A Numerical illustration

Inverse demand is $P(q,t) = a_0 - a_1 e^{-\lambda_2 t} - bq$, states of the world are distributed according to $f(t) = \lambda_1 e^{-\lambda_1 t}$, and rationing is anticipated and proportional. a_0, a_1, $\lambda = \frac{\lambda_1}{\lambda_2}$, and bQ^∞ where $Q^\infty = \frac{a_0 - p_0}{b}$ is the maximum demand for price p_0, are the parameters to be estimated. λ is estimated by Maximum Likelihood using the load duration curve for France in 2010. The same load duration curve provides an expression of a_0 and a_1 as a function of bQ^∞. The average demand elasticity η is then used to estimate bQ^∞. Two estimates of demand elasticity at price $p_0 = 100$ €/MWh are tested: $\eta = -0.01$ and $\eta = -0.1$, respectively the lower and upper bound proposed by Lijesen (2007). The resulting estimates are

$$\begin{array}{c} for\ \eta = -0.1 \\ \begin{cases} bQ^\infty = 1\ 873\ €/MWh \\ a_0 = 1\ 973\ €/MWh \\ a_1 = 1\ 236\ €/MWh \\ \lambda = 1.78 \end{cases} \end{array}, \ and \ \begin{array}{c} for\ \eta = -0.01 \\ \begin{cases} bQ^\infty = 18\ 727\ €/MWh \\ a_0 = 18\ 827\ €/MWh \\ a_1 = 12\ 360\ €/MWh \\ \lambda = 1.78 \end{cases} \end{array}.$$

Generation costs are those of a gas turbine, $c = 72$ €$/MWh$ and $r = 6$ €$/MWh$ as provided by the International Energy Agency, IEA (2010). The regulated energy price is $p^R = 50$ €$/MWh$, from Eurostat[1].

B Physical capacity certificates

B.1 No short sale condition

Suppose first the SO imposes no condition on certificates sales. Producer n's expected profit, including revenues from the capacity market is: $\Pi^n_{CM}(k^n, \phi^n, \mathbf{k}_{-n}, \phi_{-n}) = \Pi^n(k^n, \mathbf{k}_{-n}) + \phi^n H(\Phi)$. Since ϕ^n does not enter $\Pi^n(k^n, \mathbf{k}_{-n})$,

$$\frac{\partial \Pi^n_{CM}}{\partial k^n}\left(\frac{K}{N}, ..., \frac{K}{N}\right) = \frac{\partial \Pi^n}{\partial k^n}\left(\frac{K}{N}, ..., \frac{K}{N}\right):$$

[1]Table 2 Figure 2 from http://epp.eurostat.ec.europa.eu/statistics_explained/images/a/a1/Energy%_prices_2011s2.xls

the certificate market has no impact on equilibrium investment.

Suppose now the SO imposes $k^n \geq \phi^n$. Consider the case where producers first sell credits, then install capacity. When selecting capacity, each producer maximizes $\bar{\Pi}^n_{CM}(k_n, \mathbf{k}_{-n})$ subject to $k^n \geq \phi^n$. The first-order condition is then

$$\frac{\partial \mathcal{L}^n}{\partial k^n} = \frac{\partial \bar{\Pi}^n}{\partial k^n} + \mu_1^n,$$

where μ_1^n is the shadow cost of the constraint $k^n \geq \phi^n$. Suppose first $\hat{\phi}^n < \hat{k}^n\ \forall n$, then $\mu_1^n = 0\ \forall n$ and $\hat{k}^n = \frac{K^C}{N}$ at the symmetric equilibrium. When selecting the amount of credits sold, the producers then maximize $\phi^n H(\Phi)$. Given the shape of $H(.)$, the symmetric equilibrium is $\hat{\phi}^n \geq \frac{K^*}{N}$. But then, $K^C > \Phi \geq K^*$, which is a contradiction, hence $\hat{\phi}^n = \hat{k}^n$.

Since $k^n = \phi^n$ at the equilibrium, producer n program is

$$\max_{k^n} \Pi^n_{CM}(k^n, \mathbf{k}_{-n},) = \Pi^n(k^n, \mathbf{k}_{-n}) + k^n H(K)$$

We prove below that $\left(\frac{K^*}{N}, ..., \frac{K^*}{N}\right)$ is the unique symmetric equilibrium.

B.2 Equilibrium investment if generation produces at capacity before the cap is reached

Suppose $\hat{t}(K, c, N) \leq \hat{t}_0\left(K, \bar{p}^W\right)$. As observed by Zöttl (2011), the profit function $\Pi^n\left(k^1, ..., k^n, ..., k^N\right)$ is not concave in k^n, so one must separately consider a positive and negative deviation from a symmetric equilibrium candidate to prove existence of the equilibrium. Consider first a negative deviation, i.e., $k^1 < \frac{K^*}{N}$ while $k^n = \frac{K^*}{N}$ for all $n > 1$. Since $K = k^1 + \frac{N-1}{N}K^* < K^*$,

$$\frac{\partial \Pi^1_{CM}}{\partial k^1}\left(k^1, \frac{K^*}{N}, ..., \frac{K^*}{N}\right) = \frac{\partial \Pi^1}{\partial k^1}\left(k^1, \frac{K^*}{N}, ..., \frac{K^*}{N}\right) + r.$$

Analysis of the two-stage Cournot game (Zöttl (2011) for $\alpha = 1$, Léautier (2013) for $\alpha \in (0,1)$) yields:

$$\begin{aligned}\frac{\partial \Pi^1}{\partial k^1}\left(k^1, \frac{K^*}{N}, ..., \frac{K^*}{N}\right) &= \int_{t^1}^{\hat{t}(K,c,N)} \left(\rho\left(\hat{Q}\left(k^1,t\right)\right) + k^1 \rho_q\left(\hat{Q}\left(k^1,t\right)\right)\frac{\partial \hat{Q}}{\partial k^1} - c\right) f(t)\, dt \\ &+ \int_{\hat{t}(K,c,N)}^{\hat{t}_0\left(K,\bar{p}^W\right)} \left(\rho(K) + k^1 \rho_q(K) - c\right) f(t)\, dt \qquad \text{(B.1)} \\ &+ \int_{\hat{t}_0\left(K,\bar{p}^W\right)}^{+\infty} \left(\bar{p}^W - c\right) f(t)\, dt - r,\end{aligned}$$

where t^1 is the first state of the world where producer 1 is constrained, $\hat{Q}\left(k^1,t\right) = k^1 + (N-1)\,\phi^N\left(k^1,t\right)$ is the aggregate production, and $\phi^N\left(k^1,t\right)$ is the equilibrium production from the remaining $(N-1)$ identical producers, that solves

$$\rho\left(k^1 + (N-1)\,\phi^N\left(k^1,t\right)\right) + \phi^N\left(k^1,t\right)\rho_q\left(k^1 + (N-1)\,\phi^N\left(k^1,t\right)\right) = c.$$

