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EFFICIENT USE OF RENEWABLE ENERGIES INTEGRATION INSTRUMENTS UNDER PEAK-LOAD PRICING – FIXED FEED-IN TARIFFS VS. BONUS SYSTEMS

by

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and

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Abstract

A global GHG certificate trading system (or alternatively a Pigou tax) is recognized as the first best instrument for combating Global Warming in textbook economics. Currently such a system is still not in place and is at best expected for 2020. For various reasons however some countries (notably the EU) are willing to adopt a frontrunner approach. Yet it is questionable whether going for a pure certificate trading system is the best choice under such circumstances. As an alternative, specific support schemes for carbon free technologies like renewables may be envisaged, e. g. production subsidies in the form of feed-in tariffs or market based bonus markups.

Two policies, feed-in tariffs and the market based bonus system, are investigated in an analytical comparison. It is shown, that long-run stationary prices at the target renewable energy level will indeed guarantee the achievement of the envisaged renewable quantity target. Contrarily, this is not so when a stationary bonus is granted and on the other hand correlation of renewable feed-in with the load curve leads to market price changes. Effective remuneration of renewable energy production under a bonus regime then follows market prices. If no compensation through the stationary bonus takes place, failure of renewable installation and consequently GHG emission targets are the consequences.

A current policy proposal by Sensfuß (2009) and Rohrig et al. (2011) is shown to have similar consequences. Renewable energy producers shall have the option to opt for the promotion framework on a short-term basis. This option will of course guarantee the target GHG emissions quantity, because the feed-in tariff acts as a price floor, but will also certainly lead to overinvestment in renewable capacity. This is simply due to the increasing average remuneration. The remuneration floor acts analogously to a negative correlation of renewable energy production with the load duration curve, which leads to increasing market prices in the analytical model. The appropriate long-run price signal should therefore be lower with lower feed-in tariffs and bonuses. Alternatively lower renewable capacity installation goals are necessary to achieve economic efficiency.

A parameterization of the analytical model and stylized adaptation to German renewable policy illustrates the significance of the discussed effects. The German case would suffer increasing market prices and excess renewable capacity new built if market price reactions are not mirrored in bonus markup adaptations. The Sensfuß-Rohrig proposition would have a similar impact.

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1 Introduction

Germany is one of the leading countries worldwide to promote environmental measures against climatic warming. Renewable energy generation is close to the 20 percent target and capacity from renewable is about one third of total capacity.[1] By 2020 even 35 % are envisaged.

The implementation of variable renewable production bonus schemes in Germany schemes was forwarded by Sensfuß (2009) and Rohrig et al. (2011). As an alternative to the already existing feed-in tariff they propose a sliding bonus system. Markups in this system are temporally variable and are calculated by the feed-in tariff minus the current wholesale price. Renewable energy suppliers are allowed each month to decide upon the promotion instrument they want to use. At first glance this seems to be a promising approach: over- or underpromotion and consequently -investments are obviated and socially optimal development goals are achieved and greenhouse gas emissions reduced.

The two policies, feed-in tariffs and the market based bonus system, are investigated in an analytical comparison. It is shown that long-run stationary prices at the target renewable energy level will indeed guarantee the achievement of the envisaged renewable quantity target.

Contrarily, this is not so when the proposal of Sensfuß and Rohrig et al. is implemented. Whereas the stationary target for renewable energy new built capacity is only achieved by the appropriate long-run signal, the option to opt for the promotion framework will of course assure the target quantity, but under negative correlation of renewable generation with the peak segment will certainly lead to overinvestment in renewable capacity. This is simply because of the increasing average market price, the average price of remaining conventional energy, which is due to the remuneration floor given by the feed-in tariff and the higher expected remuneration during on-peak market price periods. In effect, this increases long-run overall renewable remuneration, which in turn increases renewable capacity new built. The option to opt in and out of the bonus system should thus be seen critically.[2]

The remainder of the paper is organised as follows: Section 2 describes some recent literature on the subject and gives some further motivation. The general analytical model, without direct reference to the Sensfuß-Rohrig proposition, and discussion is conducted in chapter 3. The

[1] BNetzA (2011).

[2] This is similar for longer time periods like over the life cycle of the generation unit. If e.g. market prices prospectively rise the present value may be increased by first opting for the feed-in tariff and then changing to the market based bonus scheme.

peak-load pricing model is chosen as adequate partial equilibrium model for the (conventional) electricity market and extended to cope with wind and other renewable energies introduces the model structure. Further, it is extended for cost potential curves gicing signals for possible market integration. Market equilibria in the presence of the two policy instruments, feed-in tariffs and mark-ups on long-run wholesale prices, are discussed. In a short notice it is shown how the proposed German model will alter previously derived results. In section 4 a stylized application is provided allowing a preliminary parameterization and approximation of derived effects. Section 5 concludes.

2 Motivation

Electricity generation from renewable energy sources is promoted in the European Union and beyond. Despite economists claiming that the optimal instrument for climate change mitigation is a uniform tax or a system of tradable GHG emission certificates[3], political practice in Germany and elsewhere has come to use a combination of various policy instruments in order to cope with the issue of global warming. There has been a long-lasting debate on the benefits and drawbacks of this mix of policy instruments[4].

While many main-stream economists tend to emphasize the economic efficiency of the first-best instruments with respect to the internalization of GHG damages, various arguments are brought forward by ecologists, policy makers and some economists to justify deviations from this central policy goal.

Even if the principle of specific instruments for the support of renewable generation is agreed upon, there is still disagreement on the means. Again standard economic theory makes a strong case for a uniform system of tradable quotas, an approach put into practice notably in the UK with the Renewable Origin Certificates (ROCs) and in various parts of the U.S. under the label of Renewable Performance Standards (RPS).

Germany and other countries by contrast have implemented fixed feed-in tariffs. Spain has switched from a system of feed-in tariffs to a bonus or premium model at least for wind energy.

The arguments put forward in favour of specific support schemes for renewables notably focus on positive externalities of learning or research spillovers[5] and a reduction of further negative environmental externalities (Butler, Neuhoff (2004)) like emissions of NOxes and

[3] Weitzman (1974).

[4] Fisher, Newell (2008); Lehmann, Gawel (2011); Himmes, Weber (2011); Butler, Neuhoff (2008); Rohrig et. Al. (2011); Weber et. Al. (2009); Weimann (1995); Yamin (2004).

[5] Fisher, Newell (2008); Lehmann, Gawel (2011); Himmes, Weber (2011).

SOxes. Another argument put forward particularly in favour of fixed feed-in tariffs is the reduction in capital costs induced by the lower revenue risk associated with feed-in tariffs as compared to quota systems (Rohrig et. al. (2011); Weber et. al. (2009)).

In the light of these additional policy goals other instruments than taxes or emissions permits appear justifiable as well. E.g. Fisher and Newell (2008) investigate the suitability of some first- and indirect second-best instruments of GHG emissions reduction to achieve different policy goals not only of emissions reduction but also like renewable energy production, R&D, or economic surplus.

Under restrictive assumptions also indirect instruments like production subsidies for renewable generation can contribute to the achievement of an efficient GHG reduction.[6] Particular care has to be taken in applying these instruments, because further problems may arise by their indirect application and primary policy goals may then be missed easily.

One problem potentially arising from this oblique policy is addressed in this article. Production subsidies are granted as partial subsidies in the form of market based bonus schemes as well as feed-in tariffs covering full cost of the last unit assuring the renewable energy production goal.

By applying the bonus scheme it is usually hoped, first, to increase competition[7] in conventional and renewable energy production and, second, to reduce subsidies saving on economic distortions from redistribution. On the other hand, correlation of high demand and high renewable energy generation times will lead to decreasing market prices and vice versa. Thereby, part of the remuneration may be missing and the incentive to install desired renewable capacity is removed. For a negative correlation of demand and renewable energy generation excessive investment occurs. This leads for both deviations to welfare losses. These are a convex combination of GHG emission costs and remaining system costs and can be explained as follows. When the renewable goal is missed system costs will be lower, but this will be overcompensated by higher GHG emission prices and costs. In the case of excess renewable capacity installation GHG emissions will cost less but increased system costs overcompensate this effect. Consequently deviations in both directions reduce welfare. However, these welfare considerations are not addressed in detail, because they are straightforward and can be derived from the fact that the renewable target is set in a way

[6] Restrictive assumptions have to be made though. E.g. incentives for dynamic efficiency are reduced and only based on sufficient knowledge about potential renewable and conventional cost potential curves setting of sensible GHG-related renewable energy targets is imaginable. Other instruments will nevertheless have to complement the production subsidies to create necessary incentives in e.g. conventional generation.

