Obviously Strategy-Proof Auctions for Energy Efficiency

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Abstract
In many countries, in order to address the goal of maximizing the energy efficiency and the adoption of renewable energy sources, there have been recently used market-based instruments, and in particular, energy efficiency auctions and renewable energy auctions. Nevertheless, it has been observed that the recent application of this instruments still has some drawbacks.

In this work, we propose energy efficiency auctions and renewable energy auctions that allows to address some of these drawbacks. The design of these auctions is based on the concept of obviously strategy-proof auctions and their characterization in terms of greedy algorithms.

Keywords
Mechanism Design, Greedy Algorithms, Extensive-Form Games

1. Introduction

In the last years there has been a large adoption of so-called market-based instruments for renewable energy and energy efficiency. According to the definition of the International Partnership for Energy Efficiency Cooperation [1] provided in response to G7 Members after the mandate assigned by the G7 Energy Ministerial in May 2015 and by the World Bank [2], these are

> *Instruments that set a policy framework specifying the outcome (e.g., energy savings, cost-effectiveness) to be delivered by market actors, without prescribing the delivery mechanism and the measures to be used.*

Essentially, these market-based instruments do not prescribe regulations obliging energy actors to adopt energy-efficient or renewable energy resources, i.e. it does not prescribe the means through which the desired outcomes should be reached. Instead, the market-based instruments only define the outcomes and provide incentives to energy actors to achieve these outcomes *in the ways and times that are better suited to their features and expertise.*

Essentially two kinds of market instruments have been considered:

- *Obligations*, according to which energy actors are required to carry out a certain level of activities involving renewable energies or energy savings. The costs of these activities are charged to final users, that in turn are supported by the administration;
- *Auctions*, in which different renewable energy or energy savings projects can bid, and "better" projects (in terms either of the energy efficiency that it may achieve, or of the requested bid) are directly supported by the administration.

While obligations have been initially preferred, since the outcome is directly prescribed, it does not allow administration to keep their expenses limited. For this reason, there has been in recent years an increasing interest towards auctions.

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The first example of these kinds of auctions dates back to 1990s and in the first 2000s in UK, Ireland and France [3, 4, 5] focusing on renewable energy. Outside of Europe, these auctions have been also implemented in China and in Latin America [6, 7, 8, 9]. Moreover, in the last ten years there has been a renewed interest in this instrument for incentivizing renewable energy in Europe (where its adoption has been driven by EU policies) [10, 11, 12, 13, 14] and worldwide [15, 16, 17, 18, 19, 20]. At the same time, there have been many auction scheme issued with the goal of energy savings: Rosenow at al. [21] listed 46 schemes in 25 countries until 2019.

These auction instruments still have some issues, that we briefly discuss in Section 3. Most of these issues are related with the risk of providing insufficient incentives for participation of valid projects. For this reason, among the other requirements, it is deemed as necessary to design auctions scheme that are *simple*.

The design of simple auctions has been a relevant subject in mechanism design in the last years. There are indeed some works that provided (not completely satisfactory) definitions of simplicity. For example, Hartline and Roughgarden [22] defined comparative simplicity, i.e., one mechanism turns out to be more complex of another if the former can be simulated by the latter by just adding some agents; this is inspired by a famous result by Bulow and Klemperer [23], that shows that a revenue-maximizing mechanism for single item guarantee the same revenue of a social-welfare maximizing mechanism if the latter is run with one more agent. Anyway, while this definition is clearly effective in comparing different mechanisms, it fails to state whether a mechanism is simple or not. Another approach has been taken by Brânzei and Procaccia [24] that defined *verifiably truthful mechanisms*, in which agents are equipped with an algorithm that is able to check that the mechanism is incentive compatible. Unfortunately, these algorithms can run for long time and are known only for quite limited scenarios. Moreover, this framework needs that the participants move their trust from the complex mechanism to a possibly complex verification algorithm, solving in this way the problem only partially. Yet another approach is to consider mechanisms that are clearly simple. One example is given by *posted price mechanisms*, where a price is set for the items to sell and the agent must only check whether there is a set of items for which their valuation is above the set price. Mechanisms with these features have been proposed in multiple settings [25, 26, 27, 28, 29]. Clearly, posted-price mechanisms are a too narrow set of simple mechanisms: e.g., ascending auctions, and more in general *deferred acceptance algorithms* [30], are usually believed to be simple, even if they are not posted price.

