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DO DYNAMIC TARIFFS PROMOTE INVESTMENT IN RENEWABLES? THE CASE OF A NON-REGULATED MONOPOLY

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ABSTRACT

We consider a non-regulated monopolist supplier of electricity that may use renewable and/or non-renewable resources to produce electricity. Renewable resources require an *ex ante* investment and generate an uncertain output having fixed operating costs. Non-renewable resources are perfectly dispatchable and have variable operating costs proportional to output. We find that dynamic tariffs promote investment in renewables in all scenarios except one where output from renewables when weather conditions are favorable is so large that the monopolist prefers to curtail excess energy. Only in that scenario, dynamic tariffs decrease investment. In any case, dynamic tariffs are welfare-improving in that both the monopolist and consumers become better off.

1. INTRODUCTION

Climate change made energy policy an even more important issue in global governance. The transition from energy production strongly dependent on fossil fuels to one based on renewable resources is a shared aspiration, as made evident by the Paris Agreement on climate change (Layer et al., 2017). One of the supranational bodies most involved in this endeavor is the European Union (Helm, 2014), which has carried out a package of structural measures, the 2020 Energy Strategy, with the objective of improving energy efficiency by 20%, increasing the share of renewable energy to 20%, and reducing greenhouse gas emissions by 20% (Kanellakis et al., 2013).

Decarbonization in the European Union requires a paradigm change in the productive sector of member countries. It is reasonable to expect the stimulus to renewable energies to significantly increase their market share (Bergaentzlé et al., 2019), but for this push to take place within a well-defined institutional framework, appropriate instruments are needed to manage the transition to renewable energies (Zhou et al., 2019). It would be important to foster the reduction of electricity consumption in peak periods, and to avoid or at least defer costly investments in production and transmission capacity, which would likely lead to an increase of average electricity prices (Ericson, 2011).

Electricity is a good with very particular characteristics. Production is determined by rigid restrictions in the short term and, most importantly, electricity cannot be stored. These characteristics cause, at certain times, overproduction that is not matched by demand and whose only costs are those associated with raw materials and maintenance. At other times, in contrast, capacity constraints increase costs and, consequently, prices (Borenstein, 2005).

Dynamic pricing is a demand-side management technique that has been proposed as a response to these problems. By charging different prices at different hours of the day according to the current conditions of demand and supply, dynamic pricing attempts to shape demand in order to achieve more efficient outcomes. In particular, dynamic pricing reduces the maximum peak load, reduces the opportunity cost implicit in wasting the maximum load outside consumption peaks, and reduces the need for peak capacity investments (Dutta and Mitra, 2017).

The literature on dynamic tariffs distinguishes three major types of dynamic tariffs: time-of-use pricing, critical peak pricing, and real time pricing. Time-of-use tariffs are the most widely used but the least dynamic among dynamic tariffs. They usually consist of a connection charge and consumption-dependent charges under a fixed timetable for a long period. Critical peak tariffs involve the announcement of extraordinary events, penalizing or even interrupting consumption during those critical peak periods. The purest form of dynamic tariffs is real-time pricing, whereby prices change at regular intervals of one hour or a few minutes, rapidly adjusting to the conditions of supply and demand. Different combinations of these characteristics are also possible (Ericson, 2011; Layer et al., 2017).

In a context of energy transition, where renewable energies are increasingly important in electricity generation, it is important to understand whether dynamic tariffs are a relevant instrument for the promotion of renewable energies. Uncertainty and intrinsic variability of weather conditions have a significant impact on the level of renewable energy production, aggravating the problem of matching demand and supply of electricity. As a result, the level of production of renewable energies may not coincide temporarily with the level of demand for electricity, thus the energy network may act as a sink or source depending on whether there is excess demand or supply (Philippou et al., 2016).

Bearing this in mind, we develop a model where a monopolist supplier of electricity may use renewable and/or non-renewable resources to produce electricity. Production using renewable resources requires an *ex ante* investment and is subject to uncertainty and variability of weather conditions (which may be more or less propitious to the production of energy using renewable resources). By contrast, output from non-renewable resources is assumed to be perfectly controllable. We assess the impact of dynamic tariffs vis-à-vis static tariffs on economic outcomes, such as investment in renewable energy production, price, quantity consumed, profit and consumer surplus.

