GrEnFIn

Greening Energy Market and Finance

Strategic interaction of centralised and distributed generation

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Project website: http://grenfin.eu

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Agenda

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A bit of a context

- Climate change & decarbonization of electricity (1/3 of fuel combustion comes from power systems, IEA 2015)
- Renewable energy sources (wind & solar energy)
- No added carbone but intermitency (volatil and non-dispatchable)
- Some renewable energy sources are distributed: connected at a low level of the distribution network
- Rooftop PV leads to self-consumption

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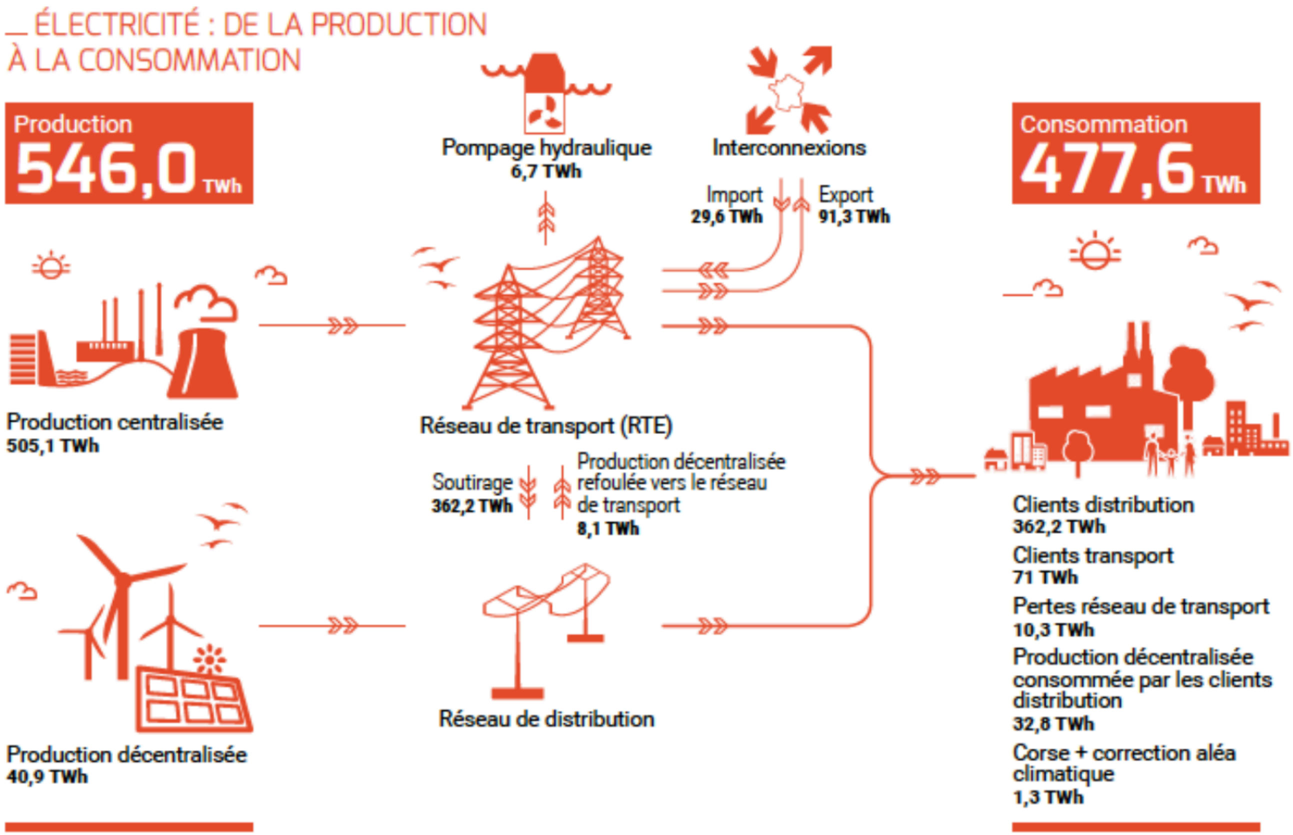
Distributed generation in France



