Multi-Objective Auctions for Utility-Scale Solar-Battery Systems
The Case of ASEAN and East Asia

Toba, Natsuko; Jamasb, Tooraj ; Maurer, Luiz; Sen, Anupama

Copenhagen Business School
HANDELSHØJSKOLEN

Department of Economics

Copenhagen Business School

Working paper 03-2023

Multi-Objective Auctions for Utility-Scale Solar-Battery Systems: The Case of ASEAN and East Asia

Natsuko Toba
Tooraj Jamasb
Luiz Maurer
Anupama Sen

Department of Economics – Porcelænshaven 16A, 1. DK-2000 Frederiksberg

CSEI Working Paper 2023-03

CBS
DEPARTMENT OF ECONOMICS
COPENHAGEN BUSINESS SCHOOL

WORKING PAPER

Copenhagen School of Energy Infrastructure | CSEI

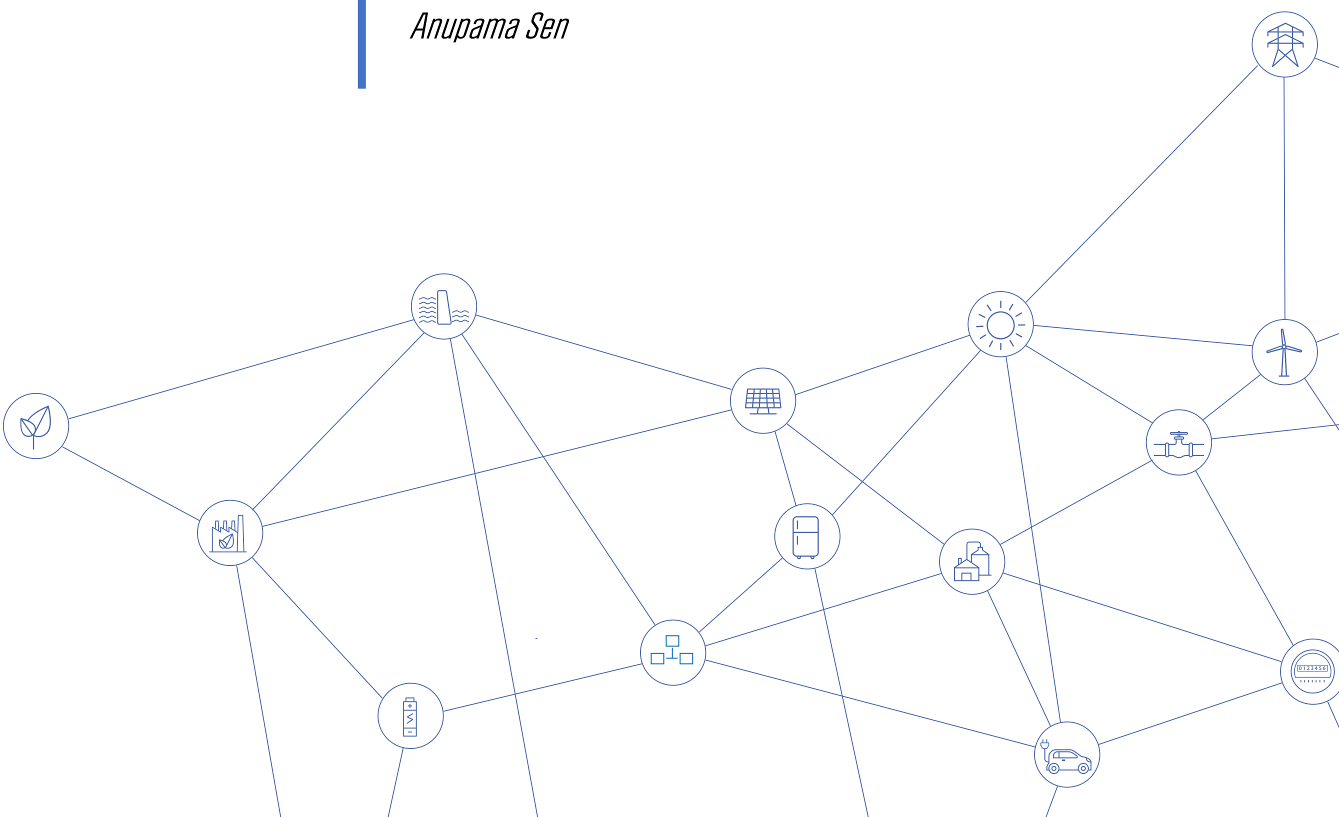
Multi-Objective Auctions for Utility-Scale Solar-Battery Systems: The Case of ASEAN and East Asia

Natsuko Toba

Tooraj Jamasb

Luiz Maurer

Anupama Sen



Multi-Objective Auctions for Utility-Scale Solar-Battery Systems: The Case of ASEAN and East Asia

Natsuko Toba[*]
International Finance Corporation, World Bank Group, US

Tooraj Jamasb
Copenhagen School of Energy Infrastructure, Department of Economics, Copenhagen Business School, Denmark

Luiz Maurer
LM Engineering and Consulting, Richmond, US

Anupama Sen
Smith School of Enterprise and the Environment, University of Oxford, UK

15 January 2023

Abstract

Globally, auctions are increasingly popular to competitively promote and procure renewable energy technologies to meet energy, social, and climate change objectives. To do so, auction designs need to accommodate technological progress, declining costs, and increasing demand for Environmental, Social and Governance (ESG). This chapter focuses on auctions of large scale solar photovoltaic (PV) and battery energy storage system (BESS) in Southeast and East Asia. It revisits the theoretical and conceptual frameworks of auctions while focusing on the ESG component from the perspective of key stakeholders, such as investors, government, bidders, and communities regarding efficient allocations of risks, costs, and benefits. The chapter then relates this framework to real-world practices and international evidence on solar PV as well as those without BESS. The analysis shows that integrating ESG in the auction designs and business models is possible and could benefit business and sustainable development.

Key words: Renewable energy, solar power, battery storage, auction design

JEL Classifications: D0, D4, D8, L0, L1, L9

----

*Corresponding author. International Finance Corporation, The World Bank Group, Washington D.C., 20433, United States. Email: ntoba@ifc.org

1. Introduction

Southeast Asian Nations (ASEAN) and East Asia are dynamic regions under transitions, especially energy, into sustainable growth pathways. According to International Monetary Fund (IMF) in October 2022, while Asia's economic performance remains relatively sound in an increasingly sluggish global economy, it is expected to expand at a much lower rate than in the preceding two decades (IMF, 2022). Among the 16 Least Developed Countries (LDC) under the United Nations' category on the path to graduation, ten are World Trade Organization (WTO) members, including ASEAN members: Cambodia, Lao PDR and Myanmar. The phasing-out of international support measures associated with LDC status could present challenges for graduating LDCs to integrate into the global economy, such as stricter compliance with climate and other environmental, social and governance (ESG) regulations. For instance, six global brands that source garments and footwear from Cambodia wrote to the government in August 2020, stating that the proposed increase in coal power generation could reduce the country's prospects of attracting future investment (Voice of America, 2020).

According to the International Energy Agency (IEA, 2022), Southeast Asia will see rapid growth in energy demand. In the Stated Policies Scenario (STEPS) based on the existing policy settings, the oil-dominated demand rises over 3 percent per year from 2021 to 2030, at higher growth over the last decade. Renewables, natural gas and coal demand all rise quickly. Coal continues to dominate the electricity sector, though its share of generation declines from 42 percent today to 39 percent by 2030 in the STEPS.

For East and Southeast Asia, the International Renewable Energy Agency (IRENA) has estimated average annual investment needs for renewable energy and energy efficiency to total US$582 billion under its Planned Energy Scenario (PES) and US$830 billion under the Transformative Energy Scenario (TES) during 2016-2050 (IRENA, 2020a; base year of US$ prices unavailable). This investment requirement is significant despite the decreasing costs of renewable energy. For example, IRENA reports that total installed costs for utility-scale solar PV plants fell by 81 percent between 2010 and 2020, from US$4,731 per kilowatt (kW) to US$ 883/kW (IRENA, 2022; information on nominal or real prices unavailable).

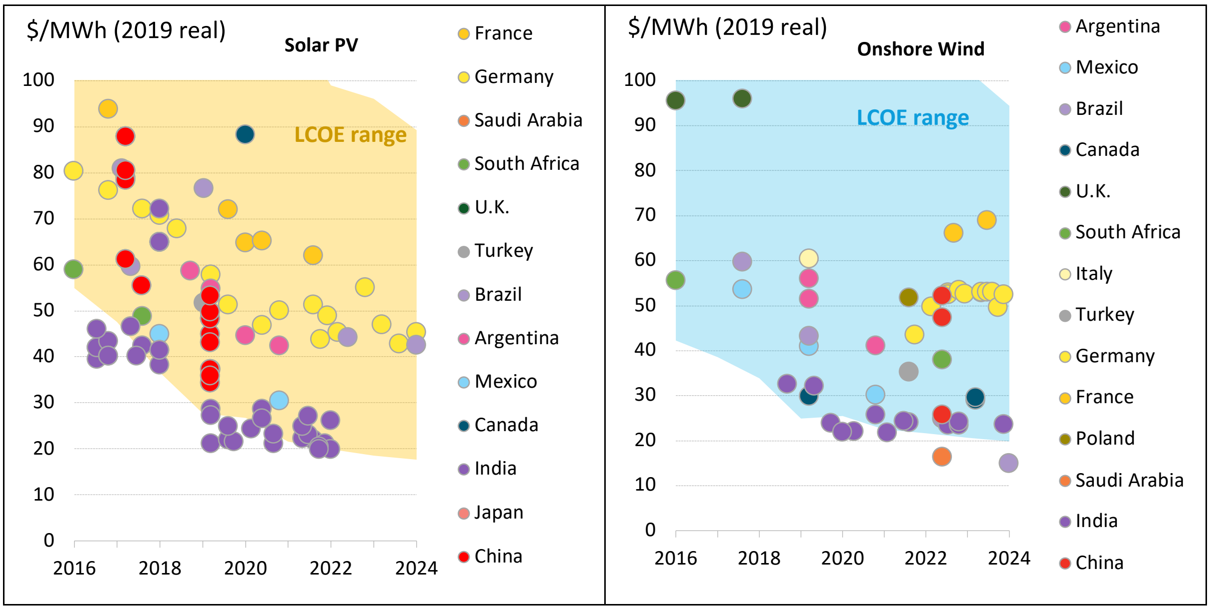
IEA reports prices of utility scale lithium-ion battery from US$4,285 per kilowatt-hour (kWh) in 2010 to US$1,568/kWh in 2017 (IEA, 2020; information on nominal or real prices unavailable). Nevertheless, amid fierce electric vehicles (EVs)' demand for lithium-ion phosphate batteries, the S&P Global-owned IHS has predicted a battery module price increase of 5 percent in 2022 will drive up the overall cost of stationary battery projects by around 3 percent. The business data company IHS Markit has predicted that lithium-ion battery prices will not fall until 2024, thanks to rising metal prices and demand for EVs, and China's near monopoly on the industry (Hall, 2022). Solar PV system prices have also been increasing during 2021-2022, mainly due to supply chain constraints (Stevens, 2022).

In the wake of soaring fossil fuel prices from 2021 to 2022, solar power has been contributing to meeting electricity demand in Asia and enhancing energy security. An estimated contribution of solar generation in seven key Asian countries, including China, India, Japan, South Korea, Vietnam, the Philippines, and Thailand, avoided potential fossil fuel costs of approximately US$34 billion from January to June 2022, equivalent to 9 percent of total fossil fuel costs during the same period (Edianto et al., 2022).

Power systems that aspire to have high penetration rates of renewables, but which face mainly variable renewable resources, will likely need a range of storage technologies. Those technologies should be procured through a competitive process to meet the least-cost objective of the power system.

