Feed-in Tariffs: The way to make the transition happen?

FEED-IN TARIFFS: THE WAY TO MAKE THE TRANSITION HAPPEN?

An integrated assessment to determine an optimal feed-in tariff

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Abstract

Since the call for renewable energy diffusion is increasing, the need for instruments to accelerate the diffusion of renewable energy sources is apparent. This thesis examines the possibilities for policymakers to implement such mechanisms that help the development of renewable energy. Feed-in tariffs are considered one of the most effective instruments to achieve renewable energy development goals. Existing literature is analysed on the performance of the feed-in tariffs both in terms of theoretical as well as empirical grounds. After this analysis recommendations are made that follow from up-to-date literature that provide the requirements for optimal feed-in tariff design. These recommendations are taken into account while providing mathematical models that reveal the dynamics behind feed-in design. These models will show the possibilities to increase feed-in tariff efficiency.

The study has a number of limitations which the reader should be aware of. The amount of time available did not allow for extensive research to find estimations on parameters in the models. This resulted in the incomprehensiveness of these models in terms of uncertainty in technological developments. It is recommended to refer to other research for the estimation of the right parameters and effect sizes. With these limitations in mind, the objective of this study is not to come with new mechanisms nor to come with new theory or data, but rather the aim is to provide an overview of what is available in literature as well as to illustrate these theories by means of mathematical models. Other shortcomings of the models presented as well as further discussion on the use of support mechanisms, are included in the last part of the thesis. This thesis concludes by stating that the support of renewable energy sources is justified because it is only with support mechanisms that renewable energy diffusion takes place on a scale large enough to capture its environmental benefits. Furthermore from both theoretic as well as empirical analysis follows that feed-in tariffs are an attractive option, when adequately designed, to achieve renewable energy diffusion targets.

1 Introduction

The upcoming decades are full of challenges that require attention. Climate change is stressed by many as one of the greatest challenges. To assure that future generations have access to the same natural resources as the current ones, adequate policies and measures need to be taken. Renewable energy sources (RES) are one answer to mitigate the emissions of carbon dioxide by human activity that are the main cause of this climate change. But the challenge for RES is the competition of conventional energy sources that persist due to the differences in price and maturity of technology. There are ways to stimulate and increase the deployment of RES. Feed-in tariffs are an increasingly popular price-based instrument to increase the adoption of RES. This thesis will look into the dynamics of Feed-in tariffs (FITs). A lot of literature is written on this subject. The objective of this thesis is therefore not to come with new theory but rather to fit the existing perspectives together. Therefore this thesis also includes a model that provides the mathematical foundation of the existing theory. The thesis is build-up out of three parts. The first part will be a literature review, including a comparison of the different support mechanisms, an analysis of the empirical data and a determination of the characteristics of an optimal FIT design. In the second part a series of models is included to show the recommended change in the design of FITs in line with the dynamic process, with learning effects, to which the renewable energy technologies are subjected to. The models should give an impression on the processes that policymakers need to take into account when designing an optimal FIT policy. Different policy goals will result in different Feed-in levels. Finally the third part will discuss the drawbacks of the models, i.e. the missing parameter values in the model and their implications. Consequently recommendations will be made on further research that could answer the question on the optimal FIT level. The thesis will end with the conclusions.

2 LITERATURE REVIEW ON FEED-IN TARIFFS

2.1 INTRODUCTION

2.1.1 Justification of RES supporting policies

As the importance of the transition to a cleaner energy system is increasingly recognized worldwide, the schemes that provide this transition need to be analysed thoroughly. It is apparent that we need effective and efficient policy instruments to stimulate energy sources that will guarantee energy supply as well as environmental sustainability. The problem for renewable energy sources (RES) is that they lack the technological maturity and often also the adequate level of economic performance (Menanteau, 2003). The benefits of a better environment and a stable climate along with less energy dependency are not represented in the returns to investments. Since these 'goods' have a non-excludable and non-rivalry character the investors lose the incentive to invest in these goods that are essentially free. As pointed out by Batley et al. (2001), the problem of free-riding also persists in the behaviour of consumers with the consequence that although given the choice they are not willing to pay a higher amount for 'green' electricity. Therefore support mechanisms are needed to bridge the gap towards the both more economically as well as technologically advanced conventional energy sources.

When only considering the objective to reduce greenhouse gasses by developing RES, economic factors are must not be ignored. Legal regulatory policies that limit conventional energy production and make RES obligatory would fulfil this objective but do not take into account the costs that these regulations imply, let alone the distortion in the energy market. Additionally, as Jaffe et al. (1999) puts forward, regulations provide no incentive to make improvements beyond what is imposed. Therefore the objective should be broadened by considering achieving environmental targets at the lowest costs, and by minimum distortion of the market. The approach that is used in practice to achieve the objectives on emission reductions is based on cost-effectiveness. This approach is the only practical one since energy policies that are based on an optimal emission reduction levels and a consequent optimal energy generation level, require parameters that are still impossible to observe (Menanteau, 2003). The cost-effectiveness approach implies stimulation of technological progress, in the form of learning processes and innovations, which ensures that the competitive level of RES with conventional energy sources (CES) is reached. This way, adoption of clean technologies is realised and negative externalities caused by CES are reduced. Instruments that are in line with this approach are available but vary in the extent to which they are able to achieve conditions like cost-effectiveness and minimal distortion of the energy market.

2.1.2 Directions in literature

In the field of support mechanisms for renewable energy a lot of literature is available. This literature will be categorized in to three separate directions. First of all we look at the Feed-in tariff in comparison to other renewable energy stimulation mechanisms. What makes a FIT better suitable than other mechanisms? The literature that provides an answer to this is among others Menanteau, 2003; Sawin, 2004; Dinica, 2005 and Bürer, 2009. Secondly we look at the performance of FITs in several countries that implemented them by assessing them according to relevant criteria. This offers us a look into the empirical evidence that justifies the use of this instrument. Literature in this direction that we use is Sijm, 2002; Rowlands, 2003; Butler, 2004 and Del Río, 2007. Third direction is what implications the results from the previous literature have for the optimal design of a FIT. Literature used for this is Lesser, 2007 and Klein, 2007.

With regards to energy policies another point should be noted. As Menanteau (2003) states, a simple but effective solution to the problem of fair competition between energy sources is to implement an optimal environmental tax. The tax will offer the right incentive for technical innovation and a change in consumer behaviour. However this is only true when taking into account the economical aspects and not considering that taxes are unpopular and might not create the right focus on RES since the tax might imply a focus only on electricity savings instead.

2.2 ANALYSIS OF LITERATURE

2.2.1 Comparison of different support mechanisms

To answer the question as to why a Feed-in tariff is the preferable support mechanism for RES we need to know what the alternatives are and what is taken into consideration selecting the best mechanism. The mechanisms can be divided into price-based mechanisms and quantity-based mechanisms. The Feed-in tariff is a price based policy mechanism, which means that the price at which utilities are obliged to purchase renewable energy is set (Del Río, 2007). The quantity-based mechanisms imply that an objective set by authorities will be reached either through a competitive bidding process which results in the lowest price at which green energy producers will supply this amount, or the authorities will set quota on green energy producers after which they can trade in green certificates. When looking at the mechanisms behind feed-in tariffs and competitive bidding processes they are two sides of the same coin. The price-based mechanism sets the price P_{in} that, with the respective marginal cost curve of an energy producer, leads to a consequent amount of production Q_{out}. With a quantity-based mechanism the amount of production Q_{in} is set and with the same marginal cost curve, a consequent price P_{out} will be reached. Green certificates would result in the same prices as would be the case in a competitive bidding scheme when marginal cost curves are the same. All three mechanisms result in efficient allocation of produced amounts. In principle both mechanisms (price- and quantity-based) should have similar results, as the authority either simply fixes the price or the quantity to reach the same target (Menanteau, 2003).

However two important factors prevent this and result in different outcomes between mechanisms. There is imperfect information and uncertainty on the one hand and differences in dynamic efficiency on the other hand. The former implies that when the marginal cost curves are not known, with price-based mechanisms the resulting amount of production is not known (might not reach the target) and with quantity-based mechanisms the resulting price is not known (might become too costly) (Menanteau, 2003). Differences in dynamic efficiency are caused by differences in (1) cost reduction pressure and (2) ability to invest in R&D. For the first, the pressure to reduce costs is only felt by competitors, thus only in cases of competitive bidding schemes and green certificates, although this is perhaps compensated by the fact that the learning effect is greater for feed-in tariffs as they result in larger capacities. For the second, the surplus from profit attained by technological progress, goes to producers in the case of FITs and to consumers in the case of competitive bidding schemes. Green certificates will have only a limited increase in producer surplus and therefore FITs will result in the largest part of the profit allocated to R&D investments (Menanteau, 2003).

