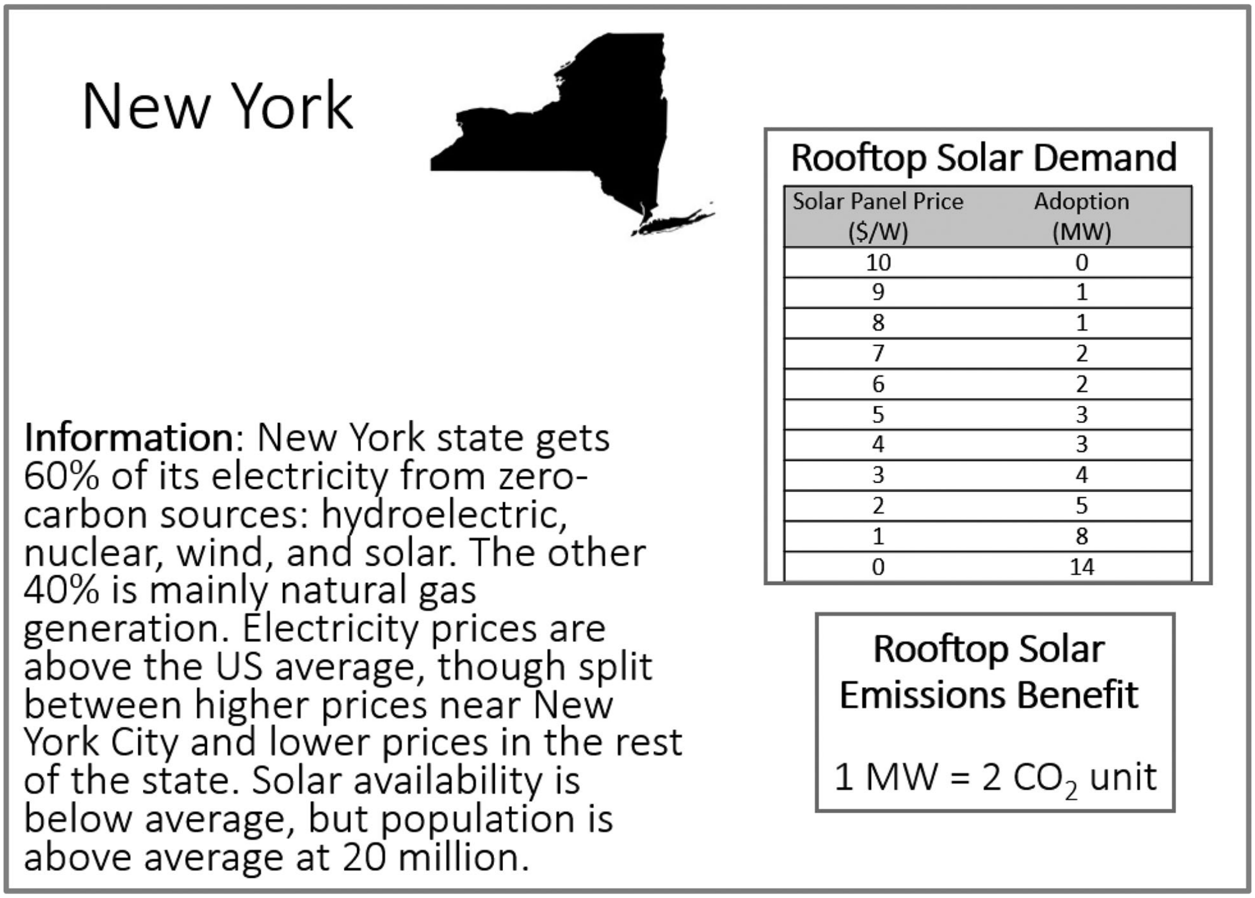
Game Design Approach

In translating this body of research into a game, there were a variety of concepts that we wanted to integrate. The first and most important was the idea of subsidy and technological progress interacting to allow early subsidies to bring down the cost of an emerging technology, presumably followed by lower subsidy levels as the technology becomes more competitive. This would require some form of multiperiod decision-making, representing different years or decades of subsidy. Second, we wanted to include different regions with different circumstances, each making independent but interacting decisions. This requires the definition of different regions (U.S. state in this case), each with unique properties. Third, we wanted players to think about the importance of consumer adoption patterns when considering the choice of subsidy level, especially the idea that expensive technologies have some amount of adoption, but that the adoption increases significantly as costs fall. Finally, we wanted players to confront all of these factors when they made some kind of decision about the optimal subsidy level. And we wanted the game to be playable with a simple set of materials to enable dissemination: printouts, simple game markers (such as small cubes or coins), and play money.

