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Abstract

The number of prosumers -consumers equipped with decentralized production- is expected to increase following the revised Renewable Energy Directive (2018/2001) and the rising energy prices. The economic literature suggests there is room for demand-side storage that can take two forms: decentralized or centralized. The schemes promoting investments in solar capacity physically allow for only one type of demand-side storage. One may wonder about the conditions under which consumers invest in different technologies. We build a stylized microeconomic model of the energy market and perform a numerical evaluation, using publicly available data from France, to compare two regulations—price and quantity—from our representative consumer's and the Distributed System Operator's points of view. The two energy regulations lead to three types of profiles: consumers, prosumers, and storers. These profiles are in line with previous studies focusing on price regulation. With quantity regulation, a grid tariff such that consumers invest in storage depends on endogenous parameters. The results suggest that with the current price regulation in France, only a smaller feed-in-tariff would encourage investments in decentralized hydrogen-based storage. A grid tariff such that consumers inject energy into the grid would not reflect the cost of centralized hydrogen-based storage. However, a quantity regulation would be less costly to support.

JEL Classification: D15, D24, Q41, Q42, L94

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1 Introduction

Over the past decade, the cost of solar photovoltaic (PV) rooftop panels has significantly declined.[1] This cost reduction has translated into massive investments in decentralized solar capacity (Schill et al., 2017). Rooftop solar panels allow consumers to produce and self-consume energy—to become prosumers. In the European Union (EU), the revised Renewable Energy Directive (2018/2001) addresses barriers to self-consumption and activities such as energy solar and the sale of surplus solar production. This directive, combined with rising energy prices, is expected to increase the number of prosumers (IEA, 2019a).[2] Today, three different energy consumption and sale schemes exist buy-all sell-all, net metering, and real-time self-consumption (IEA, 2019a). Under the buy-all sell-all scheme, all solar production is sold to the grid at a fixed retail energy price (e.g., France), whereas self-consumption is possible under the two latter schemes. Under net metering, consumers receive compensation based on their net energy consumption (e.g., in Quebec, Brazil, etc.). This compensation can take the form of an energy credit, allowing the retrieval of the injected energy at a later date. Real-time self-consumption (e.g., Denmark, France, etc.) is close to net metering, but consumers may sell surplus production to the grid for a feed-in-tariff (FiT). In this paper, we determine the conditions under which consumers invest in solar capacity and store energy under different regulations.

The main limitation of solar energy production is its intermittency, as it depends on exogenous factors, i.e., climatic conditions. Thus, intermittent production calls for flexibility solutions such as demand response or energy storage. 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] Fabra et al. (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.

[1] For example, in Germany and China, the levelized cost of solar electricity (LCOE) from solar PV fell by 77% (IRENA, 2018) between 2010 and 2018. In Germany, this cost decrease results in a LCOE below the retail electricity price (Lang et al., 2016).

[2] For instance, in France, residential PV capacity is expected to increase by more than one-third by 2024.

[3] The EU expects that about 72% of residential consumers will be equipped with technologies allowing for real-time pricing by 2020 (JRE-SESI, 2020). However, in most countries, a complete roll-out is a condition for starting to implement such tariffs (Gautier et al., 2021).

Thus, without consumers equipped with enabling technologies, real-time prices may not provide enough flexibility to compensate for renewables' intermittency. Furthermore, this mechanism raises concerns because real-time prices in Spain have been regressive, according to Cahana et al. (2022). Both batteries and hydrogen-producing electrolyzers are candidates for residential energy storage because of their small size and expected cost reductions (IEA, 2020). Today the main limitation of a large-scale deployment of these technologies is their high prices. 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) use is another concerning point. New technologies such as solid oxide electrolysis cells (SOEC) limit the use of such materials. Articles 36 and 54 of 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).[4] Today, different hydrogen-based storage solutions are under development. For instance, the German company PICEA has developed a solar-hydrogen system with a total capacity ranging from 20 kWh for short-term storage to 300 kWh for long-term storage. A large-scale version for either medium-sized companies or residential energy communities (i.e., centralized storage) is also available: PICEA+.

In this paper, we consider energy storage as the only flexibility solution and build a stylized microeconomic model of the power sector to study investments in solar and storage by consumers connected to the grid. First, we consider that the regulator sets a real-time self-consumption ("price regulation") 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 a net metering ("quantity regulation") scheme such that consumers can store energy in the grid. This setting is compatible with centralized storage.

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 (Durmaz, 2016; Helm and Mier, 2018; Ambec and Crampes, 2019) and under alternative market configurations (Ambec and Crampes, 2019; Andrés-Cerezo and Fabra, 2020). They characterize charge and discharge patterns

[4] Zakeri et al. (2021) estimate that a combined PV and storage system could reduce consumers electricity bills by 80-88% in the United Kingdom.

of storage operations by a benevolent central planner and profit-maximizing firms. Storage increases investments in renewable energy while decreasing carbon emissions in a competitive market (Helm and Mier, 2018; Ambec and Crampes, 2019). Market power creates distortions, as it reduces investments in storage capacity (Andrés-Cerezo and Fabra, 2020) and might even increase carbon emissions unless accounting for the social cost of carbon (Ambec and Crampes, 2019). This lower level of investment in comparison to the first-best is a direct consequence of the limited profitability of storage operations. Different empirical contributions (Sioshansi et al., 2009; Monica Giulietti and Waterson, 2018; Antweiler, 2021; Butters et al., 2021; Karaduman, 2022; Lamp and Samano, 2022), have highlighted that in line with theoretical predictions (Durmaz, 2016; Antweiler, 2021; Karaduman, 2022), storage deployment reduces price volatility. However, as storage operators generate margins by arbitraging short-run inter-temporal electricity price differences, reduced price volatility limits the profitability of storage. Thus, decreasing the incentives to invest in such technologies. Nevertheless, investments in storage increase consumers' surplus, and 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 storage applications on the demand side are relevant as decentralized storage deployment can be less expensive than transmission capacity expansions needed for supply-side or nodal storage. As already mentioned, in the EU, energy storage ownership is limited to producers, aggregators, and consumers. Thus, in a context with an increasing share of intermittent renewable energy 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 et al. (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 capacity costs are small enough. Other papers (Durmaz et al., 2017; Dato et al., 2020, 2021) 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 on 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. Also, one may wonder about 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 under development 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 possible energy regulations, a price one compatible with decentralized storage and a quantity one compatible with 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 instruments with quantity regulation: the grid tariff and the share of stored energy that can be retrieved by consumers. Otherwise, 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. We aim to determine the regulation that secures non-negative profits for the DSO and is compatible with power-to-gas 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 under which consumers invest in solar capacity is the same under both energy regulations. In line with the literature (Durmaz et al., 2017; Dato et al., 2020, 2021), we find that consumers invest in storage when the avoided costs of storing energy rather than selling it to the grid in the first period, when climatic conditions are unfavorable, are greater than the capacity cost. With quantity regulation, consumers invest in storage when the regulator

sets a small enough grid tariff. The latter depends on the energy exchanged with the grid that is endogenous in our model. We observe that with the 2030 capacity costs in France, only a FiT smaller than the current one could encourage investments in decentralized storage. If the government instead switched to quantity regulation, a grid tariff such that consumers inject energy into the grid would not reflect the cost of centralized storage. With price regulation, only if financially compensated the DSO breaks even. In contrast, with quantity regulation, its revenues are always positive. In the case of our representative consumer, these revenues could finance the difference between a grid tariff encouraging storage and the cost of centralized storage. We conclude that if the government anticipates that consumers will engage in storage activities, a quantity regulation would be less costly to support.

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 compares the two regulations using a case study. Section 5 concludes.

2 The model

We consider a two-period economy with $t \in [1, 2]$, in which the government may implement a quantity-or price-based energy regulation to encourage investments in decentralized production. Our aim is to study the impact of these two possible energy policies on individual equipment decisions as well as their effect on the grid operator's revenues.

Consumers We follow the literature and consider a representative consumer who derives utility $U(q_t^i)$ from consuming q_t^i units of energy (Dato et al., 2020, 2021; Durmaz et al., 2017).[5] This consumer can install solar capacity $K \in [0, 1]$ at unit cost r. The maximal size of the solar capacity $\bar{K}$ is determined by exogenous factors (roof size, garden 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

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

favorable at $t = 1$ and that $K_1 = K$. Production at $t = 2$ is determined by climatic conditions:

$$K_2 = \begin{cases} K & \text{if} \quad i = f \\ 0 & \text{if} \quad i = u \end{cases}$$

This consumer can buy energy from the grid at a fixed retail price p.[6] When connected to the distribution network, it incurs a yearly fixed fee equal to A.[7]

Distributed System Operators 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 government sets a distribution tariff d such that the DSO breaks even, which accounts for about $\psi = 20 - 30\%$ of the final energy retail price $d = \psi p$ (Gautier et al., 2018).

3 Consumers under different energy policies

In this section, we analyze consumers' individual equipment decisions under the two different energy policies.

3.1 Price regulation

In this section, we assume that the government opts for price-based energy regulation. Consumers equipped with rooftop solar panels can sell their surplus solar energy production to the grid at a FiT τ established by the government. Thus, energy exchanges with the grid g_t^i can be negative or positive. The injected and retrieved energy might be valued at different levels. We define:

$$\phi_t^i = \begin{cases} p & \text{if the consumer retrieves energy from the grid} \\ \tau - \psi p & \text{if the consumer injects energy to the grid} \end{cases}$$

In addition, consumers can invest in a small fuel cell of capacity $S \in [0, \bar{S}]$ at a unit cost r_s. The maximal storage capacity $\bar{S}$ is exogenous, i.e. depends on the size of the largest

[6] Dato et al. (2020), Dato et al. (2021), Durmaz et al. (2017) consider dynamic prices instead.
[7] This fee may include a subscription charges paid to retailers and to the DSO.

commercially available fuel-cell. This storage technology suffers from energy losses estimated at $1-\lambda$. The representative consumer problem is:

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

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

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

Our problem is similar to Durmaz et al. (2017) and Dato et al. (2020) who consider, respectively, a two-period and a four-period model in which consumers invest in rooftop solar panels and batteries. In addition, their consumers may be equipped with smart meters, and excess solar production is rewarded at the energy price.