Altogether this implies that the mechanisms are different in effectiveness and efficiency. So in the next part we will compare feed-in tariffs, competitive bidding processes and green certificates with each other on the basis of the following criteria:

- Installed capacities
- Social costs
- Incentive to reduce costs and prices
- Incentive to innovate

Table 1 shows the characteristics of the different support mechanisms and their implications for these criteria, based on Menanteau (2003). From this overview we can conclude that FITs have in theory the best prospect to be successful in accomplishing the target of implementing renewable energy. We do not only look at Menanteau (2003), but we also show the results from Bürer (2009) in table 1, because he takes the perspective of the investor into account. This provides us a more integrated analysis. Bürer (2009) looks at the policy preferences of private investors in innovative clean energy technology firms. As Bürer (2009) puts it, this added perspective "(…)compensates for the inherent limitations of a quantitative ranking using generic policy types."

Another paper that looks into the investor's perspective is Dinica (2007). According to Dinica (2007) the typology of the support

table 1: Overview results of comparison; source: own elaboration

Menanteau (2003)

	Feed-in tariffs	Competitive bidding schemes
Installed capacities	High (+) + Low risk + Low transaction costs	Limited (-) - Lower margins with respect to risk - low profitability margins
Net social costs	High (-) - high capacities put pressure on public budget - price might be transferred to clients of electricity utilities	Limited (+) + controllable subsidies by progressively revealing shape of the cost curve by successive quota's
Incentive to reduce costs and prices	Insufficient (-) - low flexibility - price stability resulting in increased share of subsidies - lobby to keep FIT high	High (+) + high flexibility + reduction of prices through successive tendering procedures + seizes opportunities to cut production costs
Incentive to innovate	High (+) + establishes sustainable technical progress + surplus from technological progress goes to producers	Low (-) - reduced profitability margins imply less investment capacity for R&D - surplus goes to consumers/taxpayers

Brürer (2009)

	Feed-in tariffs	Competitive bidding schemes
Investment preference	High + effective way to reduce investment risk + set 'a steady cash flow' + high signal intent and consistency + good track record, 'seen' as effective mechanism	Low - higher investment risk - seen as "big corporation" policy, and hence as having neutral or negative effects on smaller, entrepreneurial firms

systems is as in figure 1. Competitive bidding schemes fall into category (area) 4 since bidding schemes involve competition which puts pressure on the profitability margins.

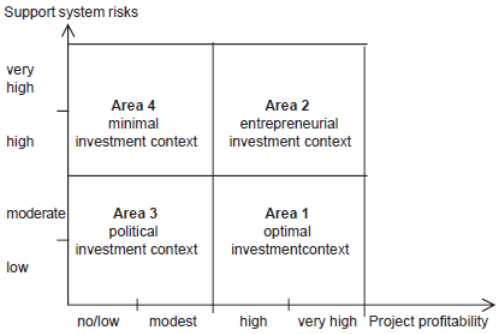

Figure 1: Typology of support systems; source: Dinica (2007) p. 6

Furthermore the risks are higher because both future profitability as well as the allocation of subsidies after the tendering procedure are uncertain. For Feed-in tariffs the situation is different. Profitability is high because price stability implies that, when technological progress takes place, costs are reduced while revenues remain the same. This means that risk is low, depending on the length of the pay-off period. Therefore FITs can be assigned to category (area) 1.

Altogether the argumentation presented by the theory justifies that we from now on focus on FITs as support mechanism in this thesis, as this mechanism is in theory the best suited to achieve emission reduction targets. To further strengthen this position, we will look at empirical evidence that the advantage of FITs over alternative support mechanisms.

2.2.2 Performance of FITs: empirical analysis

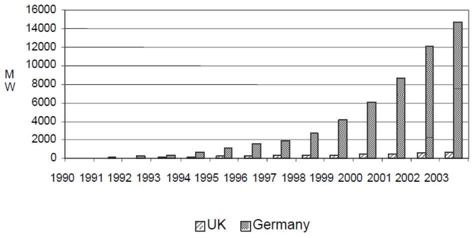

Figure 2: Difference in installed wind power capacities between Germany (FIT) and the UK (CBS); source: Butler (2004) p. 5

From figure 2 it is already clearly visible, in practice, countries that implemented FIT schemes show the highest capacity build-up. Countries that adopted alternative support mechanisms, such as competitive bidding schemes in the UK (represented in this figure), do not reach the same build-up targets. In analysing the performance of FITs we follow Sijm (2002). We compare the results of FIT schemes that were implemented in Germany and Denmark.

In Germany a FIT scheme has been officially implemented since 1991 called the 'Electricity Feed-in Law' (EFL). They have revised their system in 2000 and replaced it with a new system called 'Renewable Energies Law' (REL).

Under the EFL the producers of wind energy received a fixed price per kWh that was set at 90 percent of the final consumer price. However the EFL system made use of a differentiated FIT. This implies that the FIT rate was set according to the output of RES.

In terms of capacity build-up the EFL worked very effectively. With only 31 MW installed in 1990 this was already 1133 MW in 1995. The capacities showed incredible growth rates. Average annual growth rates amounted 105, 40, 70 percent for '90-'95, '95-2000 and '90-2000 respectively (BTM Consult ApS, 2001). By the end of 2000 the capacity amounted 6107 MW of onshore windpower, a 45 percent share of the total installed capacity in western Europe. However most of the MW capacity was in wind turbines since the EFL was only effective with respect to this RES. The FIT for wind energy was fixed relatively high compared to other forms of RETs. This is a profitable prospect for investors in wind energy but in the long run this implies that social costs rise rapidly and uncontrollably as the share of RES increases. The EFL did not have any mechanisms to keep the costs within reasonable limits nor did it have any stimulation of competition between energy producers. Therefore resistance within the German electricity industry began to grow. The locations where wind energy was the most profitable (i.e. where geographical and meteorological conditions are most favourable) were provided a competitive advantage not compensated by the EFL. The FIT was as high 9 cents per kWh whereas the avoided costs were only 2 cents (Rehnelt, 1998). The main criticisms on the EFL were, in short, cost-inefficiencies and distortion of competition. The cost-inefficiencies were mainly that costs were rising rapidly as the shares of renewable energy of total energy supply increased, and that the FIT did not decrease when cost reductions were made. The latter also implied that there was no incentive to innovate. All of these drawbacks lead to a revised and improved energy law, the REL. Under this law the authorities tried to minimise the drawbacks of the EFL by setting some new conditions: (1) the FIT became linked to the generation cost of the RES instead of the consumer prices, (2) competition was improved by permitting RES generated by the utilities sector to be eligible for FITs, (3) FITs became digressive, i.e. FITs are lower as capacity is higher, (4) FITs could be revised bi-annual depending on cost reductions and degree of market introduction, (5) costs of the FITs were shared among all the grid companies throughout the country, not burdening only the utilities in the regions with favourable generating conditions.

The same developments were visible in Denmark. Their pre-2000 Feed-in law was based on avoided costs for biomass and on 85 percent of the consumer price in case of wind energy. The difference with Germany was the added production subsidy and tax refund. This resulted in a high internal rate of return, making wind energy profitable in even the regions that had the least favourable conditions. Altogether the Danish also decided that the burden on the state budget would be too high, also given the increasing shares of RES. To solve this however they used a different approach than the Germans. The system for supporting renewable energy sources was changed into a green certificate trading scheme. Only the existing renewable energy capacity would receive FITs for a period of ten years. New RES plants would only receive FIT for 10 years and a green certificate per kWh, but no further output subsidies. From 2003 onward new plants received only the market price plus a green certificate per kWh produced (Sijm, 2002).

Since Denmark adopted this new system they have experienced stagnation in the build-up of renewable energy capacity (Rowlands, 2005). This may partly be explained by the scepticism towards green certificates among green investors, since green certificates are one of the lowest support mechanisms ranked by preference of investors (Bürer, 2009).

2.2.3 Implications for optimal design of FITs

As became clear both from theory and practice, there are advantages and disadvantages linked to FITs. Since it is the single most effective mechanism FITs are for now the instrument that is best suited to achieve RES build-up targets. However this does not imply that there is no more scope for improvement. According to Huber et al. (2001) there are some fundamental criteria for FIT design that mitigate many of the problems faced when implementing FITs. These criteria are as follows:

- The cost curve of the renewable energy technology is flat and predictable with high probability.

- The Feed-in tariffs decrease over time in line with the expected learning curve of the investment costs.
- The time period over which a producer receives a guaranteed price is limited, i.e. a feed-in tariff is limited to a certain, pre-defined duration.
- Granted feed-in tariffs should be lower if actual output of renewable electricity is higher.

Indeed if these criteria are met, much less problems would occur with a FIT scheme. However in practice, it is not as simple to fulfil these conditions. As Sijm (2002) notes, the shape of the cost curve is often very difficult to determine. Costs tend to increase as capacity increases (static cost curve) and they tend to decrease with technological progress over time (dynamic cost curve). Hence, to determine a appropriately declining FIT is very complicated. The points described might also become in conflict with the incentive to invest in capacity, as a too sharp decrease in FIT might take away the certainty and price stability benefits.