[7] Reichenbach and Requate (2012) e.g. analyze the interplay of market power and learning curves for renewable energy production.

minimizing these two cost elements. In this article, the analysis is restricted to the sole investigation of deviations from renewable targets.[8]

3 Analysis

3.1 Peak-load pricing and renewable

The Peak-Load Pricing model as developed e. g. by Boiteux (1949), Steiner (1957), Crew and Kleindorfer (1981), or Crew et al. (1995) describes the long-term equilibrium in prices, capacities and production in the electricity market. It takes into account that various generation technologies with different capital intensities exist and that prices will reflect short term marginal costs given a competitive environment, except for the period of peak load.
The standard version of the peak-load pricing model may be summarized graphically as shown in Fig. 1.

Analytically, the peak-load pricing model may be characterized by the following set of equations:
Load duration curve:

$$D(t) = \sum_{i=1}^{I} d_i(t)\, Q_i$$

with the customer groups i with annual demand Qi and load profile di(t). Thereby $\int_{t=0}^{T} d_i(t) = 1$.

Generation cost curves:

$$C_n(t) = c_n^{inv} + c_n^{op} t$$

Intersection points between generation cost curves:

$$t_n = \frac{c_n^{inv} - c_{n+1}^{inv}}{c_{n+1}^{op} - c_n^{op}}$$

Equilibrium capacities:

$$K_n = K_n^C - K_{n-1}^C$$

with cumulative capacities:

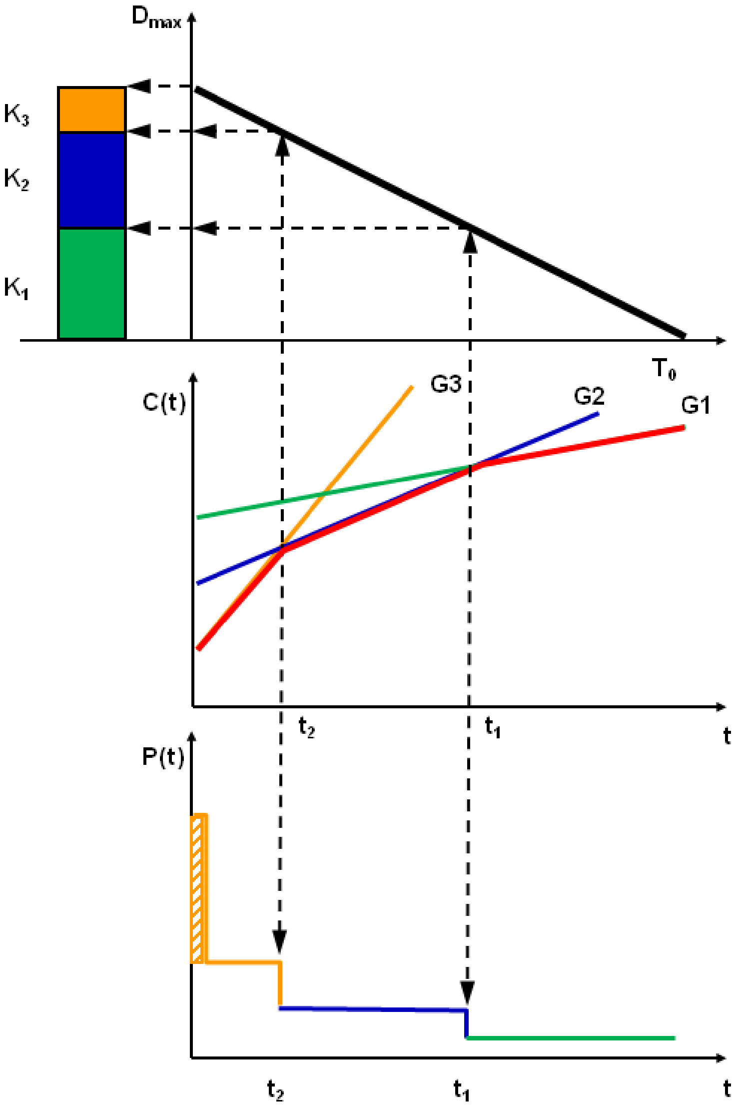
$$K_n^C = D(t_n)$$

[8] We omit reactions on the GHG emissions market or of tax adaptations, because they are of second order relativizating but not changing effects described in this article.

Prices in the equilibrium are then given by:

$$p(t) = c_{k(t)}^{op}$$

with the relevant segment of the generation curve being given by:



$$k(t) = \min\{j | t_j \leq t\}$$

Fig. 1. Peak-load pricing equilibrium with a) generation capacities, b) load duration curve, c) generation cost curves and d) prices

The model can be best generalized to cover the peak-load period by stipulating that there is a technology N corresponding to load curtailment which is available at zero investment cost.

The variable cost of this last technology is then very high since it corresponds to the value of lost load (VOLL) of the customers.

Total system cost in equilibrium is then given by:

$$C^G = \sum_{n=1}^{N} c_n^{inv} K_n + c_n^{op} Q_n$$

With the quantity produced by technology n given by:

$$Q_n = K_n t_n + \int_{t_{n-1}}^{t_n} D(t) - D(t_{n-1})\, dt$$

Inclusion of renewables

Intermittent renewables like wind and solar with zero variable costs are best introduced into the peak-load-pricing model by considering the residual load curve $D^R(t)$ to be covered by conventional generation after deduction of renewable generation $R(t)$:

$$D^R(t) = D(t) - R(t)$$

Renewable generation is then dependent on the installed capacity KRen, a capacity factor F describing the quality of the site considered (e.g. dependent on average wind speed) through the number of annual full load hours and a generation profile r(t) satisfying $\int_{t=0}^{T} r(t)dt = 1$.

$R(t) = r(t)FK^{Ren}$ and $Q_{Ren} = \int_{t=0}^{T} R(t)\, dt$

Cost for renewables are then proportional to the installed capacity:

$$C^R = c^{inv,R} K^{Ren}.$$

Simplification for analytical treatment

For the subsequent analysis, linear shapes for the load duration curves are assumed. We further restrict ourselves to the two conventional technologies coal and gas for the analytical treatment.

We then distinguish between different possible influences of additional renewable generation on the load duration curve. In a first case, case A, a positive correlation might occur due to e.g. offshore wind or solar power generation, whereas in a second case, negative correlation might be induced by onshore wind for example.

K_1 and K_2 are the capacities of coal and gas respectively. K_T gives total conventional capacity Superscript R denotes the analogous variables including renewable generation.

