Market Design for Energy Markets with Intermittent Technologies

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February 11, 2020

Abstract

Enforced by pressing climate issues and by rising political pressure, renewable energy sources (RES) become an increasingly important aspect of modern energy markets. However, the current electricity market designs especially in Europe do not adequately address the issue of increased intermittency. Newly emerging technologies allow for consumer specific load dropping without compromising the network. Real time pricing, while working well in theory, is unfeasible in different aspects for end consumers. By commoditizing the reliability of supply between consumers and retailers we propose a novel way to link consumption and production risk. We develop a theoretical market model with consumers, retailers and generators. By splitting the consumer demand into tranches and contracting specific levels of reliability, the consumer is able to take on risk according to individual appetite. The retailer solves the constrained profit maximization problem of having the most cost-efficient energy portfolio, taking into account the contracted reliability levels. Additionally, we show how marketing reliability would lead to changes in contract structure between generators and retailer in order to preserve incentive compatibility. We show that by marketing supply security, the overall welfare of the system can be increased.

1 Introduction

The energy landscape is in the process of fundamental change. On the one hand, the change in the energy mix and electrification of areas that previously relied on fossil energy sources, will be impactful. On the other hand, with increasing digitization also of the energy sector, new decentralized control measures have arisen such as smart metering (Kaufmann et al., 2013). The energy sector in general will lean more towards electricity in the future and hereby replace other forms of energy, e.g., e-mobility or electric heating (Tamme et al., 2001; Kåberger, 2018). Electrification is an important pillar for achieving the European climate targets, also due to an increasing share of RES in the energy mix. Financial competitiveness of RES and dwindling support of conventional energy sources such as coal lead to an even stronger integration.

RES, however, exhibit an inherent degree of intermittency due to their reliance on natural, uncontrollable factors (wind, sun, etc.). Currently, the flexible dispatching of conventional energy production is able to cover short-term fluctuations in demand on household levels. In absence of a large storage system, maintaining a reliable energy supply would require building large flexibly dispatched capacity reserves, especially when the intermittent technology is important in the energy mix. In addition, intermittent electricity generation is source of additional risk that makes the wholesale electricity prices unpredictable. It also reduces those prices due to its zero fuel cost, affecting the incentive for investment in conventional generation. However, the market is lacking the right incentives to internalise those externalities and to provide the appropriate back-up capacities. This is because, there is no specific market where both consumers and system operators could trade electricity reliability.

On the consumer side, the demand for reliability is based on the value that is given to electricity interruptions. Electricity reliability is valued differently depending on the electricity attributes and the type of electricity services. This value of continuous electricity service is also called the "value of lost load" (VoLL). Several studies have evaluated the VoLL (Woo et al., 2014; Shivakumar et al., 2017; and Morrissey et al., 2018) which varies from near zero (when charging an electric vehicle late in the evening for instance), to tens of thousands of euros per MWh (at the hospital for example) (Hogan, 2016).

On the generator side, all the costs for suppling the electricity should be considered, including the intrinsic value of generation capacities that contribute to maintain electricity reliability even though it is not often used to produce electricity. In this sense, electricity prices should reflect both short-run marginal and the marginal cost of meeting the electricity reliability, otherwise they are not sufficient to cover all the supply costs leading to the "missing money" problem (Hogan, 2016). One alternative solution for this missing money problem is to develop a specific market (often referred to as the capacity market) outside the energy market where generators are paid for their capacities. However, Hogan (2016) argues that improving the energy price formation is optimally desirable to ensure reliable electricity at least cost and this should be the top priority.

With the phase-out of different conventional energy sources (e.g., coal or nuclear energy), it becomes important to investigate the ability of current energy market design to deal with uncertainties and at the same time preserve investment incentives for renewable energy production (Jahn and Korolczuk, 2012). Especially in a scenario with increased volatility of production and reduced back up capacity, guaranteeing the supply security of non-plannable demand can be a complex task (Heinrichs and Markewitz, 2017). There are a number of attributes related to electricity that consumers may consider in their preference for energy services. In addition to the volumetric electricity consumption (kWh), consumers also value the demand capacity (kW), reliability of supply, environmental impact, etc. Therefore, any mechanism that provides electricity differentiation products to consumers by targeting the electricity attributes would help them to efficiently satisfy their energy demand. Reliability differentiation is one example of this mechanism (see Hartman et al., 1991; Pepermans, 2011; and Woo et al., 2014). Imposing a full electricity reliability may not be optimal as it would require substantial investments in backup capacities with a high bill payment from consumers while some consumers may prefer to have a lower electricity bill and accept a lower reliability. However, pricing reliability as a private good would require a deployment of smart grid technologies making possible to drop loads individually.

Not only the energy portfolio changes but also its control mechanisms. Smart metering technologies have been widely cited as a game-changing piece of technological progress; instead of having centralized net stabilization procedure, smart meters open up the possibility of targeted stabilization measures. While the energy saving potential of smart meters has been critically discussed, they give rise to new potential business models (Darby, 2010). Retailers in future scenarios will be able to selectively drop loads and hereby have new possibilities to tailor contracts to the individual needs of consumers. It also provides the technological basis for proponents of real time pricing on consumer level. The current market design with its implicit supply guarantee makes it difficult to find innovative business models in that regard. Especially in Europe, energy-only-markets are the predominant market structure with the exception of capacity markets in a few countries. Retail markets and consumer contracts are most commonly based on a contractually fixed rate per energy consumed with a guaranteed supply for all consumers. Any sustainable future market design will have to be reassessed in light of technological development (Parag and Sovacool, 2016; Aparicio et al., 2012).

