Prosumers: Grid Storage vs Decentralized Storage*

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Abstract

The number of prosumers—consumers equipped with decentralized production—should rise following the 2023 Renewable Energy Directive and increasing energy prices. The economic literature suggests a potential for demand-side storage. In this study, we present a stylized microeconomic model to analyze storage investment decisions by a representative consumer with either centralized (quantity regulation) or decentralized (price regulation) storage. Prosumers may become storers only when the cost of producing energy is sufficiently low, and this condition is more stringent under centralized storage. Additionally, there may be more storage under quantity regulation. We calibrate our model using data from France, considering two storage technologies: batteries and fuel cells. Consumers' preferred regulatory regime depends on the technology used for individual storage, with a preference for quantity regulation when utilizing a fuel cell and vice versa for batteries. The Distribution System Operator (DSO) is better off under quantity regulation, except in the case of centralized hydrogen storage. Energy storage enables the DSO to avoid operating at a loss under price regulation, and welfare is higher with energy storage under both regulations.

Keywords— Renewable Energy, Storage, Decentralized Production, Batteries, Hydrogen

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1 Introduction

The significant cost decline of rooftop solar panels over the past decade has led to massive investments in decentralized solar capacity (Schill, Zerrahn and Kunz, 2017).[1] This substantial cost decline, combined with rising energy prices, should increase the number of prosumers (IEA, 2019). The European Union is set to experience a substantial increase in installed decentralized solar capacity, aligning with the ambitious goal of reaching 40% renewable energy consumption by 2030, as mandated by the 2023 Revised Renewable Energy Directive (RED III).[2] In France, residential PV capacity is expected to increase by more than one-third by 2024 (IEA, 2019). However, solar production is intermittent and depends on exogenous climatic conditions. The increasing share of intermittent solar production calls for flexibility solutions such as demand response or energy storage.

This paper explores the conditions under which consumers optimize their energy usage, transition to prosumers, and store energy under various energy regulations. Currently, two distinct energy consumption and sale schemes enable self-consumption: net metering and real-time self-consumption (IEA, 2019). With net metering, consumers can inject their surplus solar production into the grid, effectively storing it at no cost (e.g., in Quebec). As a result, they only pay for their net energy consumption, turning the grid into a virtual energy storage device. With real-time self-consumption (e.g., Denmark, France, etc.), consumers can sell their excess solar production to the grid in exchange for a feed-in tariff (FiT).

The economic literature has long advocated for consumer exposure to real-time dynamic prices to induce efficient consumption patterns (Borenstein, 2005; Borenstein and Holland, 2005). So far, not many governments have implemented such tariffs.[3] In most countries, a complete roll-out is a condition for their implementation (Gautier, Jacqmin and Poudou, 2021). Fabra, Rapson, Reguant and Wang (2021) study the first large-scale implementation of real-time prices using Spanish data. Unlike theoretical predictions, they find that consumers do not adjust their consumption to price signals. Fabra et al. (2021) offer different explanations for this counter-intuitive finding, such as a lack of awareness and enabling technologies. Without enabling technologies, real-time prices may not provide enough flexibility to compensate for

[1] In Germany and China, the levelized cost of solar electricity (LCOE) from solar photovoltaic (PV) panels fell by 77% (IRENA, 2018) between 2010 and 2018. In Germany, the LCOE is now below the retail electricity price (Lang, Ammann and Girod, 2016).

[2] This directive sets common principles and rules to remove barriers, stimulate investments, and drive cost reductions in renewable energy technologies.

[3] The EU expects 72% of residential consumers will be equipped with technologies for real-time pricing by 2020 (JRE-SESI, 2020).

renewables' intermittency. Durmaz, Pommeret and Ridley (2022) find that this type of pricing only generates consumer welfare gains whenever consumers have access to energy storage. Furthermore, this mechanism raises concerns because real-time prices in Spain have been regressive, according to Cahana, Fabra, Reguant and Wang (2022). Regarding energy storage technologies, a lack of regulation combined with high prices has limited their large-scale deployment (Parra and Mauger, 2022).[4] Both batteries and hydrogen fuel cells are candidates for residential energy storage because of their small size and expected cost reductions (IEA, 2020a). The RED III has eliminated these regulatory barriers, providing the playing rules for energy storage activities (Gährs and Knoefel, 2020). As a result, several countries have launched programs to support the development of storage technologies (e.g., Important Projects of Common European Interest for Batteries and Hydrogen). Critical materials (e.g., lithium for batteries) are another concerning point. New technologies such as solid oxide electrolysis cells limit the use of such materials. Articles 36 and 54 of the EU Directive 2019/944 limit the ownership of storage facilities to producers, aggregators, and consumers. Thus, it is possible that in the near future, consumers may want to invest in storage capacity, especially as energy bills keep rising (IEA, 2022).[5]

In this paper, we consider energy storage as the only flexibility solution and build a stylized microeconomic model of the power sector to study solar capacity and storage investments by consumers connected to the grid. First, we consider that the regulator opts for a "price regulation", i.e., a real-time self-consumption scheme such that consumers can sell surplus production to the grid. In addition, they can invest in decentralized storage. Second, we consider that the regulator chooses instead a quantity regulation, a modified net metering scheme where consumers can store their surplus solar production in the grid at a positive storage tariff. Today, with net-metering consumers store energy in the grid for free. However, in the literature, many contributions point out that providing this service for free can put the grid in financial difficulty and may lead to an overall increase in energy prices (Borenstein and Bushnell, 2015; Gautier, Jacqmin and Poudou, 2018). This price increase is not without consequences as it may motivate even more consumers to install decentralized production as a means to cope with this high tariff. As discussed in Gautier et al. (2018), this could lead to traditional residential consumers cross-subsidizing prosumers, and raises equity issues, particularly since wealthier households are more likely to install rooftop solar panels. Thus, poorer households would bear the negative price externality

[4] This lack of regulation translated into double grid charges and unclear ownership rules.

[5] Zakeri, Gissey, Dodds and Subkhankulova (2021) estimate that a combined solar PV panels and storage system could reduce electricity bills by 80-88% in the United Kingdom.

without the means to address it (De Groote, Pepermans and Verboven, 2016). Thus, we introduce the storage tariff as a means to limit the financial losses of the grid.

The economics of energy storage has attracted the attention of many researchers over the past decade. A first strand of the literature has studied the incentives to invest in storage from a producer's point of view in perfectly competitive markets (Ambec and Crampes, 2019; Durmaz, 2016; Helm and Mier, 2018) and under alternative market configurations (Ambec and Crampes, 2019; Andrés-Cerezo and Fabra, 2023). They characterize the storage charge and discharge patterns of a benevolent central planner and profit-maximizing firms. Storage increases investments in renewable energy and decreases carbon emissions in competitive markets (Ambec and Crampes, 2019; Helm and Mier, 2018). Market power creates distortions, as it reduces investments in storage capacity (Andrés-Cerezo and Fabra, 2023) and can increase carbon emissions unless properly accounting for the social cost of carbon (Ambec and Crampes, 2019). The lower investment level compared to the first best is a direct result of the limited profitability of storage operations. Different empirical contributions (Antweiler, 2021; Butters, Dorsey and Gowrisankaran, 2021; Karaduman, 2022; Lamp and Samano, 2022; Monica Giulietti and Waterson, 2018; Sioshansi, Denholm, Jenkin and Weiss, 2009), have highlighted that in line with theoretical predictions (Antweiler, 2021; Durmaz, 2016; Karaduman, 2022), storage deployment reduces price volatility. However, storage operators generate margins by arbitraging short-run inter-temporal electricity price differences. A reduced price volatility limits the profitability of storage and decreases the incentives to invest in such technologies. Nevertheless, investments in storage increase consumer surplus, welfare and reduce carbon emissions. A competitive storage market is not feasible as other power plants distort prices (Karaduman, 2022). Karaduman (2022) compares different ownership structures and finds that social returns are larger with consumer-owned storage than with producer-owned storage. Antweiler (2021) argues that demand-side storage is relevant as it is less expensive than building transmission capacity for supply-side or nodal storage. As already mentioned, in the EU, energy storage ownership is limited to producers, aggregators, and consumers. Thus, in the context of an increasing share of intermittent renewable production in the energy mix, consumer-owned storage may be an alternative. Closer to this paper, a second strand of the literature has focused on consumers' incentives to invest in decentralized storage. Andreolli, D'Alpaos and Moretto (2022) and Boampong and Brown (2020) consider a setting where consumers cannot feed their surplus solar production into the grid. In such a case, consumers invest in decentralized storage only when the capacity costs are small enough. Other papers (Dato, Durmaz and Pommeret, 2020,2; Durmaz et al., 2022) analyze investments in decentralized storage when consumers inject energy into the grid at a FiT valued at the retail price. In addition to small capacity costs, their findings suggest that dynamic prices motivate investments in storage capacity. However, as previously mentioned, dynamic pricing raises equity concerns as it is regressive (Cahana et al., 2022). Also, without enabling technologies, adapting consumption patterns may not be possible. Thus, one might wonder about the conditions under which consumers invest in storage with fixed retail prices. As well as the outcome when excess solar production is no longer rewarded at the energy price. We integrate both features in our model. The economic literature has so far ignored the possibility of consumers investing in a large-scale facility, i.e., centralized storage. This could be possible thanks to technological solutions such as PICEA+. According to Zakeri et al. (2021), aggregated storage offers higher private savings than decentralized storage to all consumers. In the context of these new technologies, one may wonder about the storage solution that is the least costly to deploy. This question is challenging since the policy instruments differ in the two types of energy consumption and sale schemes.

We compare two energy regulations, a price one compatible with decentralized storage and a quantity one compatible with a centralized one. They differ in two economic dimensions: first, consumers can only sell energy with price regulation, and second, the policy instruments available to the regulator are not the same. There are two policy instruments with quantity regulation: the storage tariff and the share of stored energy that can be retrieved by consumers. Conversely, with price regulation, there is only one instrument: the FiT. We perform a numerical evaluation of the model, using publicly available data from France, to compare the two regulations – price and quantity – from our representative consumer's and the Distributed System Operator's (DSO) points of view. Different storage technologies such as batteries and fuel-cells are considered. We aim to determine the regulation that secures non-negative profits for the DSO and is compatible with storage. More broadly, we asses the conditions for consumers to store energy and the cost of funding this activity.

We find that both regulations lead to the same profiles: consumers, prosumers, and storers. Despite investments in solar and storage capacity, consumers never exit the grid: they buy from the grid when climatic conditions are unfavorable. Moreover, the threshold value of the solar capacity cost for consumers to invest in solar capacity is the same under both energy regulations. These findings depart from the literature where the two regimes do not provide the same incentives to become prosumers, in general, net metering provides more incentives to become a prosumer (Brown and Sappington, 2017; Durmaz et al., 2022; Gautier et al., 2018). This difference is related to the fact that in our model, consumers can only inject energy into the grid when there is surplus solar production, this is not necessarily the case in other contributions. We show that consumers might transition into becoming energy storers only when their solar capacity is substantial enough to yield production surpluses during favorable conditions, surpassing their own consumption needs. With decentralized storage, surplus energy production carries a positive marginal benefit as consumers can sell the excess. Consequently, the marginal cost associated with achieving a significant maximal production capacity is higher under price regulation. In instances where maximal production capacity is attained, quantity regulation permits consumers to conserve energy during unfavorable periods, whereas price regulation enables both energy conservation and selling. As a result, returns from energy storage tend to be diminished under price regulation. The Distribution System Operator (DSO) profit experiences a clear increase under quantity regulation when the energy sold to consumers is assessed at the DSO level. However, if this valuation scenario is not applicable, the contrast in DSO profits between quantity and price regulation hinges on the volume of energy flowing through the grid. In instances where consumers cease purchasing from the grid without storing, this volume is greater under price regulation. Conversely, when consumers opt for storage, the outcome is reversed, as all stored energy under quantity regulation passes through the grid. The overall impact remains uncertain or ambiguous. With price regulation, it is the inter-temporal arbitrage between transferring surplus solar production to a later period to save money by limiting consumers' reliance on the grid, and the opportunity cost from selling this surplus solar production to the grid, compared to the investment costs, that drives storage investments. That is the choice between either gaining money instantaneously thanks to surplus solar production or maybe saving money at a later date. With quantity regulation, it is the inter-temporal arbitrage between transferring surplus solar production to a later period to save money by limiting consumers' reliance on the grid, the marginal utility of instantaneous energy consumption, and the storage tariff. Other contributions also find that it is inter-temporal arbitrages that drive investments in energy storage. However, those arbitrages differ from the ones in our paper. In Andreolli et al. (2022), consumers cannot inject energy into the grid so the inter-temporal arbitrage considers only future energy prices and capacity costs. In Dato et al. (2020); Durmaz et al. (2022) the decision to install storage is driven by the difference between inter-temporal marginal energy consumption utilities. In their model, the price varies depending on the time of the day, and the FiT is set at the energy price. Thud, it is this arbitrage between speculative energy prices that drives investment in decentralized storage.

We calibrate our model using data from France, considering two storage technologies: batteries and fuel cells. Provided that the solar and storage capacity costs are sufficiently low, like in 2030, we find that when a fuel cell is used for decentralized storage, then consumers always prefer quantity regulation. Indeed, when able to recover all grid-stored energy, they buy less energy from the grid during the second, compared to price regulation. This compensates for a storage tariff beyond the capacity cost of individual hydrogen storage but below the energy price. Thus, allowing them to save money during the second period. When able to retrieve just a share of the grid-stored energy, to incite consumers to grid-store energy, the DSO sets a storage tariff well below the capacity cost of individual hydrogen storage. Instead, when a battery is used for decentralized storage, then consumers always prefer price regulation. When able to recover all grid-stored energy, they buy less energy from the grid during the second period, however, as the round-trip efficiency of individual batteries is already quite high, this energy gain does not compensate for a storage tariff beyond the capacity cost of individual batteries. When able to retrieve just a share of the grid-stored energy, the highest storage tariff that incites consumers to store energy is above the capacity cost of individual batteries. The DSO is better off with quantity regulation except when hydrogen is used for centralized storage as the storage tariff that incites consumers to grid-store energy is above the DSO's costs to supply back this energy. In terms of welfare, a quantity regulation is preferred when the DSO allows consumers to retrieve all their grid-stored energy. Conversely, when it depends on the round-trip efficiency of a specific technology, then a price regulation is preferred. Finally, when consumers store energy, this increases the DSO's revenues with price regulation and quantity regulation when all grid-stored energy can be recovered. With price regulation, the DSO no longer operates at a loss. Conversely, when consumers cannot recover all grid-stored energy, then the DSO is better when consumers do not store energy. This is related to the fact that although the DSO's costs are similar in both cases, the storage tariff that incites consumers to grid-stored energy is lower. Conversely, consumers are better off with price regulation we then do not store energy, and worst-off with quantity regulation. This is in line with Durmaz et al. (2022) findings in the case of batteries. In terms of welfare, energy storage is desirable with price and quantity regulation.

The remainder of this paper is organized as follows. Section 2 presents the general theoretical framework. Section 3 studies consumers' choices under different energy regulations. Section 4 presents a quantitative application of our results. Section 5 concludes.

2 The model

We consider a two-period economy with $t \in [1, 2]$ where a regulator may implement a quantity or a price-based energy regulation to encourage investments in decentralized production. Our objective is to investigate the impact of these energy policies on individual equipment decisions. These policies are analyzed in a simplified version of (Dato et al., 2020,2; Durmaz et al., 2022).

Consumers We consider a two-period model where a representative consumer derives per period utility $U(q_t)$ from consuming q_t units of electricity.[6] At the beginning of the first period, the consumer may install solar capacity $K \in [0, \bar{K}]$ at unit cost r. The maximal size of the solar capacity $\bar{K}$ is determined by exogenous factors (roof size, etc.). Intermittent solar production depends on exogenous climatic conditions. We consider two states of nature $i \in \{f, u\}$ with respective probabilities ρ_f and $1-\rho_f$. We can interpret ρ_f as the solar energy capacity factor in a given location. If $i = f$, climatic conditions are favorable, and solar technology produces energy up to its installed capacity K. Otherwise, when $i = u$ conditions are unfavorable and solar production is zero. We assume that the climatic conditions are favorable at $t = 1$ and that $K_1 = K$.[7] Production at $t = 2$ is determined by climatic conditions : $K_2 = K(=0)$ if $i = f(=u)$.