Despite of the complications to derive a FIT that is without all drawback and problems described earlier, there are possibilities to improve the FIT design.

Klein (2008) concluded in his paper that the best practices for FIT design should include:

- Continuity and long term investment policy
- Technology specific tariff levels
- Mechanisms should be provided to ensure penetration and improve integration of RES into the grid
- A premium tariff option can be applied to increase market orientation
- Tariff degression to provide incentives for cost reduction
- Stepped tariffs to reflect different power generation costs within the same technology
- Extra premiums to reach policy goals

Of course some remarks are important when observing these conditions. First of all the investments are dependable upon the duration of the guaranteed FIT, however there should be flexibility to revise the FIT to keep the FIT in line with the policy goals. This is the first trade-off. In the design of FITs there are many trade-offs that need to be balanced out to achieve an efficient outcome. The second trade-off is in the technology specific tariffs, which should reflect the different energy generation costs. The technology specific tariffs will offer an incentive to choose the RES that is most cost-efficient at that location. However this should not imply that RES, which are in the emergence phase and consequently behind in terms of technological development, are not supported and therefore build. Next to this there should also be a certain mechanism that ensures that RES producers can sell their electricity on the market. This could be a purchase obligation, however there are alternatives. It is important to keep in mind the socio-economic impact that consequently arises when the burden of the FIT costs is allocated. One way to limit the costs over time is to implement tariff degression, which implies that to maintain the same profit RES-generators are provided an incentive to reduce costs. Another way of keeping costs within limits and to stimulate equal competition across regions is to implement a stepped FIT. This implies that RES-generators in favourable regions receive a lower FIT to prevent overcompensation of these producers. This also implies that more sites are exploited and that clustering, with its negative social-political consequences as elaborated by Lauber (2004), is avoided. However there is a third trade-off in this respect that there should remain an incentive to choose the efficient RET and efficient location to achieve the cost-efficient outcome. The fourth and last trade-off with regard to Klein's conditions occurs when deciding upon allocating extra premiums during peak demand situations. On the one hand this may smooth the supply of RES into the grid, on the other this may lead to complexity in terms of the additional administrative burden.

To add to the discussion of how to reach an economically efficient FIT design, Lesser (2007) concludes in his paper that there is a way of making FITs more efficient by implementing both a capacity payment as well as a market-based price payment. Before elaborating on this two-part FIT, Lesser (2007) first determines the fundamental qualifications that must be fulfilled by a FIT design. These qualifications are:

- FITs should be set at an adequate level, i.e. not too high, creating unnecessary costs for consumers, nor too low, inadequate to achieve the goals.
- FIT payment should be linked to the production of renewable energy, to make sure that production is actually realised.
- FITs should be designed to cover both short- as well as long-term goals, i.e. first market penetration, secondly technological advancement.
- FITs should be designed to maximise the rate of technological improvement for each RET covered.
- FITs should have minimal reliance on administrative information, since RES producers will not provide information truthfully.

The last point is a very important obstacle in the development of an efficient FIT design. We will elaborate on this point in the discussion section of this thesis. Lesser (2007) states that a two-part FIT will replace the structure in which the FIT is administratively determined by a two-step process of (1) capacity payment determined by an auction and (2) energy payment tied to spot-market prices. The possible problem with this approach is that there is risk with respect to the returns of investment. The investors need to determine these returns by looking at the sum of capacity- and spot market price payments. The risk is in the latter, since energy prices on spot markets tend to fluctuate heavily. According to Lesser (2007) this can be compensated by investors by way of incorporating the risk premium during the auction process. This risk allocation mechanism is more efficient when investors are assumed to know best what their proposed technological and cost reduction developments are compared to administrative authorities. Furthermore overcompensation is avoided because through the bidding process the future market expectations will be revealed. In short, the exposure of truthful information will result in efficient outcomes.

2.3 SUMMARY

From this literature review we may observe several important principles. First of all we saw that, in comparison with other support mechanisms, the FIT is both in theory as in practice the most effective mechanism. The real cause of the difference in effectiveness is mainly due to the ability of FITs to provide certainty over longer periods of time, minimising risk, making it popular among investors. From empirical data it becomes even more evident that FITs are the single most effective RES support mechanism. What also becomes clear however is that the FIT mechanism has some significant drawbacks. Among others these include: high costs, lack of incentive to innovate, market distortion and lack of truthful information. To make sure that these drawbacks are minimised we looked at the literature that provided the blueprint for a more efficient FIT. Next to some fundamental criteria determined by Menanteau (2003), Lesser (2007) and Klein (2008), that need to be fulfilled to design an adequate FIT, market based mechanisms as proposed by Lesser (2007) could provide a solution to the inefficiencies encountered in the design process.

3

Model for a Feed-in Tariff Design

In this part of the thesis the feed-in tariff that leads to a greater use of renewable energy sources will be investigated using several models. We start out with some simple models which we will later on develop into more comprehensive models by adding important parameters and equations. This way we try to approach the real-life problems and constraints.

MODEL 1 (static, without fit)

Definitions:

Indices: s = renewable sources, conventional sources (s = energy sources)

Parameters:
β_0 = renewable supply function intercept
β_1 = price elasticity of supply for renewable energy
β_2 = conventional supply function intercept
β_3 = price elasticity of supply for conventional energy
β_4 = demand function intercept
β_5 = price elasticity of energy demand

Variables:
TC = total costs in current US$
P = price level of energy in current US$
DE = demand in MW for energy
SE_s = supply MW of each energy source

Objective function

$$\min \left\{ TC = \sum_s \left(P_s * SE_s \right) \right\}$$

Equalities

$$(1) \quad DE = \sum_s (SE_s)$$

$$(2) \quad P = \beta_0 + \beta_1 * SE_{renewable}$$

$$(3) \quad P = \beta_2 + \beta_3 * SE_{conventional}$$

$$(4) \quad P = \beta_4 + \beta_5 * DE$$

$$TC = \text{free} \quad ; \quad DE, SE_s, P \geq 0$$

In the first models we limit ourselves to two sources: renewable (RES) and conventional energy (CES). We know the cheapest option will be chosen when minimizing total costs of the energy sources. This is the problem for investments in renewable energy sources. In the absence of governmental stimulation policy instruments, the cheap option (conventional energy sources) is always preferable to the expensive one (renewable energy sources). This is reflected in the model when we assume that β_0 is much higher than β_2, and therefore the price must be very high before supply of renewable energy will be realised.

In figure 3.1 the underlying idea of the problem is visible. As long as the supply curve and therefore the marginal cost curve of RES is higher than those of the CES, a market price is reached at which there is no supply of RES.

In this first simple model the environmental benefits of renewable energy sources are not included. These benefits are related to clean air and mitigating climate change which can be seen as public goods

(Menanteau, 2003). Therefore investors will not invest in renewable energy as long as the environmental benefits of renewable energy investments are not reflected in the returns.

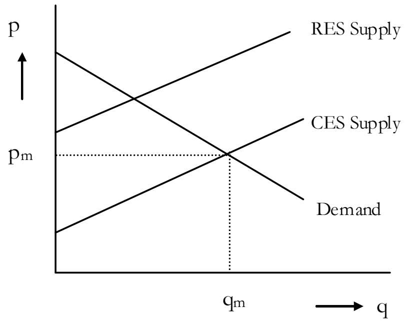

Figure 3.1: Supply and demand for energy in basic model

To lower the negative externalities of conventional energy sources we include an emission cap in the model. Just as in practice, where many governments define goals to have reduced the emissions of carbon dioxide within a certain period of time. This is reflected in the following model when conventional energy sources are assigned an emission factor. The emission constraint will then make sure that not necessarily the cheapest but the cleanest energy source is picked.

We add a new parameters and a new equation to our previous model:

Parameters EF = Emission factor of CES (ton CO_2/MW)

ME = Maximum of emissions (CO_2)

Constraint (1) $EF * SE_{conventional} \leq ME$

As we make the models more complex we start to make our model dynamic by including time periods. We also include now the FIT. In the previous model the costs were high when considering that since consumers are obliged to purchase renewable energy, otherwise not staying within the limits of the emission constraint, the market price will rise rapidly, according to the supply curve of RES. Moreover the consumers are not compensated for these higher costs. From now on a FIT will be installed to make sure that RES-generators will supply more renewable energy at constant prices. However in the new model when we make the constraint more stringent as time goes by the FIT will have to increase to keep the renewable energy competitive. We do not have an indefinite budget however, so the new objective function will imply a minimisation of the FIT, as that can be seen as the cost for the policymaker which he wishes to minimise.