Li [31] provided a definition of simple mechanisms that attracted large interest in the community, through the concept of Obviously Strategy-Proof (OSP) mechanisms. This notion essentially states that for simplicity not only the outcome of a mechanism matters, but also its implementation. E.g. Vickrey's famous second-price auction has been observed to be played truthfully less often when implemented via a sealed-bid auction, than when it is implemented via an ascending auction. Thus the definition of OSP formally captures how implementation details matter. Specifically, it looks at a mechanism as an extensive-form game, and demands that strategy- proofness holds among sub-play of the game. Li [31] also proves that these mechanisms are exactly the ones that are recognized as truthful by agents lacking contingent reasoning abilities.

We here want to discuss how to design OSP energy efficient and renewable energy auctions, and to discuss how other issues of current auctions can be addressed within this OSP framework.

2. Related Works

OSP has been a topics of many papers recently. A group of these papers [32, 33, 34, 35] have investigated OSP in different contexts, often highlighting impossibility results and proposing viable mechanisms under certain assumptions. Bade and Gonczarowski [36] further explored this notion across various settings, including single-peaked preferences, also studied by Arribillaga et al. [37, 38]. Pycia and Troyan [39] studied OSP mechanisms in domains where monetary transfers are not permitted, providing a useful characterization for such scenarios.

OSP mechanisms in setting with money have been characterized for binary allocation problems [40] and for general single-dimensional problems [41]. These works are built on the top of the tools of OSP cycle monotonicity [42], that may be of independent interest for the design of OSP auctions. Lower bounds to the approximation of OSP mechanisms for combinatorial auctions are established by Shiri [43] to complement the upper bounds given by de Keijzer et al. [44]. Mackenzie [45] introduced a revelation principle for OSP mechanisms. Ferraioli and Ventre [46] derived explicit formulas for the payment functions of OSP mechanisms. OSP mechanisms with verification have been also considered [47, 48].

Several variants of OSP have been proposed. k-OSP [49, 50] is a notion that bridges the gap between OSP and SP. On the opposite, an even more stringent notion of OSP, termed SOSP, has been defined by Pycia and Troyan [51] and recently characterized by Ferraioli and Ventre [52]. Another related line of research concerns non-obviously manipulable (NOM) mechanisms [53], where the absence of contingent reasoning skills is proposed to limit agents' misbehavior, as opposed to limiting strategyproofness (as in OSP). Recent work has provided characterizations for single-dimensional domains [54, 55] and a general recipe for their design [56]. This concept has been applied to school choice, two-sided matching, auctions, bilateral trade [53], voting [57, 50], fair division [58, 59], and hedonic games [60, 61].

3. Energy Efficient and Renewable Energy Auctions and Their Issues

Energy Efficient and Renewable Energy Auctions are procurement auctions, in which: (i) the auctioneer, typically the government, sets some desired level of energy saving or of renewable energy production capacity, and a maximum amount of money that they are intended to spend; (ii) project developers may submit projects describing the actions that they are intended to take in order to achieve the desired result in terms of energy savings and renewable energy, and a level of desired financial support; (iii) the auctioneer runs an auction scheme for deciding the projects at which the financial support is guaranteed (via feed-in tariffs, i.e. guaranteed price received for unit of renewable energy produced or energy saved, or via feed-in premiums, i.e., support payments received on top of market prices); (iv) the awarded projects should finally realize the submitted project (with a possible penalty to pay in case of failure).

This kind of instrument turns out to be particularly useful in presence of information asymmetry between government and project developers: the government does not know the actual cost of the means necessary to achieve the desired level of renewable energy or energy saving, while project developers do. On the other side, the competition among project developers allows the government to keep limited the incidence of these costs on the budget.