We consider that some form of energy storage is available to consumers (electricity can be stored in the first period and transferred to the second period), either centralized (quantity-based regulation) or decentralized (price-based regulation). In the price-based regulation, the consumer may invest in a storage device of capacity $S \in [0, \bar{S}]$ at a unit cost r_s.[8] This storage technology suffers from energy losses estimated at $1 - \lambda$, so that the amount of energy available in the second period is λS. We also assume that the consumer can purchase and sell energy from the grid, which might be valued at different tariffs. Energy is purchased from the grid at a fixed retail price p and can be sold at price $\tau < p$.[9] In

[6]We assume $U(.)$ to be a standard concave, twice differentiable, continuous function.

[7]In France, only consumers equipped with decentralized production can install decentralized storage. Thus, we depart from the literature (Dato et al., 2020,2; Durmaz et al., 2022) by implicitly considering that energy can only be stored from solar panels. Notice that under this hypothesis, adding uncertainty regarding climate conditions at $t = 1$ would not add any major insights to our analysis. Indeed, if there is no sun at $t = 1$, it is straightforward to comment that prosumers would never be able to become storers.

[8]The maximal storage capacity $\bar{S}$ is exogenous, i.e. depends on the size of the largest commercially available storage device.

[9]Dato et al. (2020), Dato et al. (2021), Durmaz et al. (2022) consider dynamic prices instead. We depart from these papers by characterizing the consumer profiles with a FiT that may be smaller than the retail energy price. The FiT is strictly lower than the energy retail price in most European Union countries. Spain is the only EU country without support measures for prosumers (Mir-Artigues, del Río and Cerdá, 2018).

the quantity-based regulation, consumers are not able to sell excess production to the grid. Energy is purchased from the grid at the fixed retail price p and excess production can be stored in the form of an energy credit R at a unit cost α set by the regulator. In such a case, consumers may retrieve from the grid a quantity $\lambda^G R$ at no cost in the second period, where λ^G is set by the regulator.

Distributed System Operators DSOs are natural monopolies in charge of managing the distribution network. A DSO incurs two types of costs: a fixed cost F per consumer and a variable cost c per each kWh distributed. The distribution tariff d is set by the regulator. To allow for an easy comparison of the costs and benefits of the two regulation regimes, we will consider that all the energy sold to the grid under price regulation is valued at the grid level. Under quantity regulation, we will denote the storing cost of the grid α_G.

3 Investment decisions under different energy policies

3.1 Price regulation

In this section, we assume that the regulator chooses price regulation. Consumers equipped with solar panels can sell their surplus solar energy to the grid at a FiT established by the regulator. Thus, energy exchanges with the grid can be negative or positive. Denote g_1 the quantity exchanged at $t = 1$, and g_2^i, the quantity exchanged at $t = 2$ with climatic conditions $i \in \{u, f\}$. The energy purchased and sold is valued at different levels. We define:

$$\phi_t^i = \begin{cases} p & \text{if the consumer purchases energy from the grid} \\ \tau & \text{if the consumer sells energy to the grid} \end{cases}$$

In addition, consumers can invest in a storage device of capacity $S \in [0, \bar{S}]$ at a unit cost r_s. This storage technology suffers from energy losses estimated at $1-\lambda$. Consumers also incur a fixed subscription fee A. The representative consumer problem is:

$$\max_{K,S,g_1,g_2^f,g_2^u} U(K - S + g_1) - \phi_1 g_1$$

$$+\beta\left(\rho_f[U(K + \lambda S + g_2^f) - \phi_2^f g_2^f] + (1-\rho_f)[U(\lambda S + g_2^u) - \phi_2^u g_2^u]\right) - r_s S - rK - A$$

$$\text{subject to} \quad \bar{K} \geq K, \quad K \geq 0, \quad \bar{S} \geq S \quad \text{and} \quad S \geq 0$$

Consumers start investing in solar capacity when the marginal benefit from decentralized production $p(1 + \beta\rho_f)$ exceeds its marginal cost r. Let us define $\bar{r} \equiv p(1 + \beta\rho_f)$, as the maximum solar capacity cost that induces solar panel investment. When $r = \bar{r}$, the size of the optimal investment is driven by the marginal utilities of consumption. For all values of $r \in [0, \bar{r}[$, consumers choose to invest in the maximal solar panel capacity $\bar{K}$. In our setting, storage can only occur if solar production exceeds consumers' consumption.[10] This is the case when solar capacity cost falls under $\hat{r} \equiv \tau(1 + \beta\rho_f)$. The excess production is then sold or stored according to the marginal benefits and costs of each strategy. Selling energy to the grid generates positive revenue for consumers (each unit is sold at price τ). Storing energy has a marginal cost of r_s and allows consumers to save purchasing at price p. The marginal benefit of storage is then $p - \tau$ and storage occurs when it exceeds its marginal cost. This is the case when $\beta\lambda(1 - \rho_f)p - (1 - \beta\lambda\rho_f)\tau \equiv \hat{r_s} \geq r_s$. Thus, the two conditions $\hat{r} \geq r$ and $\hat{r_s} \geq r_s$ must meet to observe storage, as stated in the following lemma.

Lemma 1. *Consumers invest in a storage device only if the following condition holds*

$$\frac{r}{1 + \beta\rho_f} \leq \tau \leq \frac{\beta\lambda(1 - \rho_f)p - r_s}{1 - \beta\lambda\rho_f}$$

Proof. The condition is determined by rearranging the following equations: $\beta\lambda(1-\rho_f)p-(1-\beta\lambda\rho_f)\tau \geq r_s$ and $\tau(1 + \beta\rho_f) \geq r$. $\square$

When $\frac{r}{1+\beta\rho_f} > \frac{\beta\lambda(1-\rho_f)p-r_s}{1-\beta\lambda\rho_f}$, the regulator cannot set a FiT such that consumers invest in storage.

Note that $\hat{r}$ increases with the FiT, whereas $\hat{r_s}$ decreases. This means that if the government sets a high FiT, then consumers will be more likely to invest in solar capacity. Conversely, a high FiT will limit investments in storage. The intuition is that with a high FiT, revenues from injecting surplus energy into the grid are larger than the cost. With a small FiT, the opportunity cost of storing rather than selling to the grid becomes smaller.

As the cost of solar capacity falls, solar panels will complement the grid before becoming a substitute.

[10] Consumers do not engage in *precautionary storage* (buy energy to store it) as in Durmaz (2016). In a setup with responsive consumers, i.e. exposed to dynamic pricing, they find that consumers do engage in precautionary storage. This result is related to *prudence* ($U^{'''}(.) > 0$) because it reduces the cost of unpredictability in price spikes. Their results do not hold in our setup because consumers are exposed to a fixed energy price, so there is no consumption risk.

Given that $U'^{-1}(.)$ is increasing and $p \geq \tau$ the energy that transits through the grid is smaller when solar panels are viewed as substitutes for the grid than when they are viewed as complements.

We can summarize the possible profiles under price regulation (when $p \geq \tau$) as follows :

- Consumers do not invest in solar capacity or storage if $r > \bar{r}$.
- Consumers invest in solar capacity if $\bar{r} \geq r$.
- Consumers invest in solar capacity and storage if $\hat{r} \geq r$ and $\hat{r_s} \geq r_s$.

3.2 Quantity regulation

In the quantity regulation setting, consumers equipped with solar PV panels may buy energy from the grid but can no longer sell it ($g_1 \geq 0$, $g_2^u \geq 0$ and $g_2^f \geq 0$). When equipped with solar PV panels, surplus solar production can be injected and stored into the grid in the form of an energy credit R at a unit cost of α. In such a case, at $t = 2$, consumers may retrieve $\lambda^G R$ units of energy from the grid at no cost. The storage tariff α, as well as the share of energy stored in the grid that can be retrieved from the grid λ^G, are set by the regulator.

The consumer problem writes

$$\max_{K,R,g_1,g_2^f,g_2^u} U(K - R + g_1) - pg_1$$

$$+\beta \left(\rho_f[U(K + \lambda^G R + g_2^f) - pg_2^f] + (1 - \rho_f)[U(\lambda^G R + g_2^u) - pg_2^u]\right) - \alpha R - rK - A$$

$$\text{subject to } g_1,\ g_2^f \text{ and } g_2^u \geq 0, \quad 0 \leq K \leq \bar{K}, \text{ and } R \geq 0$$

Similar to the price-regulation case, consumers start investing in solar capacity when the marginal benefit from decentralized production $p(1 + \beta\rho_f)$ exceeds its marginal cost r, i.e. when $r \leq \bar{r}$. When $r \leq \ddot{r} \equiv (1+\beta\rho_f)U'(\bar{K})$, the consumer stops purchasing from the grid in the first period. In the quantity-regulation case, this excess production cannot be sold. All the excess production that is not stored has a marginal benefit equal to zero. The consumer stores a quantity R that balances the marginal benefit and cost of storage. Any unit stored generates a marginal benefit of p. The marginal cost of storage includes the storage cost α and the loss in the marginal utility to transfer the unit from the first to the second period. We observe storage when $\alpha \leq \bar{\alpha} \equiv \beta\lambda^G(1-\rho_f)p - (1-\beta\lambda^G\rho_f)U'(\bar{K})$. Observe that $\bar{\alpha}$ increases with λ^G.

We can summarize the possible profiles under quantity regulation as follows.

- Consumers do not invest in solar capacity or storage if $r > \bar{r}$.
- Consumers invest in solar capacity if $\bar{r} \geq r$.
- Consumers invest in solar capacity and storage if $\ddot{r} \geq r$ and $\hat{\alpha_s} \geq \alpha_s$.

3.3 Quantity versus Price regulation

The energy regulations differ in two dimensions. First, consumers are only allowed to sell energy under price regulation. Second, under a quantity regulation, the regulator has two policy instruments: the storage tariff α, and the share of stored energy that can be retrieved by consumers λ^G; whereas under a price regulation, the regulator only has one instrument, the FiT τ.

In the previous sections 3.1 and 3.2, we studied the profiles that emerged under price and quantity regulation.

Proposition 1. *Regardless of the energy regulation, consumers install solar panels if the solar capacity cost is:*

$$r \leq \bar{r} = (1+\beta\rho_f)p$$

Proof. See case 1 in Appendix A.1 and Appendix A.2. □

The threshold value of the solar capacity cost for which consumers install solar capacity represents the cost of buying energy from the grid in favorable states of nature over two periods. As a result, regardless of the energy regulation, consumers install solar capacity if the cost of solar capacity is sufficiently low. Both regulations provide enough incentives for consumers to invest in decentralized production. Conversely, in the literature, the two regimes do not provide the same incentives to become prosumers, in general, net metering provides more incentives to become a prosumer (Brown and Sappington, 2017; Durmaz et al., 2022; Gautier et al., 2018). This difference is related to the fact that consumers can only inject energy into the grid when there is surplus solar production, this is not necessarily the case in other contributions. Thus, here the decision to become a prosumer only depends on the marginal cost of energy storage compared to the avoided costs.

Consider now that consumers invest in maximal solar capacity $\bar{K}$. As already explained, consumers may invest in storage technology if and only if the solar capacity cost is sufficiently small. The condition under price regulation writes

$$r \leq \hat{r} = (1 + \beta\rho_f)\tau$$

and $\tau = U'(\bar{K} + g_1^* - S^*) = U'(\bar{K} + \lambda S^* + g_2^{f*})$ with g_1^* and g_2^{f*} negative.

With quantity regulation, the condition writes

$$r \leq \ddot{r} = (1 + \beta\rho_f)U'(\bar{K})$$

Under price regulation, consumers invest in storage technology if the storage capacity cost is such that:

$$r_s \leq \hat{r_s} = \beta\lambda(1 - \rho_f)p - (1 - \beta\lambda\rho_f)\tau$$

whereas with quantity regulation consumers invest in energy storage if the storage tariff is such that:

$$\alpha \leq \bar{\alpha} = \beta\lambda^G(1 - \rho_f)p - (1 - \beta\lambda^G\rho_f)U'(\bar{K})$$

Given that $U'(.)$ is decreasing, and that $\tau > U'(\bar{K})$, we obtain the following proposition.

Proposition 2. *We have that $\ddot{r} \leq \hat{r}$: the storage technology must be more competitive with quantity regulation compared to price regulation for consumers to invest in storage.*
If both regulation regimes offer the same efficiency of the storage technology ($\lambda^G = \lambda$), we have $r_s < \bar{\alpha}$: storage occurs at a larger cost under quantity regulation.

Consumers may become storers only if their solar capacity is sufficiently large so that they have production in favorable states that exceed their consumption. Under price regulation, excess production has a positive marginal benefit because it can be sold by consumers. As a consequence, the marginal cost of solar production that induces large maximal production capacity is larger under price regulation. When maximal production capacity is reached, quantity regulation only allows consumers to save energy on unfavorable periods whereas price regulation allows both saving and selling. The returns of storage are then smaller under price regulation.

In our model with price regulation, it is the inter-temporal arbitrage between transferring surplus solar production to a later period to save money by limiting consumers' reliance on the grid (p), and the opportunity cost from selling this surplus solar production to the grid (τ), compared to the investment costs (r_s), that drives storage investments. That is either gaining money instantaneously thanks to surplus solar production or maybe saving money at a later date. With quantity regulation, it is the inter-temporal arbitrage between transferring surplus solar production to a later period to save money by limiting consumers' reliance on the grid (p), the marginal utility of instantaneous energy consumption ($U'(.)$), and the storage tariff (α). Other contributions also find that it is inter-temporal arbitrages that drive investments in energy storage. However, those arbitrages differ from the ones in our paper. In Andreolli et al. (2022), consumers cannot inject energy into the grid so the inter-temporal arbitrage considers only future energy prices and capacity costs. In Dato et al. (2020); Durmaz et al. (2022) the decision to install storage is driven by the difference between inter-temporal marginal energy consumption utilities. In their model, the price varies depending on the time of the day, and the FiT is set at the energy price. Thud, it is this arbitrage between speculative energy prices that drives investment in decentralized storage.

3.4 Implications for the DSO

Let us now compare the DSO profits under the two regimes.

Denoting $\tau' = \tau - d$ (p and τ are prices net of the distribution cost for consumers) the variable[11] DSO's profit under price regulation writes :

$$\pi^P_{DSO} = \begin{cases} (d-c)(1+\beta)U'^{-1}(p) \quad \text{if} \quad r > \bar{r} \\ (d-c)[(1+\beta\rho_f)(U'^{-1}(p)-\bar{K}) + \beta(1-\rho_f)U'^{-1}(p)] \quad \text{if} \quad \hat{r} \le r \le \bar{r} \\ (d-\tau'-c)(1+\beta\rho_f)(U'^{-1}(\tau)-\bar{K}) + (d-c)\beta(1-\rho_f)U'^{-1}(p) \quad \text{if} \quad r \le \hat{r} \quad \text{and} \quad r_s > \hat{r_s} \\ (d-\tau'-c)[(U'^{-1}(\tau)-\bar{K}+\bar{S}) + \beta\rho_f(U'^{-1}(\tau)-\bar{K}-\lambda\bar{S})] + (d-c)\beta(1-\rho_f)(U'^{-1}(p)-\lambda\bar{S}) \\ \text{if} \quad r \le \hat{r} \quad \text{and} \quad r_s \le \hat{r_s} \end{cases}$$

[11]A DSO incurs two types of costs: a fixed cost F per consumer and a variable cost c per each kWh distributed.