MODEL 2 (dynamic, with FIT)

Definitions:

Indices: s = renewable sources, conventional sources (s = energy sources)

t = 2010, 2015, 2020 (t = time periods)

Parameters: β_0 = renewable supply function intercept

β_1 = price elasticity of supply for renewable energy

β_2 = conventional supply function intercept

β_3 = price elasticity of supply for conventional energy

β_4 = demand function intercept
β_5 = price elasticity of energy demand
EF = emission factor conventional energy in ton CO_2/MW
ME_t = maximum of emissions in ton CO_2 in year t
Variables: TC = total costs in current US$
P_t = price level of energy in current US$ in year t
DE_t = demand in MW for energy in year t
$SE_{s,t}$ = supply MW of each energy source in year t
FIT_t = feed-in tariff in current US$ in year t

Objective function

$$\min \left\{ TC = \sum_t \left(FIT_t \right) \right\}$$

Equalities

$$(1) \quad DE_t = \sum_s \left(SE_{s,t} \right) \qquad \forall t$$

$$(2) \quad P_t = \beta_0 + \beta_1 * SE_{renewable,t} - FIT_t \qquad \forall t$$

$$(3) \quad P_t = \beta_2 + \beta_3 * SE_{conventional,t} \qquad \forall t$$

$$(4) \quad P_t = \beta_4 + \beta_5 * DE_t \qquad \forall t$$

Constraint

$$(1) \quad EF * SE_{conventional,t} \leq ME_t \qquad \forall t$$

TC = free ; DE, $SE_{s,t}$, P_t, FIT_t ≥ 0

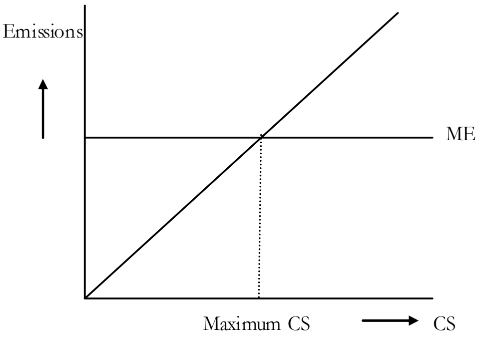

Figure 3.2: Emission constraint resulting in maximum CS

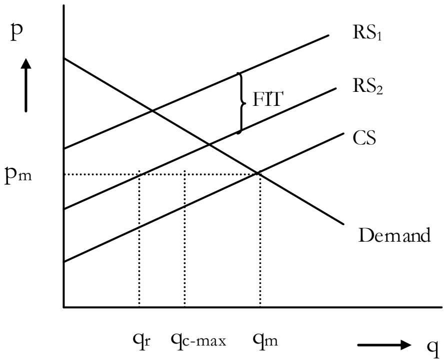

Figure 3.3: Energy supply and demand with FIT

In this model we find the basic framework in which we can implement a feed-in tariff. In this model, with high supply of CES and low supply for RES at the market price, the optimal FIT will be high. As showed in figure 3.2 the emission constraint leads to a maximum of conventional energy supply. When this constraint is binding enough so that the energy demand at the market price cannot be fulfilled by only CES, a FIT will be installed high enough to assure that RES will fill the gap (see figure 3.3).

Numerical example 1:

Parameter	**Year**	**ME_t**	**P**	**FIT**	**DE**	**RS**	**CS**
$\beta_0 = 4$	2010	7	2.050	2.85	6.5	3	3.5
$\beta_1 = 0.3$	2015	5	1.750	3.75	7.5	5	2.5
$\beta_2 = 1$	2020	3	1.450	4.65	8.5	7	1.5
$\beta_3 = 0.3$	2025	1	1.150	5.55	9.5	9	0.5
$\beta_4 = 4$	2030	0	1.000	6.00	10.0	10	0
$\beta_5 = -0.3$							

Objective:	$\min \left\{ TC = \sum_t (FIT_t) \right\}$	TC = 22.8

In this simple example we the total costs are still somewhat high relative to what we will observe in the coming models there is potential to reach lower levels of costs, as we shall see.

This model does not take into account that there are other factors that have an influence on the supply curves. In practice the prices of RES are decreasing due to technological progress, which implies lower costs. For CES prices will increase as natural resources become scarcer and the costs of exploitation become higher. Furthermore taxes and legal environmental restrictions also cause an increase in CES costs. However, when the price over time for CES increases and for RES decreases, there will be a moment in time for which the supply curve for RES will cross the supply curve of CES. The FIT will then be equal to zero. In terms of keeping the cost of FITs low while setting more ambitious emission reduction targets, these dynamic effects are very important. One of the most important effects influencing the level of technology is *learning by doing* (Arrow, 1962). This implies that when renewable capacity increases the costs of the technology decreases, due to gaining experience and economies of scale.
The effect will be as follows:

Variables	$TECH_t$	= technology level at time t	
	K_t	= knowledge stock at time t	
Parameters	MT	= maximum technology level for renewables	
	α_1	= learning effect	
Equality	(5)	$K_t = K_{t-1} + \alpha_1 * SE_{renewable,t}$	$\forall t$
Constraints	(2)	$TECH_{r(s),t} \leq MT_{r(s)}$	$\forall t$
	(3)	$TECH_{r(s),t} \leq K_{r(s),t}$	$\forall t$

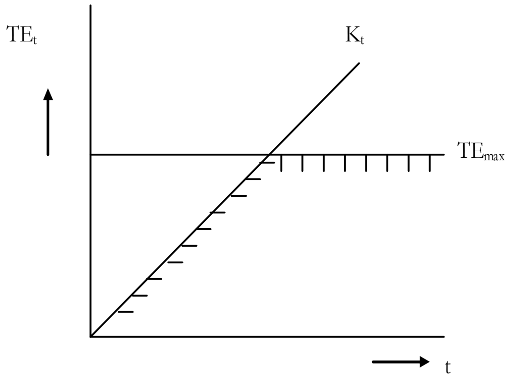

Figure 3.4: Technology development over time depending on knowledge stock

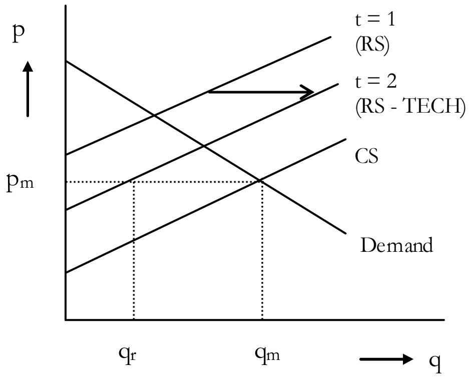

Figure 3.5: Energy supply and demand with technology development

This technology indicator ($TECH_t$) will have an affect on the renewable energy supply curve. The costs will go down as time goes by, therefore at the same market price the supply of renewable energy is increasing every time period. Same way the costs of extracting fossil fuels is increasing over time. As more

conventional energy resources are used they become scarcer, i.e. the stock is depleting over time, and that implies that the price of CES will go up with certain factor γ every unit of conventional energy used.
We include therefore another equation to our model:

Variable $SCAR_t$ = scarcity of CES at time t

Equality (6) $$SCAR_t = SCAR_{t-1} + \gamma * SE_{conventional,t} \qquad \forall t$$

This equation implies that when more fossil fuel resources are extracted they become harder to find and more expensive to bring to the market. Therefore the cost will increase by $SCAR_t$ having a negative influence on the CES supply curve. There is a limit to this process since the increase in costs implies that there won't be any supply at market prices at a certain scarcity level after which the scarcity will not increase anymore.

In the next model these effects will be incorporated. What the outcome will be depends of course on what the values of the parameters are. In any case, when the technology effect is positive and the scarcity effect negative, the FIT will be lower at each time period than for the case where these effects will not happen. The advantage of the FIT is that it is the most effective mechanism to support renewable energy, resulting in high growth rates for RES capacity. This capacity build-up at a high rate implies that the learning effect is great and occurs fast. The costs of RES can go down fast as well, resulting in lower FITs at every point in time.