Depending on whether consumers inject or retrieve energy, the DSO may retrieve a revenue per kWh equal to:

$$\theta_t^i=\begin{cases}\psi p & \text{if the consumer buys energy from the grid}\\ \psi p-\tau & \text{if the consumer sells energy to the grid}\end{cases}$$

The DSO profits are:

$$\pi(Q_1,Q_2^f,Q_2^u)=(\theta_1-c)Q_1+\beta[\rho_f(\theta_2^f-c)Q_2^f+(1-\rho_f)(\theta_2^u-c)Q_2^u]-F+A$$

Across the globe, the energy injected into and retrieved from the distribution network may be valued at different levels. We depart from previous contributions (Dato et al., 2020, 2021; Durmaz et al., 2017), where the excess solar production is rewarded at the energy price, and characterize the consumer profiles with different FiT levels. First, we consider a FiT valued at the energy price. Second, a FiT smaller than the energy retail price.

3.1.1 Feed-in-tariff valued at the energy price

In this section, we solve the consumer's problem under a price regulation and characterize the solution when the FiT is valued at the retail energy price.[8] The following proposition summarizes our results:

Proposition 1. *Under price regulation when $p = \tau$,*

- *if $r > \bar{r}$, then consumers do not invest in solar capacity or storage ($K^* = S^* = 0$).*
- *if $U'(K^*) \geq p$ and $\bar{r} \geq r$, then consumers invest in solar capacity but not in storage ($\bar{K} \geq K^* > 0$ and $S^* = 0$).*
- *if $U'(K^*) < p$ and the capacity costs are such that:*
  - *$\tilde{r} \geq r$ and $r_s > \tilde{r_s}$, then consumers invest in solar capacity but not in storage ($\bar{K} \geq K^* > 0$ and $S^* = 0$).*
  - *$\tilde{r} \geq r$ and $\tilde{r_s} \geq r_s$, then consumers invest in solar capacity and storage ($\bar{K} \geq K^* > 0$ and $\bar{S} \geq S^* > 0$).*

  then, depending on the capacity costs and the size of the energy price we may have consumers, prosumers or storers.

The threshold values $\bar{r}$, $\tilde{r}$ and $\tilde{r_s}$ are defined in Appendix A.1.1. From our results above, we find that when the capacity cost of solar energy is high ($r > \bar{r} > \tilde{r}$), consumers never invest in decentralized production. When the marginal utility from solar capacity is larger than or equal to the retail price ($U'(K^*) \geq p$), consumers only install solar capacity if its unit cost is smaller than the cost of buying from the grid over two periods when climatic conditions are favorable ($r \leq \bar{r}$). In such a case, solar energy is a complement to the grid when $i = f$.

Otherwise, when the retail price is lower than the marginal utility from solar capacity ($U'(K^*) < p$), the storage adoption decision is driven by the solar ($r < \tilde{r}$) and storage capacity costs ($r_s \leq \tilde{r_s}$). This is illustrated in Figure 1. We remark that, $\tilde{r}$ increases with the energy retail price, whereas $\tilde{r_s}$ decreases. This means that if the government sets a high retail price, then consumers will be more likely to invest in solar capacity. Conversely, a high retail price

[8] This is the case in the United Kingdom and in the United States.

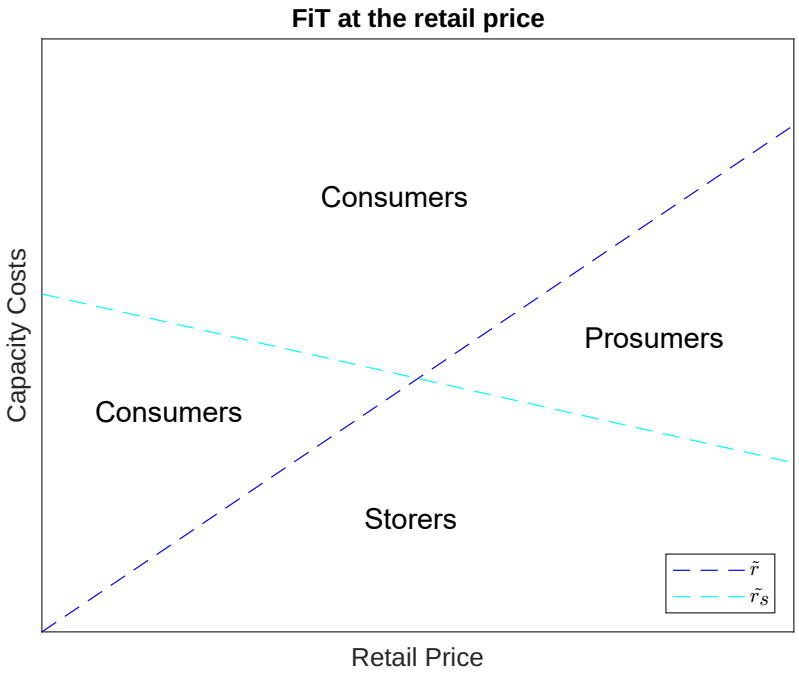

Figure 1

will limit investments in storage. The intuition is that when the energy retail price is high, solar energy may be less costly than buying from the grid, whereas the opportunity cost of storing rather than selling to the grid becomes larger. Indeed, as the FiT is evaluated at the retail price, a high energy price also implies higher revenues from injecting energy into the grid.

Like in Durmaz et al. (2017), consumers invest in storage when the avoided costs of storing energy rather than selling it to the grid in the first period, when climatic conditions are unfavorable, are greater than the capacity cost. In such a case, for consumers, solar energy is a substitute for the grid when $i = f$, and stored energy is a complement to the grid when $i = u$.

Lemma 1. *Under price regulation, when the distribution tariff accounts for a large share of the energy price*

$$\psi > \frac{1 - \beta\lambda}{1 - \beta\lambda\rho_f} = \tilde{\psi}$$

then, $\tilde{r_s} > 0$ *and consumers may invest in a small-fuel if* $r_s \leq \tilde{r_s}$.

Notice that $\tilde{\psi}$ decreases with the storage round-trip efficiency λ:

$$\frac{\partial\tilde{\psi}}{\partial\lambda} = \frac{-\beta(1-\rho_f)}{(1-\beta\lambda\rho_f)^2}$$

The round-trip efficiency of fuel-cell storage is expected to increase in the future (IEA,

2019b). Currently, the distributional tariff only accounts for about $\psi = 20 - 30\%$ of the final energy retail price (Gautier et al., 2018). Thus, it is possible that, at the moment, consumers have no incentive to invest in storage capacity, but this is likely to change in the years to come.

We compute the DSO's profits under the different cases:

$$\pi_{DSO} = \begin{cases} (1+\beta)(\psi p - c)U'^{-1}(p) - F + A \quad \text{if} \quad r > \bar{r} \\ (\psi p - c)((1+\beta)U'^{-1}(p) - (1+\beta\rho_f)K^*) - F + A \quad \text{if} \quad U'(K^*) \geq p \quad \text{and} \quad \bar{r} \geq r \\ \beta(1-\rho_f)(\psi p - c)U'^{-1}(p) - ((1-\psi)p + c)(1+\beta\rho_f)(K^* - U'^{-1}((1-\psi)p)) - F + A \\ \quad \text{if} \quad U'(K^*) < p, \quad \tilde{r} \geq r \quad \text{and} \quad r_s > \tilde{r_s} \\ \beta(1-\rho_f)(\psi p - c)(U'^{-1}(p) - \lambda S^*) - ((1-\psi)p + c)((1+\beta\rho_f)(K^* - U'^{-1}((1-\psi)p)) \\ -(1-\beta\lambda\rho_f)S^*) - F + A \qquad \text{if} \quad U'(K^*) < p, \quad \tilde{r} \geq r \quad \text{and} \quad r_s > \tilde{r_s} \end{cases}$$

Notice that as the capacity cost of solar energy decreases, consumers rely less on the grid to cover their energy demand.

3.1.2 Feed-in-tariff smaller than the energy price

In this section, we solve the consumers' program under price regulation and characterize the solution when the retail energy price is higher than the FiT[9]. The following proposition summarizes the possible profiles:

Proposition 2. *Under price regulation when $p > \tau$,*

- *if $r > \bar{r}$, then consumers do not invest in solar capacity or storage ($K^* = S^* = 0$).*
- *if $U'(K^*) \geq p$ and $\bar{r} \geq r$, then consumers invest in solar capacity but not in storage ($\bar{K} \geq K^* > 0$ and $S^* = 0$).*
- *if $U'(K^*) < p$ and the capacity costs are such that:*
  - *$\hat{r} \geq r$ and $r_s > \hat{r_s}$, then consumers invest in solar capacity but not in storage.*
  - *$\hat{r} \geq r$ and $\hat{r_s} \geq r_s$, then consumers invest in solar capacity and storage.*

[9] This is the case in most European countries.

then, depending on the capacity costs and the size of the energy price we may have consumers, prosumers or storers.

The values of $\bar{r}$, $\hat{r}^p$, and $\hat{r_s}$ are defined in Appendix A.1.2. Our results are similar to those from the previous section 3.1.1. Indeed, we retrieve the same four types of consumer profiles. The main difference here is the threshold values for solar and storage capacity costs, which determine the type of consumer observed at equilibrium when the energy price is smaller than the marginal utility from solar capacity ($U'(K^*) \geq p$).