Under quantity regulation, the variable DSO's profit reduces to :

$$\pi_{DSO}^{Q} = \begin{cases} (d-c)(1+\beta)U'^{-1}(p) \quad \text{if} \quad r > \bar{r} \\ (d-c)[(1+\beta\rho_f)(U'^{-1}(p)-\bar{K})+\beta(1-\rho_f)U'^{-1}(p)] \quad \text{if} \quad \ddot{r} \leq r \leq \bar{r} \\ (d-c)\beta(1-\rho_f)U'^{-1}(p) \quad \text{if} \quad r \leq \ddot{r} \quad \text{and} \quad \alpha > \hat{\alpha} \\ (d-c)[(1+\lambda^G\beta\rho_f)R^* + \beta(1-\rho_f)U'^{-1}(p)] + (\alpha-\alpha_G)R^* \quad \text{if} \quad r \leq \ddot{r} \quad \text{and} \quad \alpha \leq \bar{\alpha} \end{cases}$$

DSO profits are similar under price and quantity regulation as long as consumers always purchase energy from the grid ($\hat{r} \leq r$ and $\ddot{r} \leq r$). When solar capacity is sufficient to cover consumption in favorable periods, consumers stop purchasing energy from the grid under quantity regulation so that the only revenue for the DSO comes in the unfavorable state of nature. Under price regulation, consumers sell energy to the grid, which generates a strictly negative revenue to the grid, and profits are larger under quantity compared to price regulation. Also, under quantity regulation, the grid receives an additional revenue that comes from the storage activity: each unit of energy stored has a marginal benefit of $\alpha - \alpha_G$. This additional revenue may be positive or negative, depending on the regulator's choice.

The DSO profit is strictly higher under quantity regulation whenever the energy purchased by consumers is valued at the DSO level. Now consider that this is not the case, the comparison of the DSO profits under quantity and price regulation lies in the quantity of energy that passes through the grid. When consumers stop purchasing from the grid and do not store, this quantity is larger under price regulation. When consumers store, we have the opposite result since all the energy stored under quantity regulation passes through the grid. The total effect is ambiguous.

Note that we provide an analysis of the first best in Appendix A.3.1 and A.3.2. We show that consumers should invest in solar capacity whenever $r \leq (1+\beta)c$. A positive storage cannot be a socially optimal solution.

4 Case Study: France

4.1 Context

Today in France, residential consumers have the choice between two distinct energy consumption and sale schemes: the "buy-all sell-all" scheme, introduced in 2000, and the "real-time self-consumption" scheme, introduced in 2017 (IEA, 2019). Under both schemes, Électricité de France Obligation d'Achat (EDF OA) acquires renewable energy from prosumers at a price secured for 20 years by the energy regulator, the Commission de régulation de l'énergie (CRE) (Engie, 2022b). However, a key distinction exists between the two schemes: while all solar production is sold to the grid in the "buy-all sell-all" scheme, the "real-time self-consumption" scheme allows for on-site consumption.

In this paper, our focus is on how energy regulations allowing for self-consumption interact with demand-side storage. Therefore, we narrow our analysis to the current "real-time self-consumption" scheme (price regulation) implemented in France. Subsequently, we compare it with quantity regulation, not currently implemented in France but is used in other countries like Canada.

As of today, decentralized storage technologies are at different stages of development. To facilitate a meaningful comparison, we examine two potential adoption timelines, specifically 2023 and 2030, within our calibration. This approach allows for a comprehensive analysis that considers the evolving nature of decentralized storage technologies.

4.2 Data

The French energy market opened to competition in 2007; since then, residential consumers have been able to choose between different energy retailers and contracts. In our theoretical model, the retail energy price was fixed, like with the Blue Tariff contract offered by France's main electricity generation and distribution company, EDF. As of 2023, for a subscription of 9 kVA, residential customers pay a fixed retail price of 0.2276 EU per kWh and a monthly subscription fee of 15.93 EU (EDF, 2023b). According to a forecast by JPME (2023), the retail energy price is expected to reach 0.35 EU per kWh in 2030.[12] We do not have information regarding the size of the monthly subscription for 2030, but to harmonize our data, we consider a similar increase to that of the retail energy price.

The French Distributed System Operator (DSO), Enedis, charges both residential consumers and prosumers a two-part energy tariff: the public transmission system access tariff (TURPE).[13] This tariff is included in the final retail price and is defined by the CRE every five years. Today, the fixed part of the TURPE is equal to 0.32 EU per day, whereas the variable part differs depending on the season and period

[12]It is important to note that this estimate is based on a 2012 study conducted by the French Union of Electricity, and since then, no subsequent studies have provided an official estimate of the 2030 value. This represents a limitation in our calibration, as the value is somewhat outdated.

[13]The TURPE is set at the same level for residential consumers and prosumers, but this is not the case for commercial and industrial ones.

(on/off-peak) as illustrated in Table 1. For the calibration, we construct a high (November to March) and low (April to October) season-weighted average fee.[14] To serve consumers, the DSO incurs both fixed and variable costs (CRE, 2023). Today, the fixed cost is evaluated at 0.26 EU per day while operational costs depend on the season and period (Table 1). For the calibration, we construct a season-weighted average version. Once again, no information is available regarding the size of these costs and fees for 2030. To harmonize our data, we consider a similar increase to that of the retail energy price

Table 1: DSO Variable Costs and Fees in 2023 (EU per kWh)

Season	Period	Yearly Hours	Operational Cost (c)	Variable Fee (d)
High	Peak	2464	0.0115	0.067
	Off-Peak	1231	0.0125	0.0456
Low	Peak	3360	0.0075	0.0143
	Off-Peak	1680	0.0052	0.0088

Source: CRE (2023) and Enedis (2023)

As of 2023, consumers with an installed solar capacity of 9 kWc (kW Peak) or less receive a FiT of 0.1339 EU per kWh (EDF, 2023a).[15] According to Engie (2022a), a 16-solar-panel installation (25.6 m^2) with a capacity of 375W each would yield a system with a total peak power of 6 kWc. In the South of France, the yearly solar production is estimated at 1400 kWh per installed kWc (Engie, 2022). Thus, the maximal solar capacity of such an installation would be $\bar{K} = 23.013$ kWh per day. Currently, the levelized cost of energy (LCOE) for residential PV is estimated at $r = 0.068$ EU per kWh and should reach 0.049 EU per kWh by 2030 according to IRENA (2019).

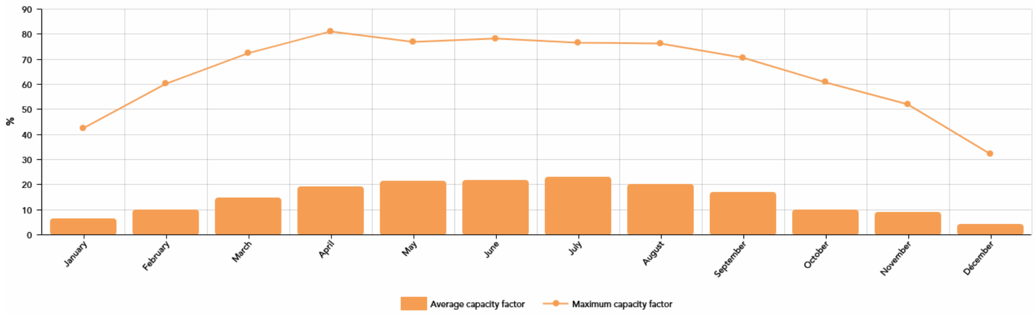
According to the Transmission System Operator (RTE) in 2020, the average solar capacity factor in France was equal to 14.65% (RTE, 2021). However, as illustrated in Figure 1, this metric highly varies during the year. Thus, we differentiate between high and low seasons in our calibration (Enedis, 2023).

According to the last national housing survey from 2020, the mean surface area of an individual French home was estimated at 114.3 m^2 (CGDD, 2022). We follow Durmaz et al. (2022) and consider consumers have CRRA preferences:

[14] The two seasons are defined by the CRE (2023).

[15] Historically, the FiT for consumers under the real-time self-consumption energy consumption and sale scheme has been around 0.10 EU per kWh. However, its size increased in February 2023. Currently, no estimates are available regarding possible future values of the FiT for residential consumers in France. Different scenarios can be considered at the 2030 Horizon. For instance, if by 2030 the French renewable capacity investment targets are met, new residential solar PV investments may no longer benefit from a FiT or its size could be reduced. To harmonize our data, we consider a similar increase to that of the retail energy price.

Figure 1: France's monthly solar capacity factor



Source: RTE (2021)

$$U_t^i(q_t^i) = \frac{(q_t^i - \bar{q})^{1-\gamma}}{1-\gamma}$$

following Elminejad, Havranek and Irsova (2022) we set the elasticity of marginal utility at $\gamma = 0.9$.[16] Since 2007, prospective homebuyers or tenants get an Energy Performance Diagnosis (EPD) with a theoretical energy consumption level based on the property's physical attributes. The EPD ranks homes from extremely efficient (A) to extremely inefficient (G). As of 2022, about 33% of the country's homes were categorized as "D" (ONRE, 2022). Since 2021, an A-class house has a theoretical consumption level between 0 and less than 70 kWh per m^2 per year. Within the houses categorized as A, an energy consumption of 60 kWh per m^2 is the most represented level (ONRE, 2022). We use this EDP theoretical energy consumption level to approximate the minimum energy consumption level of a 114.3 m^2 house. That is $\bar{q} = 18.79$ kWh per day. Table 2 summarizes the values of the different parameters.

4.3 Price-based regulation

We study consumers' incentives to store energy under France's existing price-based energy regulation, where the FiT is strictly smaller than the retail energy price (see Table 2). Under both regulatory frameworks, consumers invest in solar capacity when the cost of installing an additional kWh of solar capacity is lower than the overall cost of purchasing energy from the grid during periods of excess solar production ($r \leq \bar{r}$). In France, this condition is satisfied both in 2023 with $r = 0.068$ euros per kWh and in 2030 with $r = 0.049$ euros per kWh (see Table 3).

[16] Elminejad et al. (2022) meta-analysis suggests a risk aversion coefficient around 1 for economics and 2–7 for finance. We perform a sensitivity analysis for γ around 1 to retrieve a coefficient coherent with consumers deriving a positive utility from energy consumption.

Table 2: Parameters Values

Parameters	Notation	Value 2023	Value 2030	Unit	Source
Preferences					
Minimal Energy Consumption	$\bar{q}$	18.79	18.79	kWh	ONRE (2022)
Relative Risk Aversion	γ	0.9	0.9		Elminejad et al. (2022)
Discount Factor	β	0.95	0.95		
Technology					
Maximal Solar Capacity	$\bar{K}$	23.013	23.013	kWh/day	Engie (2022a)
LCOE Solar PV	r	0.068	0.049	EU/kWh	IEA (2019); IRENA (2019)
Market Characteristics					
Gross Energy Retail Price	p'	0.2276	0.35	EU/kWh	EDF (2023b); JPME (2023)
Subscription Fee	A	0.531	0.8166	EU/day	EDF (2023b); JPME (2023)
Gross Feed-in-Tariff	τ'	0.1339	0.2059	EU/kWh	EDF (2023a)
Solar Capacity Factor					
High Season	ρ_f	8.78	8.78	%	JPME (2023); RTE (2021)
Low Season	ρ_f	18.82	18.82	%	JPME (2023); RTE (2021)
Average	ρ_f	0.1465	0.1465	%	JPME (2023); RTE (2021)
TURPE					
Fixed Fee	A_{TURPE}	0.32	0.4925	EU/day	Enedis (2023); JPME (2023)
Variable Fee (high season)	d	0.06	0.0923	EU/kWh	Enedis (2023); JPME (2023)
Variable Fee (low season)	d	0.0125	0.0192	EU/kWh	Enedis (2023); JPME (2023)
Variable Fee (average)	d	0.0325	0.0492	EU/kWh	Enedis (2023); JPME (2023)
DSO Costs					
Fixed Cost	F	0.26	0.4002	EU/day	CRE (2023); JPME (2023)
Variable Cost (high season)	c	0.0118	0.0185	EU/kWh	CRE (2023); JPME (2023)
Variable Cost (low season)	c	0.007	0.0108	EU/kWh	CRE (2023); JPME (2023)
Variable Cost (average)	c	0.009	0.0139	EU/kWh	CRE (2023); JPME (2023)

Table 3: Threshold value for solar installation

Parameters	2023		2030	
Season	High	Low	High	Low
ρ_f	0.088	0.188	0.088	0.188
$\bar{r}$	0.247	0.268	0.379	0.413

Under price regulation, storers can only emerge once prosumers have installed the maximum solar capacity ($\hat{r} < \bar{r}$). Today's and 2030's solar capacity costs satisfy $r < \bar{r}$, resulting in $K^* = \overline{K} = 23.013$. In addition, the solar and storage capacity costs must be such that $r \leq \hat{r}$ and $r_s \leq \hat{r_s}$, respectively for prosumers to invest in storage.

Today, various individual storage technologies are in development, we examine two case studies. In the first case, consumers have the option to install a stationary lithium-ion battery, like the Tesla Powerwall. The Powerwall, with a round-trip efficiency of $\lambda = 90\%$ and a maximum capacity of $\bar{S} = 13.5$ kWh (Tesla, 2019), has a levelized cost of storage (LCOS) estimated at 0.349 EU per kWh.[17] The LCOS is projected to decrease significantly, reaching 0.0514 EU per kWh by 2030 (IEA, 2020b). In the second case, consumers can opt for a solar-hydrogen storage system, such as the one offered by the German company PICEA. This system, with a total storage capacity of $\bar{S} = 20$ kWh for short-term storage, features a large-scale version for centralized hydrogen storage called PICEA+. PICEA relies on a polymer electrolyte membrane (PEM) electrolyzer with a round-trip efficiency of $\lambda = 60\%$. As of today, the levelized cost of hydrogen (LCOH) is estimated to be 0.652 EU per kWh (HPS, 2022; IEA, 2020b).[18] The projected LCOH for 2030 is estimated to be 0.0664 EU per kWh (IEA, 2020b).[19] According to IEA (2020a), the round-trip efficiency of PEM electrolyzers is expected to reach 68% by 2030.

The condition related to the solar capacity cost is consistently met; in other words, consumers always derive a positive margin from injecting their surplus solar production into the grid. However, in contrast, the condition associated with storage capacity costs is not satisfied either today or in 2030, specifically for the solar-hydrogen system during the low season (refer to Table 4 for details).

Table 4: Price regulation threshold values for storage installation

Parameters	2023				2030			
Technology	Battery		Fuel-Cell		Battery		Fuel-Cell	
Season	High	Low	High	Low	High	Low	High	Low
$\hat{r}$	0.08	0.143	0.08	0.143	0.123	0.22	0.123	0.22
$\hat{r_s}$	0.109	0.056	0.048	-0.003	0.168	0.086	0.099	0.019

This latter condition implies that the opportunity cost of injecting energy into the grid during the first period is strictly smaller than the potential gains from transferring this energy to the second period. Storers' solar production that is not consumed or injected into the grid during the first period is transferred to the second one, where it may be consumed or injected into the grid. This transferred energy allows prosumers to save money and generate revenues when climatic conditions are favorable. Prosumers only

[17] According to Selectra (2023), the cost of a Tesla Powerwall with a capacity of 13.5 kWh is estimated at 10,200 EU in France. In our analytical model, consumers never store energy from the grid, thus the total output of a 10-year lifetime Tesla Powerwall is estimated at 37,800 kWh (SkylineSolar, 2023).

[18] The current price of the PICEA system, designed to last 25 years, is estimated at 54,000 EU and can deliver about 6,000 kWh per year (PV Europe, 2018).

[19] LCOH corrected for the cost of solar energy.

decide to invest in storage when the difference between these potential gains and the opportunity cost is sufficiently large compared to the cost of installing storage capacity. In theory, a sufficiently high difference between the energy price and the FiT could make this condition hold and trigger investments in storage. However, from Lemma 1, we know that only a FiT that satisfies $\frac{r}{1+\beta\rho_f} \leq \tau \leq \frac{\beta\lambda(1-\rho_f)p-r_s}{1-\beta\lambda\rho_f}$ provides incentives to invest in storage. The left side of this equation always holds, indeed, prosumers derive a positive margin from injecting their surplus solar production into the grid.[20] Conversely, in 2023, the storage capacity cost for both batteries and the hydrogen system, in comparison to the retail energy price, is such that the right side of the condition from Lemma 1 never holds; this is also the case in 2030 during the low season (see Table 5).