As the renewable energy sector progresses, policies must reflect the changing market conditions and new technical and socioeconomic challenges and ensure inclusive and just transition well beyond the energy sector. Falling costs for new technologies, growing variable renewables (i.e., solar and wind) in the power system, and greater emphasis on climate and other ESG objectives by policymakers and stakeholders have altered the conditions for new market entrants and new power generation projects. An instrument on the rise has been the use of auctions to promote competition for the market, as policymakers seek to procure renewable electricity at the lowest possible price, while fulfilling other social or economic objectives. While enough data for statistical analysis are available, compared with earlier feed-in tariff schemes with government-set prices, general trends of auction prices might better reflect the trends in technology costs (Figure 1).

Figure 1: Levelized bids for auctions across the G-20 countries by project commissioning year, 2016-2024



Source: Bloomberg New Energy Finance (BloombergNEF, 2021).

Note: To make the winning auction tariffs comparable across countries, BloombergNEF levelizes the capacity-weighted average winning tariff, i.e., they estimate the average inflation-linked tariff for the lifetime of the project. BloombergNEF removes the effect of subsidies, standardizes inflation, and adds a merchant tail for the lifetime of the project after the auction tariff expires. Levelized bids are shown by their commissioning dates.

The morality aspect in competitive markets is increasingly important for investors, shareholders, and consumers (Tirole, 2017, 2021; Dewatripont and Tirole, 2022). Financiers' demand for return on ESG have been on the rise; global debt issued for ESG purposes is expected to reach US$1.3 trillion in 2022 (Institute of International Finance, 2022) from about US$30 billion in 2013 reported by Bloomberg New Energy Finance (BloombergNEF). The European Union (EU) will require funds to disclose information about how they reduce the possible negative effects of their investments from 2023.

According to a 2022 report, major impediments to institutional investments in emerging and frontier markets are that institutions and fund managers are increasingly applying ESG considerations in their investment strategy that excluded or down-weighted emerging and frontier markets (Theobald, 2022). However, some investors used an active ESG approach in addition to, or instead of, ESG screening, by identifying investment opportunities to improve ESG outcomes using the Sustainable Development Goals (SDGs) as a set of targets (Theobald, 2022).

This study will focus on the auctions to procure utility-scale solar photovoltaics (PV) and battery energy storage systems (BESS) with a long-term power purchase agreement (PPA) for about 15-25 years or a sufficient cost recovery period for the following two reasons.

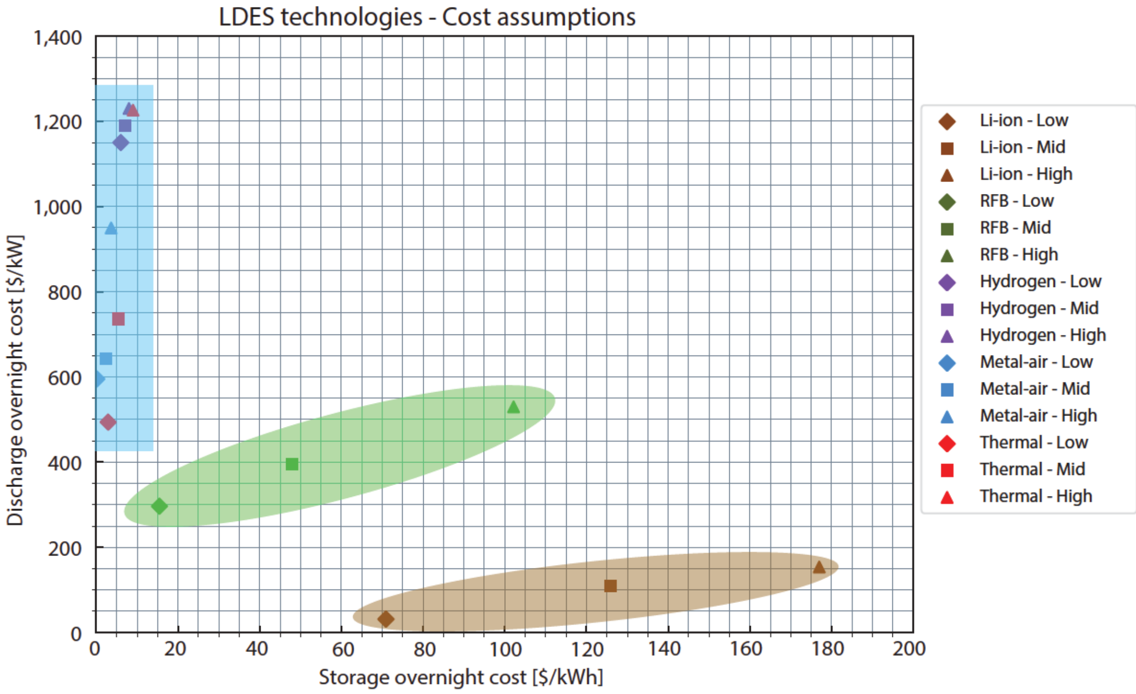
First, a few countries in ASEAN and East Asia have wholesale electricity markets based on auctions in energy markets (e.g., the day-ahead and real-time markets) and capacity markets including forward markets, such as Japan, Korea and Singapore. Many ASEAN countries retain a state-owned single buyer model (centralized agent who purchases power from generators) with purchased electricity from the private independent power producers (IPPs) with PPAs and often their own power generations, such as Vietnam, Cambodia, Indonesia and Lao PDR. While countries with centralized power purchasing agent models may not have competitive electricity markets, the auctions for contracted amount of electricity procurement provide opportunities for bidders to compete for specific market segments under the PPAs.

Second, as companies aspire, or are required, to decarbonize their activities, corporate renewable energy PPA volumes are increasing but hardly provide 24/7 renewable energy power as of 2022 (LDES Council, McKinsey and Company, 2022). Achieving 100 percent decarbonization with variable renewable energy requires long-duration energy storage (LDES) technologies. As shown in Figure 2, technologies with low energy capacity costs and high power-capacity costs (the blue area) are most suitable for longer duration storage applications (up to multiple days) and less frequent charge discharge cycles. Examples include metal-air batteries, hydrogen, and thermal storage with low round-trip efficiency (RTE) and pumped hydro storage with medium RTE. Technologies with intermediate capabilities, including redox flow batteries (RFBs) with medium RTE, are in the green area. Technologies in the brown area, including lithium-ion battery high RTE, are better suited to shorter duration applications (a few hours) and more frequent cycling. Electric vehicle (EV) battery development has significantly improved the prospects for short-duration electricity storage. Meanwhile, long-duration storage technologies have not experienced similar help from other market drivers (MIT 2022).

Small-scale renewable energy and storage system, such as small islands, tends to achieve higher penetration into 24/7 renewable energy power target, as shown in

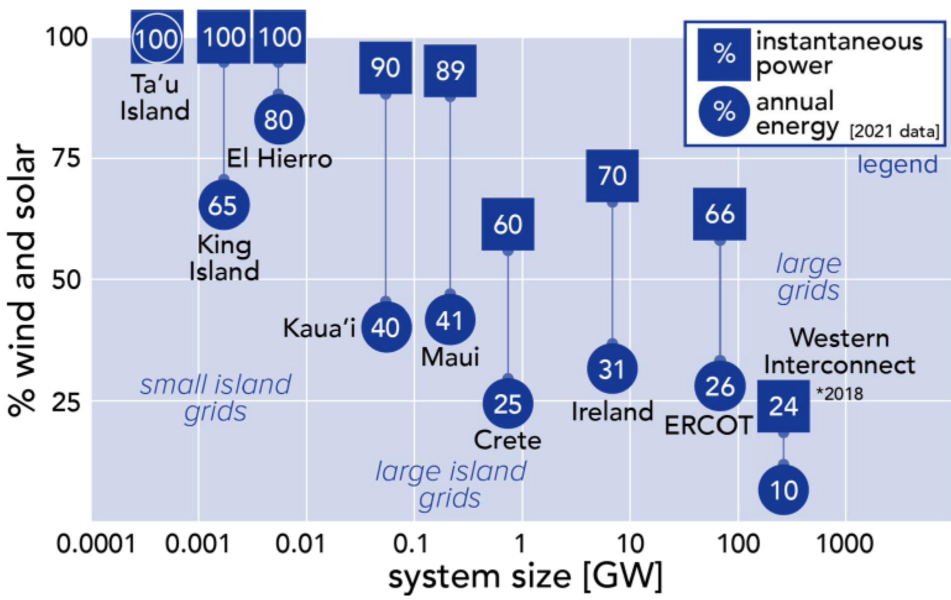
Figure ***3***. Use of lithium-ion battery for a longer duration in a larger system to complement wind power, such as Ireland, is assessed to be too expensive (Newbery, 2020). Competitive auctions improve the transparency of renewable energy PPAs by enabling investments in clean, dispatchable capacity that drive down costs and more accurate climate and ESG compliance.

Figure 2: Three classes of energy storage technologies, grouped by discharge power and storage overnight capital costs in 2050 (US$ 2020 prices)



Source: Massachusetts Institute of Technology (2022).
Note: LDES represents long duration energy storage, and RFB represents redox flow battery.

Figure 3: Instantaneous power vs. annual energy by grid system size



Source: Kroposki (2022)
Note: ERCOT represents Electric Reliability Council of Texas

The focus of this chapter on ESG is aligned with and more comprehensive than the Paris Agreement on climate change and is especially relevant to renewable energy whose locations tend to be in ecologically and socioeconomically sensitive areas. Climate is part of ESG and is an abiotic factor of natural ecosystem. Thus, if the global community only invests in climate mitigation, adaptation, and resilience regardless of its investment impacts on the other parts of the natural ecosystem, our planet will not be sustainable. "E" of ESG and climate are inseparable. According to a United Nations report (UNEP 2022), climate, biodiversity, and land degradation goals will be out of reach unless investments into nature-based solutions quickly ramp up to US$384 billion/year by 2025, more than double of the current US$ 154 billion/year as of 2022. Annually, private capital only represents an estimated 17 percent (US$26 billion) of total investments into nature-based solutions. Private sector actors will have to combine net zero with nature positive. Nature-related Financial Disclosures (TNFD) is now rolling out as well.

The remainder of this chapter is organized as follows. Section 2 develops a theoretical and conceptual framework of auction markets where demand and supply have their own ESG objectives. Then, it assesses risks and measures to mitigate and manage those risks with country examples. It also discusses the complementary role of auctions among other market instruments in mitigating risks. Section 3 briefly reviews the relevant auction methods and the contractual forms. Section 4 discusses several business models with some country examples. Section 5 discusses the key findings of the literature reviews. Section 6 is the conclusion noting that ESG integration in competition could be possible and higher impacts could be achievable with broader policy supports.

2. Conceptual and theoretical framework

2.1. Static, Dynamic and Incentive Framework

2.1.1. Static Framework

The main objectives of auction design include efficiency, fairness, transparency, and simplicity subject to the firms' (bidders') incentive compatibility, individual rationality, and participation constraints. This analysis uses a simplified framework building on Tirole (2017, 2021) and Dewatripont and Tirole (2022). This framework assumes a unit-demand (official selecting a bidder, also representing consumers and public interest) and n sellers (bidders), $i \in \{1, \ldots, n\}$. To compete for the market, sellers select a price p_i and a ESG choice a_i, both in $\mathbb{R}^+$. Higher values of a_i index a higher level of ESG choice, at least in the relevant range $[0, \widehat{a_i}]$ where $\widehat{a_i} \leq +\infty$. Choice a_i has welfare impact $W_i(a_i)$, with $W"_i < 0$ and $W'_i(0) = +\infty$. Thus, there exists $\widehat{a_i}$ such that $W_i(a_i) > 0$ if and only if $a_i < \widehat{a_i}$. Let $a = (a_1 \ldots . a_n)$ denote the vector of ESG choices.