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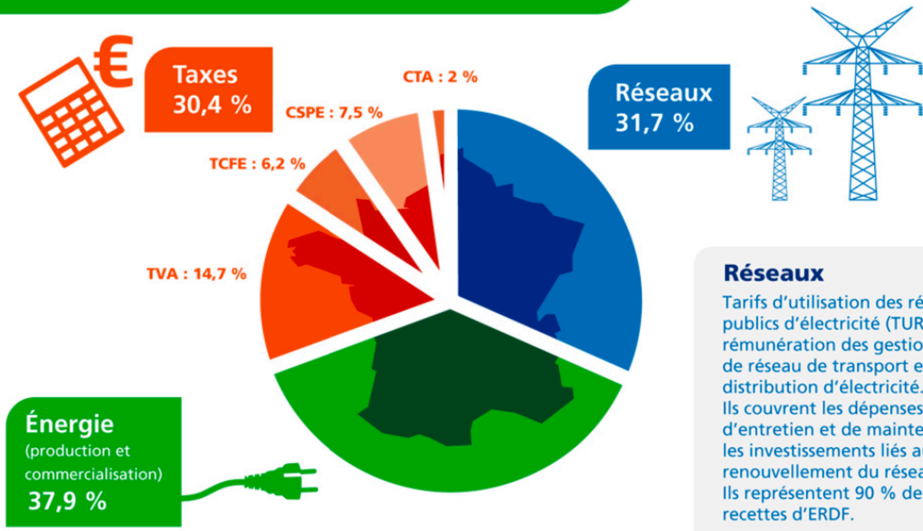
Your electricity bill

MIEUX COMPRENDRE LE PRIX DE L'ÉLECTRICITÉ

COMMENT EST COMPOSÉE UNE FACTURE D'ÉLECTRICITÉ EN FRANCE ?

Taxes

- **TVA** : en métropole, elle est à 5,5 % sur l'abonnement et les taxes locales correspondantes et à 19,6 % sur la consommation et les taxes correspondantes.
- **TCFE** : taxe sur la consommation finale d'électricité. Réservée aux communes, aux départements et à l'État.
- **CSPE** : contribution au service public de l'électricité, visant à compenser les charges liées aux missions de service public mises à la charge de certains fournisseurs d'énergie.
  Elle sert notamment à financer : les surcoûts de production d'électricité dans les îles, les politiques de soutien aux énergies renouvelables, le tarif social en faveur des clients démunis.
  Elle est calculée en fonction de la consommation électrique.
- **CTA** : contribution tarifaire d'acheminement, servant à financer les retraites des employés des industries électrique et gazière.



Réseaux

Tarifs d'utilisation des réseaux publics d'électricité (TURPE) : rémunération des gestionnaires de réseau de transport et de distribution d'électricité.
Ils couvrent les dépenses d'entretien et de maintenance, les investissements liés au renouvellement du réseau.
Ils représentent 90 % des recettes d'ERDF.

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Distributed generation in the economic literature

- True cost of renewable energy sources: externality cost induced by intermitency Joskow (2011), Borenstein (2012)
- Economic viability of renewable energy in the market Green & Leautier (2015)
- Efficient metering Gautier, Jaqmin & Poudoux (2017)

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Our field of inquiry

- Distributed generation gives consumers generation capacities.
- At the expense of investing in solar PV, consumers may reduce their bill.
- Knowing that consumers have now an alternative way of getting energy, centralised generation firms may reconsider their selling price.
- Does this new deal between producers and consumers drastically change the equilibrium retail price?

Remarks

- It is not a problem of price elasticity of consumption.
- The consumer has to invest in distributed generation to potentialy reduce their electricity bill.

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Example in a static deterministic externality-free framework

The consumer with captive electricity demand d can investment α in distributed generation and buy $d - \alpha$ at the price of centralised electricity p. Her objective is to minimize:

$$J_c(\alpha) = \frac{c}{2}\alpha^2 + p\,(d - \alpha)$$

The poducer can invest in a generation capacity q, decide the price p at which he sells electricity to the consumer but commit to satisfy the residual demand of the consumer. His objective is to minimize:

$$J_g(q, p) = \frac{k}{2}q^2 - p\,(d - \alpha) + \frac{\lambda}{2}\,(d - \alpha - q)^2$$

The demand d could be elastic w.r.t. p. The model would just melt the effect of elasticity and the effect of investment in distributed generation.
Up to now, we don't say much about the timing of the decisions.