Lemma 2. *Under price regulation, consumers invest in a small-fuel if the solar and storage capacity costs verify:*

$$\hat{r} \geq r \quad \textit{and} \quad \hat{r_s} \geq r_s$$

and the government sets a FiT:

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

When solar production covers energy consumption in favorable weather conditions, consumers prefer to sell energy to the grid rather than store it if the costs of solar and storage capacity are such that $\frac{r}{1+\beta\rho_f} > \frac{\beta\lambda(1-\rho_f)p-r_s}{1-\beta\lambda\rho_f}$. Indeed, in such a case, the government cannot set a FiT such that consumers invest in storage. Otherwise, if $\frac{r}{1+\beta\rho_f} \leq \frac{\beta\lambda(1-\rho_f)p-r_s}{1-\beta\lambda\rho_f}$, provided that the capacity costs are such that $\hat{r} \geq r$ and $\hat{r_s} \geq r_s$, then the government can set a FiT such that consumers invest in storage capacity ($S > 0$). Thus, when the energy loss from storage is large, even if the storage capacity cost is small, consumers might prefer to sell energy to the grid rather than store it.

We remark 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 when the FiT is high, the revenues from injecting surplus solar energy into the grid are larger than the cost of solar production. With a small FiT, instead, the opportunity cost of storing rather than selling to the grid becomes smaller. This is illustrated in Figure 2.

We remark that, here both $\hat{r}$ and $\hat{r_s}$ increase with the energy retail price. This means that

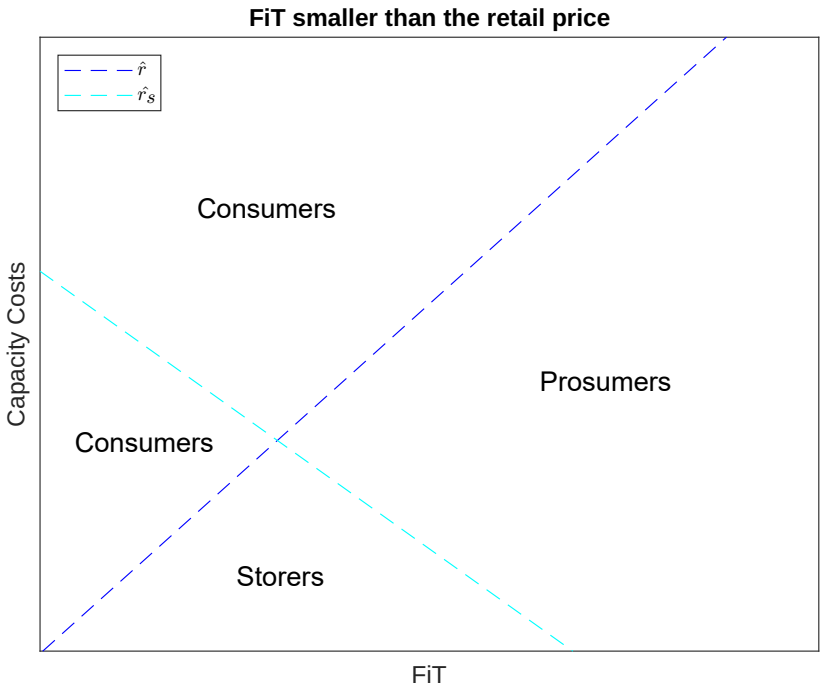

Figure 2

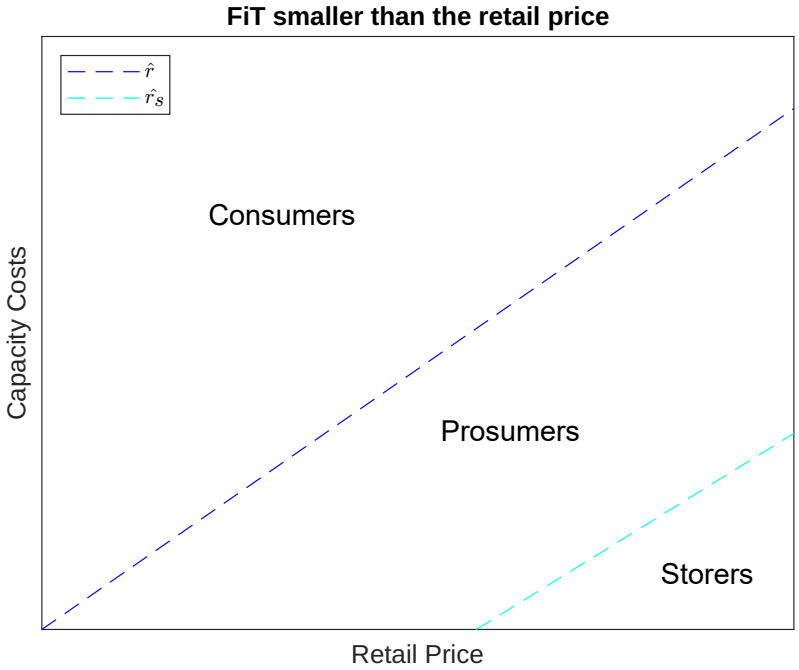

Figure 3

if the government sets a high retail price, then consumers will be more likely to invest in solar and storage capacity. The intuition is that when the energy retail price is high, not only solar energy may be less costly than buying from the grid, but also whereas the opportunity cost of storing rather than selling to the grid becomes smaller. Indeed, as the FiT is smaller than retail price, a high energy price also implies larger saving from storing rather than injecting energy into the grid. This is illustrated in Figure 3.

We compute the DSO's profits under the different cases:

$$\pi_{DSO} = \begin{cases} (1+\beta)(\psi p - c)U'^{-1}(p) - F + A \quad \text{if} \quad r > \bar{r} \\ (\psi p - c)((1+\beta)U'^{-1}(p) - (1+\beta\rho_f)K^*) - F + A \quad \text{if} \quad U'(K^*) \geq p \quad \text{and} \quad \bar{r} \geq r \\ \beta(1-\rho_f)(\psi p - c)U'^{-1}(p) + (1+\beta\rho_f)(\psi p - \tau - c)(K^* - U'^{-1}(\psi p - \tau)) - F + A \\ \text{if} \quad U'(K^*) < p, \quad \hat{r} \geq r \quad \text{and} \quad r_s > \hat{r_s} \\ \beta(1-\rho_f)(\psi p - c)(U'^{-1}(p) - \lambda S^*) + (\psi p - \tau - c)((1+\beta\rho_f)(K^* - U'^{-1}(\psi p - \tau)) \\ -(1-\beta\lambda\rho_f)S^*) - F + A \qquad \text{if} \quad U'(K^*) < p, \quad \hat{r} \geq r \quad \text{and} \quad r_s > \hat{r_s}^p \end{cases}$$

As the cost of solar capacity falls, solar panels will serve as a complement to the grid before becoming a substitute. Given that $U'^{-1}(.)$ is increasing and $\tau < p$ 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.

3.2 Quantity regulation

In this section, we assume that the government opts for quantity-based energy regulation. Consumers equipped with rooftop solar panels may buy energy from the grid but cannot longer sell it, i.e., we always have $\phi_1 = \phi_2^f = \phi_2^u = p$ and $g_1 \geq 0$, $g_2^u \geq 0$ and $g_2^f \geq 0$. When equipped with solar panels, surplus solar production can be injected and stored in the grid at $t = 1$, in the form of an energy credit R at a unit cost of α. In such a case, at $t = 2$, consumers may retrieve "free" λ^G energy from the grid. The grid tariff α, as well as the share of energy stored in the grid that can be retrieved from the grid λ^G at $t = 2$, are set by the regulator. We adapt our representative consumer problem from the previous section 3.1 and set $S = R$, $r_s = \alpha$, and $\lambda^S = \lambda^G$. We now have six constraints: $\bar{K} \geq K$, $K \geq 0$, $R \geq 0$, $g_1 \geq 0$, $g_2^f \geq 0$, and $g_2^u \geq 0$.

Depending on whether consumers inject or retrieve energy, the DSO has a revenue per kWh equal to:

$$\theta_t^i = \begin{cases} \psi p \quad \text{if the consumer buys energy from the grid} \\ \alpha \quad \text{if the consumer injects energy to the grid} \end{cases}$$

We solve the consumer's problem and characterize the solution with quantity regulation. The following proposition summarizes the possible profiles:

Proposition 3. *Under quantity regulation,*

- *if* $r > \bar{r}$*, then consumers do not invest in solar capacity or store energy in the grid* ($K^* = R^* = 0$)*.*
- *if* $U'(K^*) \geq p$ *and* $\bar{r} \geq r$*, then consumers invest in solar capacity but do not store energy in the grid* ($\bar{K} \geq K^* > 0$ *and* $R^* = 0$)*.*
- *if* $U'(K^*) < p$ *and* $\dot{r} \geq r$ *then consumers invest in solar capacity and store energy provided that the government sets a grid tariff* $\bar{\alpha} = \alpha$*.*

then, depending on the capacity costs and the size of the energy price we may have consumers, prosumers or storers.

The values of $\bar{r}$, $\ddot{r}$ and $\bar{\alpha}$ are defined in Appendix A.2. We have several takeaways from the above results. Notice that consumers do not engage in *precautionary storage* (buy energy to store it). In a setup with responsive consumers, i.e. exposed to dynamic pricing, Durmaz (2016) finds 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 result do not hold in our setup because consumers are exposed to a fixed energy price, so there is no consumption risk. In our paper, there is one exception: if the regulator sets $\lambda^G = 1$ and the grid tariff is zero ($\alpha = 0$), we may observe that some consumers buy energy to store.[10].

Consumers simultaneously buy energy from the grid at the first period and invest in solar capacity when the marginal utility from solar capacity is greater than or equal to the retail energy price ($U'(K^*) \geq p$) and the solar capacity cost is small ($r < \bar{r}$). In such a case, solar energy is a complement to the grid when $i = f$.