MODEL 3 (dynamic, with FIT and Learning Effect)

Definitions:
Indices: s = renewable sources, conventional sources (s = energy sources)
t = 2010, 2015, 2020 (t = time periods)
Parameters: β_0 = renewable supply function intercept
β_1 = price elasticity of supply for renewable energy
β_2 = conventional supply function intercept
β_3 = price elasticity of supply for conventional energy
β_4 = demand function intercept
β_5 = price elasticity of energy demand
α = learning effect
γ = scarcity effect
EF = emission factor conventional energy in ton CO_2/MW
ME_t = maximum of emissions in ton CO_2
Variables: FIT_t = feed-in tariff in current US$ in year t
TC = total costs in current US$
P_t = price level of energy in current US$
DE_t = demand in MW for energy
$SE_{s,t}$ = supply MW of each energy source
$SCAR_t$ = scarcity of CES at time t
K_t = knowledge at time t

Objective function

$$\min \left\{ TC = \sum_t FIT_t \right\}$$

Equalities

(1) $$DE_t = \sum_s \left(SE_{s,t} \right) \qquad \forall t$$

(2) $$P_t = \beta_0 + \beta_1 * SE_{renewable,t} - FIT_t - TECH_t \qquad \forall t$$

(3) $$P_t = \beta_2 + \beta_3 * SE_{conventional,t} + SCAR_t \qquad \forall t$$

(4) $$P_t = \beta_4 + \beta_5 * DE_t \qquad \forall t$$

(5) $$K_t = K_{t-1} + \alpha_1 * SE_{renewable,t} \qquad \forall t$$

(6) $$SCAR_t = SCAR_{t-1} + \gamma * SE_{conventional,t} \qquad \forall t$$

Constraints

(1) $$EF * SE_{conventional,t} \leq ME_t \qquad \forall t$$

(2) $$TECH_t \leq MT \qquad \forall t$$

(3) $$TECH_t \leq K_t \qquad \forall t$$

TC = free ; $DE, SE_{s,t}, P_t, FIT_t, K_t, TECH_t, SCAR_t \geq 0$

Numerical example 2:

Parameter	**Year**	**ME_t**	**P**	**FIT**	**DE**	**RS**	**CS**	**TECH**	**SCAR**
$\beta_0 = 4$	2010	7	2.050	2.850	6.500	3.000	3.500	0.000	0.391
$\beta_1 = 0.3$	2015	5	2.100	2.750	6.333	3.833	2.500	0.300	0.732
$\beta_2 = 1$	2020	3	2.050	2.767	6.500	5.000	1.500	0.683	1.027
$\beta_3 = 0.3$	2025	1	1.900	2.867	7.000	6.500	0.500	1.183	1.177
$\beta_4 = 4$	2030	0	1.800	2.567	7.333	7.333	0.000	1.833	1.177
$\beta_5 = -0.3$									
MT = 5									
$\alpha_1 = 0.1$									
$\gamma = 0.1$									
Objective:	$\min \left\{ TC = \sum_t (FIT_t) \right\}$						TC = 13.8		

As we see here in this example we can significantly lower the total costs, compared to example 1, just by accounting for technological progress and scarcity effects.

An important feature missing in this model is the effect of R&D investments. Surely when the investments in R&D are high this will have an effect on the costs of renewable energy technology. However the same effect is reached by a higher FIT resulting in greater capacity and therefore a greater learning effect. Another perspective is that when R&D investments at time t = 0 are high, this implies that a lower FIT is needed in later years because the reduction in costs due to R&D investments has made RES already more competitive. Note that the optimal balance between high R&D investments now versus high FIT payments later, depends on the effect size of both. This trade-off can be included in the model as follows:

Variables $TECH_{r(s),t}$ = technology level at time t

$RD_{r(s),t}$ = R&D investments at time t in current US$

$K_{r(s),t}$ = knowledge stock for each renewable energy source at time t

Parameters $MT_{r(s)}$ = maximum technology level for each renewable energy source

Equality

(5) $$K_t = K_{t-1} + \alpha_1 * SE_t + \alpha_2 * RD_t \qquad \forall t$$

Constraints

(2) $$TECH_t \leq MT \qquad \forall t$$

(3) $$TECH_t \leq K_t \qquad \forall t$$

Next to the change in the technology equation the model should also make a decision, otherwise it will choose a indefinite amount of R&D investments, and there is only a certain amount of budget. The optimal allocation of funds between the FIT and the R&D investments should follow from:

Objective Function $$\min \left\{ TC = \sum_t \left(FIT_t + RD_t \right) \right\}$$

We can now see what the governmental expenses are over time. Since we assume here that in this model the government pays for the FIT and also the R&D investments. This model has a policymaker perspective. The government will want to stimulate technological development and RES capacity build-up, while at the same time limit the costs that these objectives entail.

Numerical example 3:

Parameter	**Scenario**	**Year**	**ME$_t$**	**P**	**FIT**	**DE**	**RS**	**CS**	**TECH**	**SCAR**	**K**	**R&D**
$\beta_0 = 4$	$\alpha_2 = 0.2$	2010	7	2.050	0.717	6.500	3.000	3.500	2.133	0.00	2.133	9.167
$\beta_1 = 0.3$		2015	5	2.100	0.533	6.333	3.833	2.500	2.517	0.35	2.517	0.000
$\beta_2 = 1$		2020	3	2.050	0.433	6.500	5.000	1.500	3.017	0.60	3.017	0.000
$\beta_3 = 0.3$		2025	1	1.900	0.383	7.000	6.500	0.500	3.667	0.75	3.667	0.000
$\beta_4 = 4$		2030	0	1.800	0.000	7.333	7.333	0.000	4.400	0.80	4.400	0.000
$\beta_5 = -0.3$												
$MT = 5$	$\alpha_2 = 0.3$	2010	7	2.050	0.333	6.500	3.000	3.500	2.517	0.00	2.517	7.389
$\alpha_1 = 0.1$		2015	5	2.100	0.150	6.333	3.833	2.500	2.900	0.35	2.900	0.000
$\gamma = 0.1$		2020	3	2.050	0.050	6.500	5.000	1.500	3.400	0.60	3.400	0.000
		2025	1	1.900	0.000	7.000	6.500	0.500	4.050	0.75	4.050	0.000
		2030	0	1.800	0.000	7.333	7.333	0.000	4.400	0.80	4.783	0.000
Objective:	$\min \left\{ TC = \sum_t \left(FIT_t + RD_t \right) \right\}$							$\alpha_2 = 0.2$	TC = 11.233			
								$\alpha_2 = 0.3$	TC = 7.922			

In this numerical example we see that the option to invest in R&D is used in the first year to create the necessary knowledge early on resulting in lower FITs in the future. When the effect size of R&D investments is even higher the result is even lower total costs. Of course everything depends here on the real effect size of R&D investments, which is difficult to estimate.

Another way of letting the model choose an optimal FIT is to define a target constraint on the level of renewable energy supply that should cover the total demand for energy. An example of these targets is the 20% of total demand of energy from RES, that Spain wants to achieve in 2020. To let the model calculate the optimal FIT that corresponds with such a target (e.g. $TARG_t$ would be 0.2 in $t = 2020$), we could include the following equation:

Variable $TARG_t$ = renewable energy proportion target at time t

Constraint (4) $$SE_{renewable,t} \geq TARG_t * DE_t \qquad \forall t$$

$$0 < TARG_t \leq 1$$

A goal of the government might be that they want to see that their renewable energy mix becomes more divers, e.g. to benefit from a better energy supply stability. Since we will keep the model simple we subdivide the renewable energy sources into mature (e.g. wind, PV) and immature (e.g. CSP) renewable energy sources. The difference is in the level of competition that both have relative to CES. We will change the model to show the implications of the above.

MODEL 4 (dynamic, with 'differentiated' FIT and Learning Effect)

Definitions:

Indices: s = renewable sources, conventional sources (s = energy sources)
t = 2010, 2015, 2020 (t = time periods)
sub- r(s) = mature RES, immature RES (r(s) = renewable sources)

Parameters:
β_0 = mature renewable energy supply function intercept
β_1 = price elasticity of supply for mature renewable energy
β_2 = conventional supply function intercept
β_3 = price elasticity of supply for conventional energy
β_4 = demand function intercept
β_5 = price elasticity of energy demand
β_6 = immature renewable energy supply function intercept
β_7 = price elasticity of supply for immature renewable energy
β_8 = technology spill-over effect
$\alpha_{r(s)}$ = learning effect for each renewable energy source
$\lambda_{r(s)}$ = R&D effect for each renewable energy source
γ = scarcity effect
EF = emission factor conventional energy in ton CO_2/MW
ME_t = maximum of emissions in ton CO_2
$TARG_t$ = share of renewable energy supply target in year t
$MT_{r(s)}$ = maximum technology level for each renewable energy source

Variables:
$FIT_{r(s)}$ = feed-in tariff per renewable energy source in current US$ in year t
TC = total costs in current US$
P_t = price level of energy in current US$
DE_t = demand in MW for energy
$SE_{s,t}$ = supply MW of each energy source
$SCAR_t$ = level of scarcity of CES at time t
$K_{r(s),t}$ = knowledge stock for each renewable energy source at time t
$RD_{r(s),t}$ = R&D investments per renewable energy source in current US$ in year t

Objective function

$$\min \left\{ TC = \sum_{r(s),t} \left(FIT_{r(s),t} + RD_{r(s),t} \right) \right\}$$

Equalities

(1) $$DE_t = \sum_s \left(SE_{s,t} \right) \qquad \forall t$$

(2) $$P_t = \beta_0 + \beta_1 * SE_{mature,t} - FIT_{mature,t} - \left(TECH_{mature,t} \right) \qquad \forall t, r(s)$$