We initially discussed a variety of competitive design ideas, where players would compete to lower solar costs as much or as quickly as possible or to maximize net benefits from the technology. These suffered from the problem that the game would either become noninteractive between players or give a strong advantage to some players: if each player faced the same independent problem of choosing the optimal subsidy, then the players become inefficient versions of a spreadsheet optimizer and can only interact by comparing some form of final score. If each player represents a different state or country, then any reasonable victory condition strongly favors some regions over others, due to differences in subsidy budget, solar resource, population, or other differences that we wanted to intentionally highlight. As a result, we settled on more of a cooperative role-playing design, where each player represents a state policymaker setting state-level subsidy for rooftop solar. This setup allows for greater mechanical interaction between players through a common measure of technological progress. In practice, it also encourages discussion and comparisons between players about the differing strategy/logic for each state. And even though players know that the game is fundamentally cooperative, most players naturally take on some of the self-interested strategy of their state, attempting to minimize their subsidy spending and/or increase in-state installation of rooftop solar.

In game development and testing, we tried a variety of mechanics and concepts. While we describe some of these in the following, this discussion is focused on the final design of the game. The game includes five players, representing the states of California, New York, Arizona, Hawaii, and Minnesota. An example "state sheet" is shown in figure 2. These states were chosen in order to represent a wide range of populations, energy profiles, and solar availability—each of these affect the costs or benefits of rooftop solar, including reduced emissions of fossil plants from adopting clean energy. The different technoeconomic situation in different states is represented by two properties in the game: a lookup table that represents the demand curve (upper right table named "Rooftop Solar Demand") as a function of rooftop solar cost and a single number representing the emissions displaced from a unit of clean energy (box named "Rooftop Solar Emission Benefit"). Additional background information about each state's energy profile, solar availability, and population is provided on the card (lower left), mainly as an explanation to aid in players' thinking as the representative of that state. We also considered having differing levels of total funding for subsidy in each state but found that the gameplay worked better if players did not have much of a budget constraint and were given an amount that was large enough to rarely run out by the end of the game: US$50 or US$100 of "play money," with each paper dollar representing roughly US$1M of funding.

The rooftop solar demand table indicates the extent to which a state's total consumer adoption of rooftop solar changes with solar panel prices: the higher the price, the lower the adoption. For instance, the table for New York indicates that a one-dollar decrease in solar price from US$10/W to US$9/W will increase total adoption by 1MW. While the specific numbers (demand as a function of price) were chosen to facilitate gameplay, they have the same general trends as observed demand curves (Williams et al., 2020).



New York

Rooftop Solar Demand

Solar Panel Price ($/W)	Adoption (MW)
10	0
9	1
8	1
7	2
6	2
5	3
4	3
3	4
2	5
1	8
0	14

Information: New York state gets 60% of its electricity from zero-carbon sources: hydroelectric, nuclear, wind, and solar. The other 40% is mainly natural gas generation. Electricity prices are above the US average, though split between higher prices near New York City and lower prices in the rest of the state. Solar availability is below average, but population is above average at 20 million.

Rooftop Solar Emissions Benefit

1 MW = 2 CO_2 unit

FIGURE 2. Example "state sheet" for New York, including consumer adoption lookup table (upper right) and state-level emissions benefit of rooftop solar (lower right). The information portion (lower left) had no direct gameplay relevance but did initiate discussion between participants (W = watt and MW = megawatt).

It is important for players to understand that (1) introducing government subsidy changes the effective price of solar panels, which is only useful if it changes consumer adoption; (2) the quantity of consumer adoption can directly affect the emission benefits (the more rooftop solar is adopted, the more CO_2 emissions will be reduced, resulting in more environmental benefits); and (3) each state has a different adoption pattern (as shown in table 1) since their distinctive energy profiles (e.g., existing renewable energy sources, energy prices) and solar availability will influence the adoption pattern.