When the retail energy price is greater than the marginal utility from solar capacity ($U'(K^*) \leq p$), the storage decision is driven by the unit cost of solar capacity and the grid tariff. Even if solar capacity is very cheap (we have $\underline{r} > \ddot{r}$), consumers do not store energy if the regulator sets an excessively high grid tariff, $\alpha > \bar{\alpha}$. Otherwise, if the grid tariff is low ($\alpha = \bar{\alpha}$), consumers

[10]For instance, such a regulation exist in Quebec (Canada).

will store energy but will never be completely self-sufficient. Nevertheless, solar production fully covers demand when climatic conditions are favorable. In such a case, for consumers, solar energy is a substitute for the grid when $i = f$, and stored energy is a complement to the grid when $i = u$.

We compute the DSO's revenues under the different cases:

$$\pi_{DSO} = \begin{cases} (1+\beta)(\psi p - c)U'^{-1}(p) - F + A \quad \text{if} \quad r > \bar{r} \\ (\psi p - c)((1+\beta)U'^{-1}(p) - (1+\beta\rho_f)K^*) - F + A \quad \text{if} \quad U'(K^*) \geq p \quad \text{and} \quad \bar{r} \geq r \\ \beta(1-\rho_f)(\psi p - c)U'^{-1}(p) - F + A \quad \text{if} \quad U'(K^*) < p, \quad \ddot{r} \geq r \quad \text{and} \quad \alpha > \bar{\alpha} \\ \beta(1-\rho_f)(\psi p - c)U'^{-1}(p) + R^*(\alpha - (1-\beta\lambda^G(2-\rho_f))c - \beta\lambda^G(1-\rho_f)\psi p) - F + A \\ \text{if} \quad U'(K^*) < p, \quad \ddot{r} \geq r \quad \text{and} \quad \alpha = \bar{\alpha} \end{cases}$$

Like under price regulation, as the capacity cost of solar energy decreases, consumers rely less on the grid to cover their energy demand. Nevertheless, depending on the size of the grid tariff, consumers might inject energy into the grid when solar panels are seen as substitutes rather than complements.

3.3 Quantity vs Price regulation

The two possible energy regulations differ in two main dimensions. First, consumers are only allowed to sell energy to the grid under price regulation. Second, under a quantity regulation, the regulator has two policy instruments: the grid 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 3.1.1 and 3.1.2, we studied the profiles that emerged under a quantity and a price regulation.

Proposition 4. *Regardless of the energy regulation if the solar capacity cost is:*

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

consumers install solar panels.

The threshold value of the solar capacity cost under 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 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.

It should be noted that in our model, the quantities exchanged with the grid are endogenously determined by the policy instruments. It cannot be solved analytically. Therefore, we rely on a numerical evaluation of the model, which requires assigning values to its structural parameters. This would allow us to determine the conditions under which the DSO and consumers prefer either centralized or decentralized storage.

4 Case Study: France

In this section, we compare the two types of energy regulations—price and quantity—from our representative consumer's and the DSO's points of view. We calibrate our model for France using data from different publicly available sources. Our objective is two-fold. First, we determine the conditions under which consumers store energy. Second, we evaluate how energy consumption, production, and storage impact the DSOs' profit. Our aim is to determine the regulation that secures non-negative profits for the DSO and is compatible with power-to-gas storage. Table 1 presents the parameters used in our calibration.

4.1 Data

The French energy market fully opened up to competition in 2007; since then, residential consumers have had the choice between different energy retailers and contracts. In our theoretical model, we assumed a fixed retail price. Such a price is possible with France's main electricity generation and distribution company, Électricité de France (EDF), Blue Tariff contract. For a power subscription of 9 kVA, residential customers pay a fixed retail price of 0.174 EU per kWh. In addition, they pay a monthly subscription fee equal to 14.18 EU per month (EDF, 2022).

To encourage investments in decentralized solar capacity, in 2017 the French government

Table 1: Calibration

Parameters	Mnemonic	Value	Unit	Source
Preferences				
Subsistence Consumption Level*	$\bar{q}$	13.42	kWh	Engie (2021)
Relative Risk Aversion	γ	0.9		
Discount factor	β	0.95		
Technology				
Maximal Solar Capacity	$\bar{K}$	23.013	kWh/day	Engie (2022a)
Levelized Cost of Solar Energy	r	0.049	EU/kWh	IEA (2019a)
Maximal Storage Capacity	$\bar{S}$	20	kWh	HPS (2022)
Levelized Cost of Hydrogen	r_s	0.051	EU/kWh	IEA (2019b)
Power-to-gas round-trip efficiency	λ	68.5	%	IEA (2019b)
Market Characteristics				
Energy Retail Price	p	0.174	EU/kWh	EDF (2022)
Subscription Fee	A_{RETAIL}	0.47	EU/day	EDF (2022)
Capacity Factor Solar Energy	ρ_f	14.65	%	RTE (2021)
Feed-in-tariff	τ	0.1	EU/kWh	EDF (2021)
TURPE				
Fixed Fee	A_{TURPE}	0.32	EU/day	Enedis (2022)
Variable Fee (withdrawal)	d_r	0.048	EU/kWh	Enedis (2022)
Variable Fee (injection)	d_i	0.003	EU/kWh	Enedis (2022)
DSO Costs				
Variable cost	c	0.0224	EU/kWh	CRE (2021)
Fixed cost	F	0.2	EU/day	Enedis (2022)

introduced a FiT for surplus solar production. In France, residential consumers have the choice between two different energy consumption and sale schemes: buy-all sell-all, and real-time self-consumption (IEA, 2019a). In both cases, when solar energy production is higher than consumption, consumers may sell their surplus to EDF OA (Obligation d'Achat), the entity responsible for the purchase of renewable energy mandated by the state. This FiT set by the regulator (Commission de Régulation de l'Énergie - CRE) is guaranteed for a 20 years period (Engie, 2022b). In this paper, we focus only on the real-time self-consumption scheme as with the buy-all sell-all scheme all solar production is sold to the grid. As of 2021, for consumers with an installed solar capacity of a total power smaller than or equal to 9 kWc, the FiT was set at 0.1 EU per kWh (EDF, 2021). The Transmission System Operator (Réseau de Transport d'Électricité - RTE) estimates a capacity factor of solar energy in France equal to 14.65 % (RTE, 2021).

The DSO (Enedis) charges to consumers a lump-sum price which accounts for about 30% of the final energy price: the tariff for the use of public transmission electricity grids (TURPE).[11] The fixed part of the TURPE 6 (2021) is equal to 0.32 EU per day and takes into account all charges related to management, accounting, power and taxes.[12] As for the variable part, the DSO considers two different tariffs depending on whether energy is injected (d_i =0.003 EU per kWh) or retrieved (d_r=0.048 EU per kWh) from the grid. We consider a weighted average version, in practice, these fees depends on the season and period (on/off-peak) as illustrated in Table 2.

Table 2: DSO Variable Cost and Fees (EU per kWh)

Season	Period	Yearly Hours	Cost	Fee (d_r)	Fee (d_i)
High	Peak	2464	0.009	0.069	0.016
	Off-Peak	1231	0.011	0.042	0.012
Low	Peak	3360	0.006	0.022	0.007
	Off-Peak	1680	0.005	0.008	0.004

Source: CRE (2021) and Enedis (2022)

In what concerns the DSO's operating costs, we also construct a weighted average version equal to c=0.007 EU per kWh. This value is based on data from the CRE (2021). As for the fixed cost, it is evaluated at 0.2 EU per day (CRE, 2021).[13]

The calibration is based on values for a 70m^2 house with a subsistence consumption level $\bar{q}$ equal to 4900 kWh per year. We use the theoretical energy consumption level of a house categorized as highly efficient by the energy performance diagnosis as a proxy for this value.[14] We follow Durmaz et al (2017) and consider CRRA preferences:

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

we use a sensitivity analysis and fix $\gamma = 0.9$.

According to Engie (2022a), a 20-solar-panel installation (34m^2) yields a system with a total power of 6 kWc. Each kWc allows to produce at most 1400kWh per year (Engie, 2022),

[11] This tariff is set by the CRE for a five year period.
[12] We consider a consumers with a subscribed power of 9kVA.
[13] Thus, we have $A = A_{RETAIL} + A_{TURPE} = 0.79$ EU per day.
[14] In France, since 2007, an energy performance diagnosis based on the physical characteristics of a building must be given to new buyers or tenants of a home. This diagnosis provides a theoretical energy consumption level on based on the physical characteristics of the house. A house is considered as highly efficient (class "B") since 2021 when its theoretical consumption level is between 70 -110 kWh per m2 per year.

thus we assume a maximal solar capacity $\bar{K}$ equal to 23.013 kWh per day. As for storage, different hydrogen-based solutions are currently under development. For instance, the German company PICEA has developed a solar-hydrogen system with a total capacity ranging from 20 kWh for short-term storage to 300 kWh for long-term storage. A large-scale version for either medium-sized companies or residential energy communities (i.e., centralized storage) is also available: PICEA+. For solar and storage technologies, we consider 2030 technological costs, as the second type of technology is not yet available in the market. The storage technology relies on a polymer electrolyte membrane (PEM) electrolyzer, with a round-trip efficiency estimated at $\lambda = 65.5\%$ at the 2030 horizon. The 2030 levelized cost of solar energy (LCOE) and the levelized cost of hydrogen (LCOH) are respectively estimated at 0.049 EU per kWh and 0.051 EU per kWh (IEA, 2019a,b).

4.2 Results

We first consider the benchmark situation under France's current regulation. We know from our theoretical results that $r \leq (1+\beta\rho_f)p$ is a required condition for solar capacity installation under both regulations. This condition is met in our calibrated scenario at the 2030 horizon because $\bar{r} = 0.2 > 0.049$ EU per kWh. Thus, the current regulation provides enough incentives to invest in solar capacity.