We find that dynamic tariffs do not influence the regime of energy production, that is, on whether production: is exclusively based on non-renewable resources (non-renewable regime); uses renewable resources but also non-renewable resources to match demand when renewable resources do not suffice (mixed regime); or is exclusively based on renewable resources (renewable regime). The monopolist always chooses the production regime that is more efficient, independently of whether tariffs are static or dynamic. If the productivity of renewable energy production is relatively low even with favorable weather conditions, then only non-renewable resources are used. If the productivity of renewable energy production is relatively high even with unfavorable weather conditions, then only renewable resources are used. If productivity is intermediate, then both renewable and non-renewable resources are used.

Nevertheless, dynamic tariffs do have a significant quantitative impact on investment in renewable energy production, and thus on prices, quantities, profit and consumer surplus. In the mixed regime, dynamic tariffs stimulate investment. In the renewable regime, the impact of dynamic tariffs on investment depends on the ratio between the productivities of renewable energy production with favorable and with unfavorable weather conditions. If this ratio is so high that the monopolist prefers to dispose of excesss supply when conditions are favorable, then dynamic tariffs reduce investment. If it is not that high, then dynamic tariffs stimulate investment. In all scenarios, dynamic tariffs improve welfare: the profit of the monopolist and consumer surplus are both unambiguously higher with dynamic tariffs.

2. A BRIEF SURVEY OF THE LITERATURE

Technological innovation and consumer empowerment are introducing complex challenges to the design of electricity tariffs, as recognized by Wood and Farouqui (2010) and Zhou et al. (2017), among others. While, previously, electricity flows travelled from generation through transmission and down to distribution, high levels of distributed energy resources may generate flows in the opposite direction. Therefore, traditional tariff design based on assuming passive consumers cannot deal adequately with the new paradigm of smart distribution networks and active consumers.

Electricity tariffs can be static or dynamic. The advantages of static tariffs are their simplicity and the low risk faced by consumers. On the other hand, they require significant capacity investments to meet peak demand. Dynamic tariffs, by contrast, adjust to supply and demand conditions, providing incentives for consumers to shift demand from peak periods to off-peak periods, reducing the need for investments in production and transmission capacity.

Commonly used electricity pricing policies are briefly described below (Dutra and Mitra, 2017; EURELECTRIC, 2017; Layer et al., 2017; Simshauser and Downer, 2014; Faruqui and Palmer, 2012; Quillinan, 2011):

1. Flat tariffs: Price is constant and independent of demand and supply. Consumers are not affected by variations in the cost of power supply, and thus have no incentive to shift demand from peak to off-peak periods.
2. Block rate tariffs: Price depends on the consumption level of the consumer. There are multiple blocks, and prices may increase or decrease across blocks.
3. Seasonal tariffs: Price varies across seasons, reflecting the varying demand due to the greater need for heating in the winter and for cooling in the summer.
4. Time-of-use tariffs: Price varies in a pre-declared way along the day, being higher during peak hours and lower during off-peak hours.
5. Variable peak pricing: Price in peak hours varies daily according to supply and demand conditions. Consumers are informed about peak prices beforehand.
6. Critical peak tariffs: In a limited number of days per year, utilities may declare a critical event and charge a higher price during a short period. Peak hours and price may be pre-declared or event-specific. Instead of being charged a higher price, consumers may receive a rebate if their consumption is low at critical peak periods.
7. Real-time pricing: Price adjusts at regular intervals of one hour or a few minutes, reflecting current conditions of supply and demand.

While flat and block tariffs are static, the other pricing policies described above are more or less dynamic. The purest form of dynamic pricing is, of course, real-time pricing. It may provide important efficiency gains, but requires advanced technology to communicate prices to consumers and to collect and transfer consumption data. Borenstein (2009) explained the superiority of dynamic tariffs in terms of economic efficiency, and also that dynamic tariffs reduce the exercise of market power by sellers. In our model, by contrast, the exercise of market power is not limited by dynamic tariffs. This may be due to the consideration of a monopolistic instead of an oligopolistic market structure.