Pareto optimum

The economic optimum is given by the best trade-off of α and q to minimize the sum of both objective functions. The social planner would solve:

$$\inf_{\alpha,q} J_g(q,p) + J_c(\alpha).$$

The price is just a transfer between the producer and the consumer and disappers from the objective. The optimal quantities are:

$$\alpha_e = \frac{1}{1+\gamma} d, \quad q_e = \frac{c}{k}\frac{1}{1+\gamma} d,$$

with $\gamma = \frac{c}{k} + \frac{c}{\lambda}$.
No surprise: trade-off depends on relative costs of both technologies c and k.
Further, there is price that will realise the economic equilibrium above. It is given by:

$$p_e = \left[\frac{1}{c} + \frac{1}{k} + \frac{1}{\lambda}\right]^{-1} d.$$

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Market equilibrium

Market = non-regulated market. Pure *Laissez-faire* between the two players.
In these conditions, it is not possible to define the market equilibrium as a triplet $(\alpha^\star, q^\star, p^\star)$ such that:

$$\inf_{\alpha} J_c(\alpha) = J_c(\alpha^\star) \quad \inf_{q,p} J_g(q,p) = J_g(q^\star, p^\star).$$

Because, this definition does not reflect the timing of the decisions:

- First, the producer makes an investment q for which he claims the price p in exchange of his commitment to satisfy the consumer's demand.
- Knowing the price p of centralised electricity, the consumer can decide the level of distributed generation α.
- It is not a simultaneous equilibrium but a hierarchical equilibrium.
- Competition between several producers or consumer's price elasticity are not necessary to define an equilibrium. Hierarchical ordering of decisions is enough.

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Market equilibrium as a Stackelberg equilibrium

Knowing that the consumer will minimize $J_c(\alpha)$ for any given p, the producer can compute the consumer's best respons $\alpha_s(p)$ and deduce the optimal price p_s and quantity q_s.

This market equilibrium is given by:

$$p_s = \left(1 + \frac{\gamma^2}{1+2\gamma}\right) p_e, \quad \alpha_s = \left(1 + \frac{\gamma^2}{1+2\gamma}\right) \alpha_e, \quad q_s = \left(1 - \frac{\gamma}{1+2\gamma}\right) q_e,$$

with $\gamma = \frac{c}{k} + \frac{c}{\lambda}$.

The Stackelberg price is higher than the Pareto price and so is the distributed generation. And there is a welfare loss.

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Beyond static deterministic model

Limitations

- No intermittency of the distributed generation
- No transmission and distribution infrastructure cost
- No carbon externality
- No dynamics of investment

- Overcoming those limitations thanks to newly analytical optimization technics... but at the expense of some violence made to economic hypothesis by the linear-quadratic dynamic framework.
- Next model relies on a joint work with Huyên Pham (Paris University) and Matteo Basei (EDF R&D) published in *Math. Methods in Operations Research*, 2020.

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Model

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Model

We consider two players:

- a representative consumer who can invest in solar panels to self-consume electricity
- a representative firm who can invest in centralised emissive generation to satisfy consumer's residual demand consumer decides the level of solar panel to invest in.

And two situations:

- social optimum: a social planner who seeks the optimal trade-off between distributed and centralised generation
- market *laissez-faire*: a Stackelberg game between the firm (Leader) and the consumer (Follower): the firm announces the energy price and then, the consumer decides the level of solar panel to invest in.

We focus on the long-term behaviour of each player and on stationary states.