Table 5: Price regulation threshold values for storage installation

Parameters	2023				2030			
Technology	Battery		Fuel-Cell		Battery		Fuel-Cell	
Season	High	Low	High	Low	High	Low	High	Low
$\frac{r}{1+\beta\rho_f}$	0.063	0.058	0.063	0.058	0.045	0.042	0.045	0.042
$\tau - d$	0.074	0.121	0.074	0.121	0.114	0.187	0.114	0.187
$\frac{\beta\lambda(1-\rho_f)p-r_s}{1-\beta\lambda\rho_f}$	-0.159	-0.16	-0.507	-0.488	0.205	0.161	0.132	0.103

At the 2030 horizon, a downward modification of the FiT, such that the right-hand side of Lemma 1 constraint is satisfied, would be sufficient to encourage prosumers to invest in the solar-hydrogen system. Conversely, with the current storage capacity costs, modifying the FiT alone would not be enough to trigger investments in storage. Today, only an upward modification of the retail energy price or a downward modification of the storage capacity cost would enable the right side of the above condition to hold and stimulate investments in individual storage capacity. To understand how energy consumption, production, and storage patterns evolve under different values of the energy retail price and the FiT, we simulate our theoretical model.

4.3.1 Energy Consumption, Sale and Storage Patterns

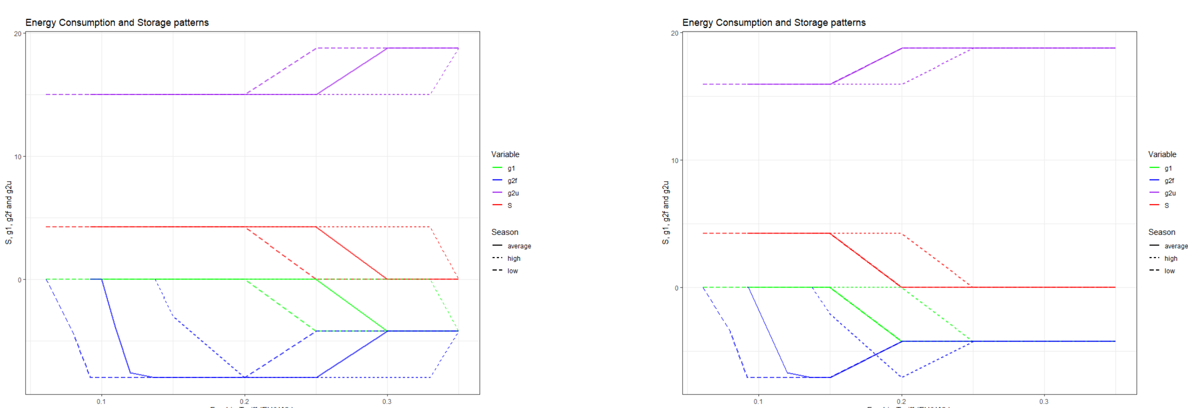
When prosumers invest in storage capacity, instead of being injected into the grid, all surplus solar production from the first period is transferred to the second one. When climatic conditions are favorable,

[20]Consumers only install storage whenever the size of the maximal solar capacity is big enough. From Lemma 1, we know that with price regulation only a FiT that satisfies the following condition $\frac{r}{1+\beta\rho_f} \leq \tau \leq \frac{\beta\lambda(1-\rho_f)p-r_s}{1-\beta\lambda\rho_f}$ provides incentives to invest in storage. A FiT such that the left side of this constraint no longer holds would imply that the marginal return of solar capacity is not enough to cover its costs.

a portion of this transferred energy is injected into the grid, with a small fraction being consumed. Consequently, the total amount of energy consumed during the second period exceeds that when prosumers do not invest in storage. When climatic conditions are unfavorable, the transferred energy is solely used for consumption. The maximum amount of energy that can be stored, representing the peak surplus solar production, is determined by the difference between two exogenous parameters: the maximum solar capacity ($\overline{K}$) and the consumer's minimal energy consumption level ($\overline{q}$). In our case study, this quantity is equal to $S^* = 4.223$ kWh.

2023 Horizon To stimulate investments in storage, the current energy retail price would need to rise by 0.3624 EU and 1.3024 EU per kWh in the case of batteries and fuel-cell technology, respectively. This would lead to a retail energy price significantly higher than the current one without the price shield implemented by the French government in 2021 (0.424 EU per kWh, according to Hello Watt (2023)). Alternatively, instead of raising the retail energy price to stimulate investments in storage, the government could consider subsidizing it. The minimum subsidy level required to meet the condition from Lemma 1 is 0.1095 EU per kWh. However, this approach would create a budget burden, as subsidies would need to be financed through non-distortionary taxes in the rest of the economy. As long as either of these strategies is pursued, the government could reduce the FiT to as low as 0.0755 EU per kWh and still encourage consumers to invest in storage. This threshold is determined by the left side of the condition from Lemma 1, which is influenced by the solar capacity cost. This suggests that the more competitive solar PV becomes, the more the government can reduce the FiT.

Figure 2: Energy Consumption and Storage Patterns 2030



Battery Technology

Fuel-Cell Technology

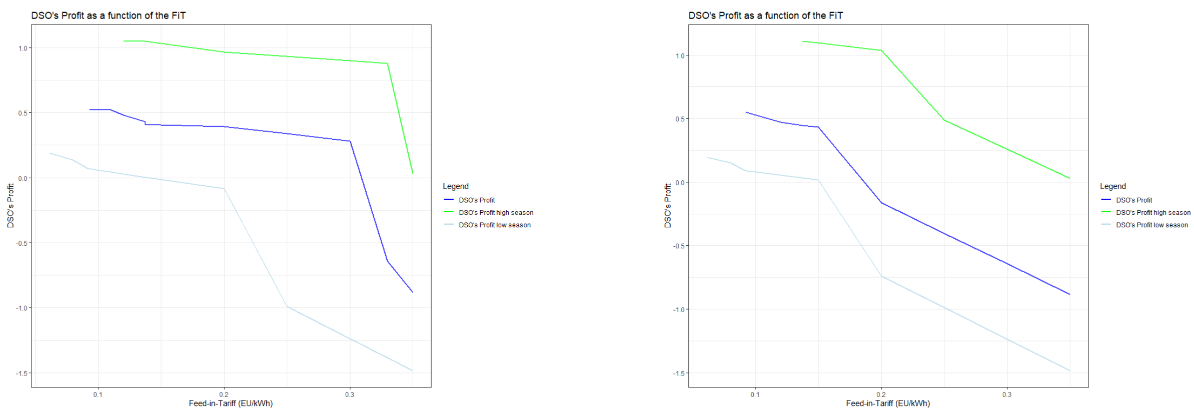
2030 Horizon Conversely, in 2030, a downward modification of the FiT would be enough to encourage prosumers to invest in storage. This is a direct consequence of the significant storage capacity cost reduction. A high FiT increases the opportunity cost of injecting energy into the grid, therefore a low FiT incites prosumers to invest in storage. Interestingly, as the FiT decreases so do the incentives to inject energy into the grid during the second period when climatic conditions are favorable (see Figure 2). Indeed, with a low FiT, the marginal utility of energy consumption is larger than the potential gains from injecting energy into the grid. Consequently, consumers consume more energy during the second period and eventually stop completely injecting energy into the grid (g_2^f progressively decreases). The minimal FiT level at which consumers invest in storage is lower during the low season, a direct consequence of the lower TURPE and more significant surplus solar production. Here, prosumers invest in storage capacity for a FiT as low as 0.093 EU per kWh, irrespective of the technology (Lemma 1). It is noteworthy that if the left side of the condition from Lemma 1 is not met, there is no solution to our optimization problem. This implies that if the FiT were to be eliminated in the future, consumers would have no incentive to invest in storage. They would remain prosumers without transitioning to storers.

4.3.2 DSO's Profits

We compute the DSO's profit as a function of the FiT, i.e., we examine the net revenues. It is as if the DSO financed the FiT; however, in practice, the government funds it via non-distortionary taxes (public funds) and ensures that the DSO always breaks even.

2023 Horizon Today, the DSO consistently operates at a loss during the low season but generates positive revenues during the high season. However, these positive profits are insufficient to offset the losses incurred during the low season. In contrast, a sufficiently high energy price that encourages consumers to invest in storage could also lead to a positive balance for the DSO. This implies that a price increase motivating consumers to store energy could establish a self-sustaining system. The price increase would generate enough revenues to fund the FiT while covering the DSO's costs, thereby reducing dependence on public funds. However, this would imply a significantly high retail energy price for consumers, particularly in the case of fuel-cell technology. Two pertinent questions arise: firstly, whether it is relevant for the government to support decentralized storage instead of centralized storage, and secondly, whether the price increase should apply to all consumers or only to prosumers. The latter question is beyond the scope of our paper. Instead, if the government chooses to subsidize the cost of storage as a means to incentivize investment in storage capacity, the DSO would not achieve a positive balance.

Figure 3: DSO's Profit 2030



Battery Technology Fuel-Cell Technology

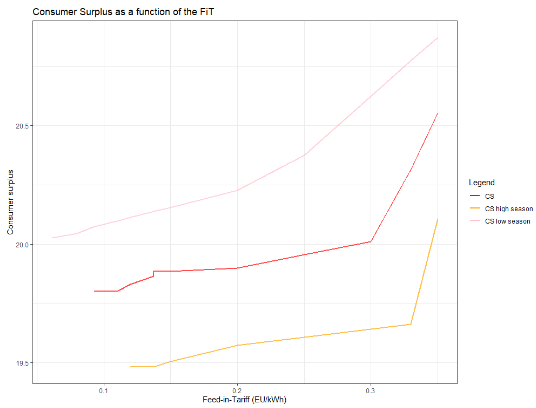
2030 Horizon Looking toward the 2030 Horizon, market conditions appear more favorable for encouraging investments in decentralized storage without distorting the retail energy price while still enabling the DSO to break even. The DSO breaks even as long as the FiT is set to encourage investments in storage (Figure 3). Once again, these positive profits suggest a self-sustaining system, where the revenues collected by the DSO are sufficient to fund the FiT without relying on public funds. Despite technological improvements, the revenues collected by the DSO are lower with the fuel-cell technology, a consequence of its lower round-trip efficiency compared to batteries.

4.3.3 Consumer Surplus

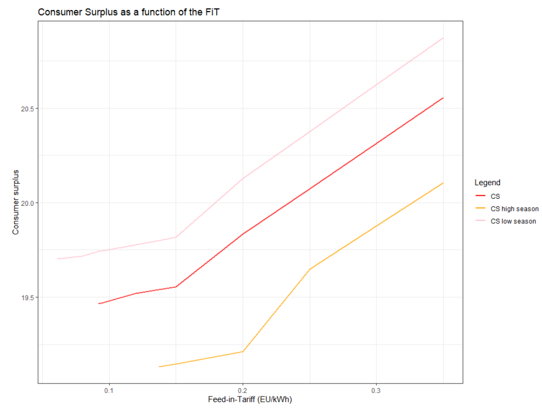
2023 Horizon Consumer surplus decreases both with the energy price and the capacity costs. Thus, if the energy retail price becomes excessively high, the savings derived from relying on stored energy rather than purchasing from the grid during the second period would no longer offset the retail energy price, resulting in a negative surplus. On the contrary, if the government opts to subsidize the storage capacity cost, consumer surplus would increase.

2030 Horizon Consumer surplus increases with the FiT (see Figure 4). As the FiT rises, so does the opportunity cost of not injecting energy into the grid. Consumers are better off when the FiT is such that they have no incentive to store energy, i.e., when it is high. This means that the economic value of storage,

Figure 4: Consumer Surplus 2030



Battery Technology



Fuel-Cell Technology

i.e., the potential savings from relying on stored energy minus the cost of storing, is not sufficiently high compared to the potential revenues from selling the surplus solar production to the grid.

4.4 Quantity-based regulation

We now consider that the government chooses a quantity-based energy regulation. Under the latter, the regulator has two policy instruments at its disposal: the storage tariff (α) and the share of grid-stored energy that prosumers can recover at a later period (λ^G). The regulator has two alternatives concerning the size of this latter parameter, either allow consumers to recover all the grid-stored energy, as observed in Brazil and Quebec, or tailor it to reflect the round-trip efficiency of a specific technology. Centralized storage benefits from scale economies, resulting in lower costs compared to decentralized storage. For instance, the 2023 LCOS for large-scale batteries is estimated at 0.27 EU per kWh (Lazard, 2023). Regarding the 2023 LCOH, as there is no available information on the performance of the PICEA+ system, we consider the same as individual hydrogen storage, namely 0.0625 EU per kWh. According to the IEA (2020b), the 2030 LCOS of large-scale batteries should reach 0.049 EU per kWh, while the LCOH of centralized hydrogen storage should reach 0.05357 EU per kWh. In our calibration, we examine four cases: $\lambda^G = 100\%$, $\lambda^G = 90\%$ (batteries), $\lambda^G = 60\%$ (fuel-cell 2023), and $\lambda^G = 68\%$ (fuel-cell 2030). The storage tariff α is initially set to 0, as France currently follows a price-based regulation.[21]

To encourage energy storage, the solar capacity cost must satisfy $r < \ddot{r}$. Given $\overline{K} = 23.013$, this condition is met with $r \leq (1 + \beta\rho_f)U'(\overline{K}) = 0.0684$. Furthermore, to incentivize energy storage, the

[21]In Quebec, a quantity-based energy regulation is in effect, allowing residential prosumers to grid-store their surplus solar production at zero cost ($\alpha = 0$).

storage tariff must be such that $\alpha < \bar{\alpha}$. In particular, consumers store energy when $\alpha = \beta\lambda^G[\rho_f U'(\overline{K} + R^*) + (1-\rho_f)p] - U'(\overline{K} - \lambda^G R^*)$, with R^* endogenous. Determining this value analytically is not possible; thus, we rely on a simulation of our representative consumer's energy consumption and storage patterns to numerically determine the storage tariff that encourages consumers to store energy.

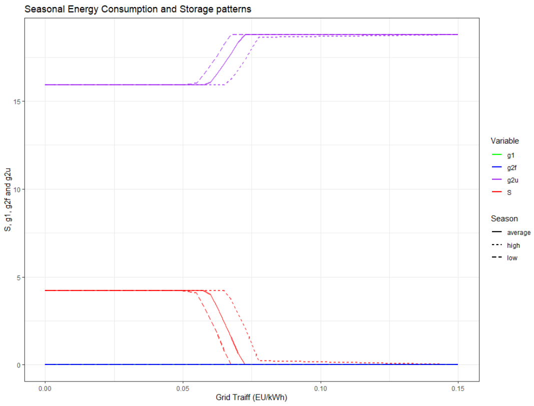
4.4.1 Energy Consumption, Sale and Storage Patterns

The quantity of grid-stored energy decreases as the storage tariff increases. The opportunity cost of transferring surplus solar production energy to the second period, rather than consuming it, rises with the storage tariff.

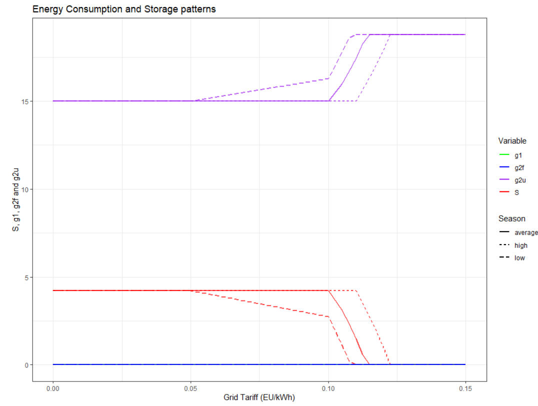
2023 Horizon Today, provided that all grid-stored energy can be recovered, a storage tariff as high as 0.12 EU per kWh would incentivize consumers to store their peak surplus solar production. In contrast, if the regulator chooses to tailor the share of energy that can be recovered from the grid to the round-trip efficiency of a specific technology, then the storage tariff that encourages consumers to grid-store their peak surplus solar production is lower. Specifically, the highest storage tariff that would encourage consumers to store their peak surplus solar production is 0.1 kWh per EU and 0.04 kWh per EU for batteries and fuel cells, respectively. These values would not cover the cost of centralized storage. Thus, if the government sets a storage tariff based on the cost of a specific technology, prosumers would have no incentive to store energy. In such a case, they would prefer to consume all their solar production during the first period.