Electricity production using renewable resources has almost no marginal cost and a highly variable and uncontrollable level of output, which aggravates the problem of equating supply and demand in the electricity grid. This suggests that dynamic tariffs may support the integration of renewables, because dynamic tariffs shape demand by penalizing consumption when residual load (demand minus renewable power output) is high and favoring consumption when residual load is low. Loisel et al. (2010) pointed out that controllability of feed-in of renewable technologies (solar and wind) is limited to curtailment. Without significant improvements in storage technologies and electricity exchange with neighboring countries, decarbonization must rely on increased demand-side flexibility. Dynamic tariffs are a valuable way to achieve this flexibility at a relatively low cost (Grünewald et al., 2015).

Our paper is related to the literature on the theory of peak pricing, which seeks to characterize the socially optimal investment and price levels in markets where demand for a non-storable good fluctuates. This literature goes back to the seminal contributions of Boiteux (1949, 1951) and Steiner (1957), who focused on deterministic environments. Crew and Kleindorfer (1976) addressed demand uncertainty, and Kleindorfer and Fernando (1993) addressed supply uncertainty. More recently, Chao (2011) investigated the case of production using intermittent renewable resources.

The traditional literature on peak pricing takes the perspective of a benevolent social planner, but there is recent research taking the perspective of a profit-maximizing firm, as in our paper. Notably, Kök, Shang and Yücel (2018) investigated the impact of peak pricing on renewable energy investments and carbon emissions. In contrast with our results, they found that flat pricing may lead to higher investment, lower carbon emissions and higher consumer surplus.

3. MODEL

A monopolist produces electricity using renewable (solar, wind) and non-renewable (coal, gas) resources. Output from renewable resources depends on the amount of investment made *ex ante*, $I \in \mathrm{IR}_+$, and on the state of nature, $\theta \in \{L,H\}$. In state θ, output per unit of investment is $R_\theta \in \mathrm{IR}_+$. Without loss of generality, we assume that $R_H \geq R_L$, which means that H is the good state (weather conditions are favorable for electricity production) and L is the bad state (weather conditions are adverse). The bad state (L) occurs with probability $\alpha \in (0,1)$, and the good state (H) with probability $1\text{-}\alpha$. Output from non-renewables does not require investment (existing capacity is sufficient), is perfectly dispatchable, and has constant unit cost, $c \in \mathrm{IR}_+$. We assume that $c<1<R_H$ for both types of resources to be potentially profitable.

We assume demand is independent of the state of nature and given by $Q_\theta = 1\text{-}P_\theta$, where P_θ and Q_θ are, respectively, price charged and quantity demanded in state θ. Dynamic tariffs allow the monopolist to set state-contingent prices ($P_L \neq P_H$). Static tariffs restrict the monopolist to set a price that does not depend on the state of nature ($P_L = P_H$).

Below, we assess the impact of dynamic tariffs (compared to static tariffs) on: investment in renewables, prices charged and quantities sold, monopolist profit, consumer surplus and total surplus.

3.1 Static Tariffs

With static tariffs, the timing of the model is the following:

1. Monopolist chooses the amount of investment in renewables, I.
2. Monopolist sets the price of electricity, P.
3. Nature determines the state of nature, θ.
4. Consumers choose their consumption level, $Q = 1\text{-}P$.
5. If demand exceeds supply from renewables, $Q > IR_\theta$, non-renewable resources are used to meet demand.

The expected profit of the monopolist is: $\pi_{ST} = PQ - \alpha c Q_L^N - (1\text{-}\alpha)cQ_H^N - I$, where $Q_\theta^N = \max\{Q\text{-}IR_\theta\ ;\ 0\}$ is the output from non-renewables in state $\theta \in \{L,H\}$. Consumer surplus is: $EC_{ST} = Q^2/2$.