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The consumer

$$\inf_{\alpha} J_c(\alpha) := \mathbb{E}\left[\int_0^\infty e^{-\rho t}\Big(c\alpha_t + \gamma\alpha_t^2 + (P_t + \theta)(D - X_t^\alpha) + \eta \mathrm{Var}[X_t^\alpha]\Big)\,dt\right]$$

- α_t is the PV capacity installation buying rate at time t
- $dX_t^\alpha = b\,\alpha_t dt + \sigma X_t^\alpha dW_t$ the dynamics of the energy produced by the panels.
- Investment cost function: c per unit investment cost, γ: per unit adjustment cost.
- D is the consumer's electricity demand taken to be constant.
- $D - X_t^\alpha$ is the energy bought by the consumer from the firm at price P_t
- Generation variance $\mathrm{Var}[X_t^\alpha]$ induces extra-cost to the consumer or a disutility.
- P_t random coefficient.

Remarks

- No model on P_t. Considered as a random coefficient.
- Transmission cost, distribution cost and taxes are taken in the θ parameter.

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The firm

$$\inf_{\nu} J_f(\nu) := \mathbb{E}_x\Big[\int_0^\infty e^{-\rho t}\Big(h\nu_t + \delta\nu_t^2 - P_t\big(D - X_t^\alpha\big) + \pi Q_t^\nu + \lambda\big(D - X_t^\alpha - Q_t^\nu\big)^2\Big)dt\Big]$$

- ν_t be the firm investment rate in generation at time t
- $dQ_t^\nu = \nu_t dt$ the dynamics of the energy produced.
- Investment cost function: c per unit investment cost, γ: per unit adjustment cost.
- Firm's generation is subject to carbon tax π.
- The firm receives $P_t\big(D - X_t^\alpha\big)$ for the consumer's residual demand purchase.
- The firm commitment to consumer's residual demand translates in a penalisation between Q_t^ν and $D - X_t^\alpha$.

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The social planner

$$\begin{aligned} J(\alpha,\nu) &= J_c(\alpha) + J_f(\nu; X^\alpha) \\ &= \mathbb{E}\Big[\int_0^\infty e^{-\rho t}\Big(C_c(\alpha_t) + C_f(\nu_t) + \theta(D - X_t^\alpha) + \pi\, Q_t^\nu \\ &\qquad + \eta \mathrm{Var}[X_t^\alpha] + \lambda\big(D - X_t^\alpha - Q_t^\nu\big)^2\Big)\Big]. \end{aligned}$$

$$dX_t^\alpha = b\alpha_t dt + \sigma X_t^\alpha dW_t, \qquad dQ_t^u = u_t dt.$$

Remarks

- The social optimum no longer depends on P_t (transfert between the consumer to the firm).

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Results

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Agents' behaviour

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Proposition 1 — Consumer's long-term behaviour

Assume the price process admits a stationary limit $\overline{P} > 0$. Then, the optimal expected cumulative production of distributed generation admits a stationary level:

$$\widehat{X}_\infty(\overline{P}) := \frac{\overline{P} + \theta - \frac{\rho c}{b}}{2\sigma^2 K}, \tag{1}$$

where $K = \frac{\gamma}{2b^2}\left(-(\rho - \sigma^2) + \sqrt{(\rho - \sigma^2)^2 + \frac{4b^2\eta}{\gamma}} \right)$, and the expected investment rate in distributed generation tends to zero.

- The consumer's compares the total cost of electricity $(\overline{P})$ plus transmission cost θ to distributed technology investment cost annuity $\rho c/b$.
- Consumer's behaviour equivalent to having an inverse demand function with elasticity $1/(2\sigma^2 K)$.
- Consumer's investment decreases with volatility, intermittency cost and adjustment cost ($\sigma \searrow \quad \eta \searrow \quad \gamma \searrow$)

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Proposition 2 — Firm's long-term behaviour

When the distributed production process has an expected stationary level $X_\infty^\alpha > 0$, the optimal cumulative production of centralised generation also admits an expected stationary level given by:

$$\widehat{Q}_\infty(X^\alpha) := D - X_\infty^\alpha - \frac{\pi + \rho h}{2\lambda}, \tag{2}$$

and the investment rate in centralised generation tends to zero. In particular, if the price process admits a stationary level $\overline{P} > 0$, the limit of the centralised production reads as:

$$\widehat{Q}_\infty(\overline{P}) := D - \widehat{X}_\infty(\overline{P}) - \frac{\pi + \rho h}{2\lambda}. \tag{3}$$

- The firm's investment corresponds to the consumer's residual demand up to a negligeable term.