In particular, increased intermittency on the production side due to RES as well as increased demand on the consumer side leads to the open questions: How can a market design ensure the reliable supply with energy for individual consumers? New challenges arise in terms of investors being able to refinance their energy generating units. Pricing at marginal cost works well in a context where there is a comparably smooth increase in marginal cost per production technology. With RES effectively having negligible marginal cost of production, this raises an additional question: How can a market design ensure investment incentives to increase the reliability of the system?

In this paper, we analyze the structure of current electricity markets of full electricity reliability, such as the German or the Swiss market. We show that the current design is creating inefficiencies in managing those new challenges. This is mainly because the marginal costs for offering full reliability exceed those that could be incurred when marketing the remaining uncertainty between the involved parties. Real-time pricing for individual households is often referred to as the first best option to manage periods of scarcity. In line with others, we briefly touch on the problems of this approach and offer an alternative that relies on the same principles without creating too much additional complexity on the consumer side (Dutta and Mitra, 2017). Within our model, we develop a new market design that is based on introducing reliability of supply as a marketable property of contracts between generators and retailers. We consider a block tariff which is in line with the inclining block tariff: (i) a relatively low "lifeline" rate associated to "essential needs," and (ii) a higher rate for extra electricity consumption in excess of those needs (Woo et al., 2014). This block tariff provides a conservation incentive to large consumers who face a higher electricity price when they consume more. In addition, we make the rate for the extra electricity consumption dependent on the electricity reliability such that a consumer pays higher electricity price for higher reliability.

We then expect to show that the optimal capacities of the conventional and intermittent electricity generation are closer to the optimal capacities under real time pricing than the capacities under the full reliability. Reliability pricing is able to create effects that are similar to those of real time pricing. In fact, pricing reliability of supply gives incentive to consumers to adjust their electricity demand depending on their preferred reliability (for instance, to reduce their demand during peak periods). Therefore, consumers will implicitly reveal their willingness to pay for the generation capacities in line with their VoLL. In this sense, our suggested market design of pricing the reliability can be considered as a second best solution and could be implemented as the best alternative to the real time pricing. We further show that such a contract design requires a subsequent change in the contracts between consumers and retailers and how an appropriate risk compensation leads to increased welfare. We contribute to the ongoing debate about energy transition and provide a new perspective on possible future market designs enabling the integration of RES.

The rest of the paper is structured as follows. Section 2 presents the model with all the parties involved in the market and the different assumptions. Section 3 analyses the investment problem under the reliability pricing market design (see Section 3.1) and under the current market of full reliability (see Section 3.2). Section 4 compares the welfare between the current market and the reliability pricing market design (see Section 4.1) and the implementation of set of possible contracts under the reliability pricing market design (see Section 4.2). Finally, Section 5 concludes.

2 Model

We model an energy market with three different involved parties: retailers, consumers and generators. The retailer is the utility company that functions as an intermediary, offering a electricity with a certain reliability R to its consumers. This level of reliability will have regulatory relevance and is therefore relevant in terms of the product quality, the retailer offers. The retailer receives its energy from two different types of generators: conventional and intermittent. The conventional generators produce with an expensive conventional technology that can be controlled and dispatched within its capacity restrictions $\overline{q_c}$ on demand. The intermittent generators produce with an intermittent technology that has marginal costs of zero and produces random output $\eta * \overline{q_r}$, where η_i is the realization of a random production factor and $\overline{q_r}$ is the intermittent capacity. In addition we model a spot market in which retailers are able to buy/sell part of their energy portfolio. Retailers are only allowed to sell in the spot market if their own customers are unaffected. While retailers are potentially able to procure energy on the spot market in times of shortage, they are not able to replace their own supply guarantees of supply with spot buys.

2.1 Consumers

For the consumers' utility regarding electricity consumption we assume increasing and concave utility for the consumption of electricity with $u'(\cdot) > 0$ and $u''(\cdot) < 0$. Consumer demand is modeled as two components: base demand d_1 and peak demand d_2 with $u'(d_1) > u'(d_2)$. Base demand and peak demand are supplied with different levels of reliability and cost.

We assume that the peak demand is uncertain while the base demand is fixed. More precisely, $d_1 = \overline{d_1}$ and $d_2 = \omega_2 \overline{d_2}$, where $\overline{d_1}$ and $\overline{d_2}$ are respectively the maximum base demand and peak demand and ω_2 is the uncertainty parameter (from 0 to 1) that describes the part of the maximum demand that is realized. Furthermore, the consumer is offered different levels of reliability over the base and peak demands: 100% of reliability (i.e.,$R = 1$) for base demand and a lower reliability for the peak demand (i.e., $R < 1$). Given this lower reliability, the consumer has a probability of $(1 - R)$ to not cover all the peak demand, which causes a damage $Dam(d_2)$ that depends on the peak demand.