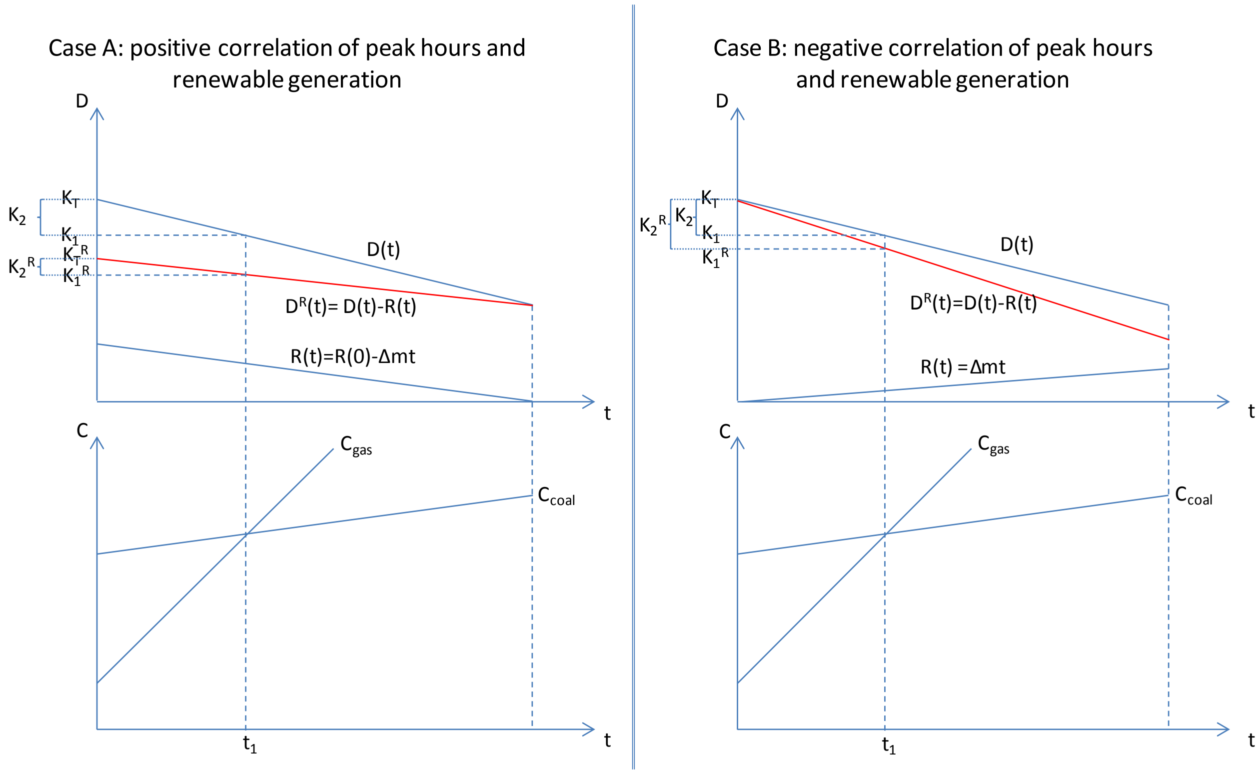


Fig. 2. Peak-load pricing equilibrium with additional renewable generation with Case A: positive correlation of peak hours and renewable generation, and Case B: negative correlation of peak hours and renewable generation

The simplification achieved by this linearization assumption allows to express $R(t)$ as a simple linear function, where $r(t)F$ reduces to Δm. The residual demand curve $D^R(t)$ is then simply derived from the load duration curve $D(t) = K_T - mt$ as

$D^R(t) = K_T^R - (m - \Delta m)t.$

In case A this leads to a flatter residual demand curve $D^R(t)$. Relatively more peak capacity is then substituted by renewable generation. In case B off-peak outweighs peak capacity substitution and consequently $D^R(t)$ becomes steeper.[9]

The simplicity of the model allows to explicitly express the degree of renewable-peak correlation as the slope of the load curves' difference, Δm. This makes an intuitive interpretation of results possible.

Further, the other variables and parameters can be expressed as $K_2 = mt_1$ and $K_1 = K_T - mt_1$. The energies produced for the two conventional technologies equal

$$Q_2 = \frac{K_2 t_1}{2} = \frac{K_2(\sqrt{(mT)^2 + T^2})}{2}$$

for gas, and for coal

[9] The case where parallel shifts occur is omitted in the subsequent analysis, for it qualitatively has the same consequences regarding its economic interpretation as either case A or case B – only quantitative impacts differ. Whether it is similar to case A or B depends on the parameterization.

$$Q_1 = K_1 t_1 + (K_{Ges} - mT)(T - t_1) + [K_1 - (K_{Ges} - mT)](T - t_1)\frac{1}{2}$$
$$= \tfrac{1}{2}\big(K_1(T + t_1) + (K_T - mT)(T - t_1)\big).$$ [10]

The cost function (cost potential curve) of the renewable technology can then be described by $\kappa(Q_{Ren}) = \beta + \gamma Q_{Ren}$ with $\gamma = \frac{c^{inv,R} K^{Ren}}{Q_{Ren}}$, which makes $\kappa(Q_{Ren}) = \alpha + c^{inv,R} K^{Ren}$. Perfect scalability of investment is thus assumed making the function consist only of a variable cost part directly given by investment per unit of energy produced.

The subsequent analytical considerations can be reduced to following intuitive argument. First, a policy goal for an optimal Q_{Ren}^{target} may be derived from emissions reduction considerations from abatement goals. Often this happens pragmatically in practice. By assuming both marginal reduction costs and cost potential curves $\kappa(Q_{Ren})$ as well as external damage to be previously known to politics, this may be done efficiently. Second, the price in the remaining market for conventional production depends on the energy supplied by renewables. The crowding out of conventional capacity leads to a decreasing or an increasing market price, the price for conventional energy, with growing renewable generation, if production of renewable energy is positively or negatively correlated with peak hours. As a result $P_{conv}(Q_{Ren})$ will decrease for case A and increase for case B. Then, for the bonus system model the remuneration in turn partly depends on the market price P_{conv} initially set to $S^{fixed} - P_{conv}(0)$, and the fixed markup $S^{bonus,stat}$. Market price dependence on Q_{Ren} leads to a feedback for the renewable capacity extension decisions with increasing extension plans. Lower renewable generation in case A will lead to a rebound effect on market price inducing it to increase, which in turn increases renewable energy remuneration asf. After these iterations a new stationary equilibrium occurs at $\left(Q_{Ren}^A, K_1^{R,A}, K_2^{R,A}, K_T^A, P_{conv}^A(Q_{Ren}^A)\right)$. Analogously the equilibrium $\left(Q_{Ren}^B, K_1^{R,B}, K_2^{R,B}, K_T^B, P_{conv}^B(Q_{Ren}^B)\right)$ is derived.

[10] The extension to several technologies is straightforward. Additional technologies will either alter average on-peak or average off-peak technology cost. As a consequence, renewable energy generation elasticity of total conventional generation cost may be increased or decreased. This does not qualitatively affect main results.

For the feed-in tariff model the remuneration of renewable energies only depends on the tariff S^{fixed} thus avoiding this feedback. Q_{Ren}^{target} is achieved.

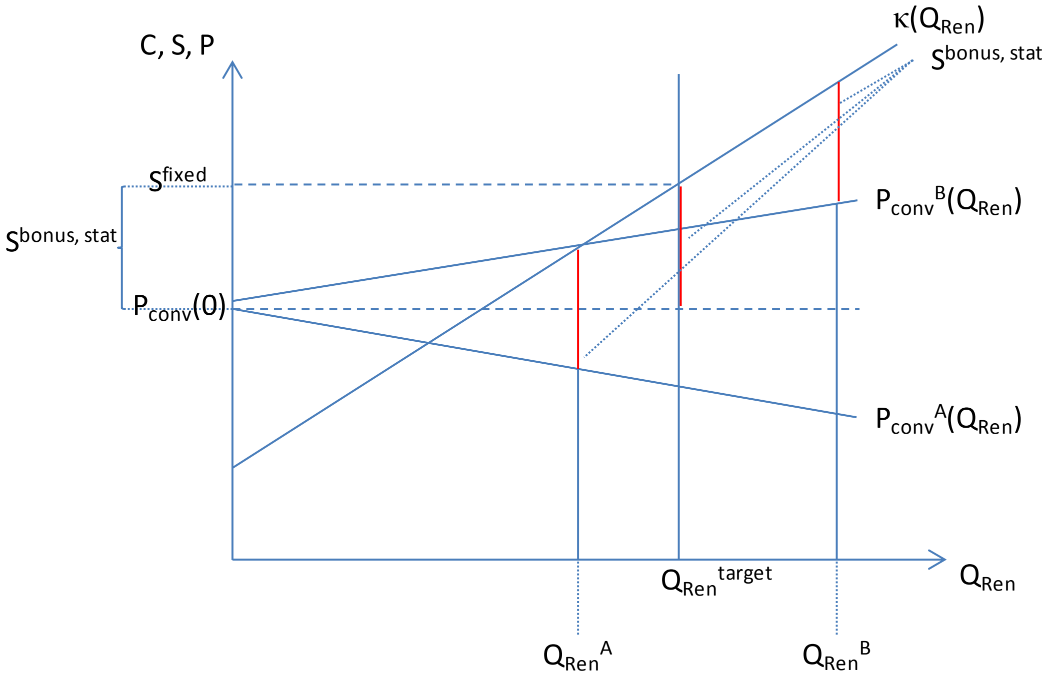


Fig. 3. Cost potential curve of renewable technologies and

The essential conclusion is to directly incorporate market price reactions from now to the envisaged optimal Q_{Ren}^{target} and to adapt the bonus accordingly.