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Proposition 3 — Social planner's long-term behaviour

The expected optimal cumulative production of the social planner's problem admits a stationary level:

$$X^*_\infty := \frac{\rho h + \pi - (\frac{\rho c}{b} - \theta)}{2\sigma^2 K^{11}} \quad Q^*_\infty := D - X^*_\infty - \frac{\pi + \rho h}{2\lambda}, \tag{4}$$

where K^{11} is a constant solution of a stochastic Ricatti algebraic system.

Property

- The social planner will invest in distributed generation iff its net cost $\frac{\rho c}{b} - \theta$ is lower than the total cost of the centralised technology $\rho h + \pi$ (distributed generation is a substitute to transmission infrastructure).

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Properties

- Social investment in distributed energy decreases with volatility, intermittency cost, and adjustment cost of both technologies γ and δ (K^{11} increasing function of both γ and δ).
- If the initial state is $Q_0 = D$ and $h = 0$ (no gain in disinvesting), high carbon tax is required to justify switching from centralised to distributed generation.

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Equilibrium price

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Asymptotic Pareto equilibrium price

An asymptotic Pareto optimum price is a constant P^* such that

$$\widehat{X}_\infty(P^*) = X^*_\infty.$$

An asymptotic Pareto optimum price P^* is said to be admissible if it is positive, if the expected long-term centralised production is positive and if the expected long-term distributed generation is positive and does not exceed the demand.

Remark

- The relation $\widehat{Q}_t(\widehat{X}_t(P^*_t)) = Q^*_t$ is always satisfied whatever P^*.

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Proposition 4 — Asymptotic Pareto efficiency

If $\rho c/b - \theta \leq \rho h + \pi$, there exists a unique admissible asymptotic Pareto optimum price and it is given by:

$$P^* := \left(1 - \frac{K}{K^{11}}\right)\left(\frac{\rho c}{b} - \theta\right) + \frac{K}{K^{11}}(\rho h + \pi). \tag{5}$$

Property

- The Pareto price is a convex combination of the total cost of the centralised technology and the net cost of the distributed technology ($K^{11} > K$).

Notation

- $P_0 := \frac{\rho c}{b} - \theta$ and $P_{_D} := P_0 + 2\sigma^2 K D$
- P_D satisfies $\widehat{X}_\infty(P_{_D}) = D$.

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Stackelberg equilibrium

Remarks

- Even if we know the analytic relation $\widehat{X}(P_t)$ for any price process P, we are not able to solve the firm's problem with the consumer's reaction to the firm's price process.
- Instead we consider the reaction of the consumer to a constant price $\hat{X}_\infty(\overline{P})$.

Stationary Stackelberg problem of the firm

$$\inf_{\overline{P}} \inf_{\nu} \mathbb{E}\Big[\int_0^\infty e^{-\rho t}\Big(h\nu_t + \delta\nu_t^2 - \overline{P}(D - \widehat{X}_\infty(\overline{P})) + \pi Q_t^\nu + \lambda\big(D - \widehat{X}_\infty(\overline{P}) - Q_t^\nu\big)^2\Big) dt\Big]. \tag{6}$$

Asymptotic Stackelberg equilibrium price

An asymptotic Stackelberg equilibrium price is a solution $P^\diamond$ of the optimisation problem above. It is said to be admissible if it is positive, if the long-term centralised capacity is positive and if the long-term distributed capacity is positive and lower than the demand.

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Proposition 5 — Stationary Stackelberg equilibrium price

Let

$$P_F(q) := \frac{\lambda\delta}{\rho\delta + \tilde{K}}\Big(\frac{\rho h + \pi}{\rho\delta + \tilde{K}} - 2\rho q\Big), \qquad \xi := 2 + \frac{\lambda}{\sigma^2 K}\Big(1 - \frac{\lambda\delta}{(\rho\delta + \tilde{K})^2}\Big),$$

with $\tilde{K} = \frac{\delta}{2}\Big(-\rho + \sqrt{\rho^2 + \frac{4\lambda}{\delta}}\Big)$.
Let q be the firm's initial capacity, and assume that $P_F(q) \leq P_D$. Then, there exists a unique Stackelberg asymptotic equilibrium price and it is given by:

$$P^{\diamond}(q) := \big(1 - \frac{1}{\xi}\big)P_D + \frac{1}{\xi}P_F(q). \tag{7}$$

Remark

- The Stackelberg price is also a convex combination of two prices: the price P_D when the consumer's investment all his demand in distributed energy and the price $P_F(q)$ corresponding to the cost of the centralised energy.