In order to make the trade-off between reliability and system efficiency gains quantifiable, we utilize Value of Lost Load as our metric for consumer losses. Differing from most empirical literature, however, we follow a more nuanced version of this approach that distinguishes between damage from electricity interruption regardless of time and a component that is proportional to the amount of unsupplied energy. Incorporating this approach into our model, our model consists of a opt-in choice for different levels of reliability. We argue that this self sorting effect would lead to significant decreases in VoLL compared to the consensus in empirical literature (Küfeoğlu and Lehtonen, 2015; Praktiknjo, 2014).

For both types of demand we assume a generic pricing model:

$$C(\cdot) = p_{i,fix} \cdot \overline{d_i} + p_{i,var} \cdot d_i$$

Further we assume no income effects. The gross utility of the consumer can be written as:

$$U(.) = u(d_1, d_2) - p_1\overline{d_1} - p_{2,var}\omega_2\overline{d_2} - p_2\overline{d_2} - (1-R)Dam(\omega_2\overline{d_2}) \tag{1}$$

The consumer will maximize the expected utility ($\mathbb{E}\,U$) given by Eq.(1) over the uncertainty parameters (demand and intermittent technology) for given levels of reliability and prices..

2.2 Retailers

The retailer is an intermediary buying electricity from generators and selling it to consumers. The retailer pays a fixed tariff ($p_{\overline{i}}$, where i denotes the type of generator) for the capacity as an option to purchase electricity from the generators whenever it is needed. In addition, a variable tariff (p_i) is paid to the generator when the retailer purchases electricity. In the case of excess (resp., deficit) of supply, the retailer can sell to(resp., buy from) to other retailers in the spot market at a price p_n (see description of the spot market in Section 2.4). The profit of the retailer can be written as:

$$\pi_r = p_1\overline{d_1} + p_{2,var}\omega_2\overline{d_2} + p_2\overline{d_2} - p_{\overline{x}}\overline{x} - p_{\overline{v}}\overline{v} - p_x x - p_n(\overline{v} + x - \overline{d_1} - \omega_2\overline{d_2}) \tag{2}$$

The retailer will maximize the expected profit ($\mathbb{E}\,\pi_r$) given by Eq.(2) over the uncertainty parameters (demand and intermittent technology) subject to the reliability constraint given in Section 2.5.

2.3 Generators

We assume that there are two types of technology that produce electricity: conventional (x) and intermittent (v). Both the generators receive a fixed payment for the capacity from the retailers while only the conventional generator is paid a variable price for electricity produced. The two technologies require fixed investment cost to install the capacity: $C_{fix}(\overline{x})$ and $C_{fix}(\overline{v})$ for the conventional and intermittent technologies, respectively. In addition, the conventional technology has a variable production cost $C_{var}(x)$. The profit for the conventional generator (π_x) and the intermittent generator (π_v) can be written as:

$$\pi_x = p_{\overline{x}}\overline{x} + p_x x - C_{fix}(\overline{x}) - C_{var}(x) \tag{3}$$

$$\pi_v = p_{\overline{v}}\overline{v} - C_{fix}(\overline{v}) \tag{4}$$

The retailers will maximize the expected profits ($\mathbb{E}\,\pi_x$ and $\mathbb{E}\,\pi_v$).

2.4 Spot Market

All retailers can participate on the spot market. The generators in our framework have no production beyond the contracted amounts with the retailers and are therefore not able to participate on the spot market. Further we assume full competition among all players on the spot market; in particular, we assume that there exists no entity that can exert market power. By assumption, any retailer can only sell energy on the spot market if the total demand of its own clients is covered at any given moment. Different cases can emerge depending on the economic incentive of the retailers to buy electricity from (or sell electricity to) the spot market.

Let $V = \eta\overline{V}$ being the production of the intermittent energy in a given period and $(D_1 + D_2)$ be the total demand a retailer faces and $\sum_i^N(D_1 + D_2)$ be the total realized demand summed over all retailers in a given period. In times of scarcity the spot market enables retailers to stock up on potential oversupply from other players in the market. All retailers that are net sellers on the spot market in a given situation are denoted by subscript j, whereas all retailers being net buyers are denoted by subscript i. We can then distinguish five different cases

1. **No Trade 1**
   $V_i > (D_1 + D_2)_i \quad \forall i$: Every retailer has sufficient energy to cover all consumer demand. The marginal cost of the retailers for securing energy is $MC_{RES} = 0$. This case is trivial and leads to zero trade.

2. **No Trade 2**
   $V + \overline{X} < (D_1 + D_2)_i \quad \forall i$: Every retailer has a deficit in covering her consumers' demand. Per imposed regulation, the own customers have priority and therefore no surplus can be allocated among other market participants. This case is trivial and leads to zero trade.