For emissions benefits, we include emission benefits that differ across states (see table 2). These are approximations based on grid emissions from the respective electricity systems: California and New York have relatively low-emissions grids, so new solar has a smaller effect on emissions than in coal-heavy Minnesota, even after considering the lower capacity factor.

The other main element of the gameplay is the technological progress tracking sheet, which provides a simple mechanism to track the falling price of unsubsidized rooftop solar (figure 3). Solar prices are assumed to be the same in every state, so the solar cost tracking sheet is common to all players and includes diminishing returns on investment for technological progress: the price of solar starts at US$10/W and drops to US$9/W after three units of cumulative adoption (across the five states). Going from US$9/W to US$8/W requires an additional six units of adoption, US$7/W requires another nine units of adoption, and so on. While this relationship does not perfectly match the power law of normal technological progress curves, it meets the same basic idea (increasing adoption needed for another unit of cost reduction) and is easy to track with game pieces without any need for calculation. As we discussed earlier, technological progress here is mainly manifested in the cost reduction of the technology: with increased consumer adoption, rooftop

Table 1. Rooftop Solar Adoption (in MWs) in Each State as a Function of Solar Price.

Solar Price ($/W)	California	New York	Arizona	Hawaii	Minnesota
0	30	14	12	4	10
1	15	8	8	4	6
2	8	5	5	4	4
3	5	4	4	3	3
4	4	3	4	3	2
5	3	3	3	3	2
6	3	2	3	2	1
7	2	2	2	2	1
8	2	1	1	2	1
9	1	1	1	1	0
10	1	0	0	1	0

Notes: Solar price starts at US$10/W but falls (moving upward on this table) throughout the game due to technological progress. These consumer adoption curves are stylistic and designed for interesting gameplay but reflect expected adoption patterns due to different population, solar resource, and electricity prices (W = watt and MW = megawatt).

Table 2. Emissions Benefits (CO_2 per Adopted MW of Solar) of Rooftop Solar in Each State, an Approximation of the Real-Life Emissions Benefits of Solar in Different Locations.

California	New York	Arizona	Hawaii	Minnesota
2	2	3	3	4

Note: MW = Megawatt.