2030 Horizon Instead, at the 2030 horizon, a storage tariff that incentivizes consumers to grid-store their peak surplus solar production would be sufficient to cover the cost of centralized storage. This outcome is influenced by the significant forecasted reduction in storage capacity costs, as well as an improved round-trip efficiency for fuel-cell technology. Like in 2023, provided that all grid-stored energy can be recovered, a storage tariff as high as 0.12 EU per kWh would incentivize consumers to store their peak surplus solar production (see Figure 5). If the regulator chooses to tailor the share of energy that can be recovered from the grid to the round-trip efficiency of a specific technology, the highest storage tariff that would encourage consumers to store their peak surplus solar production is 0.1 kWh per EU and 0.0575 kWh per EU for batteries and fuel cells, respectively (see Figure 5).

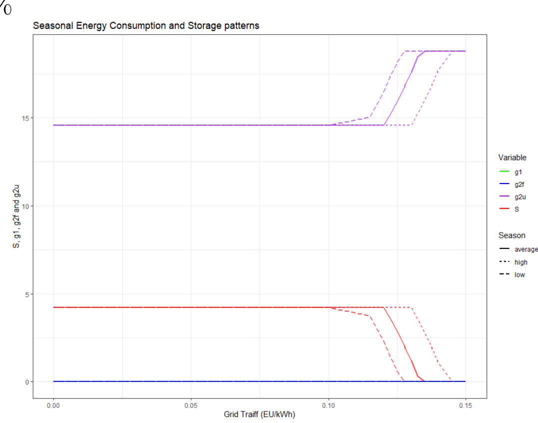
Figure 5: Energy Consumption and Storage Patterns 2030



$\lambda^G = 68\%$



$\lambda^G = 90\%$



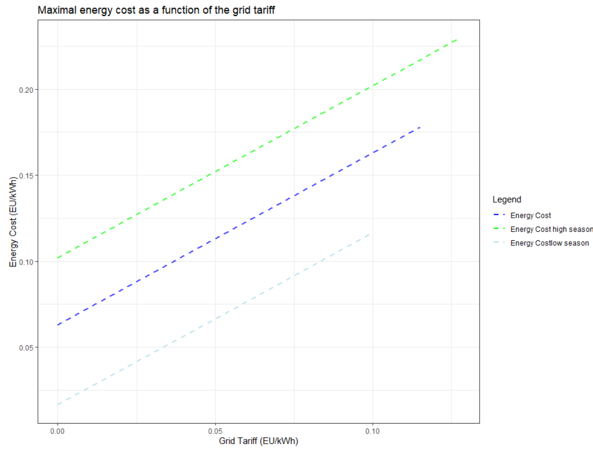
$\lambda^G = 100\%$

4.4.2 DSO's Profits

Irrespective of the share of grid-stored energy that consumers can recover during the second period, if the storage tariff does not encourage consumers to store energy, the DSO's profits remain consistently positive. In contrast, when the storage tariff encourages consumers to store energy, the DSO's profits may become negative. This is contingent on the actual cost incurred to obtain, during the second period, the energy grid stored by consumers in the first period.

2023 Horizon When the regulator allows consumers to recover all the grid-stored energy, as observed in Brazil and Quebec, the DSO's net profits hinge on the cost incurred to obtain the grid-stored energy during the second period. This cost could be linked to a specific storage technology, a non-intermittent energy source, or the wholesale market electricity price. We calculate the maximum level this cost can attain when the grid-stored energy equals consumers' peak surplus solar production, as a function of the storage tariff (see Figure 6). Presently, this maximal energy cost level is well below the LCOS of large-

Figure 6: Maximal Energy Cost such that the DSO breaks even 2023

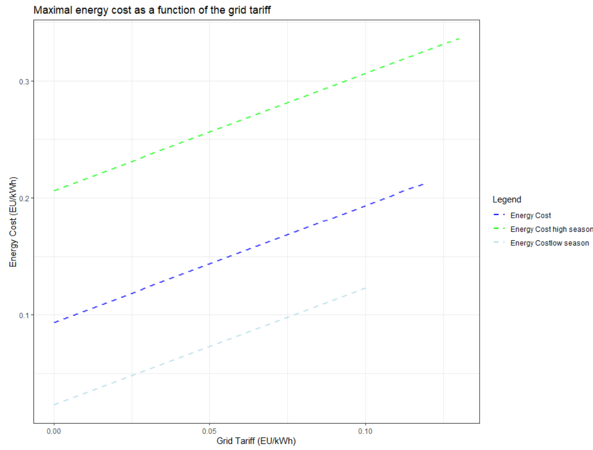


scale batteries and the LCOH of centralized hydrogen storage. Consequently, the regulator might need to explore alternative energy sources or storage technologies to recover the grid-stored energy. Options aligning with the maximal energy cost could include energy production from a gas combined cycle plant, with a LCOE evaluated at 0.064 EU per kWh, or geothermal energy at 0.075 EU per kWh (Lazard, 2023). In Quebec, where quantity regulation is in place, pumped hydro storage serves as the primary storage solution, with an LCOS evaluated at 0.018 EU per kWh. Another mature storage technology with an LCOS in line with the maximal energy cost to ensure DSO breaks even is compressed air at 0.023 EU per kWh (Storage Lab, 2023).

Alternatively, the regulator can tailor the share of grid-stored energy that can be recovered at a later period to a specific storage technology. In such a case, the DSO's net profits hinge on the gap between the storage tariff and the cost of the technology used for centralized storage. At the 2023 horizon, it becomes evident that the DSO's revenues fall short of covering either the LCOS for large-scale batteries or the LCOH for centralized hydrogen storage. Indeed, when the storage tariff encourages consumers to store energy, the DSO operates at a loss. Conversely, when consumers face a storage tariff that does not incentivize them to store energy, the DSO breaks even. As anticipated, when consumers cannot retrieve all their grid-stored energy in the second period, the gap between the highest storage tariff that motivates consumers to store their peak surplus solar production and the cost of the storage technologies is greater compared to when they can recover all grid-stored energy.

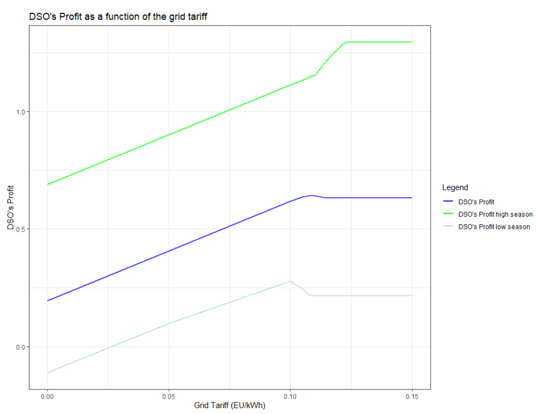
2030 Horizon In 2030, if the regulator allows consumers to recover all their grid-stored energy, the improved performance of solar production and storage technologies will present a broader range of options

Figure 7: Maximal Energy Cost such that the DSO breaks even 2030

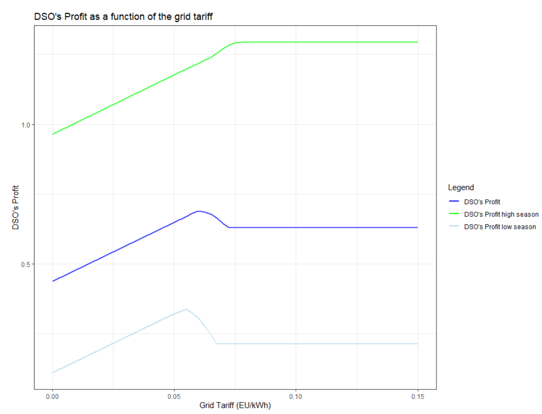


for obtaining the grid-stored energy during the second period compared to 2023 (see Figure 7). Larger-scale batteries, along with hydrogen-based systems like PICEA, would become viable alternatives.

Figure 8: DSO's Profit 2030



Battery Technology



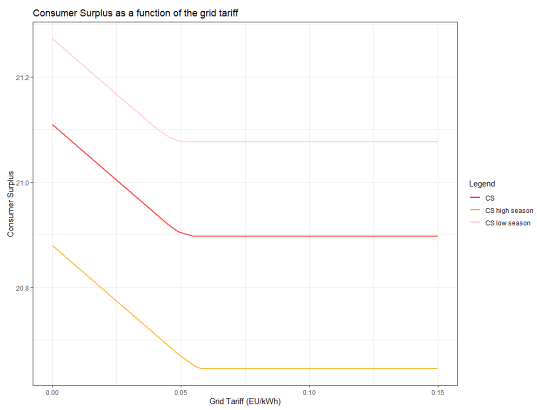
Fuel-Cell Technology

In 2030, if the regulator chooses to tailor the recoverable share of grid-stored energy to a specific storage technology—unlike in 2023— with a storage tariff encouraging consumers to grid-store energy, the DSO no longer operates at a loss (see Figure 8). This improvement is attributed to the enhanced performance of large-scale batteries and centralized hydrogen storage, enabling a storage tariff that covers the latter's cost.

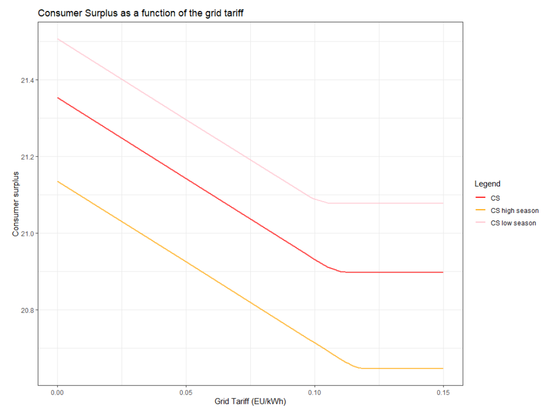
4.4.3 Consumer Surplus

Consumer surplus decreases with the storage tariff, consequently, our representative consumer is better off when the government establishes a storage tariff that encourages grid storage. Grid storage enables consumers to save money during the second period, as the grid tariff is lower than the energy price. A too-high storage tariff would instead encourage the immediate consumption of the entire surplus solar production in the initial period.

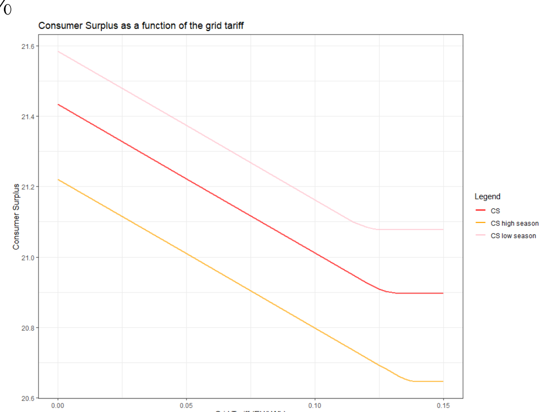
Figure 9: Consumer Surplus 2023



$\lambda^G = 60\%$



$\lambda^G = 90\%$

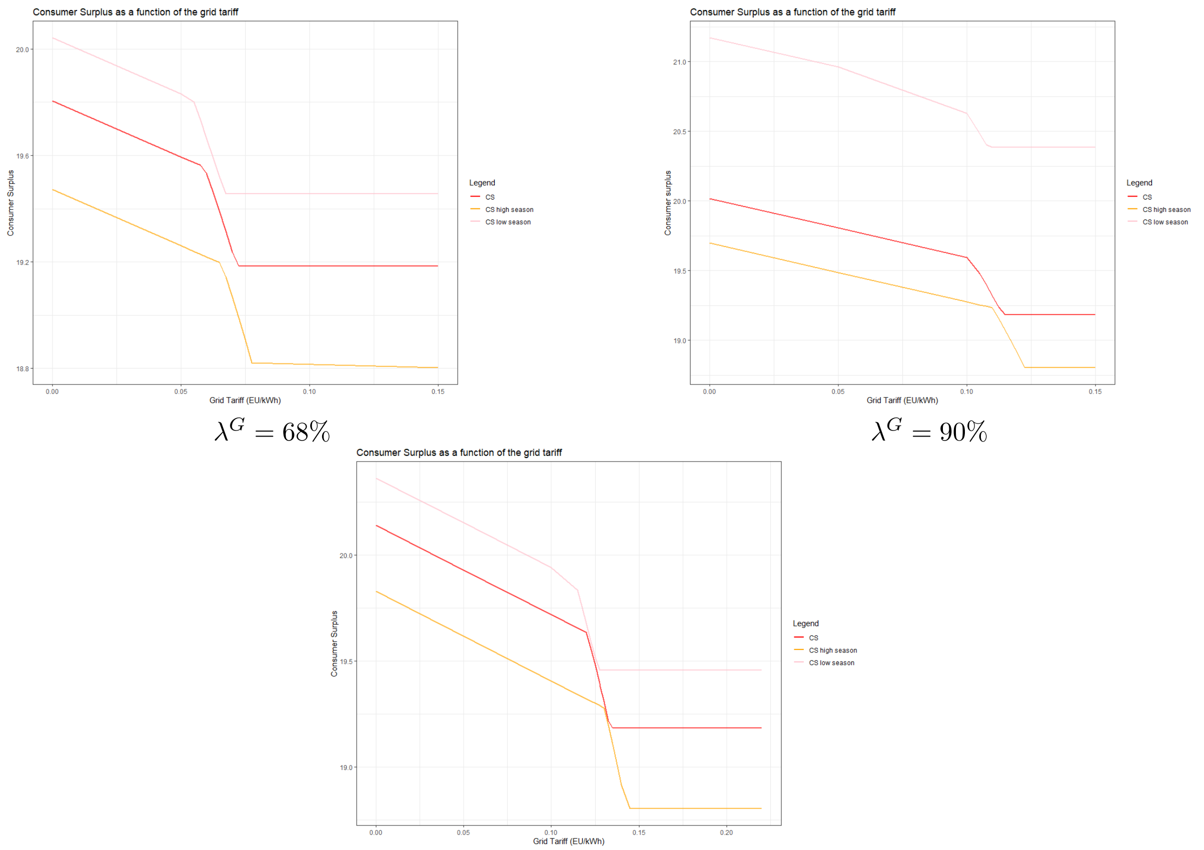


$\lambda^G = 100\%$

2023 Horizon As expected, the larger the share of grid-stored energy that consumers can retrieve during the second period, the larger the consumer surplus (see Figure 9).

2023 Horizon In 2030, we observe similar dynamics as in 2023 (see Figure 10). However, when the regulator allows consumers to retrieve all the grid stored energy, for the same storage tariff level, the consumer surplus is smaller than in 2023. This is related to the higher energy price and subscription fee compared to 2023's. This is also when the regulator chooses to tailor the share of grid-stored energy that can be recovered to the roundtrip efficiency of a specific technology if the latter remains unchanged. Indeed, although the LCOS of batteries is improved at the 2030 Horizon, at a fixed grid tariff, the consumer surplus is smaller.

Figure 10: Consumer Surplus 2030



$\lambda^G = 68\%$ $\lambda^G = 90\%$

$\lambda^G = 100\%$

4.5 Prices versus Quantities

We study how different energy regulations allowing for self-consumption could interplay on demand-side storage. The regulations differ regarding the type of policy tools available to the regulator and have different implications for the DSO. Indeed, while with quantity regulation, the policy instrument available to the regulator increases the DSO's profits, under price regulation, the policy instrument decreases the latter's revenues. In our empirical exercise, we have envisioned two possible time horizons: today and 2030. In general, we found that 2030 was a more favorable time for the deployment of storage technologies under both possible energy regulations.

Today, both regulations would present difficulties in inciting consumers to store energy due to the high storage capacity costs. With price regulation, the principal obstacle to widespread individual storage adoption is the high capacity cost compared to the retail energy price. The primary challenge lies in the fact that a simple adjustment of the FiT alone is not effective in motivating consumers to invest in storage, i.e., for the right side of the condition from Lemma 1 to be satisfied. To address this issue, the government has two main options: increase the retail energy price or subsidize the storage capacity cost to incentivize consumer investment in storage. However, both approaches come with their respective limitations. In the case of an energy price increase, concerns arise about the fairness of an overall price hike for the residential sector and the feasibility of implementing differentiated energy contracts for prosumers and consumers. As discussed in Gautier et al. (2018), the absence of differentiated energy contracts could lead to traditional residential users cross-subsidizing prosumers. This raises equity issues, particularly since wealthier households, who are more likely to install solar PV panels, would benefit more, while poorer households would bear the negative price externality without the means to address it (De Groote et al., 2016). Alternatively, subsidizing storage introduces its own set of challenges. This approach would impose a budget burden, as subsidies would need to be funded through non-distortionary taxes in the broader economy. With quantity regulation, the main challenge lies today in the fact that irrespective of the share of grid-stored energy that consumers can recover at a later period, a storage tariff designed to motivate consumer investment is inadequate to cover the cost of storing energy using larger-scale batteries or hydrogen-based solutions. Therefore, this type of regulation could only effectively encourage consumers to store and establish a self-sustaining system if more competitive production or storage technologies are employed to physically retrieve the grid-stored energy during the second period. We conclude that provided of relying on production or storage technologies more competitive than batteries or fuel cells, a quantity regulation would be a better fit to promote demand-side storage.