3. **Trade with RES**
   $\sum_i^N(D_1+D_2)_i - V_i \leq \quad \sum_j^N V_j - (D_1+D_2)_j \quad \forall i, j \; with \; j \neq i$: The deficits of some retailers to meet full demand through RES are offset by surplus of other retailers. The occurring trade is conducted at marginal cost with production only through RES. This leads to a market price $p_m = c_{RES} = 0$ and to a profit of $\Pi_j = 0$

4. **Trade with RES and conventional ES**
   $\sum_j^N V_j - (D_1+D_2)_j > (D_1+D_2)_i - V_i \quad \forall i, j \; with \; j \neq i$: The deficits of some retailers to meet full demand through RES are (at least partially) offset by the RES surplus of other retailer plus their surplus of conventional capacity. Due to the assumed competition among generators, this leads to a market price $p_m = c_{conv.} = c$ and to a profit of $\Pi_j = max[(V_j - (D_1 + D_2)_j) \cdot c_{conv}; \quad 0]$. Any retailer that can produce more efficiently than the marginal unit on the market, i.e. $MC < c_{conv}$ will not use the spot market and instead produce by their own contract.
   In a setting with conventional energy sources in which there is no energy surplus, efficient allocations use the marginal cost for non-delivery as allocation basis. This also leads to a market price $p_m = p_2 = c$, i.e. a identical market clearing price

In term of investment problem and given the additional assumptions (see Section 2.5), these cases can be summarized in two cases: total intermittent capacity is sufficient or not to cover all the demand. Let assume that there are n competitive retailers and denote by "i" the individual retailer and by "$-i$" the other $n-1$ retailers. The total demand and total intermittent capacity can then be expressed as $D_i + D_{-i}$ and $V_i + V_{-i}$, respectively with $D_i = \overline{d_{1i}} + \omega_2\overline{d_{2i}}$ and $V_i = \eta\overline{v_i}$.

Let define by $\overline{\omega}$ the threshold on ω_2, the demand uncertainty parameter, that describes the condition triggering the above two cases: $D_i + D_{-i} = V_i + V_{-i}$. The expected value "$\mathbb{E}$" will be calculated over the distribution of ω_2 using the threshold value of $\overline{\omega}$.

2.5 Reliability constraint and additional assumptions

We define reliability R as the intermediary's ability to cover the cumulative demand of all consumers, while being able to guarantee the supply of the base demand d_1

$$P(\overline{d_1} + \omega_2\overline{d_2} \leq \eta * \overline{v} + \overline{x}) = R$$
$$P(d_1 \leq \overline{x}) = 1$$

Assuming that $\overline{x} = \overline{d_1}$, the reliability constraint can be written as an implicit function of $\overline{d_2}$:

$$\overline{d_2} = g(\overline{x}, \overline{v})$$

In order to ensure the implementation of the reliability pricing market design discussed in Section 4.2, we additionally assume that the price p_2 that the consumer pays to the retailer for the peak demand d_2 is equal to the price p_x that the retailer pays to the conventional generator for the use of the conventional generation (x).

3 Investment Problem

In this Section, we analyse the investment problem from the perspective of all the parties involved in the market. First, we start with the case under the reliability pricing market design (see Section 3.1). In addition, we deduce the investment problem under full reliability market from the one under the reliability pricing (3.2).

3.1 Investment Problem under reliability pricing market design

This section focuses on the investment problem with the reliability pricing market design. For each of the parties involved, we determine the optimal capacities.

3.1.1 Retailer Problem

Using the framework described in Section 2.2, the retailer maximization program can be written as:

$$\max_{\overline{x},\overline{v}} \mathbb{E}\,\pi_r = \int_0^1 \left(\int_0^1 [p_1\overline{d_1} + p_{2,var}\omega_2\overline{d_2} + p_2\overline{d_2} - p_{\overline{x}}\overline{x} - p_{\overline{v}}\overline{v})]\phi(\omega_2)d\omega_2 + \int_{\overline{\omega}}^1 [c(\eta\overline{v} - \overline{d_1} - \omega_2\overline{d_2})]\phi(\omega_2)d\omega_2 \right)\phi(\eta)d\eta \tag{5}$$

st. $\overline{d_1} = \overline{x}$ and $\overline{d_2} = g(\overline{x}, \overline{v})$
Using the equality between total demand and total intermittent electricity generation, the threshold value $\overline{\omega}$ of ω_2 is given by:

$$\overline{d_1}_i + \omega_2\overline{d_2}_i + (n-1)(\overline{d_1}_{-i} + \omega_2\overline{d_2}_{-i}) = \eta\overline{v}_i + \eta(n-1)\overline{v}_{-i}$$

Which implies that:

$$\overline{\omega} = \frac{\eta(\overline{v}_i + (n-1)\overline{v}_{-i}) - (\overline{d_1}_i + (n-1)\overline{d_1}_{-i})}{\overline{d_2}_i + (n-1)\overline{d_2}_{-i}}$$

The FOCs with respect to $\overline{v}$ and $\overline{x}$ and assuming that $\overline{v}_{-i} = \overline{v}_i$, $\overline{d_1}_{-i} = \overline{d_1}_i$, $\overline{d_2}_{-i} = \overline{d_2}_i$ and $n = 1$, give:

$$\int_0^1 \left(\frac{2\eta c(\overline{x} - \eta\overline{v})g(\overline{x}, \overline{v}) + c(\overline{x} - \eta\overline{v})^2 g_{\overline{v}}(\overline{x}, \overline{v}) + [-2P_v + 2\eta c + 2P_3 g_{\overline{v}}(\overline{x}, \overline{v})]g(\overline{x}, \overline{v})^2}{2g(\overline{x}, \overline{v})^2} \right) \phi(\eta)d\eta = 0 \tag{6}$$

and

$$\int_0^1 \left(\frac{-2c(\overline{x} - \eta\overline{v})g(\overline{x}, \overline{v}) - 2(c - P_1 + P_{\overline{x}})g(\overline{x}, \overline{v})^2 + [c(\overline{x} - \eta\overline{v})^2 + 2P_3 g(\overline{x}, \overline{v})^2]g_{\overline{x}}(\overline{x}, \overline{v})^2}{2g(\overline{x}, \overline{v})^2} \right) \phi(\eta)d\eta = 0 \tag{7}$$