(3) $$P_t = \beta_2 + \beta_3 * SE_{conventional,t} + SCAR_t \qquad \forall t$$

(4) $$P_t = \beta_4 + \beta_5 * DE_t \qquad \forall t$$

(5) $$P_t = \beta_6 + \beta_7 * SE_{immature,t} - FIT_{immature,t} - \left(TECH_{immature,t} + \beta_8 * TECH_{mature,t} \right) \qquad \forall t, r(s)$$

(6) $$K_{r(s),t} = K_{r(s),t-1} + \alpha_{r(s)} * SE_{r(s),t} + \lambda_{r(s)} * RD_{r(s),t} \qquad \forall t, r(s)$$

(7) $$SCAR_t = SCAR_{t-1} + \gamma * SE_{conventional,t} \qquad \forall t$$

Constraints

(1) $$EF * SE_{conventional,t} \leq ME_t \qquad \forall t$$

(2) $$TECH_{r(s),t} \leq MT_{r(s)} \qquad \forall \text{ t, r(s)}$$

(3) $$TECH_{r(s),t} \leq K_{r(s),t} \qquad \forall \text{ t, r(s)}$$

(4) $$\sum_{r(s)} SE_{r(s),t} \geq TARG_t * DE_t \qquad \forall \text{ t}$$

$$\text{TC, SCAR}_t\text{, TECH}_{r(s),t}\text{, RD}_{r(s),t} = \text{free; DE, SE}_{s,t}\text{, P}_t\text{, FIT}_{r(s)} \geq 0$$

In this model we see that now the FIT is different for each renewable energy source. The model will therefore result in a different development of RES. The mature RES will only need a small FIT whereas the immature RES will need a much higher FIT. The dynamic process that will takes place here depends on the learning effect and the R&D effect for each renewable energy source. Moreover, the level of $MT_{r(s)}$ for each renewable energy source influences the decision for the FIT and R&D investments. From a short-term point of view the choice for the mature RES seems the most efficient choice because only little effort is needed to reach the competitive level. However when the potential, i.e. the $MT_{r(s)}$, for the immature RES is high, the investments now will lead eventually to greater cost reductions, which makes the immature RES the efficient option on the long term. This is yet another trade-off between the benefits now and the benefits in the future.

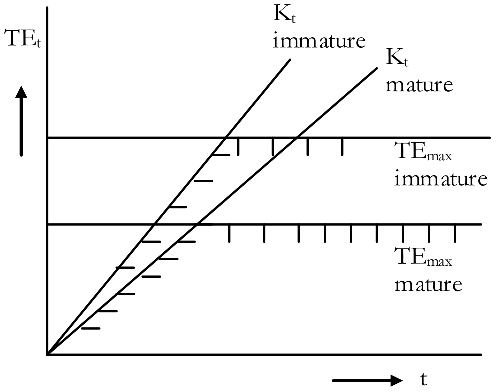

Figure 3.6: Technology development over time depending on knowledge stock for two different maturities, where the immature RES is the more efficient option in the long run.

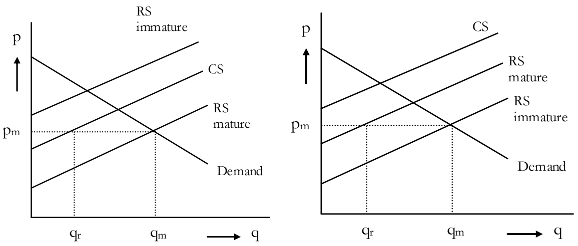

Figure 3.7a: Short run

Figure 3.7b: Long run

Figure 3.7: Energy supply and demand for two different maturities

Numerical example 4:

Parameter	Scenario	Year	ME$_t$	P	FIT	DE	RS mature	RS immature	CS	TECH	SCAR	K	R&D
$\beta_0 = 4$	$MT_{imm} = 5$	2010	7	2.400	2.150	5.333	1.833	0.000	3.500	0.000	0.350	0.000	0.0000
$\beta_1 = 0.3$		2015	5	2.350	2.367	5.500	3.000	0.000	2.500	0.183	0.600	0.183	0.0000
$\beta_2 = 1$		2020	3	2.200	2.667	6.000	4.500	0.000	1.500	0.483	0.750	0.483	0.0000
$\beta_3 = 0.3$		2025	1	1.950	3.017	6.833	6.333	0.000	0.500	0.933	0.800	0.933	0.0000
$\beta_4 = 4$		2030	0	1.800	2.900	7.333	7.333	0.000	0.000	1.500	0.800	1.567	0.0000
$\beta_5 = -0.3$	$MT_{imm} = 6$	2010	7	2.400	0.067	5.333	0.000	1.833	3.500	3.533	0.350	3.533	11.778
$MT_{mat} = 1.5$		2015	5	2.350	0.100	5.500	0.000	3.000	2.500	3.900	0.600	3.900	0.0000
$\alpha_{1,imm} = 0.2$		2020	3	2.200	0.100	6.000	0.000	4.500	1.500	4.500	0.750	4.500	0.0000
$\alpha_{1,mat} = 0.1$		2025	1	1.950	0.000	6.833	0.000	6.333	0.500	5.400	0.800	5.400	0.0000
$\alpha_{2,imm} = 0.3$		2030	0	1.800	0.000	7.333	0.000	7.333	0.000	5.850	0.800	6.667	0.0000
$\alpha_{2,mat} = 0.0$													
$\gamma = 0.2$													
Objective:	$\min \left\{ TC = \sum_{r(s),t} \left(FIT_{r(s),t} + RD_{r(s),t} \right) \right\}$							$MT_{imm} = 5$		TC = 13.100			
								$MT_{imm} = 6$		TC = 12.044			

In this numerical example we can see that when the potential in the long run ($MT_{r(s)}$) is great for the immature RET, the investment in this technology will result in lower cost over time. Less FIT is needed because R&D and learning effects are larger for the immature RET and therefore investments can be made more efficiently. However what is also visible here is that there is a certain threshold that needs to be crossed before this choice for the immature RET is made. In this example this threshold lies somewhere between 5 and 6. Below this threshold there is just too little potential for investing in the immature RET.

Finally we can include a system of budget neutrality. The implications of which are that the costs of FITs are not paid out of a government budget but rather directly reimbursed by a tax on conventional energy use. By introducing this system, the use of conventional energy would be even lower when the emission reduction target or the renewable energy share target need to be reached. The use of conventional energy needs to be taxed for the diffusion of renewable energy to take place, because the latter implies an amount of FIT. The advantage of this system is that not only will renewable energy use replace conventional energy use but also the costs are reimbursed without the need for a raise in the usual taxes, i.e. tax allocation inefficiency. The disadvantage is however that taxes are an unpopular measure and inherently politically difficult to implement. The model that includes this principle would look as follows:

MODEL 5 (dynamic, with 'differentiated' FIT, Learning Effect and budget neutrality)

Definitions:

Indices: s = renewable sources, conventional sources (s = energy sources)
t = 2010, 2015, 2020 (t = time periods)
sub- r(s) = mature RES, immature RES (r(s) = renewable sources)
c(s) = conventional energy source (c = conventional source)

Parameters:
β_0 = mature renewable energy supply function intercept
β_1 = price elasticity of supply for mature renewable energy
β_2 = conventional supply function intercept
β_3 = price elasticity of supply for conventional energy
β_4 = demand function intercept
β_5 = price elasticity of energy demand
β_6 = immature renewable energy supply function intercept
β_7 = price elasticity of supply for immature renewable energy
β_8 = technology spill-over effect
$\alpha_{r(s)}$ = learning effect for each renewable energy source
$\lambda_{r(s)}$ = R&D effect for each renewable energy source
γ = scarcity effect
EF = emission factor conventional energy in ton CO_2/MW
ME_t = maximum of emissions in ton CO_2
$TARG_t$ = share of renewable energy supply target in year t
$MT_{r(s)}$ = maximum technology level for each renewable energy source

Variables:
WTP_t = Willingness to pay at time t
$FIT_{r(s)}$ = feed-in tariff per renewable energy source in current US$ in year t
TC = total costs in current US$
P_t = price level of energy in current US$
DE_t = demand in MW for energy
$SE_{s,t}$ = supply MW of each energy source
$SCAR_t$ = level of scarcity of CES at time t
$K_{r(s),t}$ = knowledge stock for each renewable energy source at time t