3.2 Dynamic Tariffs

With dynamic tariffs, the timing of the model is the following:

1. Monopolist chooses the amount of investment in renewables, I.
2. Nature determines the state of nature, θ.
3. Monopolist sets the price of electricity, P_θ.
4. Consumers choose their consumption level, $Q_\theta = 1\text{-}P_\theta$.
5. If demand exceeds supply from renewables, $Q_\theta > IR_\theta$, non-renewable resources are used to meet demand.

The expected profit of the monopolist is: $\pi_{DT} = \alpha\ (P_LQ_L - cQ_L^N) - (1\text{-}\alpha)(P_HQ_H - cQ_H^N) - I$, and the expected value of consumer surplus is: $EC_{DT} = \alpha(Q_L^2/2) + (1\text{-}\alpha)(Q_H^2/2)$. Notice that this profit function also applies to static tariffs. The only difference is that, with dynamic tariffs, price can be state-dependent ($P_L \neq P_H$).

4. ANALYSIS

It is useful to write the profit of the monopolist as a function of investment and prices: $\pi(I,P_L,P_H) = \alpha P_L(1\text{-}P_L) + (1\text{-}\alpha)P_H(1\text{-}P_H) - \alpha c \max\{1\text{-}P_L\text{-}IR_L\ ;\ 0\} - (1\text{-}\alpha)c \max\{1\text{-}P_H\text{-}IR_H\ ;\ 0\} - I$.

Proposition 1: *Since the same profit function applies for static and dynamic tariffs, but static tariffs restrict the choice of the monopolist (P_L=P_H), the monopolist can attain at least the same profit with dynamic tariffs as with static tariffs.*

For given prices, (P_L,P_H), which determine total output, (Q_L,Q_H), an additional unit of investment in renewables reduces the expected cost from using non-renewables by αcR_L if non-renewables are used in the bad state (i.e., if $Q_L^N>0$) and, in addition, by $(1-\alpha)cR_H$ if non-renewables are also used in the good state (i.e., if $Q_H^N>0$). This leads to the following characterization on whether renewables and/or non-renewables are used as a function of the parameters of the model.

Proposition 2: *Whether renewables or non-renewables are used does not depend on whether tariffs are static or dynamic. The choice of production regime is purely based on efficiency:*

- *If investing in renewables just for producing in the bad state is more efficient than using non-renewables ($\alpha R_L>1/c$), then only renewables are used in both states. Otherwise, non-renewables are used at least in the bad state.*
- *If investing in renewables for producing in both states is less efficient than using non-renewables ($\alpha R_L+(1-\alpha)R_H<1/c$), then only non-renewables are used. Otherwise, only renewables are used at least in the good state.*

Dynamic tariffs do not have an impact on whether renewables are used or not, but have an impact on the magnitude of investment on renewables. We assess this impact separately for each of the three regimes that result from Proposition 2.

4.1 Only non-renewables are used

If only non-renewables are used ($\alpha R_L+(1-\alpha)R_H>1/c$), profit is: $\pi^N(P_L,P_H) = \alpha(P_L-c)(1-P_L) + (1-\alpha)(P_H-c)(1-P_H)$. The state of nature is irrelevant (it would only affect the output from renewables), thus prices and output are constant across states. Therefore, whether tariffs are static or dynamic is also irrelevant. Profit-maximization yields:

$$\begin{cases} P_L = P_H = \dfrac{1+c}{2} \\ I = 0 \end{cases} \Rightarrow \begin{cases} \pi = \dfrac{(1-c)^2}{4} \\ EC = \dfrac{\pi}{2} \end{cases} \tag{1}$$

Proposition 3: *If $\alpha R_L+(1-\alpha)R_H < 1/c$, only non-renewables are used. Whether tariffs are static or dynamic is irrelevant.*