The vector $\{p_{i,} \, a_i\}$ determines the net price $\widehat{p_i}$ perceived by the buyer. Seller i faces demand function $D_i(\hat{p})$ where $\hat{p} \equiv \{p_{1,\ldots} \, p_n\}$ denotes the vector of net prices, and also refers to $D_i(\widehat{p_i}, \hat{p}_{-i})$, where $\hat{p}_{-i}$ denotes the vector of net prices charged by seller i's rivals. The buyer's cost or benefit of ESG is a function $\phi_i(a_i)$ with $\phi_i'' \geq 0$ such that

$$\widehat{p_i} \equiv p_i + \phi_i(a_i). \qquad (1)$$

When the buyer is ESG irresponsible, then $\phi_i'(a_i) > 0$, as their demand decreases with the morality of the firm's offer. Conversely, ESG irresponsible buyer's demand increases with the morality of the firm's offer: $\phi_i'(a_i) < 0$. ESG neutral buyer's demand does not change with the offer of the firm's morality: $\phi_i'(a_i) = 0$.

Seller i's unit cost, c_i, may depend on her ESG choice a_i: $c_i(a_i)$ with $c'_i(a_i) \gtrless 0$. The sellers are substitutes. Hence, demand elasticity is $(\partial D_i/\partial \hat{p}_i < 0 < \partial D_i/\partial \hat{p}_j)$, and their marginal revenue is decreasing in price ($(p_i - c_i)D_i(\hat{p})$ is concave in p_i). $\eta_i(\hat{p};\sigma) \equiv (-\partial D_i/\partial \hat{p}_i)/(D_i/p_i)$ denotes the price elasticity of demand for supplier i's services.

Assumption 1 (elasticity of demand). Seller i's elasticity of demand increases with competitive pressure: $\frac{\partial \eta_i}{\partial \hat{p}_j}$.

Objective functions. Sellers care about profit and ESG impacts as part of the requirements to participate as bidders in the auction and/or as part of the requirements by the seller's (firm's) investors. Let $\alpha_i \geq 0$ denotes seller i's intrinsic ethics, that is the weight on welfare relative to that on profit.

Assumption 2 (consequentialism). As net prices determine demands, seller i's social welfare perception depends on net prices and ESG choices: $W_i(\hat{p}, \mathrm{a})$. Furthermore, perceived welfare impacts scale with actual impacts, which means proportional to demands: a non-increasing function $\Gamma_i(a_i)$ *such that* $\Gamma i(0) = +\infty$ and $\lim_{a_i \to \hat{a}} \Gamma_i(a_i) = 0$, *and* $\frac{\partial W_i}{\partial a_i}$=$\Gamma_i(a_i)\, D_i(\hat{p})$.

Seller i maximizes the sum of profit and internalized perceived social welfare as ESG impacts; letting $\alpha_i \geq 0$ denotes the intensity of her social preferences, her utility function is:

$$U_i \equiv [p_i - c_i(a_i)]D_i(\hat{p}) + \alpha_i W_i(\hat{p}, a) \equiv \left[p_i - (c_i(a_i) - \alpha_i W_i(\hat{p}, a)\frac{1}{D_i(\hat{p})})\right] D_i(\hat{p}) \equiv [p_i D_i(\hat{p}) + \alpha_i W_i(\hat{p}, a)] - c_i(a_i) D_i(\hat{p}). \tag{2}$$

That $\frac{\partial W_i}{\partial a_i}$ is proportional to demand D_i is consistent with the consequentialist approach. ESG choices are uniform over seller i's demand and so their impact is proportional to demand.

To illustrate the above concept, the following is a simplified equilibrium behavior in the case of first-price (pay-as-you-bid) auction with incomplete information. Each of n bidders' private value v (parameter) is drawn from distribution F, and is denoted as $v_i \equiv p_i(v_i) - c_i(a_i)D_i(\hat{p})$ from the above equation (2) where $p_i(v_i) \equiv p_i D_i(\hat{p}) + \alpha_i W_i(\hat{p}, a)$. Bidder will decide on the bidding price $p_i\,(v_i)$ (decision variable) and the expected utility is:

$$\mathbb{E}\,[u(p_i(v_i), v)] = [p_i(v_i) - v_i]\big(Win|p_i(v_i)\big) \tag{3}$$

By the envelope theorem, $\frac{du}{dv} = \frac{\partial u}{\partial p_i(v_i)}\frac{\partial p_i(v_i)}{\partial v} + \frac{\partial u}{\partial v} = \frac{\partial u}{\partial v}$, then, $\frac{du}{dv} = \Pr\,(Win|p_i(v_i)) = \Pr\,(lowest\ bid) = \Pr\,(lowest\ value) = F(v)^{n-1}$. Utility is rewritten as $u(v) = u(0) + \int_0^v F(v)^{n-1}dv = \int_0^v F(v)^{n-1}dv$, which is substituted into above (3) results in: $p_i(v_i) = \frac{u(p_i(v_i),v)}{\Pr\left(Win|p_i(v_i)\right)} + v_i = F(v)^{-(n-1)}\int_0^v F(v)^{n-1}dv + v$. An example of this case where $v \sim U$ on [0,1] then, $F(v) = v$, and $p(v) = \frac{v}{n} + v = \frac{v(1+n)}{n}$. The optimal bid converges to the value as $n \to \infty$, so in the limit the buyer can extract the full surplus of the bidder. In equilibrium, the bidder bids the expected value of the second lowest value given that the bidder has the lowest value.

The buyer will select the seller who bids at the lowest price p . The ESG responsible buyer may consider social welfare impacts $\hat{p} \equiv p + \phi(a)$ in selecting the bidder but will higher weight on the bid offer price p than that on $\phi(a)$. Since the auctioned quantity (demand) is fixed, seller i try to minimize the offer price p_i. Rearranging the above equations (1) and (2) will result in:

$$p_i \equiv \widehat{p_i} - \phi_i(a_i) \equiv [U_i - \alpha_i W_i(\hat{p}, a)] * \frac{1}{D_i(\hat{p})} + c_i(a_i) \quad (4)$$

In the above equations, the seller i's controllable cost is $c_i(a_i)$. Hence the seller tries to reduce either cost c_i or ESG concerns a_i or both, by increasing the efficiency, or cutting corners, such as choosing inexpensive and lower quality of inputs and reducing ESG activities and/or quality. However, as cost c_i depends on ESG efforts a_i , cutting corners could incur costs more than the bid offer p_i. For example, lower efforts on social and environmental impact assessment, mitigation and management measures and benefit sharing with local communities could delay the contract implementation and add costs and penalties. Low quality equipment may require more costs in maintenance, repair and replacement.

2.1.2. Dynamic Framework

In a dynamic intertemporal setting where auctions are held repeatedly over the years, sellers may choose not to participate in the auction and wait for the next auctions until more information about the auction process is available. However, those participating sellers will have more information through their participation in the auction than the deferred sellers. For example, assuming at the initial auction where all bidders have the same prior information, participating bidders would gain additional information by joining the auction, hence their posterior information is more than their prior information at the initial auction. In the next auction, the bidders who participated in the earlier auction have the updated increased prior information than those bidders who did not join the earlier auction. Thus, the deferred bidders could face tougher competition at the next auctions.

The above dynamic setting, based on Bergemann and Juuso (2010) and Bergemann and Välimäki (2019), the flow marginal contribution to welfare $m_i(\theta_t)$ of seller i is: $m_i(\theta_t) = M_i(\theta_t) - \delta M_i(\theta_t, h_t^*)$, where M_i is marginal welfare contribution of seller i, time $t = 0, 1 \ldots$, common discount factor $\delta \in (0, 1)$, allocation $h_t \in H$, Markovian state $\theta_t = (\theta_{1,t,\ldots\ldots,}\theta_{It}) \in \Theta$, private (Markovian) signal $\theta_{i,t+1}$ of i generated by conditional distribution function $\theta_{i,t+1} \sim P_i(\cdot\ |h_t, \theta_{it})$ and socially efficient allocation rule (after all histories C_t; the histories are bidders reporting of state θ_t and allocation):

$$a_t^*: H_t \to [0,1]'. \quad (5)$$

Expanding flow term with respect to time results in: $m_i(\theta_t) = \big(W(\theta_t) - W_{-1}(\theta_t)\big) - \delta\big(W(\theta_{t+1}|h_t^*) - W_{-1}(\theta_{t+1}|h_t^*)\big)_i$, where the first bracket indicates M_i starting at t and the second indicates M_i starting at $t+1$ and h_t^* in the right hand side. Further expending flow term with respect to identity (rearranging) results in: $m_i(\theta_t) = (W(\theta_t) - \delta\big(W(\theta_{t+1}|h_t^*)) - (W_{-1}(\theta_t) - \delta W_{-1}(\theta_{t+1}|h_t^*)\big)$, where the first bracket indicates current value with bidder i and the second indicates current value without bidder i but with h_t^* in the right hand side. Given the marginal contribution to welfare is $M_i = v_i - p_i$, and by rearranging, price bidder i is:

$$p_i = v_i - M_i \quad (6)$$

By adjusting the above equation (4) into an intertemporal setting, the above socially efficient allocation rule (4) satisfies ex post incentive and ex post participation constraint with payment p :
$$p_{i,t}\left(h^*(\theta_t), \theta_{-i,t}\right) = v_i\left(h^*(\theta_t), \theta_{-i,t}\right) - m_i(\theta_t) \quad (7)$$

2.1.3. Incentive Framework

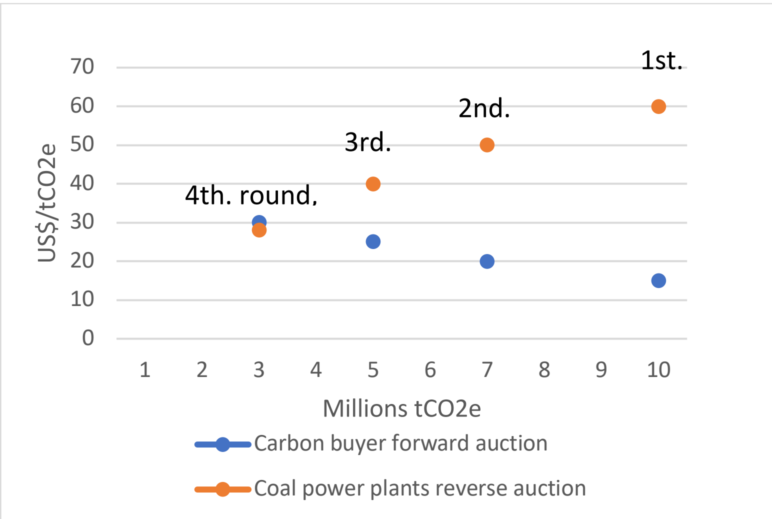
Despite the need for renewable power generation, the average age of coal power plants in Southeast Asia and East Asia is around 10-15 years (World Bank, 2022). Thus, it is important to plan the timing of retirement of coal power plants in a medium or long term to ensure a smooth and just transition. In some cases, electricity resource planning and adequacy requirement and/or the increasing ESG and climate regulations toward 24/7 green power (especially for corporates) necessitate additional renewable energy, such as solar, to replace the retiring coal power. Coal power often acts as baseload. Thus, a combination of solar PV and BESS are one of the technology options to replace the retiring coal power plants. As a means of early coal power retirement, Germany has been holding one sided and subsidized compensation auctions to purchase the capacity of coal power plants for 2020-2027 with a price cap per capacity (Reuters, 2021; World Bank, 2022).

The coordinated arrangements include staged multiple product matching auctions. For example, building on the incentive auctions of radio spectrum reallocation in 2016-2017 by the United States Federal Communications Commission (FCC) (Leyton-Brown et al., 2017; Royal Swedish Academy of Sciences, 2020), the first stage of the auctions is a reverse auction to determine a price at which coal power producers voluntarily relinquish their coal power capacity and indicate the amount of avoided carbon dioxide equivalent (CO2e) emissions by the retiring coal power capacity. The second stage of auctions is a forward auction for avoided CO2e emissions, which could be repeated until the supply prices of avoided CO2e equals the purchase prices, or small enough that the host government (or donors) will fill the gap.