$\phi^N\left(k^1,t\right) \geq k^1$ for $t \in \left[t^1, \hat{t}(K,c,N)\right]$: lower-capacity producer 1 is constrained, while the $(N-1)$ higher capacity producers are not. Since quantities are strategic substitutes, $\frac{\partial \phi^N}{\partial k^1} < 0$ and

$$0 < \frac{\partial \hat{Q}}{\partial k^1} = 1 + (N-1)\frac{\partial \phi^N}{\partial k^1} < 1.$$

$\rho\left(\hat{Q}\right) + k^1 \rho_q\left(\hat{Q}\right) - c = \left(k^1 - \phi^N\right)\rho_q\left(\hat{Q}\right)\frac{\partial \hat{Q}}{\partial k^1} \geq 0$ for $t \in \left[t^1, \hat{t}(K,c,N)\right]$. $\rho\left(K, \hat{t}(K,c,N)\right) + k^1 \rho_q\left(K, \hat{t}(K,c,N)\right) = c$, and $\rho_t(K) + k^1 \rho_{qt}(K) \geq 0$, hence $\rho(K) + k^1 \rho_q(K) - c \geq 0$ for $t \geq \hat{t}(K,c,N)$. Therefore

$$\frac{\partial \Pi^1}{\partial k^1}\left(k^1, \frac{K^*}{N}, ..., \frac{K^*}{N}\right) + r > 0$$

for $k^1 < \frac{K^*}{N}$: no negative deviation is profitable.

Consider now a positive deviation, i.e., $k^N > \frac{K^*}{N}$ while $k^n = \frac{K^*}{N}$ for all

$n < N$. Since $K = k^N + \frac{N-1}{N} K^* > K^*$:

$$\frac{\partial \Pi^N_{CM}}{\partial k^N}\left(\frac{K^*}{N},...,\frac{K^*}{N},k^N\right) = \frac{\partial \Pi^N}{\partial k^N}\left(\frac{K^*}{N},...,\frac{K^*}{N},k^N\right) + k^N H^{'}(K) + H(K),$$

and

$$\frac{\partial^2 \Pi^N_{CM}}{(\partial k^N)^2}\left(\frac{K^*}{N},...,\frac{K^*}{N},k^N\right) = \frac{\partial^2 \Pi^N}{(\partial k^N)^2}\left(\frac{K^*}{N},...,\frac{K^*}{N},k^N\right) + k^N H^{''}(K) + 2H^{'}(K).$$

Zöttl (2011) shows that, for $k^N > \frac{K}{N}$,

$$\begin{aligned}
\frac{\partial^2 \Pi^N}{\partial (k^N)^2}\left(\frac{K^C}{N},...,\frac{K^C}{N},k^N\right) &= \int_{t^N}^{\hat{t}_0\left(K,\bar{p}^W\right)} \left[2\rho_q\left(\hat{K},t\right) + k^N \rho_{qq}\left(\hat{K},t\right)\right] f(t)\,dt \\
&\quad + k^N \rho_q\left(\hat{K},\hat{t}_0\left(K,\bar{p}^W\right)\right) f\left(\hat{t}_0\left(K,\bar{p}^W\right)\right) \frac{\partial \hat{t}_0\left(K,\bar{p}^W\right)}{\partial k^N} \qquad \text{(B.2)} \\
&< 0.
\end{aligned}$$

Thus,

$$\frac{\partial \Pi^N_{CM}}{\partial k^N}\left(\frac{K^*}{N},...,\frac{K^*}{N},k^N\right) < \frac{\partial \Pi^N}{\partial k^N}\left(\frac{K^*}{N},...,\frac{K^*}{N}\right) + \frac{K^*}{N} H^{'}(K^*) + r < 0$$

since condition (2) implies $\frac{K^*}{N} H^{'}(K^*) + r < 0$.

Hence, $\left(\frac{K^*}{N},...,\frac{K^*}{N}\right)$ is a symmetric equilibrium. Finally, no other symmetric equilibrium exists since $\Pi^n\left(\frac{K}{N},...,\frac{K}{N}\right) + \frac{K}{N} H(K)$ is concave.

B.3 Equilibrium investment if the cap is reached before generation produces at capacity

Suppose $\hat{t}_0\left(K,\bar{p}^W\right) < \hat{t}(K,c,N)$. To simplify the exposition, generators are ordered by increasing capacity $k^1 \leq ... \leq k^N$, and suppose that the price cap is reached before the first generator produces at capacity. Léautier (2014) proves that the expected equilibrium profit is

$$\Pi^n\left(k^n, \mathbf{k}_{-n}\right) = \int_0^{\tilde{t}^0} \frac{\hat{Q}\left(t\right)}{N} \left(\rho\left(\hat{Q}\right) - c\right) f\left(t\right) dt + \left(\bar{p}^W - c\right)\left(\sum_{i=0}^{n-1} \int_{\tilde{t}^i}^{\tilde{t}^{i+1}} \tilde{q}^{i+1}\left(t\right) f\left(t\right) dt + k^n \left(1 - F\left(\tilde{t}^n\right)\right)\right) \tag{B.3}$$

where $\hat{Q}\left(t\right)$ is the unconstrained Cournot output in state t, $\tilde{t}^0$ is the first state of the world such that the price cap is reached, defined by $\rho\left(\hat{Q}\left(\tilde{t}^0\right), \tilde{t}^0\right) = \bar{p}^W$, $\tilde{t}^{i+1}$ for $i = 0, ..., (N-1)$ is the first state of the world such that producer $(i+1)$ is constrained, defined by $\rho\left(\sum_{j=1}^{i} k^j + (N-j)\, k^{i+1}, t\right) = \bar{p}^W$, and $\tilde{q}^{i+1}\left(t\right)$ is defined on $\left[\tilde{t}^i, \tilde{t}^{i+1}\right]$ by

$$\rho\left(\sum_{j=1}^{i} k^j + (N-j)\, \tilde{q}^{i+1}\left(t\right), t\right) = \bar{p}^W.$$

For $t \leq \tilde{t}^0$, unconstrained Cournot competition takes place. For $t \geq \tilde{t}^0$, the Cournot price would exceed the cap, hence wholesale price is capped at $\bar{p}^W$. All generators play a symmetric equilibrium characterized by $\rho\left(N\tilde{q}^1\left(t\right), t\right) = \bar{p}^W$. When t reaches $\tilde{t}^1$ generator 1 produces its capacity. For $t \geq \tilde{t}^1$, the remaining $(N-1)$ generators play a symmetric equilibrium characterized by $\rho\left(k^1 + (N-1)\, \tilde{q}^2\left(t\right), t\right) = \bar{p}^W$. This process continues until all generators produce at capacity. $\tilde{t}^N$ is such that $\rho\left(\sum_{j=1}^{N} k^j, \tilde{t}^N\right) = \bar{p}^W$, hence $\tilde{t}^N = \hat{t}_0\left(K, \bar{p}^W\right)$ previously defined. For $t > \tilde{t}^N$, since wholesale price is fixed at $\bar{p}^W$ and generation is at capacity, the SO must curtail constant price consumers.