4.2 Both renewables and non-renewables are used

If only renewables are used in the good state but non-renewables are used to meet demand in the bad state ($\alpha R_L < 1/c < \alpha R_L+(1-\alpha)R_H$), investment is such that output from renewables matches demand in the good state: $I=(1-P_H)/R_H$. Profit is: $\pi^M(P_L,P_H) = \alpha(P_L-c)(1-P_L) + (1-\alpha)\{P_H-(1-\alpha cR_L)/[(1-\alpha)R_H)]\}(1-P_H)$. With static tariffs, profit-maximization yields:

$$\begin{cases} P = \dfrac{1}{2}\left(1+\alpha c+\dfrac{1-\alpha cR_L}{R_H}\right) \\ I = \dfrac{1}{2R_H}\left(1-\alpha c-\dfrac{1-\alpha cR_L}{R_H}\right) \end{cases} \Rightarrow \begin{cases} \pi = \dfrac{1}{4}\left(1-\alpha c-\dfrac{1-\alpha cR_L}{R_H}\right)^2 \\ EC = \dfrac{\pi}{2} \end{cases} \tag{2}$$

While the outcome with dynamic tariffs is:

$$\begin{cases} P_L = \dfrac{1+c}{2} \text{ and } P_H = \dfrac{1}{2}\left[1+\dfrac{1-\alpha cR_L}{(1-\alpha)R_H}\right] \\ I = \dfrac{1}{2R_H}\left[1-\dfrac{1-\alpha cR_L}{(1-\alpha)R_H}\right] \end{cases} \Rightarrow \begin{cases} \pi = \dfrac{\alpha(1-c)^2}{4}+\dfrac{1-\alpha}{4}\left[1-\dfrac{1-\alpha cR_L}{(1-\alpha)R_H}\right]^2 \\ EC = \dfrac{\pi}{2} \end{cases} \tag{3}$$

Proposition 4: *If $\alpha R_L < 1/c < \alpha R_L+(1-\alpha)R_H$, both renewables and non-renewables are used. In this case, dynamic tariffs promote investment in renewables and increase profit and consumer surplus.*

To understand why dynamic tariffs promote investment in renewables, note that, in this regime, output from renewables matches demand in the good state. Dynamic tariffs lower price in the good state (and raise price in the bad state), thus demand in the good state increases and therefore investment also increases.

4.3 Only renewables are used

If only renewables are used ($\alpha R_L > 1/c$) investment is such that output from renewables matches demand in the bad state: $I=(1-P_L)/R_L$. Profit is: $\pi^R(P_L,P_H) = \alpha P_L(1-P_L) + (1-\alpha)P_H(1-P_H) - (1-P_L)/R_L$. With static tariffs, since consumption is constant across states, output from renewables in the good state exceeds consumption. Assuming that the monopolist is able to dispose of excess output at no cost, profit is: $\pi_{ST}^{R}(P)=(P-1/R_L)(1-P)$. Maximizing, we obtain:

$$\begin{cases} P=\frac{1}{2}\left(1+\frac{1}{R_L}\right) \\ I=\frac{1}{2R_L}\left(1-\frac{1}{R_L}\right) \end{cases} \Rightarrow \begin{cases} \pi=\frac{1}{4}\left(1-\frac{1}{R_L}\right)^2 \\ EC=\frac{\pi}{2} \end{cases} \tag{4}$$

With dynamic tariffs, the output from renewables in the good state (IR_H) may or not exceed the output that maximizes revenue ($Q_H=1/2$), thus $Q_H = \max\{IR_H \,;\, 1/2\}$. If it does not exceed, profit is: $\pi_{DT}^{R1}(P_L) = [\alpha+(1-\alpha)R_H^2/R_L^2](P_L-\beta)(1-P_L)$, where: $\beta = [R_H^2-R_LR_H+R_L/(1-\alpha)]/[R_H^2+\alpha R_L^2/(1-\alpha)]$. Maximizing, we find:

$$\begin{cases} P_L=\frac{1+\beta}{2} \text{ and } P_H=1-\frac{1-\beta}{2}\frac{R_H}{R_L} \\ I=\frac{1-\beta}{2R_L} \end{cases} \Rightarrow \begin{cases} \pi=\left[\alpha+(1-\alpha)\frac{R_H^2}{R_L^2}\right]\frac{(1-\beta)^2}{4} \\ EC=\frac{\pi}{2} \end{cases} \tag{5}$$