Figure 4 illustrates the first stage and the second stage of auctions going through four rounds until the demand (carbon buyer) and supply (coal power giving up) match. At the third stage of the auction, the corresponding freed-up coal power capacity will be matched by reverse auctions of solar PV and BESS while some backup power generations such as gas turbines may be required as solar PV and BESS alone can hardly provide 24/7 dispatchable power or replace the baseload as shown in Figure 2 and

Figure *3*. When the costs and implementation details of thermal storage retrofit strategies for thermal power plants (such as coal) become clearer in the near future, this thermal storage option could be part of the auctions.

Figure 4: Illustration of First Stage Reverse and Second Stage Forward Auctions



2.2. Risks

As in other auctions for renewable energy resources, competitive procurement of paired solar PV and BESS is subject to certain risks and hence the returns for investors and the economic and social impacts (see, e.g., Maurer et al., 2020; Cote et al., 2022; Roth et al., 2022). Thus, market designs of auctions must ensure that the benefit of market competition in auctions outweigh the costs of auctions. The auction market designs should mitigate and manage the risks for the markets to provide incentives and signals for the right investments (in terms of type, amount, timing and externalities) to deliver quality and affordable electricity to the consumers. Non-market alternatives are likely to result in welfare suboptimal, such as untransparent bilateral negotiation-based contacts with unsolicited power producers. The following is a summary of the key risks and auction formats and measures to mitigate and manage risks, which are relevant to ESG solar PV and BESS auctions.

2.2.1. Bidding

Bidders have the allocation risk of not winning in the auction. The bidders' resources spent in applying and preparing for the auction and meeting the physical prequalification criteria of the auctions are sunk costs if they do not win. The risk of sunk costs is significant if the auctioned items are limited, i.e., fixed demand and if the sunk costs are relatively large for the bidder's financial resources and project portfolio. Thus, smaller companies and local community organizations may be disadvantaged in participating in the auctions, which undermine the diversity, equity and equality of the auctions and ESG objectives (Eberhard et al., 2014; Amazo et al., 2021; Cote et al., 2022). As a rule of thumb, those sunk costs should not exceed 3–5 percent of the capital expenditure (Haufe and Ehrhart, 2018).

Expending on ESG related prequalification criteria could reduce overall costs if during the project implementation, ESG issues emerge to be too costly and/or too time consuming for the project realization. Examples of sunk costs of prequalification criteria on ESG issues include environmental and social impact assessment (ESIA) or proof of community engagement (Amazo et al., 2021). Those ESG sunk costs, especially community engagement, could be costly in terms of monetary and non-monetary values (such as political economy, efforts, time). However, inadequate community involvement can slow or halt the implementation of renewable energy projects, as in the case of, for instance, wind projects that were terminated in Mexico and Kenya (Business and Human Rights Resource Centre, 2018, cited in IRENA 2019a).

The ESG related prequalification criteria could contribute to a higher probability of timely commissioning because the bidders can reduce ESG uncertainties and can price in the costs of enhancing, mitigating, and managing the expected ESG impacts in their bids. Hence, the auction designs need strategies to reduce the sunk costs of bidders and their time in meeting ESG prequalification requirements and encourage participation.

The auctions design strategy could choose or combine the following options. One option is for the auction planner to pay the costs that are common to all bidders as requiring each bidder to pay all common costs is not resource efficient (as in China as discussed later). For example, if the site of solar PV and BESS has been already identified, the auction planner should pay those costs of EISA, community engagement, land and other permits and authorizations, which each bidder can make adjustment to reflect their idiosyncratic cases. The second option is for the auction planner to reduce the research costs and information asymmetry among the bidders (e.g., large, small, international, electric utilities, local, community-based organizations, private business companies, etc.) by sharing the indicative costs and information in the request for proposal. For instance, Hawaiian Electric Company, Inc. (Hawaiian Electric) includes indicative costs of Supervisory Control and Data Acquisition (SCADA) communications, security system interconnection, and station services (e.g., overhead lines and transformers) in request for proposal of renewable dispatchable generation and storage island of O‘Ahu (Hawaiian Electric, 2019). Similarly, requests for proposal could include indicative costs of ESG related costs to reduce information asymmetry and research costs as local bidders may have more local ESG information. The third option is to limit prequalification requirements to a preliminary social impact evaluation and evidence of community engagement, to be finalized after the bidder wins the award, with penalties for non-finalization or by tying the granting of licenses to successful finalization (Amazo et al., 2021).

Auction design should encourage participation and diversity from smaller actors and investors who are less able to cope with the complexity and competitiveness of auctions. Strategic methods such as (i) reduced prequalification, (ii) different pricing rules and (iii) quota, could affect and distort the auction outcome significantly. The lack of clear taxonomy of the protected groups could lead to free riding, as in Germany where preferential rules led to the creation of artificial citizen energy communities for onshore wind that were awarded more than 90 percent of the auction volume in 2017 (Kitzing et al., 2019; Cote et al., 2022). In Australia, proof of community engagement and benefit sharing was part of the qualification requirements for the state of Victoria's 2017 renewable energy auction scheme. However, community projects and other small-scale actors could not compete against larger and more established players due to (i) nascent community initiatives at the time of the auction, (ii) technology-neutral auction schemes, (iii) high up-front costs for proposal preparation, and (iv) the lack of economies of scale. Thus, the state of Victoria had to employ other support schemes, such as grant funding (Renewable Communities Program), to support community energy initiatives (IRENA, 2019a).

2.2.2. Awarding and contracting

Bidders (i.e., suppliers or sellers) tend to have differing information about the true demand and may have similar or different cost profile of the bid item (i.e., solar PV and BESS) but different financial profile to diversify risk and be more strategic. Winning an auction can also mean that others and the demand have better information about the value of the bid item. Meanwhile, as the lowest bid price will win, bidders also compete in lower bid prices. Thus, bidders try to shade their bids. However, bid shading could inflate the bid price or underbid the price below what could realize financially successful projects. Incidences of underbidding were observed in multi-item auctions under the uniform pricing rule in Germany where several bidders submitted bids below 1 cent €/kWh, in Spain, an auction in 2015 resulted in a clearing price of zero and in the British Contract for Difference (CfD) auctions in 2015 where two solar projects were withdrawn having submitted bids at irrationally low prices (Tongsopit et al., 2017). On the other hand, in the first price (pay-as-you-bid) single item auctions, the bidders' strategy is to bid just below the second lowest bidder as illustrated in section 2.1.1.

The underbidding risk is relevant given (i) the declining costs of solar PV and BESS and (ii) the uncertainties of their financing and material costs. In August 2022, Malaysia extended power purchase agreements from the fourth large-scale solar (LSS4) tender for large-scale PV from 21 to 25 years due to concern about the bankability of projects, due to rising material prices and fears of rising interest rates. Several project owners asked the Malaysian Energy Commission to review electricity bid prices, but the regulator rejected the requests. The LSS4 program awarded 823 MW of capacity across 30 projects. In total, it has awarded 2,457 MW, but only 1,160 MW of them were operational by the second quarter of 2022 (Table 1; Santos, 2022a).

Table 1: Examples of Auctioned Project Realization Rates

	India	Malaysia	Brazil	United Kingdom	The Netherlands	France	Ireland	California, US	China
Auction years	1997-2022	2016-2022	2009-2010	1990-2001	2011	2011	1995-2003	2011-2015	2003-2004
Technology	Wind	Solar PV	Biomass, wind, small hydro	Technology neutral	Technology neutral	Solar PV	Wind, hydro, biomass, and CHP	Technology neutral	Wind
Realization rate	25% by 2022	47% by 2022	~30% by 2014	~30%	68% by 2015	<50%	~30% by 2005	>75%	100% by 2007

Source: Wigand et al. (2016); Kreiss et al. (2017); REN21 (2022); Santos (2022a).
Note: CHP represents combined heat and power.

In India, as of early 2022, only around a quarter of the capacity awarded under auctions since 2017 had been commissioned (Table 1), and several companies that had been awarded PPAs through auctions surrendered capacity due mainly to low tariffs and rising costs. Turbine manufacturers in India are shifting their focus overseas while developers are moving from auctions and long-term PPAs to options that fetch better energy prices through direct sales to commercial and industrial customers and sales via the Indian Energy Exchange. Other longer-term challenges in India include the high cost of capital, grid connection, permitting and land acquisition for projects. Large wind and solar power projects require large areas, often leading to development on local communal lands, for example in India. Land rights issues are thus on the rise around the world (REN21, 2022).

Delays and underbuilding can be caused by factors outside the developer's control. Obtaining environmental and social permits and grid access are significant causes of underperformance in the construction phase. It is, therefore, essential to allocate those responsibilities fairly between the bidder and auctioneer. Alternatively, permits may be included as a qualification requirement, but this may limit the pool of participants in the auction. In many jurisdictions, permitting processes need to be made more transparent and streamlined. In Mexico, a social impact permit has become a bottleneck in deployment of awarded projects especially due to unclear and lengthy institutional process and became a qualification requirement in the fourth auction round, instead of a post award requirement but the auction was ultimately cancelled (IRENA 2019a).

An auction design strategy to mitigate the underbidding risk, if bidders are rational, is to reduce uncertainty. Each bidder would revise its value if they had the information about other bidders. This information might be inferred by the competitors' bids in open (but not in sealed bid) auctions. Better information and less uncertainty allow bidders to bid more wisely. Thus, the reverse clock auction, theoretically, yields lower prices. An auction planner can set time limits on completion of the projects to reduce underbidding. Maurer et al. (2020) notes reverse clock auctions are likely to become the industry standard as business models for standalone and co-located or hybrid BESS facilities mature. However, information revelation could invite bidders to implicitly collude especially with large multi-project bidders in an environment with low competition while setting a reservation price could mitigate collusion (Haufe and Ehrhart. 2018).

Vickrey auction or Vickrey-Clarke-Groves (VCG) mechanism will induce bidders to bid their true values (no shading) as their dominant strategy, because the winning bidder would be awarded the opportunity cost, regardless of the bidder's own value. For a single item, the mechanism is referred to as the second price sealed-bid auction, or simply the Vickrey auction where bidders simultaneously submit sealed bids. The highest bidder wins the item, but (unlike standard sealed-bid tenders) the winner pays the amount of the second-highest bid (in reverse auctions, the buyer pays the second lowest bid). This second price sealed bid is de facto equivalent to the English clock auction. The VCG is well researched and extended by economists, including in section 2.1.2. However, VCG is rarely applied in practice. Ausubel and Milgrom (2002) discuss several possible weaknesses of VCG mechanism, including possibilities of very low revenues (in reverse auction, very high revenues) or vulnerability to collusion.

Under-contracting risk is an auction outcome where the amount of capacity or generation contracted is less than expected. This risk may be high if an auction has a low auction participation rate and/or does not impose penalties on winning bidders who do not sign PPAs. The auction design strategy to mitigate under-contracting is to require bid bonds or impose other penalties to make it costly for selected bidders to walk away without signing contracts. A selected bidder may still choose not to sign a PPA because the financial penalties are usually larger for breaching a contract than turning down a contract (Maurer et al., 2020).

If a firm bids to supply more than its contracting capacity required in an auction, it must face the risk of over-contracting and buying from other generators on the spot market to honor his contract. A study on Chilean experience from 2006 to 2011 finds that a higher cost of over-contracting for entrants, especially smaller ones, than for incumbents could act as an entry barrier (Bustos-Salvagno 2015). The study finds that incumbents are on average, presenting lower bids than entrants, due in part to a significant difference in the cost of over-contracting, which is directly related with their level of risk-aversion. Incumbents with diversified portfolio of generating technologies have an advantage over entrants, especially the smaller ones. As a result, entrants are asking for a risk-premium that influences competition, since their bids do not represent a serious threat for incumbents (Bustos-Salvagno 2015). One of strategies to mitigate risks and increase competitions is to design auctions to cater for technology profiles (e.g., variable renewable energy). In the electricity auction in November 2014 in Chile, renewable bidders were allowed to bid for blocks of eight hours. This rule allowed solar and wind generators to bid more aggressively since they could bid when their cost of over-contracting is minimum. While the historical average was around four generators, this time, there were seventeen bidders (Bustos-Salvagno 2015).