3.2 Case A: Positive renewable generation-peak correlation

Residual demand then is $D^{R,A}(t) = K_T^R - nt$ with $n = m - \Delta m$. New total cumulated capacity in turn is $K_T^R = K_T - \Delta mT$. Then simply $K_1^R = K_T^R - nt_1 = K_T - \Delta mT - (m - \Delta m)t_1 = K_T - \Delta m(T - t_1) - mt_1$ and $K_2^R = nt_1 = (m - \Delta m)t_1$.

This leads to following new amounts of energy produced by technologies

$$Q_2^{R,A} = \frac{t_1}{2} K_2^R = \frac{t_1^2}{2}(m - \Delta m)$$

and $$Q_1^{R,A} = K_1^R t_1 + (K_T - mT)(T - t_1) + \frac{1}{2}[K_1^R - (K_T - mT)](T - t_1)$$

$$= \frac{K_1^R}{2}(T + t_1) + \underbrace{\frac{1}{2}(K_T - mT)(T - t_1)}_{=F>0}$$

$$= \frac{(T + t_1)}{2} K_1^R + F,$$

where K_1^R depends on Δm.

The market price is represented by an average of average prices of the two technologies $c_1^{avg} = \left(c_1^{inv}K_1 + c_1^{op}Q_1\right)/Q_1$, $c_2^{avg} = \left(c_2^{inv}K_2 + c_2^{op}Q_2\right)/Q_2$. Price is now dependent on Q_{Ren}^A:

$$P_{conv}^A\left(Q_1^{R,A}(Q_{Ren}^A), Q_2^{R,A}(Q_{Ren}^A)\right) = \frac{Q_2^{R,A}(Q_{Ren}^A)}{Q_T^{R,A}(Q_{Ren}^A)} c_2^{avg} + \frac{Q_1^{R,A}(Q_{Ren}^A)}{Q_T^{R,A}(Q_{Ren}^A)} c_1^{avg},$$

where $Q_T^{R,A}(Q_{Ren}^A) = \int_0^T D^{R,A}(t)\,dt = \left(K_T^R - (K_T - mT)\right)T\frac{1}{2} + (K_T - mT)T = K_T T - m\frac{T^2}{2} - \Delta m(Q_{Ren}^A)\frac{T^2}{2}$.

With this knowledge a linearized $Q_{Ren}^A = \int_{t=0}^T R(t)\,dt$ can now be calculated and the interdependence of Q_{Ren}^A and Δm can be shown.

$$Q_{Ren}^A(\Delta m) = TmT - \frac{1}{2}TmT - \frac{1}{2}\left(K_T^R - (K_T - mT)\right)T$$

$$= \frac{m}{2}T^2 - \frac{1}{2}\left(K_T - \Delta mT - (K_T - mT)\right)T$$

$$Q_{Ren}^A = m\frac{T^2}{2} - m\frac{T^2}{2} + \Delta m\frac{T^2}{2}$$

$$\Delta m(Q_{Ren}^A) = \frac{2Q_{Ren}^A}{T^2}.$$

Then, $Q_T^{R,A}(Q_{Ren}^A) = \left(K_T - \frac{T}{2}m\right)T - Q_{Ren}^A$.

An increase of Q_{Ren}^A will therefore lead to an increase of Δm, which means a lower slope n of the residual load curve. Prices will naturally decrease with respect to Q_{Ren}^A

$$P_{conv}^A\left(Q_1^{R,A}(Q_{Ren}^A), Q_2^{R,A}(Q_{Ren}^A)\right) = \frac{Q_2^{R,A}(Q_{Ren}^A)}{Q_T^{R,A}(Q_{Ren}^A)} c_2^{avg} + \frac{Q_1^{R,A}(Q_{Ren}^A)}{Q_T^{R,A}(Q_{Ren}^A)} c_1^{avg}$$

This can easily be shown by demonstrating that, first, the derivation of $\frac{Q_2^{R,A}(Q_{Ren}^A)}{Q_T^{R,A}(Q_{Ren}^A)}$ w.r.t. Q_{Ren}^A is smaller 0:

$$\frac{\partial\left(\frac{Q_2^{R,A}(Q_{Ren}^A)}{Q_T^{R,A}(Q_{Ren}^A)}\right)}{\partial Q_{Ren}^A} = \frac{\partial\left(\frac{t_1^2\left(m - Q_{Ren}^A\frac{2}{T^2}\right)}{2\left(K_T - \frac{T}{2}m\right)T - 2Q_{Ren}^A}\right)}{\partial Q_{Ren}^A} < 0?$$

$$\Leftrightarrow \frac{\left(-2\frac{t_1^2}{T^2}\right)\left(2\left(K_T - \frac{T}{2}m\right)T - 2Q_{Ren}^A\right) - \left(t_1^2\left(m - Q_{Ren}^A\frac{2}{T^2}\right)\right)(-2)}{\left(2\left(K_T - \frac{T}{2}m\right)T - 2Q_{Ren}^A\right)^2} < 0$$

$$\Leftrightarrow m < \frac{K_T}{T},$$

and the derivation of $\frac{Q_1^{R,A}(Q_{Ren}^A)}{Q_T^{R,A}(Q_{Ren}^A)}$ will be greater 0:

$$\frac{\partial\left(\frac{Q_1^{R,A}(Q_{Ren}^A)}{Q_T^{R,A}(Q_{Ren}^A)}\right)}{\partial Q_{Ren}^A} = \frac{\partial\left(\frac{\frac{(T+t_1)}{2}\left(K_T - \frac{2Q_{Ren}^A}{T^2}(T-t_1) - mt_1\right) + \frac{1}{2}(K_T - mT)(T-t_1)}{\left(K_T - \frac{T}{2}m\right)T - Q_{Ren}^A}\right)}{\partial Q_{Ren}^A}$$

$$> 0?$$

$$\Leftrightarrow \frac{\left[\begin{array}{c}\left(-2\frac{(T+t_1)}{2T^2}(T-t_1)\right)\left(\left(K_T - \frac{T}{2}m\right)T - Q_{Ren}^A\right) \\ -\left(\frac{(T+t_1)}{2}\left(K_T - \frac{2Q_{Ren}^A}{T^2}(T-t_1) - mt_1\right) + \frac{1}{2}(K_T - mT)(T-t_1)\right)(-1)\end{array}\right]}{\left(\left(K_T - \frac{T}{2}m\right)T - Q_{Ren}^A\right)^2} > 0$$

$$\Leftrightarrow m < \frac{K_T}{T}.$$

Consequently, price decreases w.r.t. Q_{Ren}^A for case A

$$\frac{\partial\left(P_{conv}^A\left(Q_1^{R,A}(Q_{Ren}^A), Q_2^{R,A}(Q_{Ren}^A)\right)\right)}{\partial(Q_{Ren}^A)} < 0\,.$$

Under the fixed feed-in tariff, the targeted quantity Q_{Ren}^{target} will be achieved due to lacking coupling to market prices. Contrarily, for the market price based markup model, the bonus system, the average market price change will lead to a new stationary equilibrium, with new Q_{Ren}^A, by the condition

$$P_{conv}^A(Q_{Ren}^A) + S^{bonus,stat} = \kappa(Q_{Ren}^A)\,,$$

which can be transformed to

$$P_{conv}^A(Q_{Ren}^A) + \kappa\left(Q_{Ren}^{target}\right) - P_{conv}^A(0) = \kappa(Q_{Ren}^A)$$

$$\gamma Q_{Ren}^{target} = P_{conv}^A(0) - P_{conv}^A(Q_{Ren}^A) + \gamma Q_{Ren}^A$$

$$Q_{Ren}^{target} = \frac{P_{conv}^A(0) - P_{conv}^A(Q_{Ren}^A)}{\gamma} + Q_{Ren}^A > Q_{Ren}^A$$

It can be seen from this formula that inclining Q_{Ren}^A will lead to a more than proportionate increase of Q_{Ren}^{target}, or, vice versa, an incline of Q_{Ren}^{target} will lead to less than proportionate increase of the stationary equilibrium Q_{Ren}^A. As a result, a policy setting such an $S^{bonus,stat}$ will fall short of its renewable goal by $Q_{Gap}^A = Q_{Ren}^{target} - Q_{Ren}^A = \frac{P_{conv}^A(0) - P_{conv}^A(Q_{Ren}^A)}{\gamma}$.