If there is excess output from renewables in the good state, then $P_H=1/2$ and $Q_H=1/2$, and profit is: $\pi_{DT}^{R2}(P_L) = \alpha[P_L-1/(\alpha R_L)](1-P_L)+(1-\alpha)/4$. Maximizing, we obtain:

$$\begin{cases} P_L=\frac{1}{2}\left(1+\frac{1}{\alpha R_L}\right) \text{ and } P_H=\frac{1}{2} \\ I=\frac{1}{2R_L}\left(1-\frac{1}{\alpha R_L}\right) \end{cases} \Rightarrow \begin{cases} \pi=\frac{\alpha}{4}\left(1-\frac{1}{\alpha R_L}\right)+\frac{1-\alpha}{4} \\ EC=\frac{\pi}{2} \end{cases} \tag{6}$$

Observe that, with dynamic tariffs, output from renewables in the good state is above the output that maximizes revenue and profit ($IR_H>1/2$) if and only if $R_H > \alpha R_L^2/(\alpha R_L-1)$.

Proposition 5: *Suppose only renewables are used ($\alpha R_L > 1/c$). If there is not excess output in the good state ($R_H < \alpha R_L^2/(\alpha R_L-1)$), dynamic tariffs promote investment in renewables. Otherwise, they reduce investment in renewables.*

Some of our results are summarized in Figure 1. Proofs are available upon request.

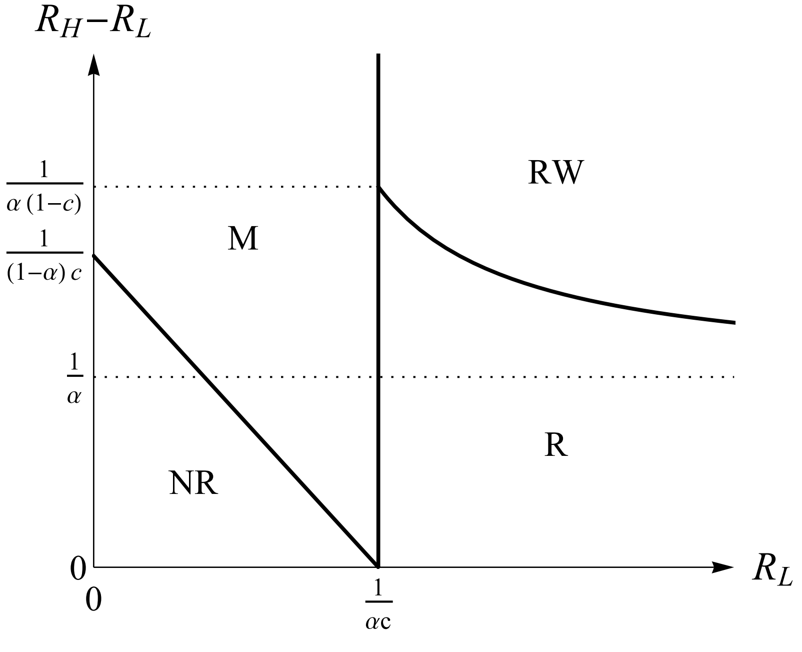

Figure 1: Energy mix as a function of the efficiency of renewables: [NR] non-renewables; [M] renewables with non-renewables as backup; [R] renewables, no curtailment; [RW] renewables, curtailment in the good state.

CONCLUSIONS

We assessed the impact of dynamic tariffs on investment in renewable energy production, considering a monopolist supplier that is not subject to any form of regulation. We found that, depending on the output of renewables per unit of investment, the monopolist may: not use renewables at all (non-renewables regime); produce using renewables with non-renewables as backup (mixed regime); or use renewables exclusively (renewables regime). Whether tariffs are static or dynamic does not influence the choice of regime by the monopolist. The most efficient regime is used by the monopolist anyway. However, the introduction of dynamic tariffs increases the magnitude of investment in renewables in the mixed regime, and may increase or decrease the magnitude of investment in renewables in the renewables regime. In the renewables regime, whether dynamic tariffs foster or hamper investment depends on the output from renewables per unit of investment when weather conditions for electricity production are favorable. If the output is so large that the monopolist disposes of excess energy, then dynamic tariffs hamper investment. Otherwise, dynamic tariffs foster investment in renewables. In all scenarios, dynamic tariffs make both the monopolist and consumers better off.

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