3.1.2 Generator Problem

Based on the framework described in Section 2.3, the conventional generator has the following program:

$$\max_{\overline{x}, x} \pi_x = p_{\overline{x}}\overline{x} + p_x x - C_{fix}(\overline{x}) - C_{var}(x) \tag{8}$$

The FOCs with respect to $\overline{x}$ and x give:

$$P_{\overline{x}} = C_{\overline{x}}(P_{\overline{x}})$$

and

$$P_x = c$$

As the contract between generators and retailers does not directly depend on the reliability constraint, the above FOCs are standard arbitrage conditions. The marginal capacity cost of each additional capacity installed by the conventional generator should be compensated with the capacity price that is paid by the retailer. In addition, whenever the retailer purchases the conventional generation, the variable price that is paid to the generator should cover the marginal cost of the conventional generation.

The intermittent generator has the following program:

$$\max_{\overline{v}} \pi_v = p_{\overline{v}}\overline{v} - C_{fix}(\overline{v}) \tag{9}$$

The FOC with respect to $\overline{v}$ gives:

$$P_{\overline{v}} = C_{\overline{v}}(P_{\overline{v}})$$

Similarly to the conventional generator, the capacity payment to the intermittent generator for each additional intermittent generation should compensate the marginal capacity cost.

3.1.3 Consumer Problem

From the consumer perspective, the framework described in Section 2.1 translates into the following program:

$$\max_{\overline{d_1},\overline{d_2}} U(.) = u(d_1, \mathbb{E}\, d_2) - p_1\overline{d_1} - p_{2,var}(\mathbb{E}\, d_2) - p_2\overline{d_2} - (1-R)Dam(\mathbb{E}\, d_2) \tag{10}$$

The FOCs with respect to $\overline{d_1}$ and $\overline{d_2}$ give:

$$p_1 = u'(\overline{d_1} + \frac{\overline{d_2}}{2})$$

and

$$p_{2,var} + 2p_2 + Dam(1-R) = u'(\overline{d_1} + \frac{\overline{d_2}}{2})$$

The above equations are household arbitrage conditions. The first equation shows that the marginal utility of cone additional unit of the base demand should compensate to unit price that the household pays. This is a standard trade-off as the base demand is fixed and the consumer is not affected by the damage related to supply unreliability. The second equation describes the consumer trade-off regarding the peak demand. The marginal cost of the peak demand has three components: (i) the variable price, (ii) the capacity price and (iii) the marginal damage of unmet demand.

3.1.4 Optimal conditions

Replacing the price solutions from the consumer and generator problems into the retailer problem, we get optimal conditions that depend only on the cost and capacities parameters:

$$\int_0^1 \left(\frac{2g(.)[c\eta(\overline{x} - \eta\overline{v} + g(.)) - g(.)C_{\overline{v}}(.)] + [c(\overline{x} - \eta\overline{v})^2 + g(.)^2(-c + Dam(R-1) + u'(\overline{x} + \frac{1}{2}g(.))]g_{\overline{v}}(.)}{2g(.)^2} \right) \phi(\eta)d\eta \tag{11}$$

and

$$\int_0^1 \left(\frac{-2c(\overline{x} - \eta\overline{v})g(.) + c(\overline{x} - \eta\overline{v})^2 g_{\overline{x}} + g(.)^2[-2c - C_{\overline{x}} - (c + (1-R)Dam)g_{\overline{x}} + u'(\overline{x} + \frac{1}{2}g(.))(2 + g_{\overline{x}})]}{2g(.)^2} \right) \phi(\eta)d\eta \tag{12}$$

Solving together the above two equations gives the optimal capacities for the conventional technology and the intermittent technology. Note that these optimal capacities also depend on the level of reliability that is contracted between retailers and consumers. A close form of these solutions would require assuming a specific form for the cost and utility functions.

3.2 Investment Problem with full reliability

Here, we assume that the utility guarantees a full reliability, i.e., $R = 100\%$. This corresponds to the current electricity market in most countries as the household does not directly pay for the reliability. The consumer pays a constant price p to the retailer for both the base and peak demands. In addition, the utility is allowed by the regulator to add a "mark-up" "m" on the price of electricity to cover the necessary cost for the full reliability.