Differentiation of equation $(B.3)$ yields

$$\frac{\partial \Pi^n}{\partial k^n}\left(k^1, ..., k^N\right) = \int_{\tilde{t}^n}^{+\infty} \left(\bar{p}^W - c\right) f\left(t\right) dt - r, \tag{B.4}$$

and

$$\frac{\partial^2 \Pi^n}{\left(\partial k^n\right)^2}\left(k^1, ..., k^N\right) = -\left(\bar{p}^W - c\right) f\left(\tilde{t}^n\right) \frac{\partial \tilde{t}^n}{\partial k^n} < 0.$$

$\Pi^n\left(k^1, ..., k^N\right)$ is concave in k^n. The previous analysis then shows that $\left(\frac{K^*}{N}, ..., \frac{K^*}{N}\right)$ is the unique symmetric equilibrium.

B.4 Producers extra profits from the capacity markets

Léautier (2014) shows that, for common values of the parameters, $\hat{t}_0\left(K, \bar{p}^W\right) < \hat{t}\left(K, c, N\right)$. This is the case considered to evaluate Δ. At a symmetric equilibrium, equation $(B.3)$ yields

$$\Pi^n\left(\frac{K}{N}, ..., \frac{K}{N}\right) = \frac{1}{N}\left(\begin{array}{c} \int_0^{\tilde{t}^0} \hat{Q}\left(t\right)\left(\rho\left(\hat{Q}\left(t\right), t\right) - c\right) f\left(t\right) dt + \left(\bar{p}^W - c\right) \int_{\tilde{t}^0}^{\hat{t}_0\left(K, \bar{p}^W\right)} \tilde{Q}\left(t\right) f\left(t\right) dt \\ +K\left(\left(\bar{p}^W - c\right)\left(1 - F\left(\hat{t}_0\right)\right) - r\right) \end{array}\right),$$

$\Delta = \Pi^n\left(\frac{K^*}{N}, ..., \frac{K^*}{N}\right) + r\frac{K^*}{N} - \Pi^n\left(\frac{K^C}{N}, ..., \frac{K^C}{N}\right)$ is then estimated numerically.

C Financial reliability options

The equilibrium is solved by backwards induction. In the second stage, producers solve the equilibrium of the option market, taking $(k^n, \mathbf{k}^{-n})$ as given.

We assume that including the option market does not decrease investment, i.e., $K \geq K^C\left(\bar{p}^S\right)$. As suggested by Cramton and Ockenfels, the SO imposes the restriction that all capacity is sold forward: $\theta^n \geq k^n$. This restriction is made operational by conditioning profits from the option market to $\theta^n \geq k^n$. Since these profits are positive, $\theta^n \geq k^n$ is a dominant strategy, hence holds.

C.1 Derivation of the profit function if the strike price is reached before generation produces at capacity

If reliability options are in effect, the price cap is eliminated. For simplicity, assume that the strike price is reached before the first generator produces at capacity, and denote $\tilde{t}^0$ this state of the world. For $t \geq \tilde{t}^0$, consumers consume as if the price was $\bar{p}^S$, since they internalize the impact of the reliability option. As long as total generation is not at capacity, the wholesale price is indeed $\bar{p}^S$, and the equilibrium is identical to the previous one. When total generation reaches capacity, since consumers consume using constant price $\bar{p}^S$, the SO must curtail constant price consumers. The wholesale price reaches the $VoLL$. Generators must then rebate the difference between the wholesale price and the strike price, in proportion to the volume of options sold.

The resulting equilibrium profit is

$$\begin{aligned}
\Pi_{RO}^{n}\left(k^{n},\mathbf{k}_{-n}\right) &= \int_{0}^{\tilde{t}^{0}}\frac{\hat{Q}\left(t\right)}{N}\left(\rho\left(\hat{Q}\right)-c\right)f\left(t\right)dt \\
&\quad+\left(\bar{p}^{S}-c\right)\left(\sum_{i=0}^{n-1}\int_{\tilde{t}^{i}}^{\tilde{t}^{i+1}}\tilde{q}^{i+1}\left(t\right)f\left(t\right)dt+k^{n}\int_{\tilde{t}^{n}}^{\hat{t}_{0}\left(K,\bar{p}^{S}\right)}f\left(t\right)dt\right) \\
&\quad+\int_{\hat{t}_{0}\left(K,\bar{p}^{S}\right)}^{+\infty}\left(k^{n}\left(\rho\left(K,t\right)-c\right)-\frac{\theta^{n}}{\Theta}K\left(\rho\left(K,t\right)-\bar{p}^{S}\right)\right)f\left(t\right)dt-rk^{n} \\
&= \Pi^{n}\left(k^{n},\mathbf{k}_{-n}\right) \\
&\quad+\int_{\hat{t}_{0}\left(K,\bar{p}^{S}\right)}^{+\infty}\left(k^{n}\left(\rho\left(K,t\right)-c\right)-\frac{\theta^{n}}{\Theta}K\left(\rho\left(K,t\right)-\bar{p}^{S}\right)-k^{n}\left(\bar{p}^{S}-c\right)\right)f\left(t\right)dt \\
&= \Pi^{n}\left(k^{n},\mathbf{k}_{-n}\right)+\left(k^{n}-\frac{\theta^{n}}{\Theta}K\right)\int_{\hat{t}_{0}\left(K,\bar{p}^{S}\right)}^{+\infty}\left(\rho\left(K,t\right)-\bar{p}^{S}\right)f\left(t\right)dt \\
&= \Pi^{n}\left(k^{n},\mathbf{k}_{-n}\right)+\left(k^{n}-\frac{\theta^{n}}{\Theta}K\right)\Psi\left(K,\bar{p}^{S}\right).
\end{aligned}$$