In France, we have a FiT that is strictly smaller than the energy retail price $\tau < p$. Thus, from the Proposition 2, we know that the capacity costs must verify $\hat{r} \leq r = 0.049$ and $\hat{r_s} \leq r_s = 0.051$ for consumers to invest in storage. However, with the current FiT this conditions is not verified at the 2030 horizon as $\hat{r_s} = 0.0062 < 0.051$. We know that if $\frac{r}{1+\beta\rho_f} \leq \frac{\beta\lambda(1-\rho_f)p-r_s}{1-\beta\lambda\rho_f}$, then the government may be able to set a FiT such that consumers invest in storage capacity. This conditions is verified as $0.0505 = \frac{\beta\lambda(1-\rho_f)p-r_s}{1-\beta\lambda\rho_f} > 0.043 = \frac{r}{1+\beta\rho_f}$.

The current FiT is too large for consumers to invest in storage capacity $\tau - \psi p = 0.097 \notin [0.043; 0.0505]$, thus to encourage investments in storage the government would need to set a smaller FiT.[15] This is illustrated in Figure 4.

We compute the DSO's profit as a function of the FiT chosen by the government; with this specification, it is as if the DSO's financed the FiT. We remark that regardless of the FiT

[15] Here, we consider $\psi p = d_i$ as consumers inject energy into the grid.

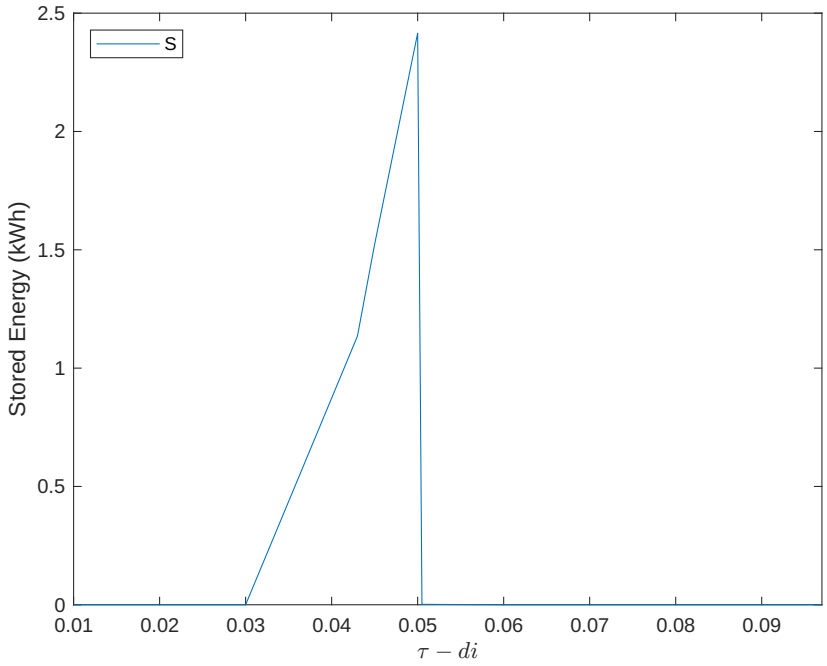

Figure 4: Level of Stored Energy

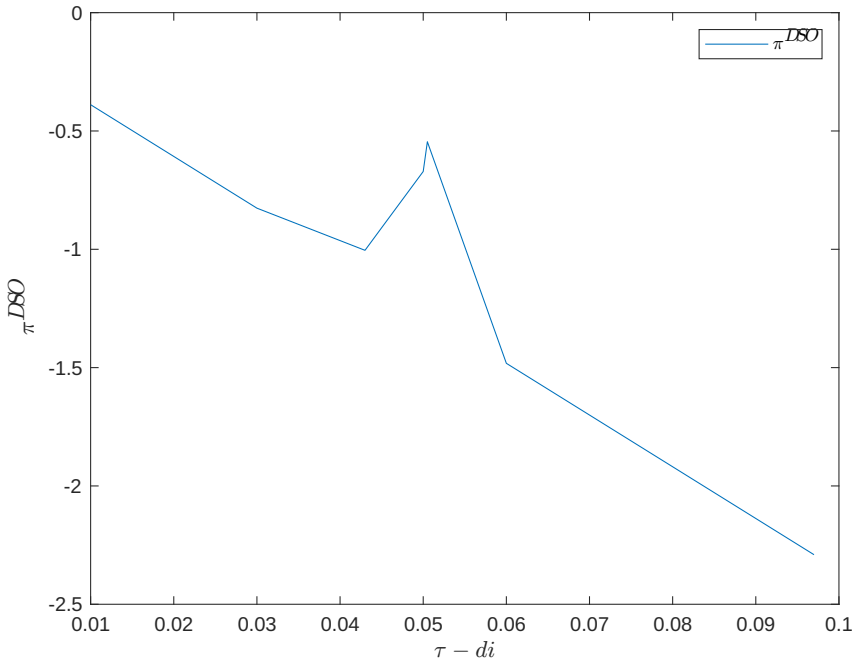

Figure 5: DSO' Revenues

size, the DSO's revenues are always negative (Figure 5). In practice, the DSO always breaks even, and the FiT is in fact financed by the government. Thus, the distance between the blue curve and 0 represents the amount of public funds such that the DSO breaks even for our representative consumer. When there is no energy storage, that is, when $\tau - d_i \notin [0.043; 0.0505]$, the larger the FiT, the more public funds must be transferred to the DSO for it to break even. Otherwise, when the consumer stores energy, i.e., when $\tau - d_i \in [0.043; 0.0505]$, the budget

burden is reduced because the consumer injects less energy into the grid. However, if we consider the entire energy system, when consumers store energy less decentralized renewable energy is available in the system at the first period. Nonetheless, this also implies more energy available at the second period.

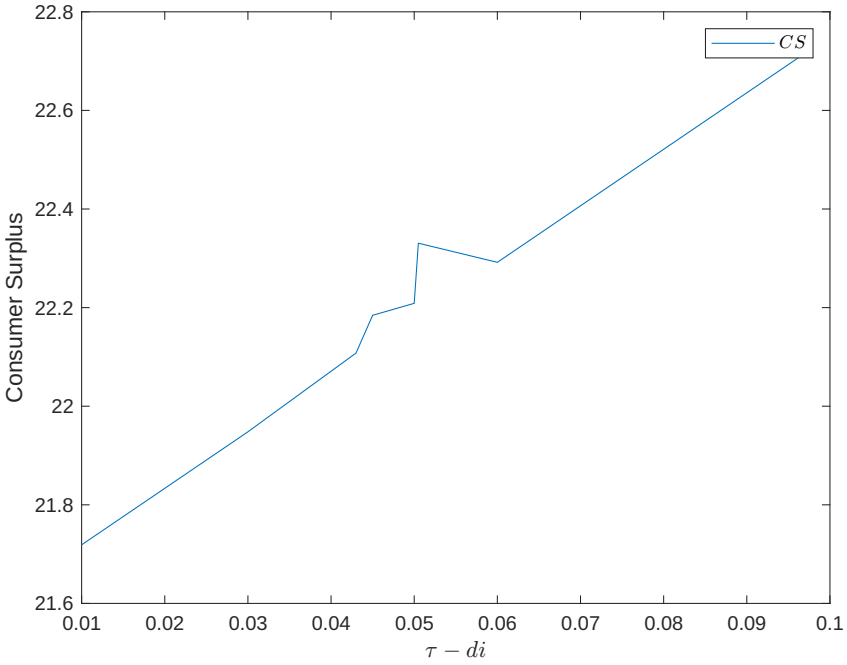

Figure 6: Consumer Surplus

In what concerns the representative consumer, in general, its surplus increases with the FiT. The intuition is that a larger FiT implies larger revenues from injecting energy. We remark that when $\tau - d_i \in [0.005; 0.06]$, the opportunity cost of storing rather than selling to the grid is greater than when $\tau - d_i \in [0.06; 0.065]$. Thus, our representative consumer surplus can be greater when there is energy storage than when there is not.

We now consider that the government instead opts for quantity regulation. In particular, we assume that when consumers inject their surplus solar production into the grid R, the latter goes to a centralized storage facility. This centralized storage facility relies on power-to-gas technology. Namely, the share of the injected energy that can be recovered from the grid at a later period depends on the round-trip efficiency of hydrogen technology: $\lambda^G = \lambda = 0.685$. From Proposition 3, we know that under quantity regulation, the solar energy capacity cost must verify $\ddot{r} = (1 + \rho_f)U'(K^*) \leq r = 0.049$ EU per kWh, and the government needs to set a grid tariff $\alpha = \bar{\alpha} = \lambda^G[\rho_f U'(K + \lambda^G R) + (1 - \rho_f)p] - U'(K - R)$ for consumers to inject/store

energy into the grid. The first condition is met in France whenever $33.21 \geq K^*$, and because our representative consumer can install maximum solar capacity equal to $\bar{K} = 23.013 < 33.21$, the condition is always met. Notice that $\bar{\alpha}$ depends on $K^* = \bar{K}$ (given that $\ddot{r} \geq r$) and $R^* = \lambda^{G^{-1}}[U'^{-1}(p) - g_2^u]$. Thus, we simulate our representative consumer choices for different grid tariff levels to determine $\bar{\alpha}$, as $g_2 u$ is endogenous in our model (Figure 7).