3.2.1 Retailer Problem

In term of investment problem, previous retailer program is modified as the following: $p_1 = p_{2,var} = p + m$, $p_2 = 0$ and $\overline{d_2} = g_1(\overline{x}, \overline{v})$, where $g_1(\overline{x}, \overline{v})$ is an implicit function from the reliability constraint when $R = 100\%$.

$$\max_{\overline{x},\overline{v}} \mathbb{E}\,\pi_r = \int_0^1 \left(\int_0^1 [(p+m)(\overline{d_1} + \omega_2 \overline{d_2}) - p_{\overline{x}}\overline{x} - p_{\overline{v}}\overline{v})]\phi(\omega_2)d\omega_2 + \int_{\overline{\omega}}^1 [c(\eta\overline{v} - \overline{d_1} - \omega_2\overline{d_2})]\phi(\omega_2)d\omega_2 \right) \phi(\eta)d\eta \quad (13)$$

st. $\overline{d_1} = \overline{x}$ and $\overline{d_2} = g_1(\overline{x}, \overline{v})$

The FOCs with respect to $\overline{v}$ and $\overline{x}$ become:

$$\int_0^1 \left(\frac{2\eta c(\overline{x} - \eta\overline{v})g_1(\overline{x},\overline{v}) + c(\overline{x} - \eta\overline{v})^2 g_{1\overline{v}}(\overline{x},\overline{v}) + [-2P_v + 2\eta c + (p+m-c)g_{1\overline{v}}(\overline{x},\overline{v})]g_1(\overline{x},\overline{v})^2}{2g_1(\overline{x},\overline{v})^2} \right) \phi(\eta)d\eta = 0 \quad (14)$$

and

$$\int_0^1 \left(\frac{-2c(\overline{x} - \eta\overline{v})g_1(\overline{x},\overline{v}) - 2(c - p - m + P_{\overline{x}})g_1(\overline{x},\overline{v})^2 + [c(\overline{x} - \eta\overline{v})^2 + (p+m-c)g_1(\overline{x},\overline{v})^2]g_{1\overline{x}}(\overline{x},\overline{v})^2}{2g_1(\overline{x},\overline{v})^2} \right) \phi(\eta)d\eta = \quad (15)$$

Under full reliability, the above two equations give optimal conventional and intermittent capacities.

3.2.2 Consumer Problem

Given the changes mentioned in the retailer investment problem, the consumer problem is also modified as the following:

$$\max_{\overline{d_1},\overline{d_2}} U(.) = u(d_1, \mathbb{E}\, d_2) - (p+m)(\overline{d_1} + \mathbb{E}\, d_2) \quad (16)$$

The FOCs with respect to $\overline{d_1}$ and $\overline{d_2}$ become:

$$p + m = u'(\overline{d_1} + \frac{\overline{d_2}}{2})$$

and

$$p + m = u'(\overline{d_1} + \frac{\overline{d_2}}{2})$$

Under the guarantee of full reliability, each unit of base and peak demands have the same values for the consumer who pays an uniform electricity price.

3.2.3 Optimal conditions

Note that the generator problem does not change. Using the above FOCs together with the FOCs from the generator problem, the optimal conditions become:

$$\int_0^1 \left(\frac{2g_1(.)[c\eta(\overline{x} - \eta\overline{v} + g_1(.)) - g_1(.)C_{\overline{v}}(.)] + [c(\overline{x} - \eta\overline{v})^2 + g_1(.)^2(-c + u'(\overline{x} + \frac{1}{2}g_1(.))]g_{1\overline{v}}(.)}{2g_1(.)^2} \right) \phi(\eta)d\eta = 0 \tag{17}$$

and

$$\int_0^1 \left(\frac{-2c(\overline{x} - \eta\overline{v})g_1(.) + c(\overline{x} - \eta\overline{v})^2 g_{1\overline{x}} + g_1(.)^2[-2C_{\overline{x}} - (c - u'(\overline{x} + \frac{1}{2}g_1(.))(2 + g_{1\overline{x}})]}{2g_1(.)^2} \right) \phi(\eta)d\eta = 0 \tag{18}$$

Solving these two optimal equations will give optimal capacities for the conventional and intermittent technologies. In the next step, we plan to do a comparison analysis of these optimal values under pricing reliability market design and full reliability design. We expect to show that the current electricity market design is inefficient compare to the reliability pricing market design which is close to the first best of real time pricing.

4 Model Analysis

In this section, we first do a welfare comparison to investigate the parametric conditions that define the efficiency of the reliability pricing market design. Second, we explore the implementation of this contract under the reliability pricing market design.

4.1 (Preliminary) Welfare comparison

Consider the expected utility for the representative consumer as well as for the retailer. By comparing joint utility under a contract structure marketing reliability and an adequate reference scenario, we can determine the ranges of parametrization that need to hold. With $R < 1$:

$$\mathbb{E}\, U(.)_{cons.,R} = u(d_1, \mathbb{E}\, d_2) - p_1\overline{d_1} - p_{2,var}(\mathbb{E}\, d_2) - p_2\overline{d_2} - (1 - R)Dam(\mathbb{E}\, d_2) \tag{19}$$

$$\pi_r = p_1\overline{d_1} + p_{2,var}\,\mathbb{E}(\omega_2\overline{d_2}) + p_2\overline{d_2} - p_{\overline{x}}\overline{x} - p_{\overline{v}}\overline{v} - p_x x - p_n(\overline{v} + x - \overline{d_1} - \omega_2\overline{d_2})$$