2.2.3. Construction and Operation

Nonrealization risk is the failure of auction winners to implement their contracted projects. The selected bidders may choose to opt out before signing a contract. The project realization rate is often low (Table 1) for reasons such as underbidding, low prequalifications, cost increases, timing, permits, ESG impacts, unavailability or more remote location of grid connections than expected, and premature projects (Kreiss et al., Tongsopit et al., 2017; 2017; Kitzing et al., 2019; Szabó et al., 2020). In China, the government secured the land and procuring environmental permits and most of the participating bidders were state-owned companies that could cross-subsidize their wind projects and bid low prices (Wigand et al., 2016). In Germany, project realization deadline can be extended once in cases where a lawsuit has been filed against a project. Lawsuits against the construction of onshore wind projects are not uncommon in Germany (Tongsopit et al., 2017). Conflicting policy objectives (e.g., lowest price versus local content) in the auction designs could, as in Indonesia, result in a low percentage of the winning projects realized (Tongsopit et al., 2017).

An auction market design strategy to improve realization rates could include a high financial prequalification and an adjusted physical prequalification relative to sunk costs, penalties covered by financial prequalifications (e.g., bid bonds), and increasing competition (Kreiss et al., 2017; Kitzing et al., 2019; Haufe and Ehrhart, 2018). Higher prequalification and penalties could increase bidding prices and reduce participation but increasing competition could offset such impacts. In Germany, increasing competition and decreasing support level may contribute to high project realization rates (Haufe and Ehrhart, 2018). On the contrary, a survey in 2021 found that project developers tend to be less willing to accept auctions with high levels of competition (Cote et al., 2022). Kremer (2022) notes a low ratio of private to social return under low entry barriers.

On grid connection challenges, auctions are used to allocate grid-connection. Portugal held two large-scale tenders in 2019-2020 to resolve a glut of grid permit requests for solar projects. Some 52 percent of grid-connection capacity awarded in those auctions went to PV or PV and BESS projects. The projects gain full access to the wholesale and ancillary services market and the option to sign a PPA with a utility or corporate off taker. All projects under this merchant option will pay the system operator €5-40/MWh for 15 years for grid access for their lifetime (BloombergNEF, 2021).

A theoretically and empirically proved auction market design with a low complexity for the bidders could facilitate an appropriate bidding strategy to optimize the ESG and overall outcomes. The auction should minimize the incentives for strategic supply reduction, which could be mitigated with diversifying markets with forward and wholesale markets. A long-term auction schedule ensures a degree of certainty for investors to avoid risks. An ad-hoc auction undertaken without the future auction schedule could force bidders to underbid to limit their losses under advanced development. A study shows that continuity in auction rounds, instead of ad-hoc auction, increases long-term certainty for participation, as in California (Kitzing et al., 2019). The analysis finds that auction frequency depends on context and technology (Kitzing et al., 2019). In general, lower auction frequency is appropriate for technologies with fewer bidders and larger projects (e.g., offshore wind) and more frequent rounds for technologies with more potential participants (e.g., solar PV) (Kitzing et al., 2019). In China, solar PV auction was heled every year during 2019-2021 and renewable energy auction has been held every two years in the United Kingdom since 2015, and every three months in Italy during 2019-2022 (BloombergNEF, 2021).

2.3. Role of Auction among other Policy Instruments

As each policy instrument has its own strength, selection and design of complementary mix of instruments could better mitigate and manage risks in scaling up solar PV and BESS in the electricity market. For example, Kwon analyzes (2020) South Korea's policy mix effects among auctions, feed-in tariffs (FIT) for small solar PV producers and renewable portfolio standards (RPS) summarized as follows. South Korea's long term contract auction schemes with a sliding premium can (i) alleviate price risk for renewable electricity suppliers under RPS by fixing remuneration over long periods, (ii) counteract less competitive pressures under FIT with auction's intense market competition and (iii) influence in renewable energy certificates' (RECs)' spot prices and provide a reference price for FIT rates, thus reducing asymmetric information. Weekly renewable energy certificates (REC) spot market could mitigate sales risks under the long-term contract auction scheme due to only two rounds of bidding opportunities per year. FIT can lower RPS's price risks and mitigate transaction costs and sales risks of long-term contract auctions. Intense RPS market competitions could counteract less competitive pressures under FIT. Those complementary situations may be apparent in the following example. An introduction of long-term contract auctions in 2017 resulted in a fall in REC spot prices due to a rapid increase in small and medium solar PVs in the market. The re-introduction of FIT for small solar PV suppliers in 2018 led to a further fall in REC spot prices, which resulted in lower REC spot prices than long-term contract auction prices, implying that the current REC spot prices may be lower than breakeven prices for small solar PV. Hence, an increase in the RPS target may be required to reverse falling trends of REC prices.

More than one policy instruments providing diverse market opportunities are particularly relevant for a solar PV and BESS system given the ability of BESS to substitute for, or complement, other elements of a power system (including generation, transmission, distribution, and demand response). Furthermore, with uncertain climate change impacts on electricity demand and supply, sophisticated markets and analysis could help better plan, operate, and regulate the power systems of the future and to ensure that these systems are reliable and efficient. In Australia, the Hornsdale plant (wind power and BESS) participated in an auction for frequency regulation and uses part of storage for price arbitrage in the wholesale market, which could allow revenue and risk diversification based on a complementarity between price arbitrage (MWh) with frequency regulation (MW).

Forward auction markets can mitigate potential prices significantly above marginal costs in the wholesale spot markets (e.g., day ahead, real time, etc.). As shown in Figure 5 (forward price higher than spot wholesale spot market (Cramton 2020)) and

Figure ***6*** (forward price lower than wholesale spot market), a dominant market player in wholesale market could have less incentive to bid much higher than its marginal cost in the spot market as their forward sales secured under the long term contact auction place it in a more balanced position (Cramton 2020). This type of bidding behavior can be seen from a large electricity supplier with many projects in its portfolio or a supplier building a lager capacity than the capacity required by the auction. In the latter case, bidders may bid some of its capacity into the auction to anchor some of its revenues and sell the remainder of the capacity on the spot market or to corporate off-takers. A winner of the July 2022 auctions in Chile, a 253 megawatt-peak (MWp) solar and 1 gigawatt-hour (GWh) BESS project, will sell a portion of the electricity to distribution companies under 15-year PPAs and the remaining electricity to private off-takers (NS Energy 2022). In such a case, the auction price could be lower than a solar PV/BESS system wholly dedicated to the auction could achieve by diversifying the risks and achieving economies of scale. Brazil held multiple auctions for hydropower plants, where the developer sells most of the energy in the regulated market under the auction scheme and sells part of the remaining energy via corporate forward contracts. Solar PV/BESS suppliers' behavior across those different markets need to be closely monitored and audited. The regulator needs to mitigate anti-competitive behaviors and unreasonable cross subsidies, as well as evading ESG obligations outside the contract under auction.

Figure 5: Case 1. Forward Auction Contract Could Mitigate Market Power in Spot Market

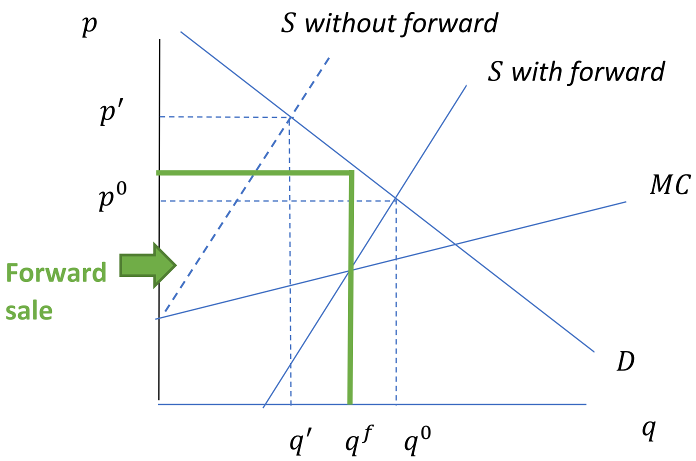
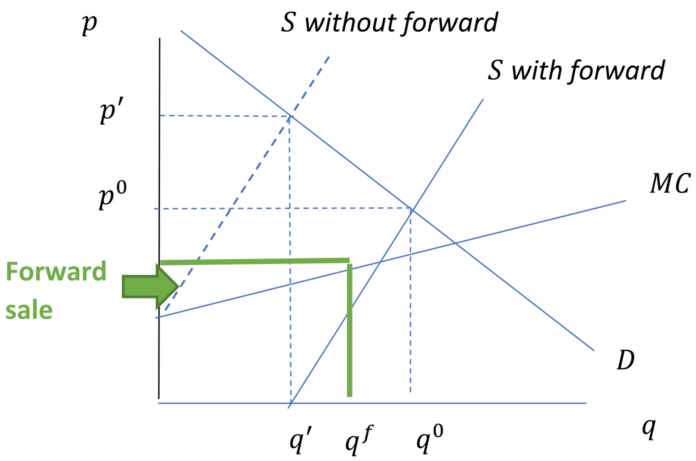


Figure 6: Case 2. Forward Auction Contract Could Mitigate Market Power in Spot Market



3. Modalities of Auctions and Contractual Agreements

3.1. Specific Technology or Technology-Neutral Auctions

Auction designers need to decide on technology neutral or technology specific auctions depending on the objectives (Table 1). The relative merits of technology-neutral auctions compared to technology-specific auctions are to encourage diverse participants, competition, and hence lower costs. In December 2017, a technology-neutral auction was held in Colorado in the United States. Although storage capacity was not explicitly solicited, 105 of the 430 proposals included storage components with the median solar PV and BESS bid price being 20 percent lower than the cheapest one under PPA in the United State at that time (Lackner et al 2019).

The demerits of technology-neutral auctions compared to technology-specific auctions are that they limit diversifications, such as technology type, location and companies. Different technologies have different characteristics regarding planning, costs, construction and operations and are, therefore, impacted differently by the same prequalification criteria and realization periods. Ensuring a level playing field in auction designs, such as ceiling prices, material and financial prequalification, penalties and realization deadlines could become challenging. Rather than holding one technology neutral auction, holding several auctions for each technology could make auction design easier, but could also reduce competition for technologies that have limited application or are relatively new. For example, a high level of competition can be realized in technology-specific auctions, such as those for ground-mounted solar PV in Germany, influenced by sector characteristics, such as previous level of support (Wigand et al., 2016). Technological neutrality has been especially popular in Latin America (IRENA 2019a).

3.2. Auction Contact Types

Major auction contact types are PPAs (most developing countries) and contracts for differences (e.g., United Kingdom and Italy). Examples of PPAs are (i) blended tariff including solar PV plus BESS (e.g., Malawi; Arizona, United States; and Israel), (ii) solar energy tariff and BESS capacity payment (e.g., Nevada, United States; Portugal; Uzbekistan), (iii) time variant tariff (e.g., Chile; Nevada and Arizona, United States; and India) and (iv) a monthly lump-sum payment based on the theoretical maximum output of the PV minus penalties for BESS unavailability and underperformance (e.g., Hawaii, United States). The first type (i) is the simplest PPA but does not offer different benefits hence the values of multiple services that BESS can provide. The last one (iv) is for a small system that needs long firm energy.