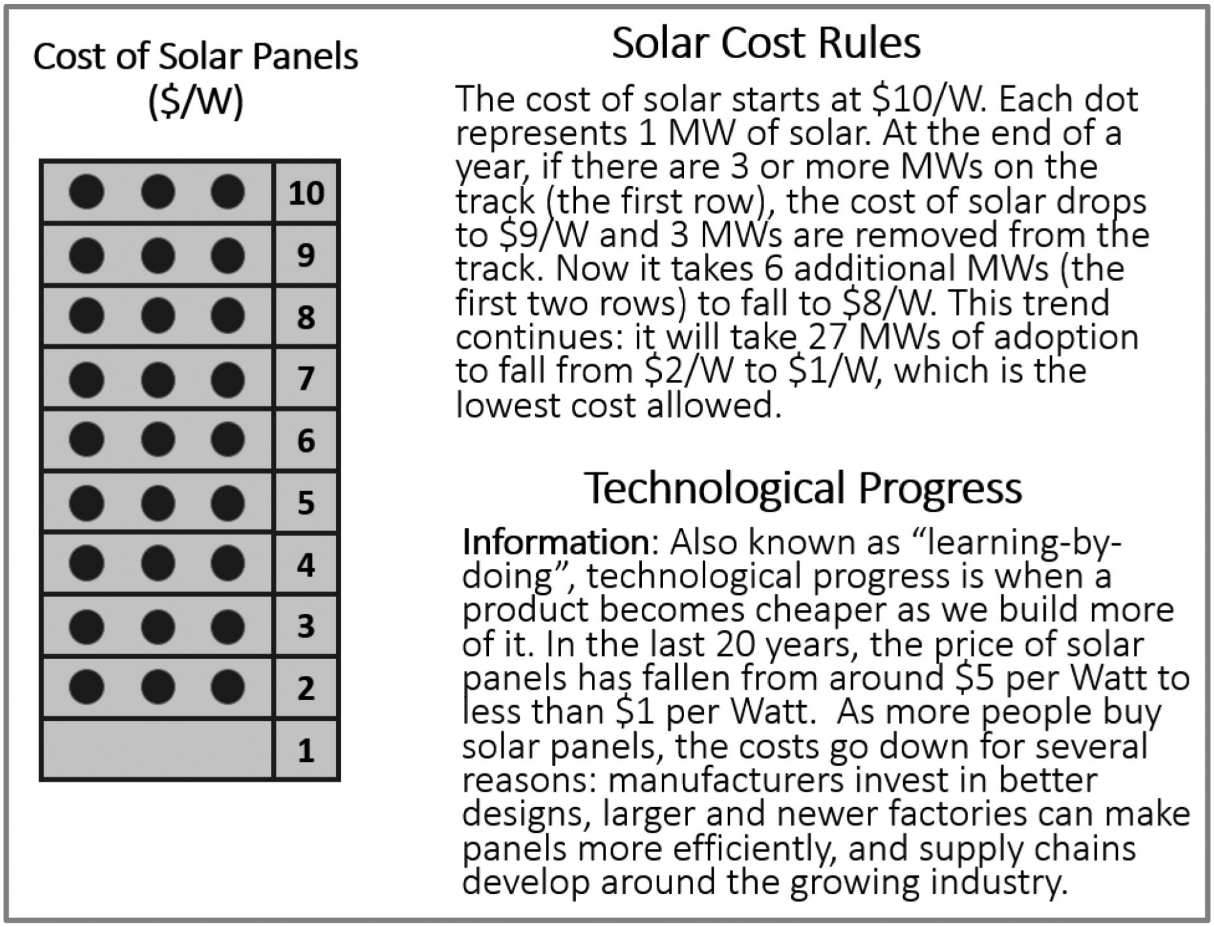
solar panels are produced at lower costs (also known as learning by doing), and this cost-reduction can have a follow-on effect on inducing more adoptions. It is also important for players to understand that each state's solar panel adoption contributes to the technological progress (i.e., cost reductions) in a national market. This means that states with greater consumer adoption will help bring down the price of solar panels, thereby benefiting other states with less adoption.

Gameplay proceeds sequentially through seven rounds total (i.e., each player has seven turns). In each turn, the active player (representing a state):

1. Decides upon a subsidy level for solar in whole number values. This can be different each turn.
2. Calculates the effective cost of solar to consumers as equal to the "Cost of Solar Panels" from the technological progress tracking sheet minus the subsidy that the player chose.
3. Determines the adoption of rooftop solar at this price point from the consumer adoption lookup table on the player's state sheet. That number of "house" game pieces are placed on the technological progress track.
4. Calculates the subsidy cost as equal to the chosen subsidy times the resulting adoption this turn. Players pay this amount to the "bank" from their initial allocation of play money.
5. Calculates emissions benefits as equal to adoption times rooftop solar emissions benefit from the player's state sheet. The cumulative emissions benefit (a social good) is recorded on a common sheet or whiteboard.
6. Adjusts the price of solar if the cumulative adoption of solar is enough to knock it down. This is handled on the technological progress sheet before the next player's turn.

Thus, players actually make only one decision each turn—the level of subsidy in their state—with several effects following from that decision. The players are responsible for keeping track of their subsidy expenditure and emission benefits associated with their subsidy level and adoption in each round, which forces them to work through the various implications of their decision. In game testing, we found that players initially had trouble understanding the gameplay loop and struggled to decide the subsidy level in early turns, which can be solved by enforcing a predetermined subsidy level for the first round. We found that forcing a subsidy of US$3/W in the entire first round was helpful. While this means that players actually make no decisions in the first round, it makes onboarding into the game much faster, reducing the total playtime. We originally envisioned a version of the game that had two different technologies (wind and solar) that could each receive different subsidy offers from each state, but the version with only rooftop solar was sufficiently complex for players. Even though each player only has a single decision to make each turn (amount of solar subsidy to offer), the game's dynamics are complex enough that analytically minded players are unable to determine the optimal strategy.