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Proposition 6

If the commitment penalty is sufficiently large, the Stackelberg long-term stationary price is larger than the Pareto price.

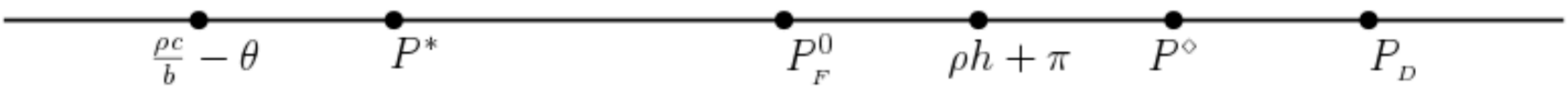

Figure: Ordering of different prices in standard situations for an initial condition with zero installed capacity of both technologies. $P_F^0 := P_F(q)$

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Property

Carbon tax on centralised generation and subsidy on distributed generation have the same efficiency to achieve a given ratio of both technologies.

In the Stackelberg price, the term $\rho h + \pi$ is multiplied by a factor $\lambda\delta/(\rho\delta + \tilde{K})^2 < 1$.
The efficiency of a carbon tax is lower than a subsidy to distributed generation.
Nevertheless, as soon as the firm's commitment is large enough, this factor is very close to one.
Increasing π or decreasing $\rho c/b$ leads the same market price respons.

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Property

In a situation where a power system is to be built from zero, the optimal strategy of the firm is high price/low market-share.
In a situation where the initial power system consists only in centralised generation, the optimal strategy of the firm is low price/large market share.

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Numerical illustration

		P^*	$P_0^\diamond$	$\tilde{P}^*$	$\tilde{P}_D^\diamond$
$\pi = 0,\ \delta = 1$	Price	80	272	n.e.	86
	$\widehat{X}_\infty$	0.3	47.6	0	1.6
$\pi = 0,\ \delta = 10^{-2}$	Price	87.5	232	n.e.	113
	$\widehat{X}_\infty$	2.0	37.8	0	8.3
$\pi = 100,\ \delta = 1$	Price	87	277	80	91
	$\widehat{X}_\infty$	1.8	49	0.3	3.0
$\pi = 100,\ \delta = 10^{-2}$	Price	127	259	87.5	140
	$\widehat{X}_\infty$	11.8	44.5	2.0	15.0

Table: Prices in €/MWh and distributed generation quantities in GW. (Left) initial state holds no generation capacities. (Right) initial state holds only centralised generation. n.e. stands for no equilibrium price. $P_0 = 79$ €/MWh and $P_D = 282$ €/MWh.

Parameters value: $\rho = 0.1$, $\sigma = 0.3$, $b = 0.15$, c such that $\rho c/b = 130$ €/MWh, $\theta = 50$ €/MWh, h such that $\rho h = 100$ €/MWh. $\gamma = 1$ €/MW^2/year, $\eta = 87.60$ €/MW^2/year, $D = 50$ GW, $\pi = 100$ €/MWh, $\lambda = 8.760e6$ €/MW^2/year.

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Conclusion
&
Perspectives

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Conclusions

- In the long-term, the *laissez-faire* strategy would lead to an investment in distributed energy sources much larger than socially desired allocations and to a much larger price for the centralised energy.
- Carbon tax has a crucial role to play in the social planner arbitrage between centralised and distributed generation.

Perspectives

- Competition between prosumers (consumers with distributed generation) and pure consumers.
- Endogeneity of the grid tariff θ. Making the distribution operator an active player of the development of distributed generation.
- Making the regulator also an active player of the game: are interventions required to correct undesired equilibria and what form whould these interventions take?
- Studies of different equilibrium configurations can be done either with static model or with dynamic models.

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