4. Solar PV and BESS Business Model

4.1. Solar PV and BESS for Peak Loads or Capacity Markets

Combining BESS with variable renewable electricity generation can meet peak load requirements and address system contingencies (such as breakdowns, planned maintenance, and extreme weather evens). Examples are in India; Australia; California, United States; and France. BESS owners may receive a much higher price for peak load power than baseload power if utilities are required to avoid shortfalls and if other supply alternatives (such as natural gas turbines) are more expensive. The Hornsdale Power Reserve with wind firm and BESS in Australia sells ancillary services, price arbitrage, and other services in different markets, and allocated 30 percent of its BESS capacity trade on a commercial basis, selling peak load electricity when spot prices were higher (IRENA 2020b). The power from a hybrid of renewable energy power generation and BESS is classified as semi-dispatchable because typical Li-ion batteries can only store electricity for four hours.

4.2. Solar PV and BESS for Time-Differentiated Supply Blocks

Time-differentiated supply blocks combine renewable energy with BESS for peak and off-peak power, with price adjustments by time of day and/or seasons of the year, and in some cases, supply location. This variable pricing structure can increase incentives for investments in BESS and reduce total system costs for power generation, transmission, and distribution.

Renewable energy auctions in Chile used a contract-for-differences arrangement with time-differentiated prices that varied by season and across three daily time blocks. The bidders were allowed to combine renewable energy generation with BESS and decide how to allocate their power deliveries across the daily and seasonal time blocks. The Government of Chile used an optimization model to meet the time-differentiated load requirements while minimizing the total system cost. Chile's auctions included a pay-as-contracted approach with differences settled at spot market prices. The Solar Energy Corporation of India used a similar, but simpler approach and two time-differentiated price blocks in an auction for renewable energy combined with BESS in 2020. They were based on peak periods. Solar PV and BESS in Nevada, United States includes off-peak and on-peak power tariffs in its PPA.

4.3. Solar PV and BESS for Semi-Dispatchable Power to Firm Up Renewable Electric Power

BESS can provide semi-dispatchable (or near-firm) power to enable suppliers to deliver grid electricity during daily peak and off-peak periods despite variable renewable energy's intermittency. This business model is also appropriate for minigrids or microgrids. Thailand conducted an auction for BESS to firm up renewable energy generation that was subdivided by nine geographic areas to reduce regional disparities in electricity access.

4.4. Solar PV and BESS for Firm Power and Dispatchable 24/7 Capacity

This business model combines BESS with renewable power generation and imposes financial penalties for failure to deliver the contracted amounts of power at all times every day. This business model assumes the absence of wholesale markets and bidders unable to buy power from other sources. As a result, the suppliers are responsible for ensuring that they can provide a reliable supply from their own generation and storage resources. This business model is appropriate for isolated areas where the physical supply of power is critical and reliable backup power sources are limited or absent. As indicated in

Figure ***3*** above, the current technology costs as of 2022 allow only small systems to supply 24/7 renewable energy electricity with storage.

4.5. BESS for Ancillary Services

BESS can provide ancillary services to an electricity grid either to a distribution company or to a power pool. BESS services have been procured for frequency regulation in Australia; Chile; and Texas, United States.

4.6. BESS as an Individual Resource of Stacked Services

Front-of-the-meter BESS can serve as an individual resource for multi-purposes or stacked services in the electricity system (e.g., Ørsted's 20 MW battery Carnegie Road Project for grid balancing services in Liverpool in the United Kingdom; Ørsted, 2019). BESS can reduce or defer the capital investments to expand peak load capacity or build or upgrade the transmission or distribution networks. They can also provide local ancillary services such as voltage control. Distribution-level BESS can also improve the quality of electricity and increase resilience to extreme weather. BESS close to renewable energy power plants make a better use of the connection assets, while BESS near the load can reduce transmission and distribution losses and congestion (Bowen et al., 2019).

One way to capture the full value of BESS services is for an integrated utility, system operator, or distribution utility to own the storage assets or have full control over them through a build, own, operate (BOO) or build, own, operate, and transfer (BOT) arrangement (IRENA, 2019b, 2019c). Those types of public-private partnerships allow the buyer to take full advantage of all the benefits of BESS for the power system.

BESS are sized to meet the requirement of the specific use for which they are designed. For example, a storage duration of 30 minutes is sufficient for the provision of frequency regulation or to smooth integration between solar and backup thermal generation. Four to six hours of storage duration are recommended for participation in capacity markets. Longer duration storage is recommended for energy-arbitrage or off-grid applications. Unfortunately, only a few of those services are currently monetized, and even fewer are traded in the market, such as power revenues from frequency containment reserve and energy revenues from trading on yearly, day ahead, intraday, hourly or imbalance markets. Table 2 summarizes business model examples above could be suitable for what kind of circumstances or objectives.

Table 2: Summary of Solar PV/BESS Business Model Example

Circumstances or objectives	Suitable Business Model
Provide peak load Fill in the gap under system contingencies	PV/BESS for Peak Load or Capacity Markets
Reduce total system costs for power generation, transmission, and distribution Provide incentives for investments in BESS	PV/BESS for Time-Differentiated Supply Blocks
Provide semi-dispatchable (or partial-firm) power to specified periods despite variable renewable energy's intermittency.	Solar PV/BESS for Semi-Dispatchable Firm Power
Support higher penetration of renewable energy toward 24/7 carbon free clean energy Cost-wise suitable for small system only given the current technological advances and costs as of 2022	PV/BESS for Firm Dispatchable 24/7 Power
Provide ancillary services to an electricity grid either to a distribution company or to an ancillary market	BESS for Ancillary Services
Substitute for, or complement, essentially all other elements of a power system, such as generation, ancillary services, transmission, distribution and demand response.	BESS as Stacked Services

5. Toward Sustainable Development and 24/7 Clean Energy Transition

Table 3 summarizes the key ESG risk mitigation and management costs vs. avoided ESG costs and realized benefits. As in section 2, if the costs of ESG risk mitigation and management costs exceed the net total of avoided ESG costs of realized benefits, the bidders would be willing to transfer their private benefits, i.e., their net revenue to the costs of ESG risk mitigation and management costs. This transfer payment between the private costs/benefits and the externalities costs/benefits (welfare) is the concept that this analysis introduced to incorporate ESG in competitive auctions. This transfer effect could be seen in the use of cheaper ESG bonds and equity than the non-ESG alternatives and grants (Kenway, 2021; Lamdouar et al., 2022; Leonard Energy, 2022). In El Salvador, the 2014 tender for solar and wind power required developers to invest 3 percent of their revenue in community social projects (IRENA, 2019a). The following are the key findings of the selected reviews of literature in addition to references already discussed in the previous sections.

Table 3: Key ESG risk mitigation and management costs vs. avoided ESG costs and realized benefits

ESG Risk Mitigation and Management Costs	Avoided ESG Costs and Realized Benefits
Environmental and social impact assessments and stakeholder engagements Benefit sharing Local employment, content, industry, and participation 24/7 clean power arrangement	Higher financial costs due to project delays Increase in capital and operations and management costs Penalty Bid bonds (securities) and sunk costs due to project cancellation Greenwashing or non-compliance Local development benefits

5.1 Toward Sustainable Development

ESG goals in renewable auctions should be part of the project definition and as such should be preconditions for project qualification. Qualified bidders would then move to the next phase, whose award is solely based on prices. The other current practices are to establish (i) one formula selection method that includes both price and non-price factors as multi-criteria (with their weights), such as in South Africa, Uganda, and Chinese Taipei and (ii) merit points adjustment to bid prices, such as in Malaysia (IRENA, 2019a; Amazo et al., 2021). Mixing monetary (price) and non-monetary (non-price) values could risk subjective judgement or lose nuances. Some projects may have low social and environmental scores (hence high risk) but due to very low prices offered, the total score becomes the highest and the projects may win, which could result in nonrealization of the projects due to the seriously negative social and environmental issues. Price-only as an award criterion is more transparent, while ensuring that awarded bids meet the requirements. If multi-criteria auctions are implemented, criteria should be specific, quantitative, and transparent to bidders.

ESG measures in auction designs should not expect too much from one project, and thus need policy support. Examples are local development, such as local factory, industry, research, and development (R&D) facility, supplies, ownership and employment. Local content is a blessing if capacity exists or easy to build, or curse if capacity hardly exists or preconditions such as regulatory framework and market potential are absent. An initial step is to understand the material and human resource requirements of different renewable technologies, to assess those requirements in the context of existing domestic resources and capabilities, and to identify ways to maximize domestic value creation by leveraging and enhancing local industries. Some countries, such as Brazil, Russia, Malaysia, Argentina, Saudi Arabia and Turkey, have imposed strict local-content requirements on auctions. Bidders can fail under such policies. South Africa discovered that the creation of a domestic manufacturing sector requires more than local content requirements, namely a convincing government commitment to renewables and visibility on future demand. The years-long delay to signing PPAs with renewable auction winners was damaging. The lack of predictability and the small local market size did little to encourage the development of a local manufacturing industry, and most players that built factories have since shut down shop (BloombergNEF, 2021). In Brazil, a reason for the delay in early projects was the nascent domestic wind industry that was not yet capable of supplying the equipment for developers to fulfil their local content quota (IRENA, 2019a).

A range of emerging options of potential storage energy technologies could provide more feasible opportunities for local supply. Currently dominant lithium-ion batteries supporting solar PV are hard to produce locally, with their very large-scale effects. Some of the upcoming technology choices for LDES, such as flow batteries, compressed air storage, thermal-electric storage, etc., could be much easier to localize because they include a large portion of mid-technology local assembly work.

Auction designs to create long term and higher skill employment opportunities are challenges needing longer term and broad policy support to provide enabling conditions. A systematic scheme can promote longer-term job opportunities. Long-term auction schedules and volumes signal market and longer-term job opportunities through a pipeline of projects. In Uganda, staggering the development of projects instead of deploying them simultaneously extended the length of employment with a learning curve, reducing costs (time and resources) on later projects. Quantitative employment targets in auctions should be accompanied by qualitative dimensions, such as quality, sustainability, and diversity. South Africa's auctions exceeded job creation targets but most of the unskilled labor provided by black citizens was short-term, and training, education and development needs may not have been prioritized. Ultimately, short-term, low-paid, unskilled jobs are not a lasting solution to poverty nor a path to sustainable development. In Senegal and Uganda, largely expatriates were skilled construction workers for renewable energy projects, while the local community held mostly unskilled positions (IRENA, 2019a). The Noor-Ouarzazate concentrated solar power (CSP) complex in Morocco offered a wide range of employment opportunities to women representing only 4 percent of the workforce at the CSP facility (IRENA, 2019a). Labor skill level development path needs a broader set of policies and measures to build local capacities as the sector evolves, such as education and skills development, which requires long-term planning. Attracting and retaining skilled workers is challenging in rural areas where large renewable energy projects are often developed and could contribute to rural economic development.

Local communities with high rates of poverty and inequality usually expect more from an electricity supply project than it can deliver. Engaging communities and maximizing benefits on the local level are crucial for project sustainability and can contribute to a just and inclusive transition. Under the Morocco Noor-Ouarzazate CSP complex, local communities made choices such as infrastructure and social services to benefit everyone including women and children, rather than cash compensation for the land lost, which would benefit only male landowners (IRENA, 2019a). The South African Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) required a community trust or a company that represents local communities and as project shareholders, communities earn dividends to be invested in community development initiatives. In Namibia, the national utility, NamPower included disadvantaged Namibians in auctions, such as 30 percent shareholding, management positions, skills and entrepreneurship development, and community investments, and local hiring (IRENA, 2019a). Local community engagement can be a lengthy process, which often involves land issues and political economy. For example, despite support by international development communities, such as donors and international finance institutions, many initially promising projects, such as Guajira in Colombia and Turkana in Kenya, continue facing challenges (Mbugua 2021; Azzopardi 2022). Other community engagements include community power initiatives in Germany and Japan, on-site participatory planning with indigenous communities in Mexico and in the Latin America and the Caribbean region (IRENA, 2019a). Especially projects financed by international finance institutions, assessment of local stakeholder engagement is part of the requirements for environmental and social impact assessments and governance.