The goal of the game is intentionally vague, as the problem is multicriteria in nature. Players are informed



Solar Cost Rules

The cost of solar starts at $10/W. Each dot represents 1 MW of solar. At the end of a year, if there are 3 or more MWs on the track (the first row), the cost of solar drops to $9/W and 3 MWs are removed from the track. Now it takes 6 additional MWs (the first two rows) to fall to $8/W. This trend continues: it will take 27 MWs of adoption to fall from $2/W to $1/W, which is the lowest cost allowed.

Technological Progress

Information: Also known as "learning-by-doing", technological progress is when a product becomes cheaper as we build more of it. In the last 20 years, the price of solar panels has fallen from around $5 per Watt to less than $1 per Watt. As more people buy solar panels, the costs go down for several reasons: manufacturers invest in better designs, larger and newer factories can make panels more efficiently, and supply chains develop around the growing industry.

FIGURE 3. The technological progress tracking sheet, common to all players. Each turn, players place a number of game pieces on the tracker (left side) equal to the new adoption of rooftop solar in their state. As the rows are filled, the price of solar falls. When the first row is filled up (three pieces), the price of solar drops to US$9/W and all pieces are removed. Now, players must fill the first two rows (six pieces total) to bring the cost of solar down to US$8/W. The trend continues, representing the diminishing returns on investment into technological progress. Similar to the Information pane on the state sheets, the Information portion here (lower right) is only for education and serves no direct gameplay purpose. Note that the current cost of rooftop solar in the United States is around US$3/W, and the initial value of US$10/W is typical of cost in 2003–2004 (W = watt and MW = megawatt).

that they should try to get the most solar adoption and emission reductions for the least government cost and that their results will be compared with previous groups. They are also told that it is up to them to decide the balance between state and national costs/benefits. Several different and partly conflicting goals are discussed: maximize solar adoption, emissions benefits, or a simplified version of net benefits, defined in the game as total emissions benefits minus total subsidy spending at the end of seven rounds of play:

$$\text{Net benefits } (\$) = \text{Total emission reductions } (\text{CO}_2 \text{ units} \rightarrow \$) - \text{Total subsidy spending in all states } (\$). \tag{1}$$

For simplicity, the CO_2 units are translated to $ one for one (i.e., a social cost of carbon of US$1/unit). We designed the quantities so that a reasonably efficient set of subsidies will lead to net benefits greater than zero, but inefficient subsidy design can produce negative net benefits. At the end of the game, total subsidy spending can be quickly calculated by looking at the remaining funds of each player (relative to their initial funds), while total emissions benefit is tracked throughout the game on a whiteboard or common sheet.

We track and report several outcomes from each game, which helps to understand player choices and consequences: individual and total subsidy expenditures, total solar adoption, total emissions benefit, final cost of solar, the net benefit metric, and "cost efficiency" (or abatement cost, in technical terms):

$$\text{Cost efficiency}\left(\frac{\$}{\text{CO}_2\ \text{reduction}}\right) = \frac{\text{Total subsidy spending in all states (\$)}}{\text{Total emission reductions (CO}_2\ \text{units)}}. \tag{2}$$

While maximizing "net benefits" in \$/W may seem like the primary goal to a policy analyst, it is clear that some players focus more on maximizing adoption or other goals that they feel are appropriate for the role that they are taking on. Regardless of their strategy or internal goals, seeing the various interactions and comparing their outcomes to other groups playing the game helps players connect their decisions to results.

We also worked up and have used several variations to the game to suit particular needs. One venue for the game was a public arts and creativity festival (described further below), where we wanted a simpler and faster version of the game. In this case, we played only three rounds (rather than seven) with the first round requiring all players to subsidize by US\$3/W. This meant that each player only made two decisions (subsidy level during turns two and three), though there was still significant discussion and consideration over these choices. Because there are fewer turns in which to reduce emissions, the net benefit calculation was adjusted to equal emissions benefits times two minus subsidy expenditure (i.e., an emissions benefit of US\$2 per unit of CO_2). For a more complex version of the game that includes some uncertainty about the future, we have players commit to a subsidy level for their next turn by placing a playing card face down in front of them. This mechanic realistically forces the player to make a policy decision without being sure of the effect and requires more consideration of the future from players.