C.2 Equilibrium in the options market

We first establish that $\frac{d\Psi}{dp}\left(K^{C}\left(p\right),p\right)<0$ and $lim_{p\rightarrow\breve{p}}\Psi\left(K^{C}\left(p\right),p\right)=0$, where $\breve{p}$ is the maximum price cap reached in equilibrium. Differentiation with respect to p yields

$$\frac{d\Psi}{dp}\left(K^{C}\left(p\right),p\right)=\int_{\hat{t}_{0}\left(K^{C}\left(p\right),p\right)}^{+\infty}\left(\rho_{q}\frac{dK^{C}}{dp}-1\right)f\left(t\right)dt.$$

Suppose $\hat{t}\left(K,c,N\right)>\hat{t}_{0}\left(K,\bar{p}^{W}\right)$. Then, $K^{C}\left(p\right)$ is defined by

$$\int_{\hat{t}_{0}\left(K^{C}\left(p\right),p\right)}^{+\infty}\left(p-c\right)f\left(t\right)dt=\left(p-c\right)\left(1-F\left(\hat{t}_{0}\left(K^{C}\left(p\right),p\right)\right)\right)=r.$$

Full differentiation with respect to p yields

$$\left(1-F\left(\hat{t}_{0}\right)\right)-\left(p-c\right)f\left(\hat{t}_{0}\right)\left(\frac{\partial\hat{t}_{0}}{\partial p}+\frac{\partial\hat{t}_{0}}{\partial K}\frac{dK^{C}}{dp}\right)=0$$

$\Leftrightarrow$

$$\frac{\partial \hat{t}_0}{\partial p} + \frac{\partial \hat{t}_0}{\partial K}\frac{dK^C}{dp} = \frac{1 - F\left(\hat{t}_0\right)}{(p-c)\, f\left(\hat{t}_0\right)}.$$

Differentiation of $\rho\left(K, \hat{t}_0\left(K,p\right)\right) = p$ yields $\frac{\partial \hat{t}_0}{\partial K} = -\frac{\rho_q}{\rho_t}$ and $\frac{\partial \hat{t}_0}{\partial p} = \frac{1}{\rho_t}$. Thus,

$$1 - \rho_q \frac{dK^C}{dp} = \frac{\rho_t}{p-c}\frac{1-F\left(\hat{t}_0\right)}{f\left(\hat{t}_0\right)} > 0,$$

therefore $\frac{d\Psi}{dp}\left(K^c\left(p\right), p\right) < 0$.

Suppose now $\hat{t}\left(K, c, N\right) \leq \hat{t}_0\left(K, \bar{p}^W\right)$. $K^C\left(p\right)$ is defined by

$$\int_{t^N\left(K^C(p)\right)}^{\hat{t}_0\left(K^C(p),p\right)} \left(\rho\left(K^C\left(p\right), t\right) + \frac{K^C\left(p\right)}{N}\rho_q\left(K^C\left(p\right), t\right) - c\right) f\left(t\right) dt + \int_{\hat{t}_0\left(K^C(p),p\right)}^{+\infty} \left(p-c\right) f\left(t\right) dt = r.$$

Full differentiation with respect to p yields

$$I\frac{dK^C}{dp} + \frac{K^C}{N}\rho_q\left(\frac{\partial \hat{t}_0}{\partial p} + \frac{\partial \hat{t}_0}{\partial K}\frac{dK^C}{dp}\right) + \left(1 - F\left(\hat{t}_0\right)\right) = 0,$$

where $I = \int_{t^N}^{\hat{t}_0}\left(\frac{N+1}{N}\rho_q + \frac{K^C}{N}\rho_{qq}\right) f\left(t\right) dt < 0$. Substituting in $\frac{\partial \hat{t}_0}{\partial K}$ and $\frac{\partial \hat{t}_0}{\partial p}$ yields:

$$-I\rho_t\frac{dK^C}{dp} - \frac{K^C}{N}\rho_q\left(1 - \rho_q\frac{dK^C}{dp}\right) = \rho_t\left(1 - F\left(\hat{t}_0\right)\right)$$

$\Leftrightarrow$

$$1 - \rho_q\frac{dK^C}{dp} = \frac{\rho_t\left(\rho_q\left(1 - F\left(\hat{t}_0\right)\right) + I\right)}{I\rho_t - \frac{K^C}{N}\rho_q^2} > 0,$$

therefore $\frac{d\Psi}{dp}\left(K^c\left(p\right), p\right) < 0$.

Finally, $K^C\left(p\right)$ converges when $p \to \breve{p}$, thus $\left(P\left(K^c\left(p\right), t\right) - c\right)$ is bounded, thus $lim_{p\to\breve{p}}\Psi\left(K^c\left(p\right), p\right) = 0$ since $lim_{p\to\breve{p}}\hat{t}_0\left(K^c\left(p\right), p\right) = 0$.

We now prove that $\theta^n = \frac{K^*}{N} \geq k^n$ for all n is a symmetric equilibrium if condition (3) holds. Differentiation of equation (4) yields:

$$\frac{\partial \Pi^n_{RO}}{\partial \theta^n}\left(\theta^n, \theta_{-n}\right) = H_{RO}\left(\Theta\right) + \theta^n H^{'}_{RO}\left(\Theta\right) - \frac{\Theta - \theta^n}{\Theta^2}K\Psi\left(K, \bar{p}^S\right),$$

and

$$\frac{\partial^2 \Pi_{RO}^n}{(\partial \theta^n)^2}(\theta^n, \theta_{-n}) = 2H_{RO}^{'}(\Theta) + \theta^n H_{RO}^{''}(\Theta) + 2\frac{\Theta - \theta^n}{\Theta^3} K\Psi\left(K, \bar{p}^S\right).$$

For $\Theta \leq K^*$,

$$\frac{\partial^2 \Pi_{RO}^n}{(\partial \theta^n)^2}(\theta^n, \theta_{-n}) = 2\frac{\Theta - \theta^n}{\Theta^3} K\Psi\left(K, \bar{p}^S\right) > 0.$$

$\frac{\partial \Pi_{RO}^n}{\partial \theta^n}$ is increasing, thus the only equilibrium candidates are $\theta^n = \frac{K^*}{N}$ and $\theta^n = k^n$. Furthermore,

$$\frac{\partial^2 \Pi_{RO}^n}{\partial \theta^n \partial \theta^m}(\theta^n, \theta_{-n}) = \left(2\frac{\Theta - \theta^n}{\Theta^3} + \frac{\theta^n}{\Theta^2}\right) K\Psi\left(K, \bar{p}^S\right) > 0,$$

thus

$$\frac{\partial \Pi_{RO}^n}{\partial \theta^n}(\theta^n, \theta_{-n}) \geq \frac{\partial \Pi_{RO}^n}{\partial \theta^n}\left(k^1, ..., k^N\right).$$