Auction designs could cope with land constraints, which are common in renewable energy projects. In Malaysia's Large-Scale Solar PV auction, plans to use land for economic activities in addition to solar generation (e.g., agricultural activities) can yield merit points to the bidder. Germany's solar PV auction provides incentives for ground-mounted projects to deploy in industrial zones rather than to use land with alternative or agricultural uses, by capping the number of sites on arable land (IRENA, 2019a).

Auction designs could be integrated within a geospatial least cost electrification roll out plan, which could help exploit synergies between the energy sector and the broader economy to optimize the benefits of the energy transition. The plan has been applied in countries, such as Kenya, Rwanda, Myanmar and Papua New Guinea and is a principle of one goal with many partners, which helps the government in policy making and working with donors and partners and can serve as investment prospectus. The plan coordinates off grid and on grid electricity and integrates demographic, geographic information system mapping techniques that combine technical, economic, demographic, and demand and supply data. With a modest cost and ability to make frequent updates make geographic information systems, the plan is a dynamic planning platform capable of undertaking rapid updates reflecting changes in key parameters (Independent Evaluation Group, 2016).

Thus, auction designs based on geospatial electrification planning could mitigate the concentration of projects in resource-rich regions. A more even regional distribution can help spread the socio-economic benefits of renewable energy projects, while also facilitating grid integration. The plan also helps reduce the trade-off between achieving socio-economic objectives and procuring electricity at low prices and align deployment policies with enabling and integrating polices. The plan will increase realization rates of the projects as it will coordinate the auction scheme with permits (e.g., Netherlands), spatial planning (e.g., Ireland and Netherlands) and grid availability (e.g., Brazil and Portugal) (Wigand et al., 2016).

Auctions designs that integrate ESG and a just and inclusive energy transition may require enabling policy support and grants whose recipients are competitively selected with monitoring, reporting and verification (MRV) requirements. They may include (i) industrial policies to strengthen domestic capabilities, such as business incubation, research and development, supplier development, support for small and medium enterprises and key industries, (ii) education and skills policies to increase technical, business and environmental management and socioeconomic development capacity, (iii) labor market and social protection policies including employment services, such as job matching jobs, on- and off-job training and labor mobility and (iv) financial policies, such as carbon pricing, green bonds and revenue recycling schemes to ensure a just transition (IRENA, 2019a).

The United States played an important role in introducing competitive bidding for the energy procured by regulated utilities to serve their customers. A key piece of legislation was the Public Utility Regulatory Policies Act (PURPA) of 1978, originally designed to increase conservation and foster co-generation. PURPA indirectly paved the road for regulators to mandate utilities to look for the most effective way to meet their customer needs – either by building new power plants or acquiring energy competitively from emerging IPPs. Different states adopted different methodologies. Initially, the prevailing approach was to establish competitive tenders or requests for proposals, and the award was based on price and non-price factors. The most important non-price factors were flexibility and dispatchability, but ESG objectives were also considered (Plummer and Troppmann, 1990). Over the years, many states have moved to pure auctions, where the price is the only factor in awarding winners. In 2002, New Jersey pioneered an auction process to procure most of its electric needs through an Internet-based auction whose winners were responsible for fulfilling all the requirements (capacity, energy, ancillary services, etc.) and the state's renewable portfolio standards (Fox 2005; BGS Undated).

5.1 24/7 Clean Energy Transition

As discussed above, solar PV and BESS can provide closer to 24/7 renewable energy power for a small and/or isolated system only as of 2022. At the same time, many enterprises especially associated with multinational companies are facing increasing pressures to use clean energy and reporting of such use. In this 24/7 clean energy context, large corporations are shifting from offsetting energy emissions mostly through Renewable Energy Certificate (REC) to time-location tracked energy procurement. Several initiatives aim to accelerate the transition to 24/7 clean energy. More than 100 global companies have joined the EnergyTag initiative, including tech giants and energy companies, such as Statkraft and Vattenfall. Through partnerships, Google and Microsoft have enabled their data centers to become more sustainable through hourly energy monitoring and matching with carbon-free sources from their clean-energy portfolios. The United Nations also launched 24/7 Carbon-Free Energy Compact in 2021.

The transition to 24/7 clean energy could contribute to higher ESG scores, which could help access to cheaper capital in a financial market eager to green investment portfolios. As initial step for enterprises in ASESAN and East Asia to a pathway to 24/7 clean energy, allowing enterprises to trade RECs or equivalent, and monitor and report type and amount of energy use would be helpful for them to remain in the global value chains and advance competitiveness. In addition, solar rooftop regulations need to be improved. In Cambodia, enterprises have challenges in installing solar PV on rooftops and cannot trade the solar power among consumers. Tariff regulations should be rationalized, for example, to set a fair level of capacity charge based on the highest amount of energy each consumer estimated to consume from the grid (i.e., excluding consumption from consumer's own generation such as rooftop solar PV) to operate, maintain and invest in the system to ensure that electricity remains available at all times to all consumers and help reduce the unnecessary high peak demand. Carefully designed tariffs are becoming even more important as increasingly variable renewable energy/consumers/building/electric vehicles need to be integrated in the system and achieve (or achieve close to) 24/7 green power.

5.1.1 Thailand partial-firm renewable energy auction case study

In 2017, Thailand conducted the third renewable energy-exclusive auction under a new Small Power Producers (SPP) Hybrid Program. This reverse auction had a total ceiling of 300 mega-watt (MW) of capacity from 10 to 50 MW power plants. The SPP Hybrid Program auction had a starting (ceiling) price of Thai Baht (B) 3.66 (US$0.11) per kilowatt hour (kWh). Bidders proposed their maximum percentage discount from the ceiling price (IRENA, 2019a; O'Mealy et al., 2020).

The third renewable energy auction in Thailand was the first country in Asia that required developers to supply partial-firm power generation (delivering electricity at full capacity during peak hours), rather than just installing new capacity. It was also the first auction in Asia that allowed bids based on either a single technology or a hybrid combining of two or more technologies to allow a consistent feed-in of power to the grid. The power purchase agreement (PPA) contracts required the power producer to deliver between 100±2 percent of the specified capacity during peak periods (between 9 am and 10 pm on weekdays) and limit power output at other times to 65±2 percent of the capacity (IRENA, 2019a; O'Mealy et al., 2020).

Of 85 bids submitted, the Thailand Energy Regulatory Commission (ERC) reported that 42 of the proposed projects had passed the pre-qualification stage and announced 17 projects with accepted bids. Fourteen were for biomass power generation, and three were hybrids with solar PV and BESS. The accepted bids ranged from 15.6 to 99.99 percent of the ceiling price. The net prices ranged from B 1.85 to 3.38/kWh (US$0.06 to US$0.11/kWh) (IRENA, 2019a; O'Mealy et al., 2020).

In March 2018, the Minister of Energy announced that the Government of Thailand (GoT) would not buy additional power from new renewable energy projects for the next five years since the country's reserve power margin was high. However, the GoT later stated that it might consider procuring new renewable energy projects that can sell electricity below the wholesale price of the Electricity Generating Authority of Thailand (EGAT). The GoT also noted that procurement of new renewable energy projects would be tied to the new Power Development Plan. Those announcements left domestic and international renewable energy developers and investors uncertain about the policy and regulatory environment for renewable energy development. As a result, some developers and investors began shifting project development plans and investments to other countries in the region (O'Mealy et al., 2020). The participants in the 2017 auction noted low winning prices for the project realizations (O'Mealy et al., 2020). As of October 2022, the GoT reportedly has a high number of uncompleted projects in past programs (Santos, 2022b).

6. Conclusions

This chapter offers the following conclusions. First, a theoretically and empirically proved auction market design with a low level of complexity for the bidders could facilitate their bidding strategy to optimize the ESG and overall outcomes. An auction market design strategy to improve realization rates could include a high financial prequalification and an adjusted physical prequalification relative to sunk costs, penalties covered by financial prequalification, and increasing competition. Design of selected policy instruments rather than one policy instrument would complement each other (e.g., PPA under long term contract auction, wholesale markets, etc.).

Second, ESG goals in renewable auctions should be part of the project definition and as such should be pre-conditions for project qualification, which will allow an award solely based on prices. Auction designs could be integrated within a geospatial least cost electrification roll out plan, which could help exploit synergies between the energy sector and the broader economy to optimize the benefits of the energy and green transition. Auctions designs that integrate ESG and a just and inclusive energy transition may require enabling policy support and grants whose recipients are competitively selected by monitoring, reporting and verification (MRV) requirements.

Third, the transition to 24/7 clean energy could contribute to higher ESG scores, which could help provide access to cheaper capital in a financial market eager to greenify investment portfolios. As initial step for enterprises in ASESAN and East Asia to a pathway to 24/7 clean energy, allowing enterprises to trade RECs or equivalent, and build capacity for them to monitor and report type and amount of energy use would be helpful to them to remain in the global value chains and advance their competitiveness.

Financial support from the Copenhagen School of Energy Infrastructure (CSEI) is acknowledged. The activities of CSEI are funded jointly in cooperation between Copenhagen Business School and energy sector partners.

References

Amazo A, Lotz B, F Wigand, Lawson S, Monteforte A, Eisendrath A, Gutierrez J, Paz A (2021) Auction Design and The Social Impact of Renewable Energy Projects. Scaling Up Renewable Energy (SURE). The United States Agency for International Development (USAID)

Ausubel L M, Milgrom P (2004) The Lovely but Lonely Vickrey Auction. Stanford Institute for Economic Policy Research

Azzopardi T (2022) Colombia opens new wind farm amid indigenous protests. Windpower Monthly. 19 January 2022. Available at https://www.windpowermonthly.com/article/1737843/colombia-opens-new-wind-farm-amid-indigenous-protests Accessed 1 Oct 2022

BGS Undated. New Jersey Statewide Basic Generation Service Electricity Supply Auction Available at https://www.bgs-auction.com/bgs.auction.overview.asp Accessed 29 Dec 2022

Bergemann D, Välimäki, J (2019) Dynamic mechanism design: An introduction. Journal of Economic Literature, 57(2), 235–274. https://doi.org/10.1257/JEL.20180892

Bergemann D, Juuso V (2010) The Dynamic Pivot Mechanism. Econometrica, *78*(2), 771–789. https://doi.org/10.3982/ecta7260

BloombergNEF (2021) Renewable Energy Auctions. NetZero Pathfinders. Bloomberg New Energy Finance (NEF). Available at https://www.bloomberg.com/netzeropathfinders/best-practices/renewable-energy-auctions/#example-2. Accessed 1 Oct 2022

Bowen T, Chernyakhovskiy I, Denholm P (2019) Grid-Scale Battery Storage: Frequently Asked Questions. Grid Integration Toolkit. Boulder, CO: National Renewable Energy Laboratory, Prepared for USAID. Retrieved from https://www.nrel.gov/docs/fy19osti/74426.pdf

Business and Human Rights Resource Centre (2018) Renewable energy and human rights. Business and Human Rights Resource Centre. Retrieved from www.business-humanrights.org/en/renewable-energy-human-rights. Cited in International Renewable Energy Agency (IRENA) 2019a

Bustos-Salvagno J. (2015). Bidding behavior in the Chilean electricity market. *Energy Economics*, *51*, 288–299. https://doi.org/10.1016/j.eneco.2015.07.003

Cote E, Đukan M, de Brauwer CPS, Wüstenhagen R (2022) The price of actor diversity: Measuring project developers' willingness to accept risks in renewable energy auctions. Energy Policy 163 (2022) 112835

Cramton P. 2020. Auctions And Market Design. Presentation. 5 November 2020. Available at https://cramton.umd.edu/auctions-and-market-design/ Accessed 2 Oct 2022

Dewatripont M, Tirole J (2022) The Morality of Markets. March 24, 2022

Eberhard A, Kolker J, Leigland J (2014) South Africa's Renewable Energy IPP Procurement Program: Success Factors and Lessons. World Bank Group, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/20039 License: CC BY 3.0 IGO."