As of 2030, the lower bound of the condition from Lemma 1 is equal to 0.093 EU per kWh, regardless of the storage technology, while the upper bound is equal to 0.2832 for the battery and 0.1898 EU per kWh for the fuel cell. Thus, with price regulation, a FiT such that $0.093 \leq \tau \leq 0.2832$ (respectively, $0.093 \leq \tau \leq 0.1898$) would encourage consumers to invest in a battery (fuel cell). With quantity regulation, the highest storage tariff that incites consumers to store their peak surplus production differs depending on the share of energy that can be recovered from the grid. Specifically, it is equal to 0.0575 EU per kWh, 0.1 EU per kWh, and 0.12 EU per kWh, respectively for $\lambda^G = 68\%$, $\lambda^G = 90\%$, and $\lambda^G = 100\%$. Like in our analytical model, with quantity regulation, the larger the share of grid-stored energy that consumers can retrieve during the second period, the more the DSO can increase the storage tariff and still ensure that consumers store their peak surplus solar production. When the storage tariff becomes as high as 0.0725 EU per kWh, 0.115 EU per kWH, and 0.135 EU per kWh, respectively for $\lambda^G = 68\%$, $\lambda^G = 90\%$, and $\lambda^G = 100\%$, then consumers no longer store energy.

Table 6: Battery 2030 Results Peak Surplus Solar Production Stored

Regulation	Price	Quantity ($\lambda = 90\%$)	Quantity ($\lambda = 100\%$)
DSO Profit	0.521	0.618	0.695
Consumer Surplus	19.8	19.595	19.633
Welfare	20.321	19.917	20.328
Policy Instrument	$\tau = 0.093$ EU per kWh	$\alpha = 0.1$ EU per kWh	$\alpha = 0.12$ EU per kWh

Table 7: Fuel-Cell 2030 Results Peak Surplus Production Stored

Regulation	Price	Quantity ($\lambda = 68\%$)	Quantity ($\lambda = 100\%$)
DSO Profit	0.548	0.414	0.675
Consumer Surplus	19.466	19.504	19.633
Welfare	20.014	19.918	20.308
Policy Instrument	$\tau = 0.093$ EU per kWh	$\alpha = 0.0575$ EU per kWh	$\alpha = 0.12$ EU per kWh

We first compare the DSO's profits, consumer surplus, and welfare under both regulations when consumers store their peak surplus production, and the policy instruments under both regulations are set such that the DSO is the less financially constrained as possible. That is, the FiT is set at the lower bound from Lemma 1, and the storage tariff is set at the highest level which incites consumers to store their peak surplus production. Welfare is defined as the sum of the DSO net revenues and the consumer surplus. For the case $\lambda^G = 100\%$, with quantity regulation, we take as a reference the capacity costs of large-scale batteries and centralized hydrogen storage to calibrate the energy cost incurred by the DSO to obtain the grid-stored energy during the second period.

Our results are presented in Table 6 and 7, respectively for the case of batteries and fuel cells. When a fuel cell is used for decentralized storage, then consumers always prefer quantity regulation. Indeed, with quantity regulation, when able to recover all grid-stored energy, consumers need to buy less energy from the grid during the second period when climatic conditions are unfavorable, compared to price regulation. This compensates for a storage tariff beyond the capacity cost of individual hydrogen storage. Furthermore, the highest storage tariff that incites consumers to grid-store energy is below the energy price, allowing them to save money during the second period. When able to retrieve just a share of the grid-stored energy, i.e., when this parameter is tailored to a specific technology, then to incite consumers to grid-store energy, the DSO sets a storage tariff well below the capacity cost of individual hydrogen storage. Thus, in that case, consumers also save more money with a quantity regulation, compared to a price one. Instead, when a battery is used for decentralized storage, then consumers always prefer price regulation. When able to recover all grid-stored energy, consumers need to buy less energy from the grid during the second period when climatic conditions are unfavorable, compared to price regulation. However, as the round-trip efficiency of individual batteries is already quite high, this energy gain does not compensate for a storage tariff beyond the capacity cost of individual batteries. When able to retrieve just a share of the grid-stored energy, i.e., when this parameter is tailored to large-scale batteries, the highest storage tariff that incites consumers to store energy is above the capacity cost of individual batteries. The DSO is better off with quantity regulation except when hydrogen is used for centralized storage as the storage tariff that incites consumers to grid-store energy is above the DSO's costs to supply back this energy. In terms of welfare, a quantity regulation is preferred when the DSO allows consumers to retrieve all their grid-stored energy. Conversely, when the latter depends on the round-trip efficiency of a specific technology, then a price regulation is preferred.

We then compare the DSO's profits, consumer surplus, and welfare under both regulations when consumers store their peak surplus production versus when they do not store energy. Again, the policy instruments are set such that the DSO is less financially constrained as possible. That is, when consumers do not store energy the FiT is set above the upper bound of Lemma 1, and the storage tariff is set beyond the highest level which incites consumers to store their peak surplus production. The results without energy storage are presented in Table 8 and 9, respectively for the case of batteries and fuel cells.

Table 8: Battery 2030 Results No Energy Storage

Regulation	Price	Quantity ($\lambda = 90\%$ and $\lambda = 100\%$)
DSO Profit	-0.595	0.63
Consumer Surplus	20.266	19.184
Welfare	19.671	19.814
Policy Instrument	$\tau = 0.29$ EU per kWh	$\alpha = 0.115$ EU per kWh and $\alpha = 0.135$ EU per kWh

Table 9: Fuel-Cell 2030 Results No Energy Storage

Regulation	Price	Quantity ($\lambda = 68\%$ and $\lambda = 100\%$)
DSO Profit	-0.114	0.63
Consumer Surplus	19.785	19.184
Welfare	19.671	19.814
Policy Instrument	$\tau = 0.19$ EU per kWh	$\alpha = 0.0725$ EU per kWh and $\alpha = 0.135$ EU per kWh

When consumers store energy, this increases the DSO revenues with price regulation and quantity regulation when all grid energy can be recovered during the second period. With price regulation, the DSO no longer operates at a loss. Conversely, when consumers cannot recover all grid-stored energy, then the DSO is better when consumers do not store energy. This is related to the fact that although the DSO's costs are similar in both cases, the highest storage tariff that incites consumers to grid-stored energy, is lower than when the latter can recover all their grid-stored energy. Conversely, consumers are better off with price regulation when they do not store energy, and worse off with quantity regulation. Our findings regarding price regulation are in line with Durmaz et al. (2022), where installing a battery does not generate any consumer surplus gains. Notice that their case without feed-ins is mathematically similar to our quantity regulation. However, the interpretation is different as with quantity regulation consumers do feed energy into the grid. In terms of welfare, energy storage is desirable with price and quantity regulation.

In France, as of 2022, only 5% of the total 30 million individual homes were categorized as highly efficientONRE (2022). Having a minimal energy consumption level below the maximal solar production that consumers can install is a necessary condition to have stores. Thus, today our finding regarding stores would only apply to 1.5 million individual homes.

5 Conclusion

In the EU, the number of prosumers should increase following the revised Renewable Energy Directive III (2023) and rising energy prices. This calls for solutions to smooth intermittent solar production. More flexibility could be provided by energy storage via batteries and hydrogen-producing electrolyzers. According to the economic literature, there is room for demand-side storage. The latter can be either decentralized or centralized. One may wonder about the conditions under which consumers invest in solar capacity and store energy. Many energy consumption and distribution schemes now encourage investments in decentralized solar production. Each scheme has specific policy instruments and physically allows for one type of demand-side storage.

In this study, we present a stylized microeconomic model to analyze storage investment decisions by a representative consumer with either centralized (quantity regulation) or decentralized (price regulation) storage. Prosumers may become storers only when the cost of producing energy is sufficiently low, and this condition is more stringent under centralized storage. Additionally, there may be more storage under quantity regulation. We calibrate our model using data from France, considering two storage technologies: batteries and fuel cells. Consumers' preferred regulatory regime depends on the technology used for individual storage, with a preference for quantity regulation when utilizing a fuel cell and vice versa for batteries. The Distribution System Operator (DSO) is better off under quantity regulation, except in the case of centralized hydrogen storage. Thus, there is a mismatch between the prefered regimes by consumers and the DSO. Energy storage enables the DSO to avoid operating at a loss under price regulation, and welfare is higher with energy storage under both regulations.

A simplified energy market model was considered to characterize and compare demand-side storage under various schemes promoting distributed solar capacity. This leaves room for extensions of the model such as the inclusion of heterogeneous consumers. We assumed a fixed retail energy price, but other contracts could be available to consumers.

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References

Ambec, S., Crampes, C., 2019. Decarbonizing Electricity Generation with Intermittent Sources of Energy. Journal of the Association of Environmental and Resource Economists 6, 1105–1134. URL: https://ideas.repec.org/a/ucp/jaerec/doi10.1086-705536.html, doi:10.1086/705536.

Andreolli, F., D'Alpaos, C., Moretto, M., 2022. Valuing investments in domestic pv-battery systems under uncertainty. Energy Economics 106, 105721. URL: https://www.sciencedirect.com/science/article/pii/S0140988321005703, doi:https://doi.org/10.1016/j.eneco.2021.105721.

Andrés-Cerezo, D., Fabra, N., 2023. Storing power: market structure matters. RAND Journal of Economics 54, 3–53. URL: https://ideas.repec.org/a/bla/randje/v54y2023i1p3-53.html, doi:10.1111/1756-2171.12429.

Antweiler, W., 2021. Microeconomic models of electricity storage: Price forecasting, arbitrage limits, curtailment insurance, and transmission line utilization. Energy Economics 101, 105390. URL: https://www.sciencedirect.com/science/article/pii/S0140988321002899, doi:https://doi.org/10.1016/j.eneco.2021.105390.

Boampong, R., Brown, D.P., 2020. On the benefits of behind-the-meter rooftop solar and energy storage: The importance of retail rate design. Energy Economics 86, 104682. URL: https://www.sciencedirect.com/science/article/pii/S0140988320300219, doi:https://doi.org/10.1016/j.eneco.2020.104682.

Borenstein, S., 2005. The long-run efficiency of real-time electricity pricing. The Energy Journal Volume 26, 93–116. URL: https://EconPapers.repec.org/RePEc:aen:journl:2005v26-03-a05.

Borenstein, S., Bushnell, J., 2015. The us electricity industry after 20 years of restructuring. Annual Review of Economics 7, 437–463. URL: https://EconPapers.repec.org/RePEc:anr:reveco:v:7:y:2015:p:437-463.

Borenstein, S., Holland, S., 2005. On the efficiency of competitive electricity markets with timeinvariant retail prices. RAND Journal of Economics 36, 469–493. URL: https://EconPapers.repec.org/RePEc:rje:randje:v:36:y:2005:3:p:469-493.

Brown, D., Sappington, D., 2017. Designing compensation for distributed solar generation: Is net metering ever optimal? The Energy Journal Volume 38. URL: https://EconPapers.repec.org/RePEc:aen:journl:ej38-3-brown.

Butters, R.A., Dorsey, J., Gowrisankaran, G., 2021. Soaking Up the Sun: Battery Investment, Renewable Energy, and Market Equilibrium. Working Paper 29133. National Bureau of Economic Research. URL: http://www.nber.org/papers/w29133, doi:10.3386/w29133.

Cahana, M., Fabra, N., Reguant, M., Wang, 2022. The distributional impacts of real-time pricing. CEPR Discussion Paper No. DP17200. Available at SSRN. https://ssrn.com/abstract=4121375.

CGDD, 2022. Les conditions de logement des ménages résidant en France en 2020. https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2022-12/datalab_essentiel_296_conditions_logements_decembre2022_0.pdf.

CRE, 2023. TURPE 6 : feuilles de calcul. https://www.cre.fr/Pages-annexes/open-data.

Dato, P., Durmaz, T., Pommeret, A., 2020. Smart grids and renewable electricity generation by households. Energy Economics 86. URL: https://ideas.repec.org/a/eee/eneeco/v86y2020ics0140988319303007.html, doi:10.1016/j.eneco.2019.1045.

Dato, P., Durmaz, T., Pommeret, A., 2021. Feed-in tariff policy in Hong Kong: Is it efficient? City and Environment Interactions 10, 100056. URL: https://www.sciencedirect.com/science/article/pii/S2590252021000015, doi:https://doi.org/10.1016/j.cacint.2021.100056.

De Groote, O., Pepermans, G., Verboven, F., 2016. Heterogeneity in the adoption of photovoltaic systems in flanders. Energy Economics 59, 45–57. URL: https://www.sciencedirect.com/science/article/pii/S0140988316301803, doi:https://doi.org/10.1016/j.eneco.2016.07.008.

Durmaz, T., 2016. Precautionary Storage in Electricity Markets. Working Papers 2016.07. FAERE - French Association of Environmental and Resource Economists. URL: https://ideas

.repec.org/p/fae/wpaper/2016.07.html.

Durmaz, T., Pommeret, A., Ridley, I., 2022. The welfare gains for prosumers. SSRN Electronic Journal URL: http://dx.doi.org/10.2139/ssrn.4086415, doi:10.2139/ssrn.4086415.

EDF, 2023a. Comment facturer son surplus d'électricité solaire à EDF OA? https://www.edfenr.com/actualites/facturer-surplus-electricite-solaire-a-edf-oa/.

EDF, 2023b. Grille de prix de l'offre de fourniture d'électricité "Tarif Bleu". https://particulier.edf.fr/content/dam/2-Actifs/Documents/Offres/Grille_prix_Tarif_Bleu.pdf.

Elminejad, A., Havranek, T., Irsova, Z., 2022. Relative Risk Aversion: A Meta-Analysis. EconStor Preprints 260586. ZBW - Leibniz Information Centre for Economics. Leibniz. URL: https://ideas.repec.org/p/zbw/esprep/260586.html.

Enedis, 2023. TURPE 6 HTA/BT: Tarifs d'Utilisation des Réseaux Publics de Distribution d'Électricité. https://www.enedis.fr/sites/default/files/documents/pdf/enedis-essentiel-turpe6.pdf.

Engie, 2022. Kilowatt-crête (kWc) : calcul de la puissance d'un panneau solaire. https://mypower.engie.fr/energie-solaire/conseils/kilowatt-crete-kwc-calcul-de-la-puissance-d-un-panneau-solaire.html.

Engie, 2022a. Quelles dimensions choisir pour mes panneaux solaires ? https://mypower.engie.fr/energie-solaire/conseils/quelles-dimensions-choisir-pour-mes-panneaux-solaires.html.

Engie, 2022b. Tarif rachat photovoltaïque : voici les prix au 2e trimestre 2022. https://mypower.engie.fr/energie-solaire/conseils/tarif-achat-photovoltaique-rachat-electricite.html.

Fabra, N., Rapson, D., Reguant, M., Wang, J., 2021. Estimating the elasticity to real-time pricing: Evidence from the spanish electricity market. AEA Papers and Proceedings 111, 425–29. URL: https://www.aeaweb.org/articles?id=10.1257/pandp.20211007, doi:10.1257/pandp.20211007.

Gautier, A., Jacqmin, J., Poudou, J.C., 2018. The prosumers and the grid. Journal of Regulatory Economics 53, 100–126. URL: https://EconPapers.repec.org/RePEc:kap:regeco:v:53:

y:2018:i:1:d:10.1007_s11149-018-9350-5.

Gautier, A., Jacqmin, J., Poudou, J.C., 2021. Optimal grid tariffs with heterogeneous prosumers. Utilities Policy 68, 101140. URL: https://www.sciencedirect.com/science/article/pii/S0957178720301338, doi:https://doi.org/10.1016/j.jup.2020.101140.