Here, the effect of the inclusion of additional conventional production technologies is easily described. An additional technology will increase productive efficiency either in the on-peak or the off-peak segment. In the first case conventional cost and thus market price $P_{conv}^{A}(Q_{Ren}^{A})$ will change to a lesser extent than without the new on-peak technology, because the on-off-peak cost differential reduces less with additional renewable installation. In other words, the elasticity ${}^{\partial P_{conv}^{A}/P_{conv}^{A}}\!\big/_{\partial Q_{Ren}^{A}/Q_{Ren}^{A}}$ reduces, which leads to a decline of Q_{Gap}^{A}. It is directly the opposite for the inclusion of an additional off-peak technology.

3.3 Case B: Negative renewable generation-peak correlation

The slope of the renewable generation function $R(t)$ now is positive, describing a more than proportionate decline of conventional off-peak generation when renewable generation increase. The slope of the residual load duration curve considering renewable generation then is again $n = m + \Delta m$. The effect on the slope is $D^{R,B}(t) = K_T^R - (m + \Delta m)t$, leading to a steeper residual load curve with relatively more peak generation.

Following capacities and energy is produced: $K_1^R = K_T - nt_1$ or $K_1^R = K_T - (m + \Delta m)t_1$, $K_2^R = nt_1 = (m + \Delta m)t_1$ and

$$Q_2^{R,B} = \frac{K_2^R t_1}{2} = (m + \Delta m)\frac{t_1^2}{2},$$

$$\begin{aligned} Q_1^{R,B} &= K_1^R t_1 + (K_T - nT)(T - t_1) + [K_1^R - (K_T - nT)](T - t_1)\tfrac{1}{2} \\ &= K_1^R t_1 + \left(\frac{1}{2}K_T - \frac{1}{2}nT\right)(T - t_1) + \frac{1}{2}TK_1^R - \frac{1}{2}t_1K_1^R \\ &= \frac{1}{2}\big((T + t_1)K_1^R + (K_T - (m + \Delta m)T)(T - t_1)\big) \\ &= K_1^R T - \frac{(T - t_1)^2}{2}(m + \Delta m). \end{aligned}$$

Market price again is given by

$$P_{conv}^{B}\left(Q_1^{R,B}(Q_{Ren}^{B}), Q_2^{R,B}(Q_{Ren}^{B})\right) = \frac{Q_2^{R,B}(Q_{Ren}^{B})}{Q_T^{R,B}(Q_{Ren}^{B})}c_2^{avg} + \frac{Q_1^{R,B}(Q_{Ren}^{B})}{Q_T^{R,B}(Q_{Ren}^{B})}c_1^{avg}.$$

Analogously,

$$Q_{Ren}^{B}(\Delta m) = \big(K_T - (K_T - nT)\big)\tfrac{T}{2} - \big(K_T - (K_T - mT)\big)\tfrac{T}{2} = (n - m)\tfrac{T^2}{2} = \tfrac{T^2}{2}\Delta m,$$

or $\Delta m(Q_{Ren}^{B}) = \frac{2Q_{Ren}^{B}}{T^2}$.

$Q_T^{R,B}(Q_{Ren}^{B})$ then is

$$Q_T^{R,B}(Q_{Ren}^B) = \int_0^T D^{R,B}(t)\,dt = \big(K_T - (K_T - nT)\big)\frac{T}{2} + (K_T - nT)T = K_T T - \frac{n}{2}T^2$$
$$= K_T T - \frac{m}{2}T^2 - \frac{\Delta m}{2}T^2$$
$$= K_T T - \frac{m}{2}T^2 - Q_{Ren}^B.$$

Prices then will naturally increase with respect to Q_{Ren}^B. This can again be shown by investigating the relative shares of $Q_1^{R,B}(Q_{Ren}^B)$ and $Q_2^{R,B}(Q_{Ren}^B)$ to new total energy supplied $Q_T^{R,B}(Q_{Ren}^B)$. If the relative importance of the peak technology will increase compared to the cheaper off-peak technology, the average price will increase.

$$P_{conv}^B\left(Q_1^{R,B}(Q_{Ren}^B), Q_2^{R,B}(Q_{Ren}^B)\right) = \frac{Q_2^{R,B}(Q_{Ren}^B)}{Q_T^{R,B}(Q_{Ren}^B)}c_2^{avg} + \frac{Q_1^{R,B}(Q_{Ren}^B)}{Q_T^{R,B}(Q_{Ren}^B)}c_1^{avg}$$

$$\frac{\partial\left(\frac{Q_2^{R,B}(Q_{Ren}^B)}{Q_T^{R,B}(Q_{Ren}^B)}\right)}{\partial Q_{Ren}^B} > 0?$$

$$\Leftrightarrow \frac{\partial\left(\frac{Q_2^{R,B}(Q_{Ren}^B)}{Q_T^{R,B}(Q_{Ren}^B)}\right)}{\partial Q_{Ren}^B} = \frac{\partial\left(\frac{\left(m + \frac{2Q_{Ren}^B}{T^2}\right)\frac{t_1^2}{2}}{K_T T - \frac{m}{2}T^2 - Q_{Ren}^B}\right)}{\partial Q_{Ren}^B} > 0$$

$$\Leftrightarrow K_T > 0\,.$$

and

$$\frac{\partial\left(\frac{\left(K_T - (m + \frac{2Q_{Ren}^B}{T^2})t_1\right)T - \left(m + \frac{2Q_{Ren}^B}{T^2}\right)\frac{(T-t_1)^2}{2}}{K_T T - \frac{m}{2}T^2 - Q_{Ren}^B}\right)}{\partial Q_{Ren}^B} < 0?$$

$$\Leftrightarrow \frac{\left[\begin{array}{c}\left(-\frac{T^2+t_1^2}{T^2}\right)\left(K_T T - \frac{m}{2}T^2 - Q_{Ren}^B\right) \\ -\left(\left(K_T - (m + \frac{2Q_{Ren}^B}{T^2})t_1\right)T - \left(m + \frac{2Q_{Ren}^B}{T^2}\right)\frac{(T-t_1)^2}{2}\right)(-1)\end{array}\right]}{\left(K_T T - \frac{m}{2}T^2 - Q_{Ren}^B\right)^2} < 0$$

$$\Leftrightarrow -K_T < 0\,.$$

The relative weight of cheap technology 1 will decrease whereas the weight of expensive technology 2 becomes greater, which induces market price to increase overall.

$$\frac{\partial\left(P_{conv}^{B}\left(Q_1^{R,B}(Q_{Ren}^{B}),Q_2^{R,B}(Q_{Ren}^{B})\right)\right)}{\partial Q_{Ren}^{B}} > 0$$

The new stationary equilibrium with new Q_{Ren}^{B} is then again derived by the condition

$$P_{conv}^{B}(Q_{Ren}^{B}) + S^{bonus,stat} = \kappa(Q_{Ren}^{B}) ,$$

which can be transformed to

$$Q_{Ren}^{target} = \frac{P_{conv}^{B}(0) - P_{conv}^{B}(Q_{Ren}^{B})}{\gamma} + Q_{Ren}^{B} ,$$

Which in turn indicates a less than proportionate increase of Q_{Ren}^{target} w.r.t. Q_{Ren}^{B}, because $\partial P_{conv}^{B}/\partial Q_{Ren}^{B}$ is positive. Q_{Ren}^{B} will therefore lie above envisaged Q_{Ren}^{target} (the first term on the RHS is negative). As a result, a policy setting such an $S^{bonus,stat}$ in case B of positive correlation of renewable energy generation with off-peak hours will exceed its renewable goal by $Q_{Gap}^{B} = Q_{Ren}^{target} - Q_{Ren}^{B} = \frac{P_{conv}^{B}(0)-P_{conv}^{B}(Q_{Ren}^{B})}{\gamma}$.