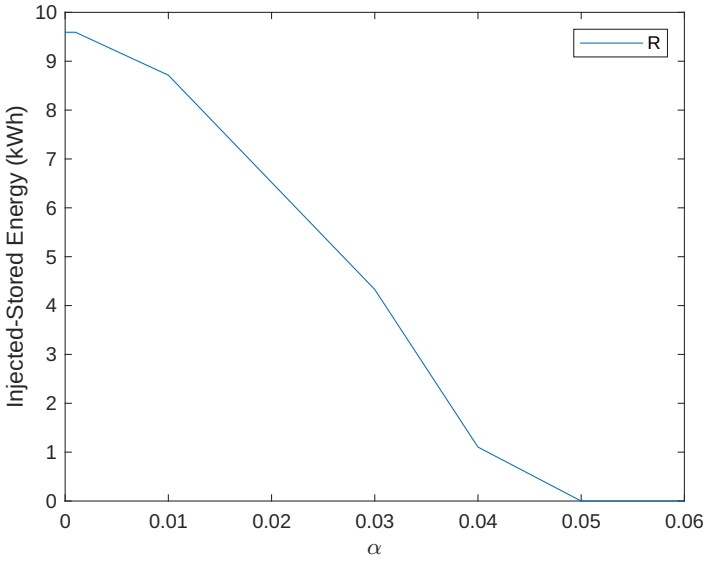

Figure 7: Level of Injected/Stored Energy

We observe that the amount of energy injected into the grid decreases with the grid tariff. The opportunity cost of transferring surplus solar production energy to the second period rather than consuming it increases with the grid tariff. It is worth noting that if the government establishes a grid tariff that reflects the cost of transferring and storing energy in the centralized facility, i.e., $r_s + d_i = 0.054$ EU per kWh, the consumer will prefer to consume all solar energy during the first period. Thus, if α is less than 0.05 EU per kWh, consumers inject energy into the grid.

We compute the DSO's profit as a function of the grid tariff chosen by the government. Regardless of the grid tariff size, the DSO's revenues are always positive or null (Figure 8), unlike what we observed under price regulation. As previously mentioned, the government finances the FiT and guarantees that the DSO breaks even. Here, as the DSO makes positive profits rather than relying on public funds to break even, the government may want to use these extra revenues to finance the difference between a grid tariff that induces consumers to inject energy into the grid and the cost of centralized storage $r_s - d_i = 0.054$ EU per kWh.

In what concerns the representative consumer, its surplus decreases with the grid tariff. The

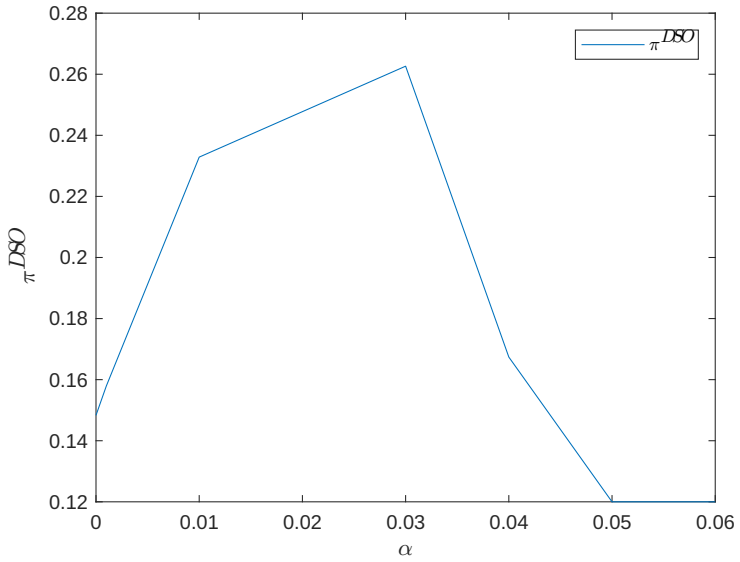

Figure 8: DSO' Revenues

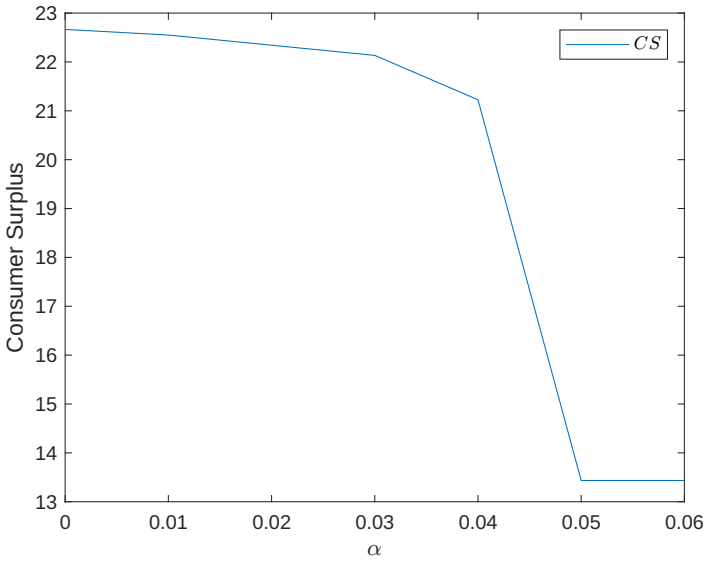

Figure 9: Consumer Surplus

consumer is better off when the government sets a grid tariff such that the consumers injects energy into the grid instead of consuming all solar production in the first period.

Decentralized solar production capacity in Europe is likely to increase in the years to come following the Renewable Energy Directive (2018/2001), thus, increasing the need for energy storage. Along with producers and aggregators, consumers are candidates for ownership of storage facilities. We have seen that both regulations need financial support for our representative consumers to store energy. Under price regulation, this translates into funds to cover the DSO's costs, while under quantity regulation, it relates to financing the difference between the grid tariff and the cost of having centralized storage. We now compare for the same level of stored energy the funds required to support this activity with both regulations.

Under price regulation, the highest level of stored energy is equal to 2.4155 kWh when the FiT is equal to 0.05 EU per kWh. In such a case, the DSO's profits are equal to 0.6712 EU over our study period; thus, for the DSO to break even, we need financial support equal to 0.6712 EU. Under quantity regulation, the level of injected/stored energy is equal to 2.4155 kWh if the grid tariff is equal to $\alpha = 0.0362674$ EU per kWh. In such a case, financial support for storage would be equal to $(r_s + d_i - \alpha) * R = 0.043$ EU over our studied period. Notice that, when $R = 2.4155$ kWh, the DSO profits are equal to 0.2147 EU; thus, no extra transfers from the government seem to be needed to cover the cost difference.

We have seen that with the capacity costs in 2030, in France, only a FiT smaller than the current one would encourage investments in decentralized storage. If the government instead switched to quantity regulation, a grid tariff such that consumers inject energy into the grid would not reflect the cost of centralized storage. With price regulation, only if financially compensated the DSO breaks even. In contrast, with quantity regulation, its revenues are always positive. In the case of our representative consumer, these revenues could finance the difference between a grid tariff encouraging storage and the cost of centralized storage. We conclude that if the government anticipates that consumers will engage in storage activities, a quantity regulation would be less costly to support.

5 Conclusion

The increasing deployment of decentralized solar capacity resulting from the cost decline of solar modules calls for solutions to smooth intermittent energy production. Energy storage through batteries and hydrogen-producing electrolyzers could provide more flexibility. The cost of these technologies should decrease in the years to come following generous support programs. In the European Union, the number of prosumers should increase following the revised Renewable Energy Directive (2018/2001) and rising energy prices. The economic literature suggests there is room for demand-side storage. The latter can take different forms: decentralized or centralized. One may wonder about the conditions under which consumers invest in solar capacity and store energy. Today, many energy consumption and sale schemes promote investments in decentralized solar production. Each of the schemes has specific policy instruments and physically allows for one type of demand-side storage.

We build a theoretical framework to study solar capacity and storage adoption by consumers under two possible energy regulations. A quantity one is compatible with centralized storage, and a price one is compatible with decentralized storage. We found that the two energy regulations lead to three types of profiles: consumers, prosumers, and storers. Moreover, the threshold value of the solar capacity cost under which consumers invest in solar capacity is the same under both energy regulations. These profiles are in line with previous studies focusing on price regulation. Indeed, consumers invest in storage when the avoided costs compared to the potential revenues from selling energy to the grid exceed the capacity costs. With quantity regulation, consumers invest in storage when the regulator sets a small enough grid tariff. The latter depends on the energy exchanges with the grid, endogenous in our model.

This difficulty motivated us to perform a numerical evaluation using french data and 2030 technological costs. The results from the calibration suggest that with the current price regulation in France, only a smaller feed-in-tariff would encourage investments in decentralized hydrogen-based storage. If the government instead switched to quantity regulation, a grid tariff such that consumers inject energy into the grid would not reflect the cost of centralized hydrogen-based storage. In what concerns the Distributed System Operator, price regulation results in negative profits. Thus, financial compensation would be necessary for it to break even. With quantity regulation, its revenues are always positive. In the case of our representative consumer, these revenues could finance the difference between a grid tariff encouraging storage and the cost of centralized storage. We conclude that if the government anticipates that consumers will engage in storage activities, a quantity regulation would be less costly to support.

We have considered a simplified model of the energy market to characterize and compare demand-side storage under different schemes promoting decentralized solar capacity. As a result, this leaves room for future work. For instance, a more realistic model should include the supply side of the energy market and heterogeneous consumers. Also, we have assumed a fixed retail energy, other types of contracts are also available to consumers. This could be included in an extension of our model.

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A Appendix

A.1 Price regulation

The Lagrangian of the consumer's problem is:

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

This yields to the following first order conditions:

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

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

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

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

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

plus the complementary slackness conditions.

A.1.1 Feed-in-tariff valued at the energy price

Case 1 Let us consider $\phi_1 = \phi_2^f = \phi_2^u = p$, 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:

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

  This is the case when the solar capacity cost is $r = \bar{r}$. 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:

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

  This is the case when the solar capacity cost is $r < \bar{r}$. It implies that $U'(\bar{K}) \geq p$ given that $U'(.)$ is decreasing.

Thus, depending on the solar capacity cost we have three different profiles: no investment ($K^* = S^* = 0$), partial solar investment ($K^* = U'^{-1}(p) - g_1$ and $S^* = 0$), and maximal solar investment ($K^* = \bar{K}$ and $S^* = 0$).