The conventional generator's profit is formulated as:

$$\pi_x = p_{\overline{x}}\overline{x} + p_x x - C_{fix}(\overline{x}) - C_{var}(x)$$

The intermittent generator's profit is formulated as:

$$\pi_v = p_{\overline{v}}\overline{v} - C_{fix}(\overline{v})$$

Computing the overall expected welfare within the model, it is given as:

$$W(\overline{d_1}, \overline{d_2}) = \mathbb{E}\left[U(.)_{cons.,R} + \pi_r + \pi_x + \pi_v\right]$$

By construction we assume perfect competition and risk neutrality among generators and therefore impose a zero profit assumption.

$$p_{\overline{v}}\overline{v} = C_{fix}(\overline{v})$$
$$p_{\overline{x}}\overline{x} + p_x x = C_{fix}(\overline{x}) - C_{var}(x) \text{ and } p_x = c_{var}$$

This gives us the welfare W considering a 2-part tariff with $R < 1$:

$$\begin{aligned} W_{R<1} = u(d_1, \mathbb{E}\, d_2) - \big(1 - (R + P(SS))\big) Dam(\mathbb{E}\, d_2) \\ - C_{fix}(\overline{x}) - C_{fix}(\overline{v}) \\ - C_{var}(x)\, \mathbb{E}(x) + p_n\big(\, \mathbb{E}(\eta\overline{v}) + x - \overline{d_1} - \omega_2 \overline{d_2}\big) \end{aligned}$$

The reference scenario of full reliability with a purely conventional generation is characterized by:

$$W_{R=1} = u(d_1, \mathbb{E}\, d_2) - p_{\overline{x}}(\overline{d_1} + \overline{d_2}) - C_{var}(x)(\overline{d_1} + d_2)$$

We claim the following proposition:

Proposition 1:
There exists a contract structure between consumers, retailers and generators with a 2-part-tariff including reliability R, that increases welfare

Proof of Proposition 1

Comparing welfare W under the scenario marketing reliability and the conventional reference scenario we find that $W_{R<1} > W_{R=1}$ if:

$$\begin{aligned} u(d_1, \mathbb{E}\, d_2) - (1 - R) Dam(\mathbb{E}\, d_2) - C_{fix}(\overline{x}) - C_{fix}(\overline{v}) - C_{var}(x)\, \mathbb{E}(x) > \\ u(d_1, \mathbb{E}\, d_2) - C_{fix}(\overline{d_1} + \overline{d_2}) - C_{var}(x)(\overline{d_1} + d_2) \end{aligned}$$

$$\begin{aligned} \iff (1 - R) Dam(\mathbb{E}\, d_2) + C_{fix}(\overline{x}) + C_{fix}(\overline{v}) + C_{var}(x)\, \mathbb{E}(x) < \\ C_{fix}(\overline{d_1} + \overline{d_2}) + C_{var}(x)(\overline{d_1} + d_2) \end{aligned}$$

Rearranging the result, we get

$$\begin{aligned} \big[-C_{v,fix}(\overline{v}) - C_{x,fix}(\overline{x}) + C_{x,fix}(\overline{d_1} + \overline{d_2})\big] + \\ \big[C_{var}(x)(\overline{d_1} + d_2) - C_{var}(x)\, \mathbb{E}(x)\big] > (1 - R) Dam(\mathbb{E}\, d_2) \end{aligned}$$

With $(1-R)Dam(\mathbb{E}\,d_2)$ being the expected VoLL under a reliability level $R < 1$, we find the condition that characterizes the efficiency gain of our system. Intuitively, having a reliability $R < 1$ increases welfare if the sum of additional fixed costs and the savings of variable costs is larger than the expected damage. As of now, we do not have closed form solutions for the retailers optimization problem yet (compare section 3 Investment Problem). Once we have the closed form solution, a better analysis will be possible.

4.2 Implementation

In this section, we explore how different contracts between the market players could be implemented. We focus on both the contract between (i) consumer and retailer and (ii) retailer and generators.

Consumer - Retailer

- **Peak demand** For the non-guaranteed tariff we have:

$$d_2 p_{2,v} + \overline{d_2} p_{2,R}$$

  With fixed payment that is set on maximum demand and corresponding reliability

$$p_{2,fix,R}\overline{d_2}$$

  If $p_{2,v} < c_{var,con}$: If retailers were to receive less compensation than it costs them to supply consumers in times RES scarcity, it would be hard to enforce supply to consumers even if it is possible.
  If $p_{2,v} >> c_{var,con}$: Supplying demand of the types d_1, d_2 can be understood as implicit differences in product quality. For d_1 with $R = 100\%$, price p_1 needs to be higher than p_2. Otherwise any retailer could recreate the superior product without the need for a product of less quality.
  Only for the case of $p_{2,v} = c_{var,con}$ we can ensure incentive compatibility for both sides Conditions for d_2 to be chosen with $p_{2,v}$ and $R < 1$, over d_2 with $p_{1,v}$ and $R = 1$:

$$u\left[Rd_2 - (p_{2,fix}(R)\ \overline{d_2} + p_{2,var}\ d_2 + (1-R)\beta)\right] > u\left[d_2 - p_1 d_2\right]$$