These twofold aspects are recognized by the literature about these auctions [62, 63] as the primary objectives: efficiency and effectiveness. *Efficiency* refers on the capacity of these auctions to trigger reduction in the prices of technologies needed for increasing the renewable energy capacity or the energy saving. These goals can be achieved in the long term (usually termed as *dynamic efficiency*) or in the short term, intended as social welfare maximization (also termed *static efficiency*). *Effectiveness* refers to the effective increment in renewable energy capacity or energy saving triggered by these auctions. Besides these primary objectives, other secondary objectives are recognized, such as *actor diversity* or *security of supply*.

In order to achieve these goals, different guiding principles have been suggested [62, 63]:

- the auction scheme should reflect the desired policy objectives;
- the auction needs sufficient competition among participants;
- the auction design should be kept as simple as possible.

Different design elements affect the extent at which these principles are achieved. E.g., if the volume of projects that the government intends to support is fixed in advance, then it may affect participation, since expensive projects can be in this way awarded, incentivizing participation of large projects, but dis-incevitivizing participation of many smaller project developers. Similarly, if the auction focuses on a single technology, this may fail to guarantee efficiency, and dis-incentivizes participation of small but largely innovative projects. Similar issues occurs if the auctioneer defines thresholds on the size of supported projects or on financial pre-qualification of the participants.

We next discuss how OSP auctions can be used in order to address these guiding principles efficiently.

4. OSP Auctions

To select an outcome $X \in \mathcal{S}$ and a payment profile $\mathbf{p}$, we run an *auction* $\mathcal{A}$. The auction sees the auctioneer interacting with the participants. Each participant i takes *actions* (e.g., saying yes/no, reporting a bid). Each action signals to the auctioneer a bid $b_i \in D_i$, not necessarily equivalent to the type t_i of this participant (i.e., the real required financial support). We then say that participant i takes *actions compatible with (or according to)* b_i and call b_i the presumed type of participant i. For an auction $\mathcal{A}$, $\mathcal{A}(\boldsymbol{b})$ denotes the outcome and the payment profile returned by the auction when the participants take actions according to their presumed types $\boldsymbol{b} = (b_1, \ldots, b_n)$.

We consider auctions in the more general extensive form. That is, we design the auction as a game Γ for the participants to play, where Γ is an imperfect-information extensive-form game with perfect recall. While this game can be defined in a standard way, we found more useful to provide the following alternative definition of *extensive-form auction* that has been proved to be equivalent to the real one in terms of obvious incentive compatibility [45, 52].

An extensive-form auction $\mathcal{A}$ is a triple $(f, p, \mathcal{T})$ where f is a function returning the outcome X associated to presumed types $\boldsymbol{b}$, p returns the payments profile associated to presumed types $\boldsymbol{b}$, and $\mathcal{T}$ is a tree, called *implementation tree*, describing how the auction is run. $\mathcal{T}$ is such that:

- Every leaf ℓ of the tree is labeled with a pair $(X(\ell), p(\ell))$, where $X(\ell) \in \mathcal{S}$ and $p(\ell) \in \mathbb{R}^n$;
- Each internal node v in the implementation tree $\mathcal{T}$ defines the following:
  - A participant $i = i(v)$ to whom the auctioneer makes a query. Each possible answer to this query leads to a different child of v.
  - A joint type space $\boldsymbol{D}^{(v)} = (D_i^{(v)}, \boldsymbol{D}_{-i}^{(v)})$ containing all types that are *compatible* with v, i.e., compatible with all the answers to the queries from the root down to node v. Specifically, the query at node v defines a partition of the current type space of $i = i(v)$, $D_i^{(v)}$, into $k \geq 2$ subdomains, one for each of the k children of node v. Thus, the joint type space of each of these children will have as the type space of i, the subset of $D_i^{(v)}$ corresponding to a different answer of i at v, and an unchanged type space for the other participants.