Gährs, S., Knoefel, J., 2020. Stakeholder demands and regulatory framework for community energy storage with a focus on germany. Energy Policy 144, 111678. URL: https://www.sciencedirect.com/science/article/pii/S0301421520304079, doi:https://doi.org/10.1016/j.enpol.2020.111678.

Hello Watt, 2023. Hello watt analyse les factures d'électricité des français. https://www.hellowatt.fr/blog/facture-electricite/.

Helm, C., Mier, M., 2018. Subsidising Renewables but Taxing Storage? Second-Best Policies with Imperfect Pricing. Working Papers V-413-18. University of Oldenburg, Department of Economics. URL: https://ideas.repec.org/p/old/dpaper/413.html.

HPS, 2022. PICEA: Your Personal Energy Transition. https://www.homepowersolutions.de/wp-content/uploads/2022/11/HPS-Presentation.pdf.

IEA, 2019. Renewables 2019: Analysis and forecast to 2024.

IEA, 2020a. Batteries and hydrogen technology: keys for a clean energy future. https://www.iea.org/articles/batteries-and-hydrogen-technology-keys-for-a-clean-energy-future.

IEA, 2020b. Projected Costs of Generating Electricity 2020. Technical Report. IEA. Paris. License: CC BY 4.0.

IEA, 2022. What is behind soaring energy prices and what happens next? https://www.iea.org/commentaries/what-is-behind-soaring-energy-prices-and-what-happens-next.

IRENA, 2018. Global energy transformation: A roadmap to 2050. Technical Report. International Renewable Energy Agency, Abu Dhabi.

IRENA, 2019. Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables. Technical Report. International Renewable Energy Agency, Abu Dhabi.

JPME, 2023. Quelle est l'évolution des prix de l'électricité? https://www.jpme.fr/evolution

-prix-electricite/.

JRE-SESI, 2020. Smart metering deployment in the european union. https://ses.jrc.ec.europa.eu/smart-metering-deployment-european-union.

Karaduman, O., 2022. Economics of Grid-Scale Energy Storage in Wholesale Electricity Markets. Working paper.

Lamp, S., Samano, M., 2022. Large-scale battery storage, short-term market outcomes, and arbitrage. Energy Economics 107, 105786. URL: https://www.sciencedirect.com/science/article/pii/S0140988321006241, doi:https://doi.org/10.1016/j.eneco.2021.105786.

Lang, T., Ammann, D., Girod, B., 2016. Profitability in absence of subsidies: A techno-economic analysis of rooftop photovoltaic self-consumption in residential and commercial buildings. Renewable Energy 87, 77–87. URL: https://www.sciencedirect.com/science/article/pii/S0960148115303384, doi:https://doi.org/10.1016/j.renene.2015.09.059.

Lazard, 2023. 2023 Levelized Cost Of Energy+. file:///C:/Users/BRAVOM~1.PER/AppData/Local/Temp/lazards-lcoeplus-april-2023.pdf.

Mir-Artigues, P., del Río, P., Cerdá, E., 2018. The impact of regulation on demand-side generation. the case of spain. Energy Policy 121, 286–291. URL: https://www.sciencedirect.com/science/article/pii/S0301421518303008, doi:https://doi.org/10.1016/j.enpol.2018.05.008.

Monica Giulietti, Luigi Grossi, E.T.B., Waterson, M., 2018. Analyzing the Potential Economic Value of Energy Storage. The Energy Journal 0. URL: https://ideas.repec.org/a/aen/journl/ej39-si1-giulietti.html.

ONRE, 2022. Le parc de logements par classe de performance énergétique au 1er Janvier 2022. https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2022-07/document_travail_60_parc_logements_dpe_juillet2022.pdf.

Parra, D., Mauger, R., 2022. A new dawn for energy storage: An interdisciplinary legal and techno-economic analysis of the new eu legal framework. Energy Policy 171, 113262. URL: https://www.sciencedirect.com/science/article/pii/S0301421522004815, doi:https://doi.org/10.1016/j.enpol.2022.113262.

PV Europe, 2018. Home Power Solutions starts distribution of Picea micro fuel cell system. https://www.pveurope.eu/power2heat/home-power-solutions-starts-distribution-picea-micro-fuel-cell-system.

RTE, 2021. Bilan Électrique 2020. https://bilan-electrique-2020.rte-france.com/production-solaire/.

Schill, W.P., Zerrahn, A., Kunz, F., 2017. Prosumage of solar electricity: pros, cons, and the system perspective. Economics of Energy & Environmental Policy 6, 7–32. URL: https://www.jstor.org/stable/26189569.

Selectra, 2023. Batterie solaire : modèles, portable et prix en 2023. https://selectra.info/energie/solaire/batterie-solaire.

Sioshansi, R., Denholm, P., Jenkin, T., Weiss, J., 2009. Estimating the value of electricity storage in pjm: Arbitrage and some welfare effects. Energy Economics 31, 269–277. URL: https://www.sciencedirect.com/science/article/pii/S0140988308001631, doi:https://doi.org/10.1016/j.eneco.2008.10.005.

SkylineSolar, 2023. Tesla Powerwall Lifespan: How Long Do They Last? https://www.skylinesolar.com.au/tesla-powerwall-lifespan-how-long-do-they-last/.

Storage Lab, 2023. Projecting the future lifetime cost of electricity storage technologies. https://www.storage-lab.com/levelized-cost-of-storage.

Tesla, 2019. Powerwall. https://www.tesla.com/sites/default/files/pdfs/powerwall/Powerwall%202_AC_Datasheet_en_AU.pdf.

Zakeri, B., Gissey, G.C., Dodds, P.E., Subkhankulova, D., 2021. Centralized vs. distributed energy storage – benefits for residential users. Energy 236, 121443. URL: https://www.sciencedirect.com/science/article/pii/S0360544221016911, doi:https://doi.org/10.1016/j.energy.2021.121443.

A Appendix

A.1 Price regulation

The Lagrangian of the consumer's problem is:

$$\mathcal{L}(.) = U(K - S + g_1) - \phi_1 g_1 + \beta\Big(\rho_f[U(K + \lambda S + g_2^f) - \phi_2^f g_2^f] + (1-\rho_f)[U(\lambda S + g_2^u) - \phi_2^u g_2^u]\Big)$$
$$-r_s S - rK - A + \eta_1(\bar{K} - K) + \eta_2 K + \eta_3(\bar{S} - S) + \eta_4 S$$

This yields to the following first order conditions:

$$\frac{\partial \mathcal{L}(.)}{\partial K} = U'(K - S + g_1) + \beta\rho_f U'(K + \lambda S + g_2^f) - r - \eta_1 + \eta_2 = 0 \quad (1)$$

$$\frac{\partial \mathcal{L}(.)}{\partial S} = -U'(K - S + g_1) + \beta\lambda[\rho_f U'(K + \lambda S + g_2^f) + (1-\rho_f)U'(\lambda S + g_2^u)] - r_s - \eta_3 + \eta_4 = 0 \quad (2)$$

$$\frac{\partial \mathcal{L}(.)}{\partial g_1} = U'(K - S + g_1) - \phi_1 = 0 \quad (3)$$

$$\frac{\partial \mathcal{L}(.)}{\partial g_2^f} = \beta\rho_f[U'(K + \lambda S + g_2^f) - \phi_2^f] = 0 \quad (4)$$

$$\frac{\partial \mathcal{L}(.)}{\partial g_2^u} = \beta(1-\rho_f)[U'(\lambda S + g_2^u) - \phi_2^u] = 0 \quad (5)$$

plus the complementary slackness conditions.

Case 1 Assume that $g_1^* \geq 0$, $g_2^{f*} \geq 0$ and $g_2^{u*} \geq 0$. From (3), (4) and (5) we have:

$$p = U'(K - S + g_1^*) = U'(K + \lambda S + g_2^{f*}) = U'(\lambda S + g_2^{u*})$$

Combining (1), (3), and (4) we obtain:

$$(1 + \beta\rho_f)p - r - \eta_1 + \eta_2 = 0$$

Combining (2), (3), (4) and (5) we obtain:

$$\eta_4 - \eta_3 - (1 - \beta\lambda)p - r_s = 0$$

we define the threshold value $\bar{r} = (1 + \beta\rho_f)p$.

Notice that, if $S > 0$, then $\eta_3 = -(1 - \beta\lambda)p - r_s < 0$ which is not possible. As a result, we have $S = 0$. Thus, there are three possible solutions:

- **No investment equilibrium**: $K^* = 0$ (and $S^* = 0$) is solution when $\eta_2 = r - (1 + \beta\rho_f)p > 0$. This is the case when the solar capacity cost is $r > \bar{r}$.
- **Partial solar investment equilibrium**: $K^* \in]0; \bar{K}[$ (and $S^* = 0$) is solution when $r - (1+\beta\rho_f)p = 0$, that is when $r = \bar{r}$. It implies that $U'(K^*) \geq p$ given that $U'(.)$ is decreasing.
- **Maximal solar investment equilibrium**: $K^* = \bar{K} > 0$ (and $S^* = 0$) is solution when $\eta_1 = (1 + \beta\rho_f)p - r > 0$, that is when $r < \bar{r}$. It implies that $U'(\bar{K}) \geq p$ given that $U'(.)$ is decreasing.

Case 2 Assume that $g_1^* < 0$, $g_2^{f*} < 0$ and $g_2^{u*} \geq 0$. From (3), (4) and (5) we have:

$$\tau = U'(K + g_1^* - S) = U'(K + \lambda S + g_2^{f*}), \quad \text{and} \quad p = U'(\lambda S + g_2^{u*})$$

Combining (1), (3), and (4) we obtain:

$$(1 + \beta\rho_f)\tau - r - \eta_1 + \eta_2 = 0$$

We know that $\eta_2 = 0$ (K must be positive when $g_1^* < 0$ and $g_2^{f*} < 0$), so a solution with $g_1^* < 0$ and $g_2^{f*} < 0$ is possible if and only if $(1 + \beta\rho_f)\tau - r \geq 0$, implying that $K^* = \bar{K}$.

Combining (2), (3), (4) and (5) we obtain:

$$\eta_4 - \eta_3 - \tau + \beta\lambda(\rho_f\tau + (1 - \rho_f)p) - r_s = 0$$

Let us define the threshold value $\hat{r_s} = \beta\lambda(1 - \rho_f)p - (1 - \beta\lambda\rho_f)\tau$. When $r \leq \hat{r} = (1 + \beta\rho_f)\tau$, the possible solutions with $g_1^* < 0$, $g_2^{f*} < 0$, $g_2^{u*} \geq 0$, and $K = \bar{K}$ are :

- **No storage**: $S^* = 0$ is solution when the storage cost is $r_s > \hat{r_s}$.
- **Partial storage**: $S^* \in]0; \bar{S}[$ is solution when $r_s = \hat{r_s}$.
- **Maximal storage**: $S^* = \bar{S} > 0$ is solution when $r_s < \hat{r_s}$.

As shown below, note that all the remaining cases on the values of g_1^*, g_2^{f*} and g_2^{u*} cannot be solution.

Case 3 Assume that $g_1^* < 0$, $g_2^{f*} \geq 0$ and $g_2^{u*} \geq 0$. From (3), (4) and (5) we now have:

$$\tau = U'(K - S + g_1^*) \quad \text{and} \quad p = U'(K + \lambda S + g_2^{f*}) = U'(\lambda S + g_2^{u*})$$

Notice that the above equations imply that $\tau > p$, which is a contradiction as $U'(.)$ is decreasing. This case cannot be a solution.

Case 4 Assume that $g_1^* < 0$, $g_2^{f*} < 0$ and $g_2^{u*} < 0$. From (3), (4) and (5) we have:

$$\tau = U'(K - S + g_1^*) = U'(K + \lambda S + g_2^{f*}) = U'(\lambda S + g_2^{u*})$$

Notice that if $S = 0$ at $t = 2$ when $i = u$, we have $U'(0) = +\infty$ which is not possible. Also, if $S > 0$ we have $\eta_3 = -(1 - \beta\lambda)(\tau) - r_s < 0$ which is not possible. Thus, this case cannot be solution to the consumer problem.

Case 5 Assume that $g_1^* \geq 0$, $g_2^{f*} < 0$ and $g_2^{u*} < 0$. From (3), (4) and (5) we have:

$$p = U'(K - S + g_1^*) \quad \text{and} \quad \tau = U'(K + \lambda S + g_2^{f*}) = U'(\lambda S + g_2^{u*})$$

Notice that if $S = 0$ at $t = 2$ when $i = u$, we have $U'(0) = +\infty$ which is not possible. Also, if $S > 0$ we have $\eta_3 = -p + \beta\lambda\tau - r_s < 0$ which is not possible. Thus, this case cannot be solution to the consumer problem.

Case 6 Assume that $g_1^* \geq 0$, $g_2^{f*} \geq 0$ and $g_2^{u*} < 0$. From(3), (4) and (5) we have:

$$p = U'(K - S + g_1^*) = U'(K + \lambda S + g_2^{f*}) \quad \text{and} \quad \tau = U'(\lambda S + g_2^{u*})$$

Notice that if $S = 0$ at $t = 2$ when $i = u$, we have $U'(0) = +\infty$ which is not possible. Also, notice that the above equations imply that $\tau > p$, we have a contradiction as $U'(.)$ is decreasing and $K + \lambda S + g_2^{f*} > \lambda S + g_2^{u*}$. This case cannot be a solution.

Case 7 Let us consider that $g_1^* \geq 0$, $g_2^{f*} < 0$ and $g_2^{u*} \leq 0$. From (3), (4) and (5) we have:

$$p = U'(K - S + g_1^{f*}) = U'(\lambda S + g_2^{u*}) \quad \text{and} \quad \tau = U'(K + \lambda S + g_2^{f*})$$

Notice that if $S = 0$, then the above equations imply that $(1-\psi)p > p$ as $U'(.)$ is decreasing and $K + g_1^* > K + g_2^{f*}$ we have a contradiction. Otherwise, if $S > 0$ we have $\eta_3 = -(1-\beta\lambda(1-\rho_f))p + \beta\lambda(1-\rho_f)\tau - r_s < 0$ which is not possible. Thus, this case cannot be a solution.

Case 8 Let us consider that $g_1^* < 0$, $g_2^{f*} \geq 0$ and $g_2^{u*} < 0$. From (3), (4) and (5) we have:

$$\tau = U'(K - S + g_1^*) = U'(\lambda S + g_2^{u*}) \quad \text{and} \quad p = U'(K + \lambda S + g_2^{f*})$$

Notice that the above equations imply that that $\tau > p$, we have a contradiction as $U'(.)$ is decreasing and $K + \lambda S + g_2^{f*} > K - S - g_1^*$. Thus, this case cannot be solution to the consumer problem.

A.2 Quantity regulation

The Lagrangian of the consumer's problem is:

$$\begin{aligned}\mathcal{L}(.) = U(K - R + g_1) - pg_1 + \beta\rho_f[U(K + \lambda^G R + g_2^f) - pg_2^f] + \beta(1-\rho_f)[U(\lambda^G R + g_2^u) - pg_2^u] \\ -\alpha R - rK - A - \mu_1(K - \bar{K}) + \mu_2 K + \mu_3 R + \mu_4 g_1 + \mu_5 g_2^f + \mu_6 g_2^u\end{aligned}$$

This yields to the following first order conditions:

$$\frac{\partial \mathcal{L}(.)}{\partial K} = U'(K - R + g_1) + \beta\rho_f U'(K + \lambda^G R + g_2^f) - r - \mu_1 + \mu_2 = 0 \tag{6}$$

$$\frac{\partial \mathcal{L}(.)}{\partial R} = -U'(K - R + g_1) + \beta\lambda^G[\rho_f U'(K + \lambda^G R + g_2^f) + (1-\rho_f)U'(\lambda^G R + g_2^u)] - \alpha + \mu_3 = 0 \tag{7}$$

$$\frac{\partial \mathcal{L}(.)}{\partial g_1} = U'(K - R + g_1) - p + \mu_4 = 0 \tag{8}$$

$$\frac{\partial \mathcal{L}(.)}{\partial g_2^f} = \beta\rho_f[U'(K + \lambda^G R + g_2^f) - p] + \mu_5 = 0 \tag{9}$$

$$\frac{\partial \mathcal{L}(.)}{\partial g_2^u} = \beta(1-\rho_f)[U'(\lambda^G R + g_2^u) - p] + \mu_6 = 0 \tag{10}$$

plus the complementary slackness conditions.