Case 2 Let us consider $\phi_1 = (1-\psi)p$ and $\phi_2^f = \phi_2^u = p$, from (3), (4) and (5) we now have:

$$(1-\psi)p = U'(K - S - g_1) \quad \text{and} \quad p = U'(K + \lambda S + g_2^f) = U'(\lambda S + g_2^u)$$

Notice that the above equations imply that $(1-\psi)p > p$, which is a contradiction as $U'(.)$ is decreasing and $K + \lambda S > K - S$. This case cannot be a solution.

Case 3 Let us consider $\phi_1 = \phi_2^f = (1-\psi)p$, and $\phi_2^u = p$, from (3), (4) and (5) we have:

$$(1-\psi)p = U'(K - g_1 - S) = U'(K + \lambda S - g_2^f), \quad \text{and} \quad p = U'(\lambda S + g_2^u)$$

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

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

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

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

we define the threshold values $\tilde{r} = (1+\beta\rho_f)(1-\psi)p$ and $\tilde{r_s} = (\beta\lambda + \psi(1-\beta\lambda\rho_f) - 1)p$.

Notice that if $K = 0$, at $t = 1$ we have $U'(0) = \infty$ which is not possible; thus, we have $K > 0$. Also, only if $\psi > \frac{1-\beta\lambda}{1-\beta\lambda\rho_f}$ we have $\tilde{r_s} > 0$. Then, depending on the size of ψ either there are two or six possible solutions:

- **Partial solar investment equilibrium**: $K^* \in]0; \bar{K}[$ and $S^* = 0$ is solution when:

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

and

$$\eta_4 = r_s - (\beta\lambda + \psi(1 - \beta\lambda\rho_f) - 1)p > 0$$

This is the case when the solar capacity cost is $r = \tilde{r}$ and the storage capacity cost is $r_s > \tilde{r_s}$ or $\tilde{r_s} \leq 0$. It implies that $U'(K^*) < p$ given that $U'(.)$ is decreasing.

- **Maximal solar investment equilibrium**: $K^* = \bar{K}$ and $S^* = 0$ is solution when:

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

and

$$\eta_4 = r_s - (\beta\lambda + \psi(1 - \beta\lambda\rho_f) - 1)p > 0$$

This is the case when the solar capacity cost is $r < \tilde{r}$ and the storage capacity cost is $r_s > \tilde{r_s}$ or $\tilde{r_s} \leq 0$. It implies that $U'(\bar{K}) < p$ given that $U'(.)$ is decreasing.

- **Partial solar and storage investment equilibrium**: $K^* \in]0; \bar{K}[$ and $S^* \in]0; \bar{S}[$ is solution when:

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

and

$$(\beta\lambda + \psi(1 - \beta\lambda\rho_f) - 1)p - r_s = 0$$

This is the case when the solar capacity cost is $r = \tilde{r}$ and the storage capacity cost is $r_s = \tilde{r_s}$. It implies that $U'(K^*) < p$ given that $U'(.)$ is decreasing.

- **Maximal solar and partial storage investment equilibrium**: $K^* = \bar{K}$ $S^* \in]0; \bar{S}[$ is solution when:

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

and

$$(\beta\lambda + \psi(1 - \beta\lambda\rho_f) - 1)p - r_s = 0$$

This is the case when the solar capacity cost is $r < \tilde{r}$ and the storage capacity cost is $r_s = \tilde{r_s}$. It implies that $U'(\bar{K}) < p$ given that $U'(.)$ is decreasing.

- **Partial solar and maximal storage investment equilibrium**: $K^* \in]0; \bar{K}[$ and $S^* = \bar{S}$ is solution when:

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

and

$$\eta_3 = (\beta\lambda + \psi(1 - \beta\lambda\rho_f) - 1)p - r_s > 0$$

This is the case when the solar capacity cost is $r = \tilde{r}$ and the storage capacity cost is $r_s < \tilde{r_s}$. It implies that $U'(K^*) < p$ given that $U'(.)$ is decreasing.

- **Maximal solar and storage investment equilibrium**: $K^* = \bar{K}$ $S^* \in]0; \bar{S}[$ is solution when:

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

and

$$\eta_3 = (\beta\lambda + \psi(1 - \beta\lambda\rho_f) - 1)p - r_s > 0$$

This is the case when the solar capacity cost is $r < \tilde{r}$ and the storage capacity cost is $r_s < \tilde{r_s}$. It implies that $U'(\bar{K}) < p$ given that $U'(.)$ is decreasing.

Thus, if $\psi \leq \frac{1-\beta\lambda}{1-\beta\lambda\rho_f}$, depending on the size of the solar capacity cost we have two possible profiles: partial solar investment ($K^* = U'^{-1}((1 - \psi)p) + g_1$ and $S^* = 0$), maximal solar

investment ($K^* = \bar{K}$ and $S^* = 0$). Otherwise, if $\psi > \frac{1-\beta\lambda}{1-\beta\lambda\rho_f}$, depending on the size of the solar and storage capacity costs we have four extra possible profiles: partial solar and storage investment ($K^* = U'^{-1}((1-\psi)p) - U'^{-1}(p) + g_2^f + g_2^u$ and $S^* = \lambda^{-1}[U'^{-1}(p) - g_2^u]$), maximal solar and partial storage investment ($K^* = \bar{K}$ and $S^* = \lambda^{-1}[U'^{-1}(p) - g_2^u]$), and maximal solar and storage investment ($K^* = \bar{K}$ and $S^* = \bar{S}$).

Case 4 Let us consider $\phi_1 = \phi_2^f = \phi_2^u = (1-\psi)p$, from (3), (4) and (5) we have:

$$(1-\psi)p = U'(K - S - g_1) = U'(K + \lambda S - g_2^f) = U'(\lambda S - g_2^u)$$

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 $\eta_3 = -(1 - \beta\lambda(1-\psi))p - r_s < 0$ which is not possible. Thus, this case cannot be solution to the consumer problem.

Case 5 Let us consider $\phi_1 = p$ and $\phi_2^f = \phi_2^u = (1-\psi)p$, from (3), (4) and (5) we have:

$$p = U'(K - S + g_1) \quad \text{and} \quad (1-\psi)p = U'(K + \lambda S - g_2^f) = U'(\lambda S - g_2^u)$$

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 $\eta_3 = -(1 - \beta\lambda)(1-\psi)p - r_s < 0$ which is not possible. Thus, this case cannot be solution to the consumer problem.

Case 6 Let us consider $\phi_1 = \phi_2^f = p$ and $\phi_2^u = (1-\psi)p$, from (3), (4) and (5) we have:

$$p = U'(K - S + g_1) = U'(K + \lambda S + g_2^f) \quad \text{and} \quad (1-\psi)p = U'(\lambda S - g_2^u)$$

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 $(1-\psi)p > p$, 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 $\phi_1 = p$, $\phi_2^f = (1-\psi)p$ and $\phi_2^u = p$, from (3), (4) and (5) we have:

$$p = U'(K - S + g_1) = U'(\lambda S + g_2^u) \quad \text{and} \quad (1-\psi)p = U'(K + \lambda S - g_2^f)$$

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 $\eta_3 = -(1-\beta\lambda(1-\rho_f\psi))p - r_s < 0$ which is not possible. Thus, this case cannot a solution.

Case 8 Let us consider $\phi_1 = (1-\psi)p$, $\phi_2^f = p$ and $\phi_2^u = (1-\psi)p$, from (3), (4) and (5) we have:

$$(1-\psi)p = U'(K - S - g_1) = U'(\lambda S - g_2^u) \quad \text{and} \quad p = U'(K + \lambda S + g_2^f)$$

Notice that the above equations imply that that $(1-\psi)p > p$, 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.

Thus, only cases 1 and 3 are solution.

A.1.2 Feed-in-tariff smaller than the energy price

Case 1 Let us consider $\phi_1 = \phi_2^f = \phi_2^u = p$, 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:

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

This is the case when the solar capacity cost is $r = \bar{r}$. 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:

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

This is the case when the solar capacity cost is $r < \bar{r}$. It implies that $U'(\bar{K}) \geq p$ given that $U'(.)$ is decreasing.

Thus, depending on the solar capacity cost we have three different profiles: no investment ($K^* = S^* = 0$), partial solar investment ($K^* = U'^{-1}(p) - g_1$ and $S^* = 0$), and maximal solar investment ($K^* = \bar{K}$ and $S^* = 0$).

Case 2 Let us consider $\phi_1 = \tau - \psi p$ and $\phi_2^f = \phi_2^u = p$, from (3), (4) and (5) we now have:

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

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

Case 3 Let us consider $\phi_1 = \phi_2^f = \tau - \psi p$, and $\phi_2^u = p$, from (3), (4) and (5) we have:

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

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

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

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

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

we define the threshold values $\hat{r}=(1+\beta\rho_f)(\tau-\psi p)$ and $\hat{r_s}=\beta\lambda(1-\rho_f)p-(1-\beta\lambda\rho_f)(\tau-\psi p)$. Notice that if $K=0$, at $t=1$ we have $U'(0)=\infty$ which is not possible; thus, we have $K>0$. Also, only if $\tau>\psi p$ (respectively. $\frac{(\psi+\beta\lambda(1-\rho_f(1-\psi)))p}{1-\beta\lambda\rho_f}>\tau$), we have $\hat{r}>0$ ($\hat{r_s}>0$). As, τ is endogenous and $\frac{\psi+\beta\lambda(1-\rho_f(1-\psi))}{1-\beta\lambda\rho_f}>\psi$, we have six cases:

- **Partial solar investment equilibrium**: $K^*\in]0;\bar{K}[$ and $S^*=0$ is solution when:

  $$r-(1+\beta\rho_f)(\tau-\psi p)=0$$

  and

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

  This is the case when the solar capacity cost is $r=\hat{r}$ and the storage capacity cost is $r_s>\hat{r_s}$. It implies that $U'(K^*)<p$ given that $U'(.)$ is decreasing.