Edianto AS, Suarez I, Waite N (2022) The sunny side of Asia. Ember, the Centre for Research on Energy and Clean Air (CREA) and the Institute for Energy Economics and Financial Analysis (IEEFA)

Fox S (2005) New Jersey's BGS Auction: A Model for the Nation Internet procurement may be used in other states. Fortnightly Magazine - September 2005. Public Utilities Fortnightly Available at https://www.fortnightly.com/fortnightly/2005/09/new-jersey%E2%80%99s-bgs-auction-model-nation Accessed on 29 Dec 2022

Hawaiian Electric Company, Inc. (2019) Request for proposal of Variable Renewable Dispatchable Generation and Energy Storage Island of O'Ahu. August 22, 2019. Docket No. 2017-0352

Independent Evaluation Group (2016) Reliable and Affordable Off-Grid Electricity Services for the Poor: Lessons from the World Bank Group Experience. World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/25391 License: CC BY 3.0 IGO.

International Energy Agency (IEA) (2020) Energy Technology Perspectives. Special Repo on Clean Energy Innovation. Specific price values are available in https://www.iea.org/data-and-statistics/charts/evolution-of-li-ion-battery-price-1995-2019, accessed on November 7, 2022

International Energy Agency (IEA) (2022) World Energy Outlook (WEO)

International Monetary Fund (IMF) (2022) Regional economic outlook. Asia and Pacific: sailing into headwinds. Washington, DC: International Monetary Fund, 2022. Identifiers: 9798400220517 (paper), 9798400221200 (ePub) and 9798400221224 (Web PDF)

Institute of International Finance (2022) Sustainable Debt Monitor. Financing the Transition. November 3, 2022

International Renewable Energy Agency (IRENA) (2018) Renewable Energy Auctions: Cases from sub-Saharan Africa. IRENA: Abu Dhabi

International Renewable Energy Agency (IRENA) (2019a) Renewable energy auctions: Status and trends beyond price, International Renewable Energy Agency, Abu Dhabi

IRENA (2019b) Innovation Landscape for a Renewable Powered Future. Abu Dhabi: International Renewable Energy Agency. https://www.irena.org/publications/2019/Feb/Innovation-landscape-for-a-renewable-powered-future

IRENA (2019c) Utility-Scale Batteries: Innovation Landscape Brief. Abu Dhabi: International Renewable Energy Agency. https://www.irena.org/publications/2019/Sep/Utility-scale-batteries

IRENA (2020a) Global Renewables Outlook: Energy Transformation 2050. Abu Dhabi.

IRENA (2020b) Electricity Storage Valuation Framework: Assessing System Value and Ensuring Project Viability. Abu Dhabi: International Renewable Energy Agency https://www.researchgate.net/publication/339738986_Electricity_Storage_Valuation_Framework_Assesing_system_value_and_ensuring_project_viability

IRENA (2022) Renewable Technology Innovation Indicators: Mapping progress in costs, patents and standards, International Renewable Energy Agency, Abu Dhabi

Hall M (2022) IHS Markit: Battery prices won't fall until 2024. 7 March 2022. PV Magazine. Available at https://www.pv-magazine.com/2022/03/07/ihs-markit-battery-prices-wont-fall-until-2024/. Accessed on 1 Oct 2022

Haufe MC, Ehrhart KM (2018) Auctions for renewable energy support – Suitability, design, and first lessons learned. *Energy Policy*, *121*, 217–224. https://doi.org/10.1016/j.enpol.2018.06.027

Kenway N (2021) ESG investors are getting 'something for nothing. 28 Oct 2021. ESG Clarity. Available at https://esgclarity.com/esg-investors-are-getting-something-for-nothing/ Accessed 1 Oct 2022

Kitzing L, Anatolitis V, Fitch-Roy O, Klessmann C, Kreiss J, Río P, Wigand F, Woodman B (2019) Auctions for Renewable Energy Support: Lessons Learned in the AURES Project. IAEE Energy Forum / Third Quarter 2019. International Association for Energy Economics (IAEE)

Kreiss J, Ehrhart KM, Haufe MC (2017) Appropriate design of auctions for renewable energy support – Prequalifications and penalties. Energy Policy 101, 512–520

Kremer M (2022) Innovation, Experimentation, and Economics. Presentation at Eighth Richard Goode Lecture. November 30, 2022. International Monetary Fund. https://www.imf.org/en/Videos/view?vid=6316368113112

Kroposki B (2022) UNIFI Consortium Overview. The Universal Interoperability for Grid-forming Inverters (UNIFI)

Kwon T (2020) Policy mix of renewable portfolio standards, feed-in tariffs, and auctions in South Korea: Are three better than one? Utilities Policy 64 (2020) 101056

Lackner M, Koller S, Camuzeaux JR (2019) Policy Brief Using Lessons from Reverse Auctions for Renewables to Deliver Energy Storage Capacity: Guidance for Policymakers. Review of Environmental Economics and Policy, volume 13, issue 1, Winter 2019, pp. 140–148 doi: 10.1093/reep/rey019

LDES Council, McKinsey and Company (2022) A path towards full grid decarbonization with 24/7 clean Power Purchase Agreements. Long duration energy storage (LDES) Council in collaboration with McKinsey and Company

Leyton-Brown K, Milgrom P, Segal I (2017). Economics and computer science of a radio spectrum reallocation. In *Proceedings of the National Academy of Sciences of the United States of America* (Vol. 114, Issue 28, pp. 7202–7209). National Academy of Sciences. https://doi.org/10.1073/pnas.1701997114

Leyton-Brown K, Milgrom P, Segal I (2017). Economics and computer science of a radio spectrum reallocation. In *Proceedings of the National Academy of Sciences of the United States of America* (Vol. 114, Issue 28, pp. 7202–7209). National Academy of Sciences. https://doi.org/10.1073/pnas.1701997114

Leonard Energy (2022) How auction design affects the financing of renewable energy projects. H2020 Project: Auctions for Renewable Energy Support. Webinar Leonard Energy 26 Jan 2022. Available at https://www.youtube.com/watch?v=u75HR7TKYKU. Accessed 1 Jun 202.

Leyton-Brown K, Milgrom P, Segal I (2017). Economics and computer science of a radio spectrum reallocation. In *Proceedings of the National Academy of Sciences of the United States of America* (Vol. 114, Issue 28, pp. 7202–7209). National Academy of Sciences. https://doi.org/10.1073/pnas.1701997114

Massachusetts Institute of Technology (MIT) (2022) The Future of Energy Storage. The MIT Energy Initiative.

Maurer L, Doyle P, Hyman E, Bauer L, Torres P (2020) Creating a Level Playing Field for Battery Energy Storage Systems Through Policies, Regulations, and Renewable Energy Auctions. Washington, DC: Crown Agents USA and Abt Associates, Prepared for USAID

Mbugua B (2021) Lake Turkana Wind Power faces storms in title tussle. People Daily. Available at https://www.pd.co.ke/business/lake-turkana-wind-power-faces-storms-in-title-tussle-101655/ Accessed 1 Oct 2022

Newbery D (2020) Implications of the National Energy and Climate Plans for the Single Electricity Market of the island of Ireland. Energy Policy Research Group Working Paper, Cambridge Working Paper in Economics 2072, University of Cambridge.

NS Energy (2020) Canadian Solar wins large solar plus BESS project in Chile's power auction. 2 Sept 2022. Available at https://www.nsenergybusiness.com/news/canadian-solar-zaldivar-solar-plus-bess-project-chiles/ Accessed 1 Oct 2022

O'Mealy M, Sangarasri T, Khalid E, Hyman E (2020) Private Sector Recommendations for Renewable Energy Auctions in Thailand and Malaysia. Washington, DC: Crown Agents-USA, and Abt Associates, Prepared for USAID

Ørsted (2019) Ørsted's first stand-alone battery storage project now complete. 1 Jan 2019. Available at https://orsted.com/en/media/newsroom/news/2019/01/orsteds-first-standalone-battery-storage-project-now-complete. Accessed 1 Oct 2022

Plummer JL, S Troppmann (eds) (1990) Competition in electricity: new markets and new structures. Arlington Va.: Palo Alto, Calif. Public Utilities Reports, Inc.; QED Research, Inc.

Renewable Energy Policy Network for the 21st Century (REN21) (2022) Renewables 2022 Global Status Report. Renewable Energy Policy Network for the 21st Century (REN21)

Reuters (2021) German auction agrees terms to close 533 MW of coal power. 14 Dec 2021. Available at https://www.reuters.com/markets/commodities/german-auction-agrees-terms-close-533-mw-coal-power-2021-12-15/. Accessed 1 Oct 2022

Roth A, Wigand F, Blanco A (2022) Policy Brief, January 2022, De-risking and scaling-up renewables through market-based policies, Practices from EU and the world – COP26 AURES II side event. Auctions for Renewable Energy Support II (AURES II).

Royal Swedish Academy of Sciences (n.d.) Background on the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 2020.

Santos B (2022a) Malaysia to grant 4-year PPA extensions to bidders in large-scale solar tender. 28 Oct 2022. PV Magazine. Available at https://www.pv-magazine.com/2022/10/28/malaysia-to-grant-4-year-ppa-extensions-to-bidders-in-large-scale-solar-tender/. Accessed on 1 Nov 2022

Santos B (2022b) Thailand introduces FIT scheme for solar, storage. 31 Oct 2022. PV Magazine. Available at https://www.pv-magazine.com/2022/10/31/thailand-introduces-fit-scheme-for-solar-storage/ Accessed on 1 Nov 2022

Stevens P (2022) Solar costs jumped in 2021, reversing years of falling prices. 10 Mar 2022. CNBC. Available at https://www.cnbc.com/2022/03/10/solar-costs-jumped-in-2021-reversing-years-of-falling-prices.html. Accessed 1 Oct 2022

Szabó L, Bartek-Lesi M, Dézsi B, Diallo A, Mezősi A (2022) D2.2, December 2020, Auctions for the support of renewable energy: Lessons learnt from international experiences – Synthesis report of the AURES II case studies. Auctions for Renewable Energy Support II (AURES II).

Theobald S (2022) Drivers of Investment Flows to Emerging and Frontier Markets. Mobilising Institutional Capital Through Listed Product Structures (MOBILIST). The United Kingdom Government's Foreign, Commonwealth and Development Office.

Tirole J (2017) Economics for the Common Good. Princeton University Press.

Tirole J (2021) Markets and Morality. The Second Sustainable Finance Center Conference Keynote Presentation. December 2, 2021. Available at https://www.youtube.com/watch?v=62zcKL3RlSY Accessed 1 Jun 2022

Tongsopit S, Amatayakul W, Saculsan PG, Nghia VH, Tirapornvitoon C, Favre R, Amazo A, Tiedemann S, Afanador A (2017) Designing Renewable Energy Incentives and Auctions: Lessons for ASEAN. September 4, 2017. The United States Agency for International Development

United Nations Environment Programme (UNEP). 2022. State of Finance for Nature. Time to act: Doubling investment by 2025 and eliminating nature-negative finance flows. Nairobi. https://wedocs.unep.org/20.500.11822/41333

Voice of America (VOA) (2020) Global Brands Say Future Orders at Risk Given Cambodia's Increasing Coal Power. 12 August 2020. Available at https://www.voacambodia.com/a/global-brands-say-future-orders-at-risk-given-cambodia-increasing-coal-power/5540674.html. Accessed 1 Oct 2022

Wigand F, Förster S, Amazo A, Tiedemann S (2016) Auctions for Renewable Energy Support: Lessons Learnt from International Experiences. Report D4.2, June 2016. Auctions for Renewable Energy Support: Effective use and efficient implementation options (AURES)

World Bank (2022) The Use of Auctions for Decommissioning Coal Power Globally. The World Bank, Washington, DC