Then,

$$\frac{\partial \Pi_{RO}^n}{\partial \theta^n}\left(k^1, ..., k^N\right) = r - \frac{K - k^n}{K^2} K\Psi\left(K, \bar{p}^S\right) > r - \Psi\left(K, \bar{p}^S\right) \geq r - \Psi\left(K^C\left(\bar{p}^S\right), \bar{p}^S\right) > 0$$

since $K \geq K^C\left(\bar{p}^S\right)$ by assumption. Thus, if condition (3) holds, $\frac{\partial \Pi_{RO}^n}{\partial \theta^n}(\theta^n, \theta_{-n}) > 0$ for all θ^n such that $\theta^n \geq k^n$ and $\Theta \leq K^*$. In particular, if $\theta^n = \frac{K^*}{N}$ for all $n > 1$, no negative deviation $\theta^1 < \frac{K^*}{N}$ is profitable.

Consider now a positive deviation, i.e., $\theta^N > \frac{K^*}{N} \geq k^N$ while $\theta^n = \frac{K^*}{N}$ for all $n < N$. We have:

$$\frac{\partial \Pi_{RO}^N}{\partial \theta^N}\left(\frac{K^*}{N}, ..., \frac{K^*}{N}, \theta^N\right) = h(\Theta) + \theta^N h^{'}(\Theta) - \frac{\Theta - \theta^N}{\Theta^2} K\Psi\left(K, \bar{p}^S\right).$$

By construction, $\Theta = \theta^N + \frac{N-1}{N} K^* > K^*$ and $\theta^N - \frac{\Theta}{N} = \frac{N-1}{N}\left(\theta^N - \frac{K^*}{N}\right) > 0$, therefore

$$H_{RO}(\Theta) + \theta^N H_{RO}^{'}(\Theta) < H_{RO}(\Theta) + \frac{\Theta}{N} H_{RO}^{'}(\Theta) < H_{RO}(K^*) + \frac{K^*}{N} H_{RO}^{'}(K^*) < 0$$

by condition (2), hence $\frac{\partial \Pi^N_{RO}}{\partial \theta^N}\left(\frac{K^*}{N},...,\frac{K^*}{N},\theta^N\right) < 0$ for all $\theta^N > \frac{K^*}{N}$. No positive deviation is profitable.

$\theta^n = \frac{K^*}{N}$ for all n is therefore an equilibrium.

We now prove $\theta^n = \frac{K^*}{N} \geq k^n$ for all n is the unique symmetric equilibrium. Since $\frac{\partial \Pi^n_{RO}}{\partial \theta^n}(\theta^n, \theta_{-n}) > 0$, no equilibrium exists for θ^n such that $\theta^n \geq k^n$ and $\Theta \leq K^*$.

Finally, consider the case $\theta^n = \frac{\Theta}{N} > \frac{K^*}{N}$ for all n:

$$\frac{\partial \Pi^n_{RO}}{\partial \theta^n}\left(\frac{\Theta}{N},...,\frac{\Theta}{N}\right) = h(\Theta) + \frac{\Theta}{N}h'(\Theta) - \frac{N-1}{N}\frac{K}{\Theta}K\Psi\left(K,\bar{p}^S\right) < 0.$$

There exists no symmetric equilibrium with $\frac{\Theta}{N} > \frac{K^*}{N}$.

C.3 Equilibrium investment

In the first stage, producers decide on capacity, taking into account the equilibrium of the options market. Denote $V^n(k^n, \mathbf{k}_{-n})$ producer n profit function:

$$V^n(k^n, \mathbf{k}_{-n}) = \Pi^n_{RO}\left(k^n, \frac{K^*}{N}, \mathbf{k}_{-n}, \frac{\mathbf{K}^*}{\mathbf{N}}\right) = \Pi^n(k^n, \mathbf{k}_{-n},) + \frac{K^*}{N}r + \left(k^n - \frac{K}{N}\right)\Psi\left(K, \bar{p}^S\right).$$

Differentiation with respect to k^n yields

$$\frac{\partial V^n}{\partial k^n} = \frac{\partial \Pi^n}{\partial k^n} + \frac{N-1}{N}\Psi\left(K,\bar{p}^S\right) + \left(k^n - \frac{K}{N}\right)\frac{\partial \Psi}{\partial K}. \tag{C.1}$$

A necessary condition for a symmetric equilibrium $k^n = \frac{K}{N}$ is:

$$\frac{\partial V^n}{\partial k^n}\left(\frac{K}{N},...,\frac{K}{N}\right) = \frac{\partial \Pi^n}{\partial k^n}\left(\frac{K}{N},...,\frac{K}{N}\right) + \frac{N-1}{N}\Psi\left(K,\bar{p}^S\right)$$

$\frac{\partial V^n}{\partial k^n}\left(\frac{K}{N},...,\frac{K}{N}\right)$ is decreasing since $\frac{\partial \Pi^n}{\partial k^n}\left(\frac{K}{N},...,\frac{K}{N}\right)$ is decreasing and $\frac{\partial \Psi}{\partial K} < 0$. $\frac{\partial V^n}{\partial k^n}(0,...,0) = \frac{\partial \Pi^n}{\partial k^n}(0,...,0) + \frac{N-1}{N}\Psi\left(0,\bar{p}^S\right) > 0$ since (i) $\frac{\partial \Pi^n}{\partial k^n}(0,...,0) > 0$ and (ii) $\Psi\left(0,\bar{p}^S\right) > 0$ by construction. $\lim_{K\to+\infty}\frac{\partial V^n}{\partial k^n}(K) = -r < 0$. Hence, there exists a unique $K^C_{RO} > 0$ such that $\frac{\partial \Pi^n_{RO}}{\partial k^n}\left(\frac{K^C_{RO}}{N},...,\frac{K^C_{RO}}{N}\right) = 0$. This is equation (5). We prove in the main text that $K^C\left(\bar{p}^S\right) \leq K^C_{RO} < K^*$.

We prove below that $k^n = \frac{K_{RO}^C}{N}$ for all n is an equilibrium, distinguishing the two cases $\hat{t}(K,c,N) \leq \hat{t}_0\left(K,\bar{p}^S\right)$ and $\hat{t}(K,c,N) > \hat{t}_0\left(K,\bar{p}^S\right)$.