- **Maximal solar investment equilibrium**: $K^*=\bar{K}$ and $S^*=0$ is solution when:

  $$\eta_1=(1+\beta\rho_f)(\tau-\psi p)-r>0$$

  and

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

  This is the case when the solar capacity cost is $r<\hat{r}$ and the storage capacity cost is $r_s>\hat{r_s}$. It implies that $U'(\bar{K})<p$ given that $U'(.)$ is decreasing.

- **Partial solar and storage investment equilibrium**: $K^* \in]0; \bar{K}[$ and $S^* \in]0; \bar{S}[$ is solution when:

$$r - (1 + \beta\rho_f)(\tau - \psi p) = 0$$

and

$$\beta\lambda(1 - \rho_f)p - (1 - \beta\lambda\rho_f)(\tau - \psi p) - r_s = 0$$

This is the case when the solar capacity cost is $r = \hat{r}$ and the storage capacity cost is $r_s = \hat{r_s}$. It implies that $U'(K^*) < p$ given that $U'(.)$ is decreasing.

- **Maximal solar and partial storage investment equilibrium**: $K^* = \bar{K}$ $S^* \in]0; \bar{S}[$ is solution when:

$$\eta_1 = (1 + \beta\rho_f)(\tau - \psi p) - r > 0$$

and

$$\beta\lambda(1 - \rho_f)p - (1 - \beta\lambda\rho_f)(\tau - \psi p) - r_s = 0$$

This is the case when the solar capacity cost is $r < \hat{r}$ and the storage capacity cost is $r_s = \hat{r_s}$. It implies that $U'(\bar{K}) < p$ given that $U'(.)$ is decreasing.

- **Partial solar and maximal storage investment equilibrium**: $K^* \in]0; \bar{K}[$ and $S^* = \bar{S}$ is solution when:

$$r - (1 + \beta\rho_f)(\tau - \psi p) = 0$$

and

$$\eta_3 = \beta\lambda(1 - \rho_f)p - (1 - \beta\lambda\rho_f)(\tau - \psi p) - r_s > 0$$

This is the case when the solar capacity cost is $r = \hat{r}$ and the storage capacity cost is $r_s < \hat{r_s}$. It implies that $U'(K^*) < p$ given that $U'(.)$ is decreasing.

- **Maximal solar and storage investment equilibrium**: $K^* = \bar{K}$ $S^* \in]0; \bar{S}[$ is solution when:

$$\eta_1 = (1 + \beta\rho_f)(\tau - \psi p) - r > 0$$

and

$$\eta_3 = \beta\lambda(1 - \rho_f)p - (1 - \beta\lambda\rho_f)(\tau - \psi p) - r_s > 0$$

This is the case when the solar capacity cost is $r < \hat{r}$ and the storage capacity cost is $r_s < \hat{r_s}$. It implies that $U'(\bar{K}) < p$ given that $U'(.)$ is decreasing.

Thus, we six possible profiles: partial solar investment ($K^* = U'^{-1}(\tau - \psi p) + g_1$ and $S^* = 0$), maximal solar investment ($K^* = \bar{K}$ and $S^* = 0$), partial solar and storage investment ($K^* = U'^{-1}(\tau - \psi p) - U'^{-1}(p) + g_2^f + g_2^u$ and $S^* = \lambda^{-1}[U'^{-1}(p) - g_2^u]$), maximal solar and partial storage investment ($K^* = \bar{K}$ and $S^* = \lambda^{-1}[U'^{-1}(p) - g_2^u]$), and maximal solar and storage investment ($K^* = \bar{K}$ and $S^* = \bar{S}$).

Case 4 Let us consider $\phi_1 = \phi_2^f = \phi_2^u = \tau - \psi p$, from (3), (4) and (5) we have:

$$\tau - \psi p = U'(K - S - g_1) = U'(K + \lambda S - g_2^f) = U'(\lambda S - g_2^u)$$

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 $\eta_3 = -(1 - \beta\lambda)(\tau - \psi p) - r_s < 0$ which is not possible. Thus, this case cannot be solution to the consumer problem.

Case 5 Let us consider $\phi_1 = p$ and $\phi_2^f = \phi_2^u = \tau - \psi p$, from (3), (4) and (5) we have:

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

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 $\eta_3 = -p + \beta\lambda(\tau - \psi p) - r_s < 0$ which is not possible. Thus, this case cannot be solution to the consumer problem.

Case 6 Let us consider $\phi_1 = \phi_2^f = p$ and $\phi_2^u = \tau - \psi p$, from (3), (4) and (5) we have:

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

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 $\tau - \psi p > p$, 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 $\phi_1 = p$, $\phi_2^f = \tau - \psi p$ and $\phi_2^u = p$, from (3), (4) and (5) we have:

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

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 $\eta_3 = -(1 - \beta\lambda(1 - \rho_f(1 - \psi)))p + \beta\lambda 1 - \rho_f\tau - r_s < 0$ which is not possible. Thus, this case cannot a solution.

Case 8 Let us consider $\phi_1 = (1 - \psi)p$, $\phi_2^f = p$ and $\phi_2^u = \tau - \psi p$, from (3), (4) and (5) we have:

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

Notice that the above equations imply that that $\tau - \psi p > p$, 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.

Thus, only cases 1 and 3 are solution.

A.2 Quantity regulation

The Lagrangian of the consumer's problem is:

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

This yields to the following first order conditions:

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

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

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

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

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

plus the complementary slackness conditions.

Case 1 Let us consider $g_1 > 0$, $g_2^f > 0$ 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:

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

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

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

we define the threshold value $\bar{r} = (1 + \rho_f)p$. The second equation implies that $R^* = 0$, provided that both $\lambda^G \neq 1$ and $\alpha \neq 0$. Otherwise, if $\lambda^G = 1$ and $\alpha = 0$; then $R^* > 0$. Thus, there are three possible solutions:

- **No investment equilibrium**: $K^* = 0$ (and $R^* = 0$) is solution when:

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

  This is the case when the solar capacity cost is $r > \bar{r}$.

- **Partial solar investment equilibrium**: $K^* \in]0; \bar{K}[$ (and $R^* = 0$) is solution when:

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

  This is the case when the solar capacity cost is $r = \bar{r}$. 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:

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

  This is the case when the solar capacity cost is $r < \bar{r}$. It implies that $U'(\bar{K}) \geq p$ given that $U'(.)$ is decreasing.

Thus, we have three possible profiles: no investment ($K^* = R^* = 0$), partial solar investment ($K^* = U'^{-1}(p) - g_1$ and $R^* = 0$), and maximal solar investment ($K^* = \bar{K}$ and $R^* = 0$).

Case 2 Let us consider $g_1 = 0$, $g_2^f > 0$ and $g_2^u > 0$ ($\mu_4 > 0, \mu_5 = \mu_6 = 0$), 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 3 Let us consider $g_1 = g_2^f = 0$ and $g_2^u > 0$ ($\mu_4 > 0$, $\mu_5 > 0$, $\mu_6 = 0$), from (8), (9) and (10) we have:

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

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

$$(1 + \rho_f)U'(K) - r - \mu_1 + \mu_2 = 0$$

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

$$\mu_3 = \alpha + U'(K - R) - \lambda^G[\rho_f U'(K + \lambda^G R) + (1 - \rho_f)p] \geq 0$$

we define the threshold values $\ddot{r} = (1 + \rho_f)U'(K)$, $\underline{r} = U'(K - R) + \rho_f U'(K + \lambda^G R)$ and $\bar{\alpha} = \lambda^G[\rho_f U'(K + \lambda^G R) + (1 - \rho_f)p] - U'(K - R)$.
Notice that if $K = 0$ we have $U'(0) = \infty$ at $t = 1$ and $t = 2$ when $i = u$ which is not possible; thus, we have $K > 0$. Also, as $U'(.)$ is decreasing and since $R > \lambda^G R$, then we have $\underline{r} > \ddot{r}$ and $\bar{\alpha} > \hat{\alpha}$. Thus, there are three possible solutions:

- **Partial solar investment equilibrium**: $K^* \in]0; \bar{K}[$ and $R^* = 0$ is solution when:

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

and

$$\mu_3 = \alpha + U'(K) - \lambda^G[\rho_f U'(K) + (1 - \rho_f)p] > 0$$

This is the case when the solar capacity cost is $r = \ddot{r}$ and the grid tariff is $\alpha > \bar{\alpha}$. It implies that $U'(K^*) < p$ given that $U'(.)$ is decreasing.

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

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

and

$$\mu_3 = \alpha + U'(K) - \lambda^G[\rho_f U'(K) + (1 - \rho_f)p] > 0$$

This is the case when the solar capacity cost is $r < \ddot{r}$ and the grid tariff is $\alpha > \bar{\alpha}$. It implies that $U'(\bar{K}) < p$ given that $U'(.)$ is decreasing.

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

$$\mu_1 = U'(K - R) + \rho_f U'(K + \lambda^G R) - r > 0$$

and

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

This is the case when the solar capacity cost is $r < \ddot{r} < \underline{r}$ and the grid tariff is $\bar{\alpha} = \alpha$. It implies that $U'(\bar{K}) < p$ given that $U'(.)$ is decreasing.

Thus, we have three possible profiles: partial solar investment ($K^* = U'^{-1}(\frac{r}{1+\rho_f})$ and $R^* = 0$), maximal solar investment ($K^* = \bar{K}$ and $R^* = 0$), and maximal solar investment and storage ($K^* = \bar{K}$ and $R^* = \lambda^{G^{-1}}[U'^{-1}(p) - g_2^u]$).

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.

Thus, only cases 1 and 3 are solution.