Observe that, according to the definition above, for every type profile $\boldsymbol{b} \in \boldsymbol{D}$ there is only one leaf $\ell = \ell(\boldsymbol{b})$ such that $\boldsymbol{b}$ belongs to $\boldsymbol{D}^{(\ell)}$. Similarly, to each leaf ℓ there is at least a profile $\boldsymbol{b}$ that belongs to $\boldsymbol{D}^{(\ell)}$. For this reason, we say that $\mathcal{A}(\boldsymbol{b}) = (X(\ell), p(\ell))$. Two type profiles $\boldsymbol{b}, \boldsymbol{b}'$ are said to *diverge* at a node v of $\mathcal{T}$ if this node has two children v', v'' such that $\boldsymbol{b} \in \boldsymbol{D}^{(v')}$, whereas $\boldsymbol{b}' \in \boldsymbol{D}^{(v'')}$.

To get the reader acquainted with this definition, we provide examples of common auction formats modeled within this framework. For sealed-bid auctions, the auctioneer interacts with participants by asking them to reveal her type: the number of available actions of each participant is equivalent to the size of her type space, and each action shrinks her type space to the singleton containing only the revealed type; the outcome and payments will be computed only after each participant revealed her type. For English auctions, the auctioneer starts with a low price, and interacts with each participant in round-robin fashion by asking them whether they would participate at the current price, removing the participant in case of negative answer, and raising the price after each non-removed participant has been queried: each participant has two actions available at each query, yes or not, with a yes shrinking the domain to all types that are at least the asked price, and a revealing that the valuation is less than current price; the outcome and payments can be computed here as soon as all participants have been removed except one (who will be the winner). A very similar approach can be used for modeling Dutch auctions.

Obvious Incentive Compatibility. An auction $\mathcal{A}$ is *strategy-proof* (SP) if for all i, all $\boldsymbol{b}_{-i} = (b_1, \ldots, b_{i-1}, b_{i+1}, \ldots, b_n)$ and all $b_i \in D_i$, $\mathsf{u}_i(t_i, \mathcal{A}(t_i, \boldsymbol{b}_{-i})) \geq \mathsf{u}_i(t_i, \mathcal{A}(b_i, \boldsymbol{b}_{-i}))$, where t_i denotes the true type of i. That is, in a strategy-proof auction the actions taken according to the true type are dominant for each agent.

An extensive-form auction $\mathcal{A}$ is *obviously strategy-proof (OSP)* if for every participant i with real type t_i, for every vertex v such that $i = i(v)$, for every $\boldsymbol{b}_{-i}, \boldsymbol{b}'_{-i}$ (with $\boldsymbol{b}'_{-i}$ not necessarily different from $\boldsymbol{b}_{-i}$), and for every $b_i \in D_i$, with $b_i \neq t_i$, such that $(t_i, \boldsymbol{b}_{-i})$ and $(b_i, \boldsymbol{b}'_{-i})$ are compatible with v, but diverge at v, it holds that $\mathsf{u}_i(t_i, \mathcal{A}(t_i, \boldsymbol{b}_{-i})) \geq \mathsf{u}_i(t_i, \mathcal{A}(b_i, \boldsymbol{b}'_{-i}))$. That is, OSP auctions require that, at each time participant i has to take an action, the worst utility that she can get if she behaves according to her true type is at least the best utility she can get by behaving differently.

Three-Way Greedy Auctions. We say that participant i is *single parameter* if she has as private information a single real number t_i and $t_i(X)$ can be expressed as $t_i f_i(X)$ for some publicly known function profile $\mathbf{f} = (f_1, \ldots, f_n)$, describing the items received by i in the outcome X.

Auctions for these single-parameter participants have been characterized in [41]. An auction is OSP in this context if and only if it is a *three-way greedy auction*, i.e., the auctioneer can interact with each participant i only in one of the following three ways:

- *greedy*, i.e., at each interaction the auctioneer asks the participant if she has the highest valuation that has not been queried yet; in case of positive answer, the auctioneer assigns an outcome to the participant that is at least as large as the outcomes she would be assigned for smaller valuations;
- *reverse greedy*, i.e., at each interaction the auctioneer asks the participant if her valuation is the lowest that has not been queried yet; in case of positive answer, the auctioneer assigns an outcome to the participant that is at most as high as the outcome she would be assigned for larger valuations;
- *split & greedy*, i.e., at the first interaction the auctioneer asks to the participant to split her domain in large valuations (i.e., valuations above a threshold fixed by the auctioneer) and small valuations (below the threshold) with the guarantee that the outcomes assigned in the first case are not worse than the outcomes assigned in the second case; after that, the auctioneer proceeds reverse greedily for the large valuations if the participant declared to have these types, and greedily on the small valuations otherwise.