C.3.1 Generation produces at capacity before the strike price is reached

Consider first a negative deviation: $k^1 < \frac{K_{RO}^C}{N}$ while $k^n = \frac{K_{RO}^C}{N}$ for all $n > 1$. Total installed capacity is $K = k^1 + \frac{N-1}{N}K_{RO}^C < K_{RO}^C$. Substituting expression $(B.1)$ for $\frac{\partial \Pi^n}{\partial k^n}\left(k^1, \frac{K_{RO}^C}{N}, ..., \frac{K_{RO}^C}{N}\right)$ into equation $(C.1)$

$$\begin{aligned}
\frac{\partial V^1}{\partial k^1}\left(k^1, \frac{K_{RO}^C}{N}, ..., \frac{K_{RO}^C}{N}\right) &= \int_{t^1}^{\hat{t}(K,c,N)} \left(\rho\left(\hat{Q}\left(k^1,t\right)\right) + k^1\rho_q\left(\hat{Q}\left(k^1,t\right)\right)\frac{\partial \hat{Q}}{\partial k^1} - c\right) f(t)\,dt \\
&+ \int_{\hat{t}(K,c,N)}^{\hat{t}_0\left(K,\bar{p}^S\right)} \left(\rho(K) + k^1\rho_q(K) - c\right) f(t)\,dt \\
&+ \int_{\hat{t}_0\left(K,\bar{p}^S\right)}^{+\infty} \begin{pmatrix} \left(\bar{p}^S - c\right) + \frac{N-1}{N}\left(\rho(K,t) - \bar{p}^S\right) \\ +\left(k^1 - \frac{K}{N}\right)\rho_q(K,t) \end{pmatrix} f(t)\,dt - r.
\end{aligned}$$

Substituting in equation (**??**), observing that $\hat{t}(K,c,N) < \hat{t}\left(K_{RO}^C, c, N\right)$ and $\hat{t}_0\left(K,\bar{p}^S\right) < \hat{t}_0\left(K_{RO}^C,\bar{p}^S\right)$ since $K < K_{RO}^C$, and rearranging yields

$$\begin{aligned}
\frac{\partial V^1}{\partial k^1}\left(k^1, \frac{K_{RO}^C}{N}, ..., \frac{K_{RO}^C}{N}\right) &= \int_{t^1}^{\hat{t}(K,c,N)} \left(\rho\left(\hat{Q}\right) + k_q^1\rho\left(\hat{Q}\right)\frac{\partial \hat{Q}}{\partial k^1} - c\right) f(t)\,dt \\
&+ \int_{\hat{t}(K,c,N)}^{\hat{t}\left(K_{RO}^C,c,N\right)} \left(\rho(K) + k_q^1\rho(K) - c\right) f(t)\,dt \\
&+ \int_{\hat{t}\left(K_{RO}^C,c,N\right)}^{\hat{t}_0\left(K,\bar{p}^S\right)} \begin{pmatrix} \rho(K) + k_q^1\rho(K) \\ -\left(\rho\left(K_{RO}^C\right) + \frac{K_{RO}^C}{N}\rho_q\left(K_{RO}^C\right)\right) \end{pmatrix} f(t)\,dt \\
&+ \int_{\hat{t}_0\left(K,\bar{p}^S\right)}^{\hat{t}_0\left(K_{RO}^C,\bar{p}^S\right)} \begin{pmatrix} \bar{p}^S - \rho\left(K_{RO}^C,t\right) - \frac{K_{RO}^C}{N}\rho_q\left(K_{RO}^C\right) \\ +\frac{N-1}{N}\begin{pmatrix} \rho(K,t) - \bar{p}^S \\ +\rho_q(K,t)\left(k^1 - \frac{K_{RO}^C}{N}\right) \end{pmatrix} \end{pmatrix} f(t)\,dt \\
&+ \frac{N-1}{N}\int_{\hat{t}_0\left(K_{RO}^C,\bar{p}^S\right)}^{+\infty} \begin{pmatrix} \rho(K,t) - \rho\left(K_{RO}^C,t\right) \\ +\rho_q(K,t)\left(k^1 - \frac{K_{RO}^C}{N}\right) \end{pmatrix} f(t)\,dt.
\end{aligned}$$

Each term is positive:

1. $\rho\left(\hat{Q}\right)+k_q^1\rho\left(\hat{Q}\right)\frac{\partial\hat{Q}}{\partial k^1}-c=\left(k^1-\phi^N\right)\rho_q\left(\hat{Q}\right)\frac{\partial\hat{Q}}{\partial k^1}\geq 0$ for $t\in\left[t^1,\hat{t}\left(K,c,N\right)\right]$

2. $\rho\left(K,\hat{t}\left(K,c,N\right)\right)+k_q^1\rho\left(K,\hat{t}\left(K,c,N\right)\right)=c$, and $\rho_t\left(K\right)+k^1\rho_{qt}\left(K\right)\geq 0$, hence $\rho\left(K\right)+k_q^1\rho\left(K\right)-c\geq 0$ for $t\in\left[\hat{t}\left(K,c,N\right),\hat{t}\left(K_{RO}^C,c,N\right)\right]$

3. $\rho_q\left(Q\right)+q\rho_{qq}\left(Q\right)<0$, hence $\rho\left(K\right)+k^1\rho_q\left(K\right)\geq\rho\left(K\right)+\frac{K_{RO}^C}{N}\rho_q\left(K\right)\geq\rho\left(K_{RO}^C\right)+\frac{K_{RO}^C}{N}\rho_q\left(K_{RO}^C\right)$ for $t\in\left[\hat{t}\left(K_{RO}^C,c,N\right),\hat{t}_0\left(K,\bar{p}^S\right)\right]$

4. $\rho\left(K_{RO}^C,t\right)\leq\bar{p}^S$ for $t\leq\hat{t}_0\left(K_{RO}^C,\bar{p}^S\right)$ and $\rho\left(K,t\right)\geq\bar{p}^S$ for $t\geq\hat{t}_0\left(K,\bar{p}^S\right)$, hence

$$\left(\bar{p}^S-\rho\left(K_{RO}^C,t\right)-\frac{K_{RO}^C}{N}\rho_q\left(K_{RO}^C\right)+\frac{N-1}{N}\left(\rho\left(K,t\right)\geq\bar{p}^S\right)\right)\geq 0$$

   for $t\in\left[\hat{t}_0\left(K,\bar{p}^S\right),\hat{t}_0\left(K_{RO}^C,\bar{p}^S\right)\right]$

5. $K\leq K_{RO}^C$, yields $\rho\left(K,t\right)\geq\rho\left(K_{RO}^C,t\right)$ for all t

Thus, $\frac{\partial\Pi_{RO}^1}{\partial k^1}\left(k^1,\frac{K_{RO}^C}{N},...,\frac{K_{RO}^C}{N}\right)>0$: a negative deviation is not profitable.