The interpretation of the inclusion of additional technologies with respect to Q_{Gap}^{B} is analogous to the one under A. An additional off-peak technology will lead to a stronger relative market price reaction and thereby relatively stronger overshooting of the renewable energy production goal and vice versa. Flatter cost curves thus in general reduce market price reactions and thereby to a reduction of Q_{Gap}.

3.4 Assessment of impacts of the Sensfuß-Rohrig proposition of optional regime switching

The recent proposition of Sensfuß and Rohrig to give renewable energy producers the choice of short term switching between the two production support regimes: These can make monthly decisions to either be remunerated receiving the fixed feed-in tariff or the market price complemented by a bonus markup. Whereas the intended renewable generation is easily achieved by the feed-in tariff by setting the remuneration (and subsidy) at $\kappa\left(Q_{Ren}^{target}\right)$. The remuneration choosing the market based bonus comprises the market price$P_{conv}^{A/B}$ at $Q_{Ren}^{A/B}$ and the statically set bonus markup $S^{bonus,stat}$.

The option to choose now increases expected remuneration, because the producer will take $\max\left(\kappa\left(Q_{Ren}^{target}\right); P_{conv}^{A/B}\left(Q_{Ren}^{A/B}\right) + S^{bonus,stat}\right) \geq P_{conv}^{A}(Q_{Ren}^{A}) + S^{bonus,stat}$. As high market price periods lead to a situation analogous to case B, the renewable energy producer will profit of higher market based remuneration in high price times and of the floor during low price times. Average remuneration in consequence lies above $\kappa(Q_{Ren}^{target})$ with all negative consequences of the situation in case B.

4 Application

For an illustration of the effects derived from the analytical comparison in chapter 3, relevant functions and parameters are estimated for the German power system and different targeted policy goals. With a total demand of about 575 TWh and the nearly 20 percent renewable energy generation, the generation from conventional power plants is about 460 TWh. Figure 1 shows the corresponding residual load duration curve. With a simple linear regression, the parameters for the demand curve $D(t) = K_T - mt$ are derived.

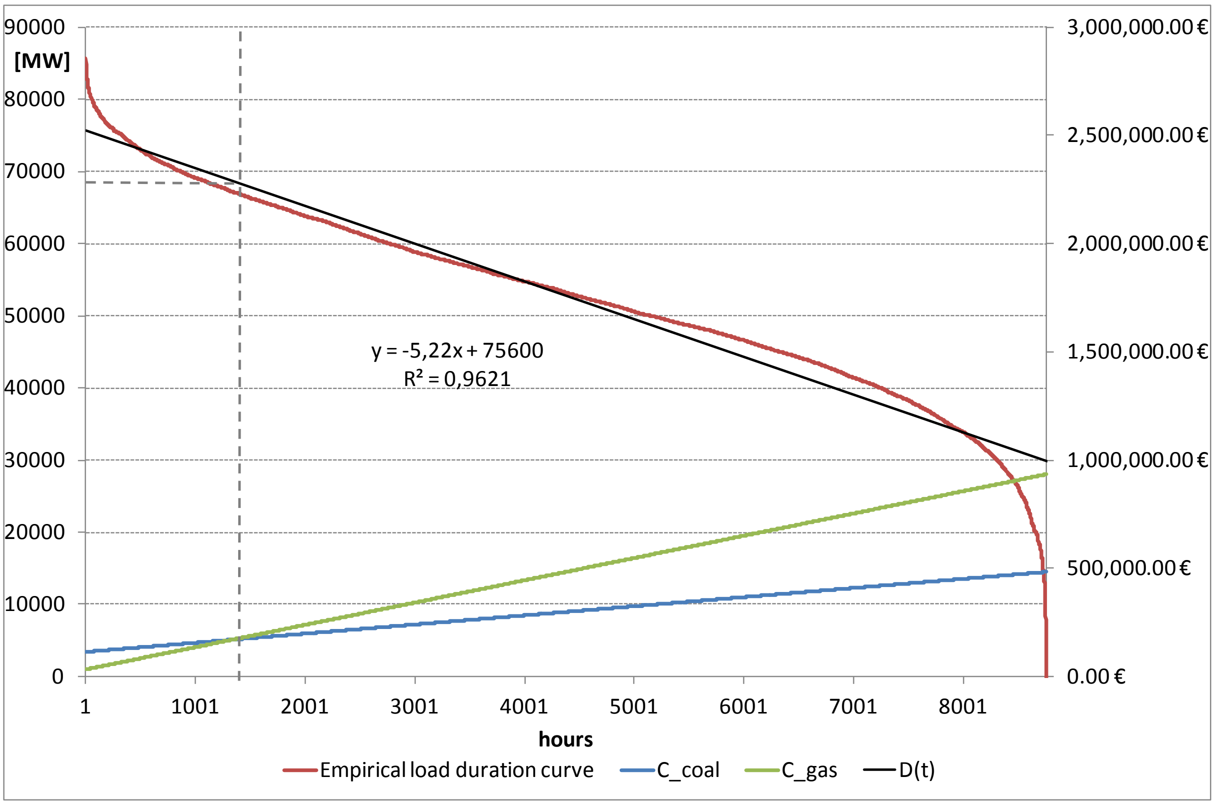


Figure 4: Peak load pricing model - Parameter estimation

As a cost-minimization the peak-load pricing model in addition requires generation cost curves, which are depicted in Figure 4. With this information the optimal power production for coal- and gas plants without further renewable feed-in can be determined.

The next step is to include new capacities in renewable energy production. As these cannot be dispatched by request, the simple inclusion as an additional technology is not possible. Rather the timely nature of their feed-in has to be respected and the residual demand curve adopted accordingly. This induces the slope of the residual demand curve $D^R(t)$ to increase in case A, in case B this slope is decreasing, i.e. becomes steeper.

For a detailed analysis of the effects derived in chapter 3, additional renewable feed-in is allowed to vary between 5 to 40 percent, which reduces or raises the slope of $D^R(t)$ from 1 MW/h to 5 MW/h. Figure 5 illustrates this sensitivity analysis for case B.