Case 1 Assume that $g_1^* > 0$, $g_2^{f*} > 0$ and $g_2^{u*} > 0$ ($\mu_4 = \mu_5 = \mu_6 = 0$), from (8), (9) and (10) we have:

$$p = U'(K - R + g_1^*) = U'(K + \lambda^G R + g_2^{f*}) = U'(\lambda^G R + g_2^{u*})$$

Combining (6), (8), and (9) we obtain:

$$(1 + \beta\rho_f)p - r - \mu_1 + \mu_2 = 0$$

Combining (7), (8), (9) and (10) we obtain:

$$\mu_3 = (1 - \beta\lambda^G)p + \alpha > 0$$

Equation $\mu_3 = (1 - \beta\lambda^G)p + \alpha > 0$ implies that $R^* = 0$. Thus, there are three possible solutions:

- **No investment equilibrium**: $K^* = 0$ and $R^* = 0$ is solution when $\mu_2 = r - (1 + \beta\rho_f)p > 0$, that is when the solar capacity cost is $r > \bar{r}(= (1 + \beta\rho_f)p)$.
- **Partial solar investment equilibrium**: $K^* \in]0; \bar{K}[$ and $R^* = 0$ is solution when $r - (1 + \beta\rho_f)p = 0$, that is when $r = \bar{r}$. It implies that $U'(K^*) \geq p$ given that $U'(.)$ is decreasing.
- **Maximal solar investment equilibrium**: $K^* = \bar{K} > 0$ and $R^* = 0$ is solution when $\mu_1 = (1 + \beta\rho_f)p - r > 0$, that is when $r < \bar{r}$. It implies that $U'(\bar{K}) \geq p$ given that $U'(.)$ is decreasing.

Case 2 Let us consider $g_1^* = g_2^{f*} = 0$ and $g_2^{u*} > 0$, we have $K > 0$ (if $K = 0$, $U'(0) = \infty$ at $t = 1$ which is not possible) and from (8), (9) and (10) :

$$p > U'(K - R), \quad p > U'(K + \lambda^G R) \quad \text{and} \quad p = U'(\lambda^G R + g_2^{u*})$$

Combining (6), (8), and (9) we obtain:

$$(1 + \beta\rho_f)U'(K) - r - \mu_1 = 0$$

A solution with $g_1^* = 0$ and $g_2^{f*} = 0$ is possible if and only if $(1+\beta\rho_f)U'(K) - r \geq 0$, implying that $K^* = \bar{K}$. Also, note that $(1+\beta\rho_f)U'(\bar{K}) = r$ implies that $U'(\bar{K}-R) + \beta\rho_f U'(\bar{K}+\lambda^G R) > r$, $\forall\ R > 0$. Combining (7), (8), (9) and (10) we obtain:

$$\mu_3 = \alpha + U'(\bar{K}-R) - \lambda^G\beta[\rho_f U'(\bar{K}+\lambda^G R) + (1-\rho_f)p]$$

Let us define $\bar{\alpha} = \beta\lambda^G[\rho_f U'(\bar{K}) + (1-\rho_f)p] - U'(\bar{K})$.

When $r \leq \ddot{r} \equiv (1+\beta\rho_f)U'(\bar{K})$, the possible solutions with $g_1^* = g_2^{f*} = 0$, $g_2^{u*} \geq 0$, and $K = \bar{K}$ are :

- **No storage**: $R^* = 0$ is solution when the storage cost is $\alpha > \bar{\alpha}$.

- **Storage**: when $\alpha \leq \bar{\alpha}$, $R^* > 0$ is solution and verifies

$$\alpha + U'(\bar{K}-R^*) - \beta\lambda^G[\rho_f U'(\bar{K}+\lambda^G R^*) + (1-\rho_f)p] = 0$$

As shown below, note that all the remaining cases on the values of g_1^*, g_2^{f*} and g_2^{u*} cannot be solution.

Case 3 Let us consider $g_1^* = 0$, $g_2^{f*} > 0$ and $g_2^{u*} > 0$, from (8), (9) and (10) we have:

$$p > U'(K-R) \quad \text{and} \quad p = U'(K+\lambda^G R + g_2^{f*}) = U'(\lambda^G R + g_2^{u*})$$

Notice that the above equations imply that $K - R > K + \lambda^G R + g_2^{f*}$ and given that $U'(.)$ is decreasing we have a contradiction. Thus, this case cannot be solution to the consumer problem.

Case 4 Let us consider $g_1 = g_2^f = g_2^u = 0$ $(\mu_4 > 0, \mu_5 > 0, \mu_6 > 0)$, from (8), (9) and (10) we have:

$$p > U'(K-R), \quad p > U'(K+\lambda^G R) \quad \text{and} \quad p > U'(\lambda^G R)$$

Notice that if $R = 0$ at $t = 2$ when $i = u$, we have $U'(0) = +\infty$ which is not possible. Also, if $R > 0$, then $\alpha + U'(K-R) - \lambda^G[\rho_f U'(K+\lambda^G R) + (1-\rho_f)U'(\lambda^G R)] = 0$, which implies that $\alpha + U'(K-R) - \lambda^G[\rho_f U'(K+\lambda^G R) + (1-\rho_f)p] < 0$ which is not possible. This case cannot be solution to the consumer problem.

Case 5 Let us consider $g_1 > 0$ and $g_2^f = g_2^u = 0$ ($\mu_4 = 0, \mu_5 > 0, \mu_6 > 0$), from (8), (9) and (10) we have:

$$p = U'(K - R + g_1), \quad p > U'(K + \lambda^G R) \quad \text{and} \quad p > U'(\lambda^G R)$$

We know that $p > U'(\lambda^G R) > U'(K + \lambda^G R)$, and $\lambda \in [0; 1]$, then $\mu_3 = \alpha + p - \lambda^{GS}[\rho_f U'(K + \lambda^G R) + (1 - \rho_f)U'(\lambda^G R)] > 0$ and we have *R=0*. This implies that at $t = 2$ when $i = u$, we have $U'(0) = +\infty$ which is not possible. Thus, this case cannot be solution to the consumer problem.

Case 6 Let us consider $g_1 > 0$, $g_2^f > 0$ and $g_2^u = 0$ ($\mu_4 = \mu_5 = 0, \mu_6 > 0$), from (8), (9) and (10) we have:

$$p = U'(K - R + g_1) = U'(\lambda^G R + g_2^u) \quad \text{and} \quad p > U'(K + \lambda^G R)$$

Notice that the above equations imply that $\lambda^G R > K + \lambda^G R + g_2^f$ and given that $U'(.)$ is decreasing we have a contradiction. Thus, this case cannot be solution to the consumer problem.

Case 7 Let us consider $g_1 > 0$, $g_2^f = 0$ and $g_2^u > 0$ ($\mu_4 = \mu_6 = 0, \mu_5 > 0$), from (8), (9) and (10) we have:

$$p = U'(K - R + g_1) = U'(\lambda^G R + g_2^u) \quad \text{and} \quad p > U'(K + \lambda^G R)$$

We know that $p > U'(K + \lambda^G R)$, then $\mu_3 = \alpha + p(1 - \lambda^G) + \lambda^G \rho_f (p - U'(K + \lambda^G R)) > 0$ and we have $R = 0$. This result implies that $K > K + g_1$ and given that $U'(.)$ is decreasing we have a contradiction. Thus, this case cannot be solution to the consumer problem.

Case 8 Let us consider If $g_1 = 0$, $g_2^f > 0$ and $g_2^u = 0$ ($\mu_4 > 0, \mu_5 = 0, \mu_6 > 0$), from (8), (9) and (10) we have:

$$p > U'(K - R), p = U'(K + \lambda^G R + g_2^f) \quad \text{and} \quad p > U'(\lambda^G R)$$

Notice that the above equations imply that that $K - R > K + \lambda^G R + g_2^f$ and given that $U'(.)$ is decreasing we have a contradiction. Thus, this case cannot be solution to the consumer problem.

A.3 First Best

A.3.1 Price regulation

The Lagrangian of the social surplus writes:

$$U(K-S+g_1)-cg_1+\beta\Big(\rho_f[U(K+\lambda S+g_2^f)-cg_2^f]+(1-\rho_f)[U(\lambda S+g_2^u)-cg_2^u]\Big)$$
$$-r_sS-rK-A+\eta_1(\bar{K}-K)+\eta_2K+\eta_3(\bar{S}-S)+\eta_4S$$

This yields to the following first order conditions:

$$\frac{\partial\mathcal{L}(.)}{\partial K}=U'(K-S+g_1)+\beta\rho_fU'(K+\lambda S+g_2^f)-r-\eta_1+\eta_2=0 \tag{11}$$

$$\frac{\partial\mathcal{L}(.)}{\partial S}=-U'(K-S+g_1)+\beta\lambda[\rho_fU'(K+\lambda S+g_2^f)+(1-\rho_f)U'(\lambda S+g_2^u)]-r_s-\eta_3+\eta_4=0 \tag{12}$$

$$\frac{\partial\mathcal{L}(.)}{\partial g_1}=U'(K-S+g_1)-c=0 \tag{13}$$

$$\frac{\partial\mathcal{L}(.)}{\partial g_2^f}=\beta\rho_f[U'(K+\lambda S+g_2^f)-c]=0 \tag{14}$$

$$\frac{\partial\mathcal{L}(.)}{\partial g_2^u}=\beta(1-\rho_f)[U'(\lambda S+g_2^u)-c]=0 \tag{15}$$

plus the complementary slackness conditions.

Assume that $g_1^*\geq 0$, $g_2^{f*}\geq 0$ and $g_2^{u*}\geq 0$. From (13), (14) and (15) we have:

$$c=U'(K-S+g_1^*)=U'(K+\lambda S+g_2^{f*})=U'(\lambda S+g_2^{u*})$$

Combining (11), (13), and (14) we obtain:

$$(1+\beta\rho_f)c-r-\eta_1+\eta_2=0$$

Combining (12), (13), (14) and (15) we obtain:

$$\eta_4-\eta_3-(1-\beta\lambda)c-r_s=0$$

we define the threshold value $r^* = (1 + \beta\rho_f)c$.

Notice that, if $S > 0$, then $\eta_3 = -(1 - \beta\lambda)c - r_s < 0$ which is not possible. As a result, we have $S = 0$. Thus, there are three possible solutions:

- **No investment equilibrium**: $K^* = 0$ (and $S^* = 0$) is solution when $\eta_2 = r - (1 + \beta\rho_f)c > 0$.
- **Partial solar investment equilibrium**: $K^* \in]0; \bar{K}[$ (and $S^* = 0$) is solution when $r-(1+\beta\rho_f)c = 0$, that is when $r = r^*$.
- **Maximal solar investment equilibrium**: $K^* = \bar{K} > 0$ (and $S^* = 0$) is solution when $r < r^*$.

Lets now study if storage can be an optimal solution. Assume that $g_1^* < 0$, $g_2^{f*} < 0$ and $g_2^{u*} \geq 0$. From (13), (14) and (15) we have:

$$c = U'(K + g_1^* - S) = U'(K + \lambda S + g_2^{f*}) = U'(\lambda S + g_2^{u*})$$

Combining (11), (13), and (14) we obtain:

$$(1 + \beta\rho_f)c - r - \eta_1 + \eta_2 = 0$$

We know that $\eta_2 = 0$ (K must be positive when $g_1^* < 0$ and $g_2^{f*} < 0$), so a solution with $g_1^* < 0$ and $g_2^{f*} < 0$ is possible if and only if $(1 + \beta\rho_f)c - r \geq 0$, implying that $K^* = \bar{K}$.

Combining (12), (13), (14) and (15) we obtain:

$$\eta_4 - \eta_3 - c(1 + \beta\lambda) - r_s = 0$$

A solution with $S > 0$ ($\eta_4 = 0$) is not possible. A positive storage cannot be solution.

A.3.2 Quantity regulation

The Lagrangian of the social surplus problem is:

$$\begin{aligned}\mathcal{L}(.) = U(K - R + g_1) - cg_1 + \beta\rho_f[U(K + \lambda^G R + g_2^f) - cg_2^f] + \beta(1 - \rho_f)[U(\lambda^G R + g_2^u) - cg_2^u] \\ -c(1 + \beta\lambda^G)R - \alpha_G R - rK - A - \mu_1(K - \bar{K}) + \mu_2 K + \mu_3 R + \mu_4 g_1 + \mu_5 g_2^f + \mu_6 g_2^u\end{aligned}$$

This yields to the following first order conditions:

$$\frac{\partial \mathcal{L}(.)}{\partial K} = U'(K - R + g_1) + \beta\rho_f U'(K + \lambda^G R + g_2^f) - r - \mu_1 + \mu_2 = 0 \quad (16)$$

$$\frac{\partial \mathcal{L}(.)}{\partial R} = -U'(K - R + g_1) + \beta\lambda^G[\rho_f U'(K + \lambda^G R + g_2^f) + (1 - \rho_f)U'(\lambda^G R + g_2^u)] \\ -c(1 + \beta\lambda^G)R - \alpha_G + \mu_3 = 0 \quad (17)$$

$$\frac{\partial \mathcal{L}(.)}{\partial g_1} = U'(K - R + g_1) - c + \mu_4 = 0 \quad (18)$$

$$\frac{\partial \mathcal{L}(.)}{\partial g_2^f} = \beta\rho_f[U'(K + \lambda^G R + g_2^f) - c] + \mu_5 = 0 \quad (19)$$

$$\frac{\partial \mathcal{L}(.)}{\partial g_2^u} = \beta(1 - \rho_f)[U'(\lambda^G R + g_2^u) - c] + \mu_6 = 0 \quad (20)$$

plus the complementary slackness conditions.

Assume that $g_1^* > 0$, $g_2^{f*} > 0$ and $g_2^{u*} > 0$ ($\mu_4 = \mu_5 = \mu_6 = 0$), from (18), (19) and (20) we have:

$$c = U'(K - R + g_1^*) = U'(K + \lambda^G R + g_2^{f*}) = U'(\lambda^G R + g_2^{u*})$$

Combining (16), (18), and (19) we obtain:

$$(1 + \beta\rho_f)c - r - \mu_1 + \mu_2 = 0$$

Combining (18), (18), (19) and (20) we obtain:

$$\mu_3 = (1 - \beta\lambda^G)c + c(1 + \lambda^G R)\alpha_G > 0$$

The second equation implies that $R^* = 0$. Thus, there are three possible solutions:

- **No investment equilibrium**: $K^* = 0$ and $R^* = 0$ is solution when $\mu_2 = r - (1 + \beta\rho_f)c > 0$, that is when the solar capacity cost is $r > r^*(= (1 + \beta\rho_f)c)$.
- **Partial solar investment equilibrium**: $K^* \in]0; \bar{K}[$ and $R^* = 0$ is solution when $r = \bar{r}$.

- **Maximal solar investment equilibrium**: $K^* = \bar{K} > 0$ and $R^* = 0$ is solution when $r < \bar{r}$.

Lets now study if storage can be an optimal solution. Let us consider $g_1^* = g_2^{f*} = 0$ and $g_2^{u*} > 0$, we have $K > 0$ and from (18), (19) and (20) :

$$c > U'(K - R), \quad c > U'(K + \lambda^G R) \quad \text{and} \quad c = U'(\lambda^G R + g_2^{u*})$$

Combining (16), (18), and (19) we obtain:

$$(1 + \beta\rho_f)U'(K) - r - \mu_1 = 0$$

A solution with $g_1^* = 0$ and $g_2^{f*} = 0$ is possible if and only if $(1 + \beta\rho_f)U'(K) - r \geq 0$, implying that $K^* = \bar{K}$. Combining (18), (18), (19) and (20) we obtain:

$$\mu_3 = \alpha_G + c(1 + \beta\rho_f\lambda^G) + U'(\bar{K} - R) - \lambda^G\beta\rho_f U'(\bar{K} + \lambda^G R) > 0$$

implying that $R^* = 0$. A positive storage cannot be solution.