  Conditions for d_2 to be chosen with p_2 and $R < 1$ at all:

$$u(d_2 - p_{2,fix}(R)\ \overline{d_2} - p_{2,var}\ d_2) > 0$$

- **Base demand** Additionally, we have d_1 being the guaranteed supply based on a conventional, controllable energy production technology. The consumers pay a fixed price per unit which corresponds to the levelized cost of energy (LCOE):

$$p_1 = c_{marg,con} + c_{con,fix} * \frac{\overline{x}}{x}$$
$$\iff p_1 = c_{marg,con} + MU$$

$p_1 \geq LCOE$ ensures that retailers do not make a loss from offering this tariff while generators can refinance their investments. Conditions for d_1 to be chosen with p_1 and $R = 1$, over d_1 with p_2 and $R < 1$:

$$u\left[d_1(1-p_1)\right] > u\left[Rd_1 - (p_2 d_1 + (1-R)\alpha)\right]$$

Conditions for d_1 to be chosen with p_1 and $R = 1$ at all, is implicitly given by the other conditions.
We have $c_{c,var} + MU = p_1 > p_{2,var} = c_{c,var}$. With risk averse consumers and without income effects, it follows that:

$$u(d_2) - u(Rd_2) \leq u\left[c_{c,var} \cdot d_2 \cdot \left(1 + MU - R - \frac{\overline{d_2} \cdot p_{2,fix}(R)}{c_{c,var} \cdot d_2}\right)\right]$$

For positive values of $\left(1 + MU - R - \frac{\overline{d_2} \cdot p_{2,fix}(R)}{c_{c,var} \cdot d_2}\right)$, it follows from concave vNM utility functions that any consumer will opt for $d_2 > 0$.

Retailer - Generator The contracts between retailer and generator consist of a two part tariff:

$$C_{c,gen}(z) = \phi_{c,var} * z + \phi_{c,fix} * \overline{z}$$
$$C_{RES,gen}(z) = \phi_{RES,fix} \overline{z}^2$$

The fixed part of the contract can be considered as an option or the retailer to purchase the contracted amount of energy. Based on the incentive compatibility constraints for the generator, the variable price for the retailer would not have to match the marginal cost of production of the generator. Instead, different contracts with varying size of the fixed and the variable portion for the same delivery schedule could be possible. However, this would incentivize the retailer to understate the actual usage of the purchase option and therefore exploit the generator:

- if $(c_{c,var} - \phi_{c,var}) > 0$ and $(c_{c,fix} - \phi_{c,fix}) < 0$: Retailers are incentivized to overstate their actual purchasing amount. This in turn would drive up prices for consumers and could be undercut by competitors.

- if $(c_{c,var} - \phi_{c,var}) < 0$ and $(c_{c,fix} - \phi_{c,fix}) > 0$: If retailers pay less than the marginal cost of production per unit, this pricing scheme would lead to arbitrage seeking on the side of retailers. Through the spot market, retailers would be incentivized to buy all available energy and resell it with profit through the spot market.

- Only for the case of $c_{c,var} = \phi_{c,var}$ and $c_{c,fix} = \phi_{c,fix}$ we can ensure incentive compatibility for both sides.

$$\Pi_C = (c_{c,var} - \phi_{c,var})z + (c_{c,fix} - \phi_{c,fix})\overline{z} \geq 0$$

The following proposition summarise the implementation of the contract under pricing reliability market design.
Proposition 2: *A contract incorporating reliability for end consumers is can be introduced without violating any incentive compatibility/participation constraints.*

5 Conclusion

In the global fight against climate change, renewable energy sources have become one of the strategic instruments of choice. Due to political targets, e.g. on EU level, the share of RES will likely increase strongly in the next decades. Their introduction is favored by the fact that they have already achieved financial competitiveness when compared to current conventional energy sources. Factoring in economies of scale and further technological prowess, RES will likely be the cost-efficient energy sources of choice in the near future.

These changes have to be addressed in the legal and financial framework energy markets provide. On the one hand, the investment into RES is accompanied by a shift of the existing cost structures; while many energy sources such as coal or gas are driven by variable costs, these are essentially zero for most RES. The shift to a higher share of initial investment cost needs to be addressed in a well-functioning market design. On the other hand, new technologies such as smart meters provide new options when developing a new market design. Retailers have new ways to ensure net stability by dropping specific loads within the system. When talking about the energy market of the future, real time pricing is often considered the first-best solution. Its practical problems for consumers, however, are imminent and have been widely discussed. Our theoretical model combines the advantage of utilizing demand side flexibility that is inherent to real time pricing. At the same time, we developed a framework that is easier to utilize for end consumers and specifically mitigates the impossible task of constant monitoring. Through adequate risk compensation we show that significant welfare increases can be achieved by integrating a large share of intermittent resources.

Our model setup is able to capture both demand as well as supply uncertainty. Currently, demand uncertainty is an exogenous variable input into our model. Future research could be conducted on how demand adaption strategies on the consumer side might change the outcome of our model.

We have pointed out similarities between the proposed reliability pricing approach and real-time pricing. Further work should be conducted on how these two frameworks might converge. Especially when splitting demand into multiple tranches, analyses should indicate that reliability pricing will approximated the outcome reached through real-time pricing.

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