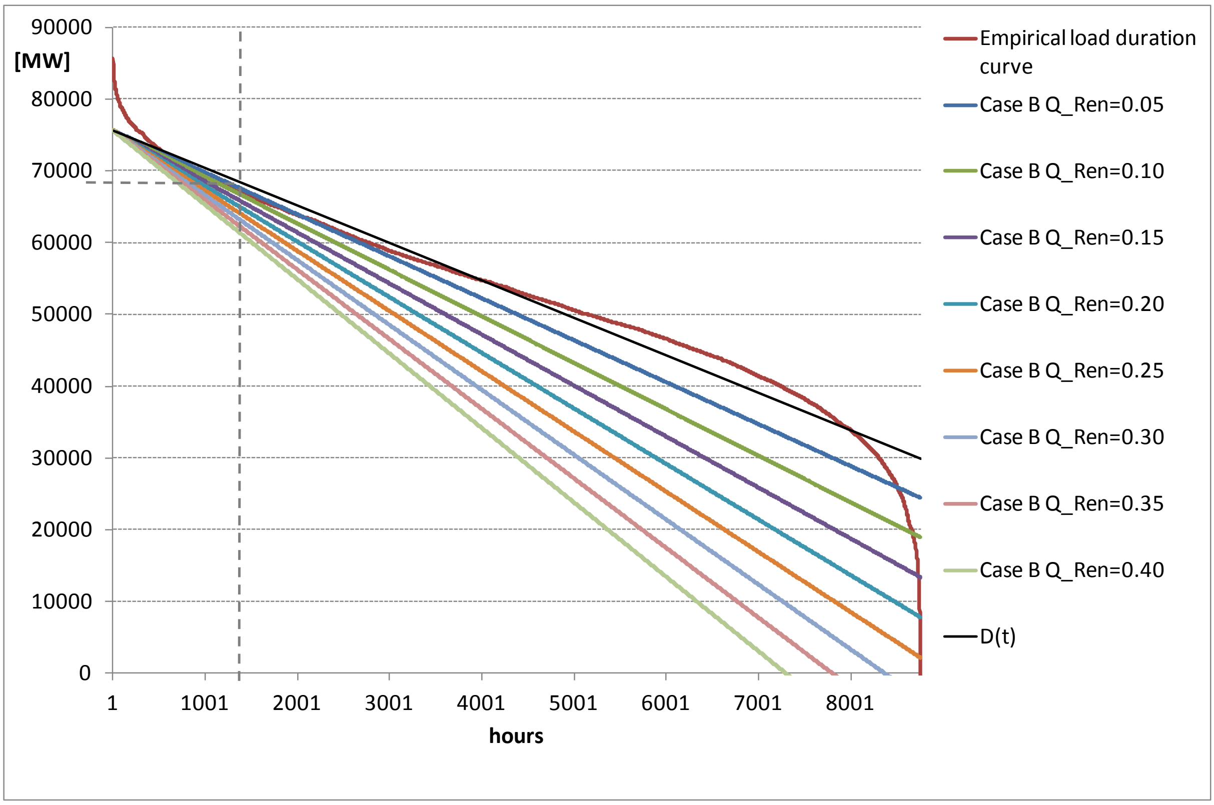


Figure 5: Residual load for different renewable new built targets

A further important function is the cost potential curve for renewables. Figure 6 depicts cost curves for onshore wind, offshore wind and solar power. For the cost function $\kappa(Q_{Ren}) = \beta + \gamma Q_{Ren}$, the parameters are calculated as a weighted average of the three cost potential curves. Thereby the weighting factors are derived from the renewable targets of the German government for the year 2015.

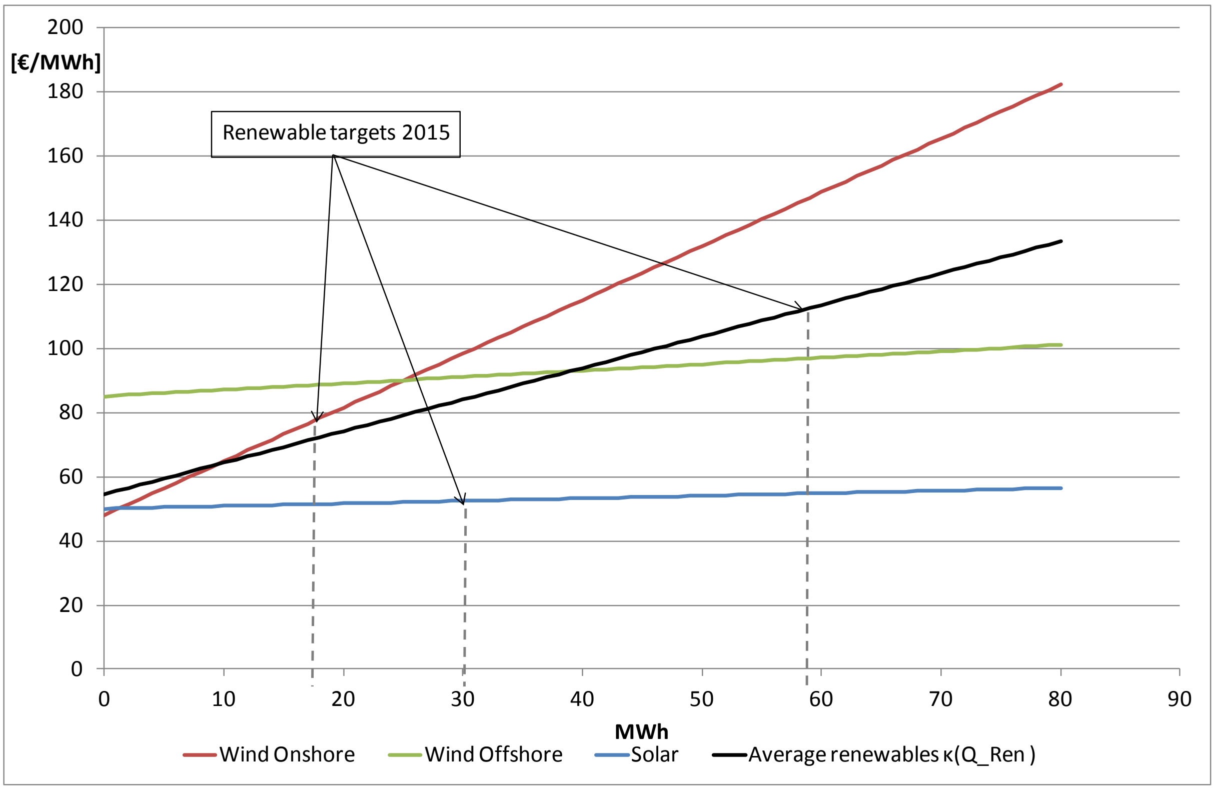


Figure 6: Cost potential curves for different renewable technologies

To obtain further insights on the correlation of load, renewable feed-in and the corresponding residual load, figure 7 shows the situation for the 20 percent additional feed-in case. This illustrates case B from chapter 3, where renewable feed-in is negatively correlated with load. This leads to the expected steepening of residual demand.

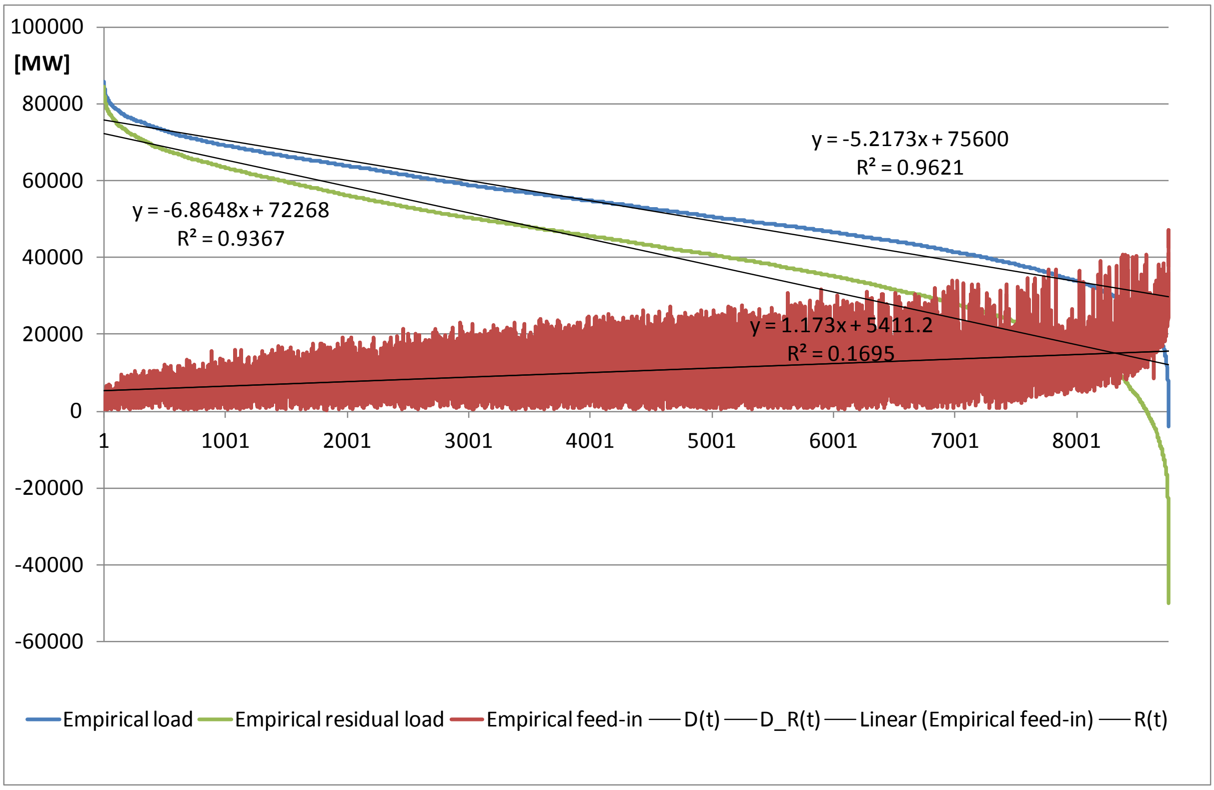


Figure 7: Correlation load, renewable feed-in and residual load

Under the bonus scheme this correlation leads to the derived deviations from targeted renewable installation. The calculation of the effective renewable feed-in for the bonus system $Q_{Ren}^{A,B}$ and the corresponding market prices $P_{conv}^{A,B}\left(Q_{Ren}^{A,B}\right)$ are depicted in figure 8 for different renewable feed-in percentages (see figure 5). Figure 8 also shows the results and compares them to the fixed feed-in tariffs system, which serves as the zero-benchmark. Case B here uses data for the actual empirical situation in Germany. Data for (hypothetical) case A is obtained by inverting renewable feed-in to obtain the opposite correlation with the load duration curve.