Solution Optimizing Net Benefits

For the base game, the optimal set of subsidy choices for each state that maximizes national net benefits (Equation 1) can be found using Solver in Excel. Shown in table 3, this optimal solution has the net benefits of 209 (\$M) and a final solar price of US\$3/W. Table 3 illustrates several of the concepts from the research project. First, it shows that the optimal strategy is to subsidize more during early periods than later ones. Second, it shows that subsidy is often more beneficial in locations where adoption is naturally lower. Third, the relatively continual subsidy in Minnesota highlights the relevance of direct benefits in scenarios where emission benefits are high. To elaborate, while the general reason for subsidizing solar is to lower long-term costs and induce later adoption, solar in Minnesota has a sufficiently high direct emissions benefit to make subsidy worthwhile even in later periods. For comparison to these results, offering no subsidy from all states in all periods results in an emissions benefit (and also net benefit) of 138 (\$M), with a final solar price of US\$5/W.

Table 3. Optimal Solution to the Base Game, Showing the Level of Subsidy Offered by Each Player in Each Turn.

	Subsidy Offered (When Forced to Whole Numbers)				
Turn	California	New York	Arizona	Hawaii	Minnesota
1	2	3	3	1	0
2	0	1	2	0	2
3	0	0	1	0	1
4	0	0	0	0	1
5	0	0	0	0	0
6	0	0	0	0	1
7	0	0	0	0	0

Notes: This results in a cumulative emissions benefit of 254 (\$M), a total subsidy expenditure of 45 (\$M), and a net benefit of 209 (\$M). The final solar price at the end of the game is US\$3/W (\$M = million dollars and W = watt).

Experience With Gameplay

After playtesting, we have used the game in two types of venues: a public-facing "arts and creativity festival" known as "Imagine RIT" (Rochester Institute of Technology) and a classroom setting. Imagine RIT (2023) is an annual spring event on the RIT campus and the busiest weekend of the university year, with hundreds of exhibits/activities. It is free and open to the public and normally attracts tens of thousands of visitors. Thus, these participants represent a broad sample from the public, none of whom visited the event with a plan to play a game making tradeoffs between government expenditure and technological progress.

At two Imagine RIT events (in 2022 and 2023), interested members of the public visiting campus would join a table to play the game. Most players were laypersons on energy issues. Two volunteers helped players learn the rules and recorded outcomes such as emissions reductions. After each game, the critical metrics (total emissions reduction, total solar adoption, final solar price, total subsidy expenditure, and net benefits) for each group were recorded on a white board, as a "high score" list. No formal evaluation of understanding before and after play was done, but discussing with participants suggested that most understood the main points of the game and the challenges involved in choosing an appropriate subsidy.

In one in-class application, we used the game as part of an introductory graduate course on energy systems, with 23 students playing for 1.25 h. In a prior course lecture, we presented the main concepts of subsidy modeling. The game rules were not distributed before class. The class was divided into five groups, with one instructor overseeing all groups. In contrast with unfamiliar participants at Imagine RIT, the students quickly understood the point of the game, as the logic comes directly from the prepared lecture. However, there were many questions on the details of implementing the rules, so it took time for one instructor to work through the question from all groups.

In the in-class and public-facing running of the game, we tracked a few important metrics across groups, as a type of "high score" tracking. The "high score" list became a useful way to quickly consider different scenarios: some groups achieve greater emissions benefits but usually at higher government costs, while other groups were better able to maximize net benefits. This allowed for two things: first, it stimulated competitive urges in some players, who sought to "beat the high score" in one metric or another. Second, it offered a comparison outcome for players to consider when they were unable to maximize one or another metric. It was common for players to explicitly discuss how certain scores could be achieved and what parts of their collective strategy should be changed to achieve it. This form of retrospection on the gameplay is particularly useful in cementing the lessons of the game, as players are not merely making decisions but reflecting on the relationship between overall strategy and final outcomes.