We remark that three-way greedy implementations allow mechanisms to interact with different agents in a different way, e.g., for some agents we can proceed greedily, while some other agents can be queried in a reverse greedy fashion. Actually, the characterization in [41] allows interleaving among these interactions, e.g., a participant may first be queried reverse greedily then greedily, in some extreme cases whose occurrence depends on the magnitude of outcomes and valuation functions. The payments offered for each outcome have been described by [46].

5. Energy OSP Auctions

We believe that OSP Auctions can be an useful tool in order to implement efficient and effective Renewable Energy and Energy Efficient auctions. In particular, we discuss how OSP auctions can help to address the above defined guiding principles of these auctions.

Simplicity. As widely discussed above simplicity is the cornerstone of OSP mechanisms. For every participant it is trivial to understand which is the best action to take at each time during the execution of the mechanism. This indeed follows the characterization of OSP as mechanisms that are truthful even for participants lacking contingent reasoning skills [31]. The characterization in terms of greedy algorithms [41], that have been naturally recognized as the simplest algorithmic technique, only confirms this feature.

Not only, but the characterization of OSP mechanism [41] turns out to be independent on the desired outcome, as long as this can be achieved or efficiently approximated by greedy-like algorithms. This in turn implies that OSP mechanisms can be designed to work with multiple requirements/desiderata of the auctioneer.

Alignment with Objectives. The last observation confirms that OSP auctions can be designed to be aligned with multiple possible objectives and consequently with multiple possible design choices. E.g., it is possible to have OSP auctions achieving or approximating the maximum social welfare, or other more complex objective functions (clearly, approximation can be negatively affected by the complexity of the objective function). It is possible to design OSP auctions when the volume of the supported project is defined in advance, and OSP auctions where there is no such budget cup. It is possible to design OSP auctions focused on single technologies or multiple technologies, or with thresholds on minimum and maximum size of the supported projects.

Not only, but the dynamical nature of this auction format allows to adapt the choices of the auctioneer as long as the auction evolves: e.g., whether many small projects have been discarded, the auctioneer can choose to prioritize remaining small projects and this choice can be immediately reflected in the OSP auction design. Similarly, the government can be able to raise the budget quota, i.e., the volume of supported projects, or the thresholds on the size of admitted projects.

It is moreover immediate to include in the OSP framework a preprocessing phase allowing for checking financial pre-qualification of the participants or the doability of the proposed project within the requested support. Moreover, it is known that monitoring and verification tools may only help in the design of efficient and effective OSP mechanisms [47, 48].

Last, but not least relevant, it has been recently observed that it is possible to include the advices resulting by this preprocessing phase within the design of OSP auctions even if these advices are not trusted, in order to improve the features of the resulting outcome whenever it is advice is correct, but do not affecting too much these feature whenever it is wrong [64].

Incentivizing Participation. The feature described above, namely the simplicity of the auctions, the easiness of designing OSP auctions able to include specific requirements, such as for example, actor diversity, and the ability to correct some features of the auction scheme online, all are useful tool in order to incentivize participation. Anonimicity and randomization can further help in foster participation. Interestingly, there has been recent evidence that these tools do not affect the design of OSP auctions, and in some case they may also improve the performances of OSP auctions [65].

6. Conclusions

In this work we proposed the design of renewable energy auctions and energy efficiency auctions according to the principles of OSP auctions. We provided evidence that this kind of auction scheme not only does not affect too much the features that these auctions can implement, but moreover it allows for a more dynamical and adaptive changing of these features, without affecting simplicity and participation.

Clearly, we recognize that OSP auctions may have severe limitation, as highlighted, in most works [32, 33, 34, 35, 40], and that OSP auctions must be carefully engineered in order to be used in real-world renewable energy and energy efficiency auctions. Still we believe that the scientific community working on the design of auctions and mechanisms, especially on the design OSP auctions, can be an useful support on government decisions about the design of future schemes.

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Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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