Objective function

$$\min \left\{ TS = \sum_t \left(WTP_t - \sum_s TC_{s,t} \right) \right\}$$

Equalities

$$WTP_t = \beta_4 * DE_t + \frac{1}{2} * \beta_5 * DE_t^2 \qquad \forall t \tag{1}$$

$$\begin{aligned} TC_{r(s),t} &= \beta_0 * SE_{mature,t} + \frac{1}{2} * \beta_1 * SE^2_{mature,t} + \beta_6 * SE_{immature,t} + \frac{1}{2} * \beta_7 * SE^2_{immature,t} \\ &+ FIT_{r(s),t} * SE_{r(s),t} + TECH_{r(s),t} * SE_{r(s),t} \end{aligned} \qquad \forall t, r(s) \tag{2}$$

$$TC_{c,t} = \beta_2 * SE_{c,t} + \frac{1}{2} * \beta_3 * SE^2_{c,t} + SCAR_t * SE_{c,t} \qquad \forall t \tag{3}$$

$$P_t = \beta_0 + \beta_1 * SE_{mature,t} - FIT_{mature,t} - TECH_{mature,t} \qquad \forall t \tag{4}$$

$$P_t = \beta_2 + \beta_3 * SE_{conventional,t} + SCAR_t \qquad \forall t \tag{5}$$

$$P_t = \beta_4 + \beta_5 * DE_t \qquad \forall t \tag{6}$$

$$P_t = \beta_6 + \beta_7 * SE_{immature,t} - FIT_{immature,t} - \left(TECH_{immature,t} + \beta_8 * TECH_{mature,t}\right) \qquad \forall t \tag{7}$$

$$K_{r(s),t} = K_{r(s),t-1} + \alpha_{r(s)} * SE_{r(s),t} + \lambda_{r(s)} * RD_{r(s),t} \qquad \forall t, r(s) \tag{8}$$

$$SCAR_t = SCAR_{t-1} + \gamma * SE_{conventional,t} \qquad \forall t \tag{9}$$

$$\sum_s FIT_{s,t} * SE_{r(s),t} = 0 \qquad \forall t \tag{10}$$

Constraints

$$EF * SE_{conventional,t} \leq ME_t \qquad \forall t \tag{1}$$

$$TECH_{r(s),t} \leq MT_{r(s)} \qquad \forall t, r(s) \tag{2}$$

$$TECH_{r(s),t} \leq K_{r(s),t} \qquad \forall t, r(s) \tag{3}$$

$$\sum_{r(s)} SE_{r(s),t} \geq TARG_t * DE_t \qquad \forall t \tag{4}$$

TC, $SCAR_t$, $TECH_{r(s),t}$, $RD_{r(s),t}$, $FIT_{r(s),t}$ = free; DE_t, $SE_{s,t}$, P_t, $K_{r(s),t} \geq 0$

In this final model, the objective function is different because we have a FIT that can be positive or negative depending on the energy source, but on balance should be zero. In order to reach the targets, the FIT must be positive for renewable supply and to reimburse these costs the FIT is negative (taxation) for conventional energy supply. To achieve an efficient outcome the objective is to maximise the net welfare, i.e. the total willingness to pay minus the total producer costs.

Every model that is described in this chapter is a more complex version of its predecessor. Although not completely comprehensive, a lot of factors influencing the efficiency of the design have been included. The problem of the models is that we have no information or data on the parameters due to the great uncertainty in future technological developments. Further research could offer adequate estimations although it might be impossible ever to provide very accurate projections in the volatile field of technology. However with the models provided in this chapter we can show that by some simple principles the efficiency of FIT design can be improved significantly.

4 Discussion and Conclusions

4.1 DISCUSSION

With our model there are still some aspects of FITs that are not covered sufficiently. First of all, FIT policy implies, in many countries where it is implemented, a purchase obligation for utilities. This purchase obligation can be seen as a way to ensure that RES will be developed. In our model we used governmental targets to make sure that there is a binding obligation to ensure RES development. These targets were either an emission constraint or a target on the share of RES in total energy demand. Germany for example introduced a 'hardship clause' of 5 percent on the purchase obligation in 1998. This implied that utilities only had an obligation to purchase renewable energy up to 5 percent of its total deliveries. This had some advantages and some disadvantages. One of the advantages was that the market distortion caused by the FIT was limited. The disadvantage however was the threat of a halt in the dynamic process when the share of renewable energy was rising above the 5 percent level (Sijm, 2002).

Next to this, one of the greatest sources of success of the FIT scheme is the fact that guaranteed prices imply low uncertainty for investors. The continuity and uncertainty aspect is not included in the model. Yet this aspect is very important. In the current model the FIT level will decrease every year assuming that there are (1) dynamic learning processes that will lead to lower costs of RES and (2) the increase in costs of CES due to scarcity. This implies that even though the targets of the government become more binding over time, the increased level of competitiveness between RES and CES will compensate this. However, since there is a lot of uncertainty on the level of technological progress and given the political inconstancy in targets and goals, the FIT levels are likely to vary over time. The advantages of the consistent and stable (high) FIT for which it is so popular among investors will then be limited. In practice this is reflected by strong lobbies to keep the FIT high. As Wagner (1999) puts it: "(…) it may be unpopular and, hence, politically difficult to reduce feed-in tariffs as existing producers have strong economic interests in ensuring continued high feed-in payments". Investors have different interests than the government. The objective for investors is to minimize costs and to maximize earnings from the FIT. The trade-off therefore is high and constant FITs with consequent high demand or declining FITs with uncertainty and lower demand. However the reduction of FITs is necessary when the costs of the FITs for either the government or the consumers is supposed to be kept within limits. It provides the energy suppliers to innovate to reduce costs. The necessary chronology of action is therefore to reduce the FIT first after which the RES producers need to innovate. If it would be the other way around, the incentive to innovate would not exist. It should be noted that the policymaker determining the FIT needs to have at least some knowledge on the possibilities to innovate, in order for him to decide on the right level of reduction. A possible answer to this I the two-part FIT suggested by Lesser (2007). The bidding process every several years will reveal truthful information on the innovation possibilities of the bidding RES suppliers.

Also important to note is that investments in R&D might reduce future prices of RES, which implies that in the future lower FITs are necessary. In our model we made the trade-off between R&D and FIT investments visible. However this trade-off is dependent upon the returns of investments in R&D in comparison to the effectiveness of FITs. If in fact the R&D investments turn out to be very ineffective in achieving cost reductions the FIT will still have to be high in the future to compensate for this. The investments will then be double, while only getting the returns (in terms of effectiveness) from one. The effectiveness of R&D has proven to be difficult to determine. Furthermore the dynamic learning process is only achieved when capacity build-up takes place and not by investing in R&D. Therefore, in the end the consideration of the arguments might be in the favour of focusing on FITs and less on investments in R&D.

Additionally, location and maturity do not play a role in this model. In terms of location there are obviously sites that have better return to investments than others. Yields and availability of the renewable resource are different for each location, according to the geographical and meteorological conditions. To prevent that only in some areas there is capacity build-up, a differentiated FIT could be implemented to assure that RES is more evenly distributed across space, this is called a *stepped* FIT. This also mitigates the problem of regional distortions in competition. In Germany for instance the northern regions experienced much more RES development than other regions. This put the utilities there into an unfavourable position, whereas the RES producers where in a very advantageous position. The utilities were heavily burdened by the costs that were the result of the high share of RES. The profitability margins for the investors were high, because their energy yields were high and the FIT was constant, hence a distortion, relative to regions with less favourable conditions, existed. The revision of the energy law resulted in a cost sharing among the utilities within the German federal republic, corresponding to their amount of energy delivered. However this solution only applies within the borders of Germany. A liberalised free market for green electricity and non-discrimination of producers is the aim of the EU. However this aim is not compatible with the FITs schemes implemented in many countries. The countries with relative high FITs will be in a disadvantageous position, when this goal is realised. Not only will the imports of green electricity and the outflow of financial resources be large (Sijm, 2002), it might also obstruct the independency of other countries' energy supply and the capacity build-up targets. The trade-off here is therefore that we either accept the market distortion and discrimination of producers or we have a free liberalised market with inherent major financial risk for countries with relatively high FITs and the risk for those countries not achieving the policy goals.

With respect to maturity, we introduced a differentiated FIT in our model. The more advanced the RET is, the less FIT it receives. This is done to stimulate the less mature RETs. To adopt support mechanisms to the level of maturity of the RET is also what is suggested by Christiansen (2001). The more mature a renewable energy technology (RET) is, the more investments have been made and the more stimulation it received in the past. This gives it an advantage over RETs that are still in the early emergence phase. The mature technologies have lower costs and the technology is developed. However, this might imply that emerging RETs are not given the same chance to develop. Sunk investments and established interests might prevent this. These emerging RETs might be very promising and effective and therefore worthwhile to stimulate. There are two problems however. First of all, there is a trade-off between stimulating less developed RETs and the choice for an efficient RES. The more advanced RETs are usually also the efficient choice when applying economic rationale. The uncertainty that exist with respect to the technological development of the less mature RETs gives also a certain risk. Which brings us to the second problem: which emerging RETs should be stimulated? Spreading the risk by supporting a large amount of RETs simultaneously is bound to become very costly. Both choices, (1) to implement FITs for emerging RETs or not and (2) which RETs are then to be supported, are therefore dependent on the level of adequate information on the expected performance of the relevant RETs.