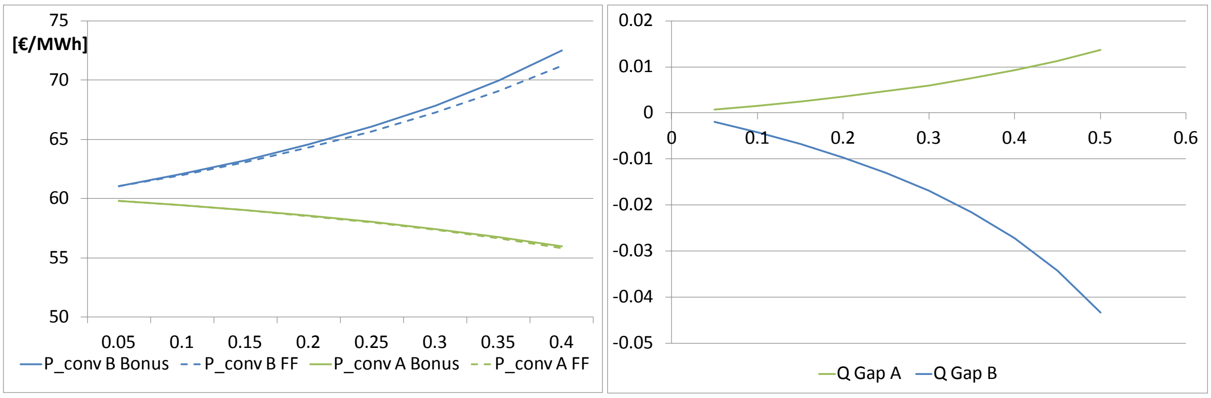


Figure 8: Comparison of market prices (lhs) and renewable feed-in gap (target minus realized feed-in) (rhs)

The application results confirm the analytical results. Market price reactions to additional renewable installation prove to be negative for the empirically relevant case of positive correlation of renewable feed-in and load (case B). For hypothetical case A, there is a negative market price reaction leading to positive gap to the renewable feed-in target. The additional incentive induced by increased market prices for case B leads to a negative gap. This corresponds to an overprovision of renewable capacity. It can further be seen that the effects for case B are always stronger than for case A. In both cases effects increase with an increasing feed-in percentage.

For a further comparison of the two instruments a closer look at total system costs (Figure 9, lhs) and subsidies (Figure 9, rhs) may be helpful.

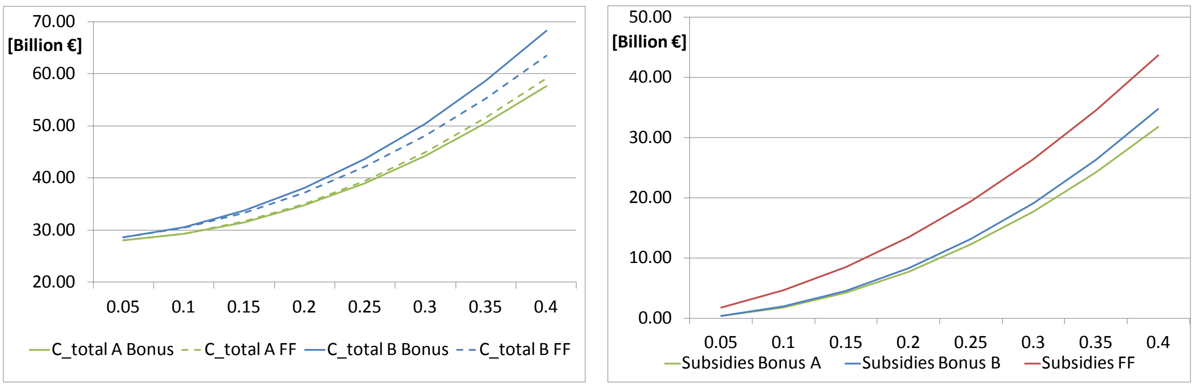


Figure 9: Total system cost for the different cases (lhs) and subsidies fixed feed-in tariffs and bonus (rhs)

The total system costs are derived by the sum of the costs from conventional power plant generation and the costs for the renewable feed-in. Taking into account the cost potential curves from figure 6 and the feed-in gap from figure 8 (rhs), it is not surprising that the bonus system for case B is the system with highest total cost. On the other hand the systems with the bonus instrument have much less subsidies than the systems with fixed feed-in tariffs. Given economic losses caused by redistribution through subsidization in the size of eventually 10 to 20 % it turns out that losses from increased system costs might easily outweigh lower subsidization advantages.

5 Conclusion

The article investigates a possible weakness of the usage of second-best instruments: Indirect addressing of policy variables may easily lead to failure of envisaged goals. Two such instruments, feed-in tariffs and market based bonus markups, are compared with respect to their ability to achieve renewable energy production targets.

A peak load partial equilibrium model is used to show that market price reactions to renewable new built lead to altered effective remuneration under the bonus scheme system. It is therefore important to consider market price reactions for the calculation of the appropriate bonus. It is shown that the direction of this adaptation depends on the correlation of renewable generation with either the on-peak or the off-peak segment. In the first case declining average market prices will lead to a shortfall of renewable capacity new built, which will then have to be compensated by higher subsidization. It is further shown that this gap in renewable capacity installation is driven by the relation of market price differential to the slope of the renewable energy production cost potential curve. A steeper cost potential curve will therefore lead to less deviation, whereas more sensitive market price reactions will lead to a greater deviation from the renewable production target. With respect to a current policy proposition in Germany, which leaves renewable energy generators with the choice to voluntarily switch between the two remuneration regimes, the analogy to case of renewable energy generation with off-peak segments is demonstrated and the inefficient overprovision of renewable energy generation is shown.

The parameterization of the analytical model for a stylized German partial equilibrium model clarifies the derived effects. Given renewable capacity installation targets of the German government these reveal to be significant. As market price reaction prove to be more pronounced when renewable generation is correlated with off-peak generation (inducing price increases), also the resulting gap is greater when renewable capacity is overprovided than in the case of renewable energy production-correlation with the on-peak segment and following underprovision of renewable capacity. It is further shown that the German renewable capacity targets are based on off-peak technologies leading to market price increases and relative overprovision or production by renewable energies. The implementation of the optional remuneration switch policy proposed by Sensfuß and Rohrig thus may cause additional difficulties strengthening existing problems. Also, these losses might easily outweigh possible advantages like economies on state burdens like lower necessary subsidization in the case of the bonus system. Lower market based bonus markups (as well as feed-in tariff subsidies) or lower renewable capacity installation goals may therefore be considered.

Of course, there are many relativizations, which have to be noticed. The employed peak-load framework assumes workable competition in the conventional production sector. The renewable production sector similarly is assumed to have no potential efficiency gains of increased competition through greater proximity to market forces. This and other effects like fewer redistributive distortions through lower necessary subsidies are advantages of the market based bonus system, which are not considered here but would be important for an overall welfare comparison of the two instruments. Effects may arise like relative competitive pressures in the segmented markets, which will have an a priori ambiguous impact on the achievement of the renewable installation target.

Further extensions of the model appear to be worthwhile. Besides the implementation of market power the explicit, endogenous integration of a GHG emissions market and differentiated feed-in tariffs would allow the additional refinement of the results. Also endogenous reactions of demand could make the discussion of another interesting rebound effect possible. These are relativizing effects possibly important for the significance of the derived results.

Finally, the stochastic nature of renewable energy production may severely influence the correlation with the load duration curve. In this article it is assumed that there is a perfect positive or negative correlation in the analytical model. The stochastic nature of the renewable energy feed-in in the application leads to an effective negative correlation with on-peak demand. In other words, the load duration curve and residual demand have a positive correlation. This is a further interesting result in the light of widely assumed on-peak correlation of e.g. photovoltaic feed-in, because it leads to increasing average market prices contrary to the expected decrease. However, an explicit analysis is beyond the scope of this article.

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