Consider now a positive deviation, $k^N>\frac{K_{RO}^C}{N}$ while $k^n=\frac{K_{RO}^C}{N}$ for all $n<N$. $K=k^N+\frac{N-1}{N}K_{RO}^C>K_{RO}^C$.

$$\begin{aligned}\frac{\partial^2V^N}{\left(\partial k^N\right)^2}\left(\frac{K_{RO}^C}{N},...,\frac{K_{RO}^C}{N},k^N\right) &= \frac{\partial^2\Pi^N}{\left(\partial k^N\right)^2}+2\frac{N-1}{N}\frac{\partial\Psi}{\partial K}+\left(k^N-\frac{K}{N}\right)\frac{\partial^2\Psi}{\left(\partial K\right)^2}\\ &= \frac{\partial^2\Pi^N}{\left(\partial k^N\right)^2}+\frac{N-1}{N}\int_{\hat{t}_0\left(K,\bar{p}^S\right)}^{+\infty}\left[\begin{array}{c}2\rho_q\left(K,t\right)\\ +\left(k^N-\frac{K_{RO}^C}{N}\right)\rho_{qq}\left(K,t\right)\end{array}\right]f\left(t\right)dt\\ &\quad -\left(k^N-\frac{K}{N}\right)\rho_q\left(K,\hat{t}_0\left(K,\bar{p}^S\right)\right)f\left(\hat{t}_0\left(K,\bar{p}^S\right)\right)\frac{\partial\hat{t}_0\left(K,\bar{p}^S\right)}{\partial K}.\end{aligned}$$

Substituting in $\frac{\partial^2 \Pi^N}{(\partial k^N)^2}$ from equation $(B.2)$,

$$\begin{aligned}\frac{\partial^2 V^N}{(\partial k^N)^2}\left(\frac{K^C_{RO}}{N},...,\frac{K^C_{RO}}{N},k^N\right) &= \int_{\hat{t}(K,c,N)}^{\hat{t}_0\left(K,\bar{p}^S\right)}\left[2\rho_q\left(\hat{K},t\right)+k^N\rho_{qq}\left(\hat{K},t\right)\right]f(t)\,dt \\ &+\frac{N-1}{N}\int_{\hat{t}_0(K,\bar{p}^S)}^{+\infty}\left[2\rho_q(K,t)+\left(k^N-\frac{K^C_{RO}}{N}\right)\rho_{qq}(K,t)\right]f(t)\,dt \\ &+\frac{K}{N}\rho_q\left(K,\hat{t}_0\left(K,\bar{p}^S\right)\right)f\left(\hat{t}_0\left(K,\bar{p}^S\right)\right)\frac{\partial \hat{t}_0\left(K,\bar{p}^S\right)}{\partial K} \\ &< 0.\end{aligned}$$

A positive deviation is not profitable. Therefore $\left(\frac{K^C_{RO}}{N},...,\frac{K^C_{RO}}{N}\right)$ constitutes an equilibrium. Furthermore,

$$\begin{aligned}\frac{\partial^2 V^n}{\partial (k^n)^2}\left(\frac{K}{N},...,\frac{K}{N}\right) &= \int_{t^N}^{t^{\bar{p}^S}}\left[2\rho_q(K,t)+\frac{K}{N}\rho_{qq}(K,t)\right]f(t)\,dt+2\frac{N-1}{N}\int_{t^{\bar{p}^S}}^{+\infty}\rho_q(K,t)f(t)\,dt \\ &+\frac{K}{N}\rho_q\left(K,\hat{t}_0\left(K,\bar{p}^S\right)\right)f\left(\hat{t}_0\left(K,\bar{p}^S\right)\right)\frac{\partial \hat{t}_0\left(K,\bar{p}^S\right)}{\partial K} \\ &< 0\end{aligned}$$

hence $\left(\frac{K^C_{RO}}{N},...,\frac{K^C_{RO}}{N}\right)$ is the unique symmetric equilibrium.

C.3.2 The strike price is reached before generation produces at capacity

Substituting expression $(B.4)$ for $\frac{\partial \Pi^n}{\partial k^n}\left(k^1,...,k^N\right)$ into equation $(C.1)$ yields

$$\frac{\partial V^n}{\partial k^n}=\int_{\tilde{t}^n}^{+\infty}\left(\bar{p}^S-c\right)f(t)\,dt+\frac{N-1}{N}\int_{\hat{t}_0(K,\bar{p}^S)}^{+\infty}\left(\rho(K,t)-\bar{p}^S\right)+\left(k^n-\frac{K}{N}\right)\frac{\partial \Psi}{\partial K}\left(K,\bar{p}^S\right)-r.$$

Suppose $k^1=...=k^{N-1}=\frac{K^C_{RO}}{N}$. Then,

$$\begin{aligned}\frac{\partial^2 V^N}{\partial (k^N)^2} &= -\left(\bar{p}^S-c\right)f\left(\tilde{t}^N\right)\frac{\partial \tilde{t}^N}{\partial K}+\frac{N-1}{N}\int_{\hat{t}_0(K,\bar{p}^S)}^{+\infty}\left[2\rho_q(K,t)+\left(k^N-\frac{K^C_{RO}}{N}\right)\rho_{qq}(K,t)\right]f(t)\,dt \\ &-\frac{N-1}{N}\left(k^N-\frac{K^C_{RO}}{N}\right)\rho_q\left(K,\hat{t}_0\left(K,\bar{p}^S\right)\right)f\left(\hat{t}_0\left(K,\bar{p}^S\right)\right)\frac{\partial \hat{t}_0\left(K,\bar{p}^S\right)}{\partial K}.\end{aligned}$$

Thus, if $k^N < \frac{K^C_{RO}}{N}$, $\frac{\partial^2 V^N}{\partial (k^N)^2} < 0$: a negative deviation is not profitable.