What is also not in our model is the technical implications that have to do with the connection of RES to the electricity grid. As Klein (2007) indicates grid connection is very important because it implies certain costs. First of all building new RES plants means that they need some connection to the grid, which already bears some costs. Next to this RES are particularly random and variable in their stability of supply. The energy grid, whether local or at a national level, is often not suitable, i.e. outdated, to accommodate the renewable electricity supply. The reinforcement of the grid to solve these problems also results in some costs. The distribution of these costs altogether must be arranged. There are directives in place in the EU that oblige EU member states to guarantee grid access for RES, and in some cases even priority access. The EU member states may choose that the costs of grid connection will be borne by the grid operators. However the distribution of the costs over RES producers, grid-connectors and consumers may be arranged in different ways. When deciding upon were the costs are allocated, some considerations are important.

- The transparency of the system
- The site efficiency
- The amount of costs
- Distance from connection point

The transparency of the system is high when RES producers only have to pay the costs of physical grid connection and not the reinforcement. However when this is the case this might imply that the choice of the production site is not efficient since the absence of reinforcement costs causes the neglect of grid capacity by RES producers. Still when all costs are borne by the RES producers, the site location might be efficient, but the transparency is lower because RES producers cannot estimate the costs in advance anymore. Furthermore the amount of costs might become too high which prevents the build-up of RES. This problem of efficiency of site locations might be solved by letting RES producers pay the amount necessary to connect to the nearest point were the capacity of the grid is sufficient. The reinforcement costs will then be gone but the problem is that the distance to this point might be large and therefore the connection costs. In general, the report "Distributed Generation Connection Charging within the European Union", by the project group ELEP (2005), recommends the use of shallow connection charging were only the connection costs need to be paid by RES producers. The consequent problems of site inefficiency and distribution of reinforcement costs, are solved, respectively, by providing financial signals to influence site choice and use-of-system tariffs that recover the costs of reinforcement (Knight et al. 2005).

Next to the problem of grid connection costs, there is also a problem of variability of energy supply. Since a lot of RES depend on external, meteorological, conditions, the stability and non-randomness of their supply cannot be guaranteed. The electricity grid is usually also not suited to facilitate the fluctuations in energy supply, particularly when the conditions can change rapidly, causing supply shocks. This problem is solved when the grid network operators can anticipate these shocks by having a forecast of energy supply. The integration of RES into the energy grid and the stability of supply can be enhanced by this forecasting system. The RES producers are then obliged to forecast what they plan to supply every hour. If their forecast is off by too much, they need to pay a penalty. Another possibility is the policy in Germany, where the quality of supply is stimulated by a bonus of 0.5 € cents/kWh.

All these considerations only apply when policymakers decide to stimulate renewable energy. A lot of scepticism exists among politicians to spend a lot of money on subsidies to speed-up a process that might intrinsically, when given the time, result in the same outcome. The processes of technological change and depletion of fossil fuel resources described before result in a level of market competition between RES and CES that enables the diffusion of the former. Especially countries that need to make this decision now and therefore are behind in terms of developing a national RES industry, might have a different perspective on the choice to stimulate the development of RES. They have the opportunity to benefit from the technological progress that is the result of effort from other nations that have made the investments in the past and still do. Together with the prospect of the rapid price increase of oil, the energy market developments might provide an incentive for these countries to free-ride. This does mean that these countries do not take into account the amount of negative externalities that this lag in time entails. The investments in renewable energy support schemes can be seen as the price of the avoided costs of these externalities. Next to this the benefits of either developing a renewable energy industry or becoming shareholder in an existing one can be significant in terms of less dependency on foreign energy. The political tensions around the imports of energy especially around importing oil from the middle east and gas from Russia, can be avoided in this way.

The goal of the EU is to have share of 20 percent for renewables in the EU energy mix by 2020. European integration implies also that nations work together in achieving these renewable energy targets. A EU-wide RES support policy is an efficient option in terms of minimal distortions in market competition. Also the distribution of RES producers over efficient site locations would be improved. Cost sharing of the development of RES among the nations would solve the free-riding problem. It must be noted however that the problem arises that this implies an increased and complex administrative burden. Furthermore as Del Río (2007) mentions in his concluding remarks, it is important to consider territorial settings in the assessment of effective support schemes. Abstract overall policy directives are not necessarily equally effective across different regions.

The EU council endorsed some binding targets for each of the EU member states, which include the 20 percent share of renewable energies in the total energy demand. The EU does not believe that cost reduction and accelerated implementation will occur without a significant contribution of public support. They furthermore stress that these processes depend on production volumes and not on time (Bloem et al. 2010). The EU member states have possibilities to contribute to the achievement of these targets, even the member states that are behind in terms of renewable energy development. There are several options. Investments can be made in (1) existing, near competitive RES, (2) emerging RETs in the development phase and (3) R&D. The first might be from an efficiency point of view the least efficient option because it is expected that these RES are so far advanced in technology and consequent cost reductions that little time might bridge the gap without the need of investing a lot of public budget. For the second option the need for investments is much higher. For the dynamic learning process to take place, these investments are necessary. As mentioned before the dynamic learning processes depend on production volumes. Furthermore research in the technology of emerging RETs can also be stimulated by investing in R&D. The policymakers can also think about measures to enlarge the market for RETs.

4.2 CONCLUSIONS

From the beginning we acknowledged the need for support mechanisms to achieve emission reduction goals and to secure the quality of public goods such as clean air and climate stability. The energy market plays a vital role in the transition to a more sustainable world. To break the deadlock of limited diffusion of renewable energy sources due to both the lack of competitiveness with conventional energy sources as well as the inability to internalise the benefits of avoided externalities, the support of renewable energy technology was considered justified.

After conceding this justification, we started out with a literature review in three stages: (1) the comparison of FITs with other alternative support mechanisms, (2) an empirical analysis of the performance of FITs and (3) the qualifications for an optimal FIT design. It became evident that FIT schemes were the effective choice in support mechanisms. Although the theory from an economic perspective does not necessarily lead to the conclusion that FITs are the most efficient option. Green certificates would be an efficient alternative from an economic point of view. However when more aspects were taken into account, with special emphasis on the investors perspective, the FIT mechanism could be seen as the effective choice. Empirical analysis would verify this finding, as we observed that growth rates and RES capacities were significantly higher in countries with an implemented FIT scheme than countries which implemented alternative support mechanisms. It is the minimisation of uncertainty and risk that provide the incentive, under a FIT scheme, for investments. There are however many drawbacks of the FIT mechanism that need to be paid attention. The high costs and the market inefficiencies resulted in the past decades in thorough revisions of the FIT schemes in different countries. The solution for these drawbacks lie in better flexibility in the FIT design. Although we also observed that when adjusting the FIT design there are a lot of trade-offs to consider. An optimal balance needs to be found to minimise the inefficiencies while at the same time maintain the right incentives. When well-defined criteria are met in practice, the benefits of effectiveness can be captured while remaining within the limits of budget spending.

In the models provided in chapter 3 we could clearly see what mechanisms were at work when (1) there would not be a FIT, (2) when a FIT would be implemented without dynamic processes, (3) the inclusion of dynamic processes and (4) the differentiated FIT. Every step would provide better understanding on the levels of FIT required to achieve the targets that were set. Although not completely comprehensive, these models were only to show some basic principles that can be applied to reach higher efficiency. The largest problems encountered during the design of such models is the uncertainty in the determination of essential parameters. The effect sizes of learning-by-doing and the returns to R&D investments are difficult to estimate. Further research in this field is necessary. Therefore the only option for these models was to explain what could happen in specific situations. This uncertainty in technological developments is also a significant problem for policymakers concerned with FIT design. One way of dealing with this uncertainty is proposed by Lesser (2007), where he suggests to reveal the 'truthful' information on technical possibilities for RES producers through an auction process to determine the level of FIT.

From the perspective of the transition to a renewable energy market, the targets set by for instance the EU imply that the further stimulation of renewable energy technologies and the build-up of respective capacities is necessary. Although the renewable energy market is growing rapidly, the influence of support mechanisms such as FITs on the acceleration of this transition is to be acknowledged by all countries that want to contribute. When ambitious targets are to be reached within reasonable time, there is no option to wait until the day arrives when the competitive level between CES and RES is reached. The process of diffusion of RES is not only dependent on time but much more on the dynamic process of learning-by-doing, capacity build-up, market penetration and enlargement and most importantly providing incentives for private sector actors to ensure an efficient and effective outcome on both the short and long term. The fundamental requirements for a transition to a renewable energy market are in providing the right regulatory framework that minimises the administrative burden and removes the obstacles in order for the private sector to take over. The FIT mechanism, when appropriately and fairly implemented, will provide the possibility of achieving this goal.

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