Relative to the "optimal" solution calculated above, players generally used greater levels of subsidy and tended to spend more government funds overall. While suboptimal from a net benefits perspective, these outcomes illustrate how focus on different metrics/outcomes drives different behavior. Furthermore, the game is somewhat forgiving of different strategies: subsidizing at higher levels does increase the subsidy expenditure but often drives a lot more technological progress and emissions benefits in the latter turns, permitting reasonably high levels of net benefits. This effect, coupled with the complexity of the dynamics in the game, also acts to conceal the optimal strategy, which encourages replayability. In both delivery settings for the game, players spent time considering which parts of their strategy seemed right and wrong and how better outcomes could be achieved.

CONCLUSION

While the game and associated materials were developed purely as an educational tool, student and general public players generally responded positively, often reporting the game as interesting and fun. We are encouraged, as this suggests that a variety of models describing real-world complexities can be transformed into reasonably entertaining games. We believe a key strategy is to first choose the dynamics/effects that are educationally important and then find the simplest implementation that illustrates them. In this case, it meant that adoption was translated into state adoption tables (table 3), and technological progress was represented by filling bigger bins of adoption as prices fell. The result was a game simple enough to run in 20 min with a group of strangers but complex enough that even sophisticated players are unable to easily find the optimal solution. In the Supporting Information, we provide all of the lecture and game materials needed for others to deliver this case study in their own venue.

SUPPORTING INFORMATION

Game materials (printouts) are available in the file "Game cards.ppt." The rules document is in the file "Saving the World with Subsidies Instructions." An individual sheet for tracking each player's actions, for use in classroom settings, is in the file "Tracking-sheet-for-gamplay.docx." A presentation that we prepared and used in class that covers both the concepts behind the game as well as the game rules is in the file "Solar subsidy policy game.ppt."

AUTHOR CONTRIBUTIONS

Development of research concept: EH, EW, QM.
Game design: EH, EW.
Game testing and refinement: EH, EW, QM.
In-class testing: EW, QM.
Writing this manuscript: EH, EW, QM.

COMPETING INTERESTS

The authors have declared that no competing interests exist.

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REFERENCES

Asensio, O. I., Mi, X., & Dharur, S. (2020). Using machine learning techniques to aid environmental policy analysis: A teaching case regarding big data and electric vehicle charging infrastructure. *Case Studies in the Environment*, *4*(1), 961302. https://doi.org/10.1525/cse.2020.961302

Azevedo, I., Donti, P., Horner, N., Schivley, G., Siler-Evans, K., & Vaishnav, P. (2019). Electricity marginal factors estimates. Retrieved October 30, 2019, from https://cedm.shinyapps.io/MarginalFactors/

Heo, J., & Adams, P. J. (2015). The estimating air pollution social impact using regression (EASIUR) model. Retrieved October 30, 2019, from https://barney.ce.cmu.edu/~jinhyok/easiur/

Hittinger, E., Williams, E., Miao, Q., Tibebu, T. (2022). How to design clean energy subsidies that work—Without wasting money on free riders. TheConversation.com. https://theconversation.com/how-to-design-clean-energy-subsidies-that-work-without-wasting-money-on-free-riders-191635

Rochester Institute of Technology. (2023). Imagine RIT. Retrieved July 6, 2023, from https://www.rit.edu/imagine/

Rooney-Varga, J. N., Kapmeier, F., Sterman, J. D., Jones, A. P., Putko, M., & Rath, K. (2020). The climate action simulation. *Simulation & Gaming*, *51*(2), 114–140. https://doi.org/10.1177/1046878119890643

Tibebu, T. B., Hittinger, E., Miao, Q., & Williams, E. (2021). What is the optimal subsidy for residential solar? *Energy Policy*, *155*, 112326.

Tibebu, T. B., Hittinger, E., Miao, Q., & Williams, E. (2022). Roles of diffusion patterns, technological progress, and environmental benefits in determining optimal renewable subsidies in the US. *Technological Forecasting and Social Change*, *182*, 121840.

Williams, E., Carvalho, R., Hittinger, E., Ronnenberg, M. (2020). Empirical development of parsimonious model for international diffusion of residential solar. *Renewable Energy*, *150*, 570–577.