Consider now a positive deviation, $k^N > \frac{K^C_{RO}}{N}$. Since producer N is the last producer to be constrained, $\tilde{t}^N = \hat{t}_0\left(K, \bar{p}^S\right)$. Substituting equation $(B.4)$ into equation $(C.1)$ yields

$$\begin{aligned}
\frac{\partial V^n}{\partial k^n}\left(\frac{K^C_{RO}}{N}, ..., \frac{K^C_{RO}}{N}, k^N\right) &= \int_{\hat{t}_0(K,\bar{p}^S)}^{+\infty} \left[\left(\bar{p}^S - c\right) + \frac{N-1}{N}\left(\begin{array}{c} \left(\rho\left(K,t\right) - \bar{p}^S\right) \\ + \left(k^N - \frac{K^C_{RO}}{N}\right)\rho_q\left(K,t\right) \end{array}\right)\right] f\left(t\right) dt \\
&\quad - \int_{\hat{t}_0\left(K^C_{RO},\bar{p}^S\right)}^{+\infty} \left[\left(\bar{p}^S - c\right) + \frac{N-1}{N}\left(\rho\left(K^C_{RO},t\right) - \bar{p}^S\right)\right] f\left(t\right) dt \\
&= -\int_{\hat{t}_0\left(K^C_{RO},\bar{p}^S\right)}^{\hat{t}_0\left(K,\bar{p}^S\right)} \left(\bar{p}^S - c\right) f\left(t\right) dt \\
&\quad + \frac{N-1}{N}\left[\begin{array}{c} \int_{\hat{t}_0(K,\bar{p}^S)}^{+\infty} \left(\rho\left(K,t\right) - \rho\left(K^C_{RO},t\right)\right) f\left(t\right) dt \\ - \int_{\hat{t}_0\left(K^C_{RO},\bar{p}^S\right)}^{\hat{t}_0\left(K,\bar{p}^S\right)} \left(\rho\left(K^C_{RO},t\right) - \bar{p}^S\right) f\left(t\right) dt \\ + \left(k^N - \frac{K^C_{RO}}{N}\right) \int_{\hat{t}_0(K,\bar{p}^S)}^{+\infty} \rho_q\left(K,t\right) f\left(t\right) dt \end{array}\right].
\end{aligned}$$

Since $K > K^C_{RO}$, then $\hat{t}_0\left(K, \bar{p}^S\right) > \hat{t}_0\left(K^C_{RO}, \bar{p}^S\right)$ and $\rho\left(K,t\right) < \rho\left(K^C_{RO},t\right)$, hence the first three terms are negative. The last term is negative since $k^N > \frac{K^C_{RO}}{N}$ and $\rho_q < 0$. Thus, $\frac{\partial V^n}{\partial k^n}\left(\frac{K^C_{RO}}{N}, ..., \frac{K^C_{RO}}{N}, k^N\right) < 0$: a positive deviation is not profitable. $\left(\frac{K^C_{RO}}{N}, ..., \frac{K^C_{RO}}{N}\right)$ is therefore an equilibrium. Furthermore,

$$\frac{\partial^2 V^n}{\partial \left(k^n\right)^2}\left(\frac{K}{N}, ..., \frac{K}{N}\right) = -\left(\bar{p}^S - c\right) f\left(\hat{t}_0\right) \frac{\partial \hat{t}_0}{\partial K} + 2\frac{N-1}{N} \int_{\hat{t}_0(K,\bar{p}^S)}^{+\infty} \rho_q\left(K,t\right) f\left(t\right) dt < 0$$

hence $\left(\frac{K^C_{RO}}{N}, ..., \frac{K^C_{RO}}{N}\right)$ is the unique symmetric equilibrium.

D Energy cum operating reserves market

Define the total surplus

$$\mathring{\mathcal{S}}\left(p, \gamma, t\right) = \alpha S\left(p\left(t\right), t\right) + \left(1 - \alpha\right) \mathcal{S}\left(p, \gamma, t\right)$$

and total demand

$$\mathring{\mathcal{D}}(p,\gamma,t) = \alpha S(p(t),t) + (1-\alpha)\mathcal{D}(p,\gamma,t).$$

The social planner's program is:

$$\begin{array}{cc} \max\limits_{\{p(t),\gamma(t)\},K} & E\left\{\mathring{\mathcal{S}}(p(t),\gamma(t),t) - c\mathring{\mathcal{D}}(p(t),\gamma(t),t)\right\} - rK \\ st: & (1+h(t))\,\mathring{\mathcal{D}}(p(t),\gamma(t),t) \leq K \qquad (\lambda(t)) \end{array}$$

The associated Lagrangian is:

$$\mathcal{L} = E\left\{\mathring{\mathcal{S}}(p(t),\gamma(t),t) - c\mathring{\mathcal{D}}(p(t),\gamma(t),t) + \lambda(t)\left[K - (1+h(t))\,\mathring{\mathcal{D}}(p(t),\gamma(t),t)\right]\right\} - rK$$

and:

$$\left\{\begin{array}{l} \frac{\partial\mathcal{L}}{\partial p(t)} = \{p(t) - [c + (1+h(t))\lambda(t)]\}\frac{\partial\mathring{\mathcal{D}}}{\partial p(t)} \\ \frac{\partial\mathcal{L}}{\partial\gamma(t)} = \left\{v_t\left[\mathring{\mathcal{D}}(p(t),\gamma(t)),\gamma(t)\right] - [c + (1+h(t))\lambda(t)]\right\}\frac{\partial\mathring{\mathcal{D}}}{\partial\gamma(t)} \\ \frac{\partial\mathcal{L}}{\partial K} = E[\lambda(t)] - r \end{array}\right.$$

First, off-peak $\lambda(t) = 0$ and $\gamma(t) = 1$. Then $p(t) = c = w(t)$. This holds as long as $\rho\left(\frac{Q}{1+h(t)}, t\right) = c \; for \; Q \leq K \Leftrightarrow t \leq \hat{t}_0^{OR}(K,c)$.

Second, on-peak, if constant price customers are not curtailed, $(1+h(t))\,\mathring{\mathcal{D}}(p(t),1,t) = K$ hence $\lambda(t) > 0$ and $\gamma(t) = 1$. Then $p(t) = c + \lambda(t)(1+h(t)) = \rho\left(\frac{K}{1+h(t)}, t\right)$ and $\lambda(t) = w(t) - c = \frac{p(t)-c}{1+h(t)} > 0$.

Finally, constant price customers may have to be curtailed, $(1+h(t))\,\mathring{\mathcal{D}}(p(t),\gamma^*(t),t) = K$ for $\gamma^*(t) < 1$ such that $(1+h(t))\,\mathring{\mathcal{D}}(\bar{v},\gamma^*(t),t) = K$. Then $(1+h(t))\lambda(t) = \rho\left(\frac{K}{1+h(t)}, t\right) - c$ as before.

The optimal capacity K_{OR}^* is then defined by $E[\lambda(t)] = r$ which yields equation (**??**).