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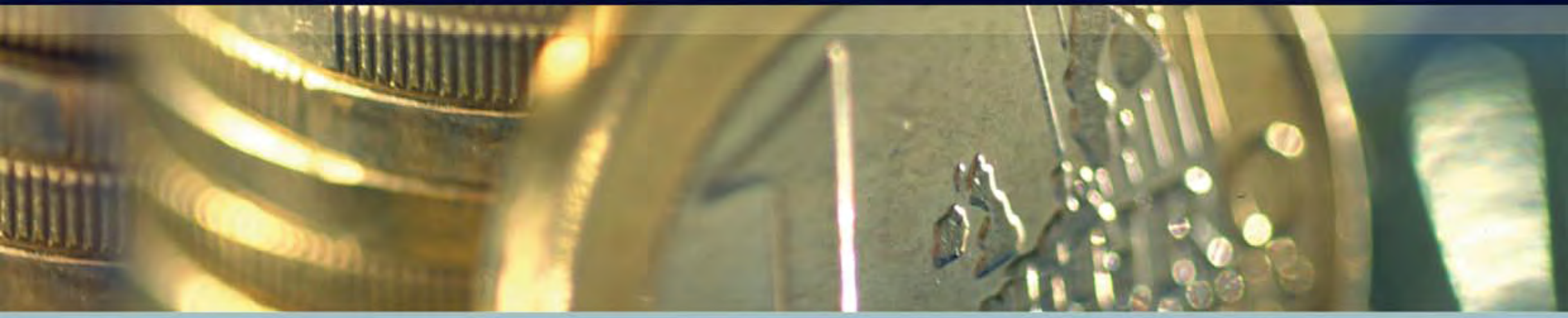

# Support schemes for renewable electricity in the EU

Joan Canton and Åsa Johannesson Lindén

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European Commission
Directorate-General for Economic and Financial Affairs
Publications
B-1049 Brussels
Belgium
E-mail: Ecfin-Info@ec.europa.eu

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# Support schemes for renewable electricity in the EU

Joan Canton and Åsa Johannesson Lindén[*]

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## Abstract

This paper discusses the level and design of support schemes used to promote renewable electricity in Europe. A theoretical model is presented to determine optimal renewable energy policies. Policies that solely aim to address environmental externalities and energy security risks are unlikely to make renewable power technologies competitive. Learning effects and spillovers are necessary to justify the need for support schemes. The analysis suggests that feed-in premiums guaranteed in addition to the electricity market price should be preferred over feed-in tariffs, which provide the eligible power producer with a guaranteed price. The premiums should be time limited and frequently reviewed. Once the technology becomes competitive, tradable green certificates would be a more suitable support instrument. As regards wind energy, the available estimates of externalities suggest that levels are probably too high in many Member States. In addition, the current promotion of photovoltaics could possibly be more cost-efficient if it targeted technology development more directly.

*JEL Code: Q42; Q48; H23*

Keywords: renewable energy, feed-in tariffs, premiums, green certificates, learning-by doing

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# 1 Introduction

The Directive on the promotion of the use of energy from renewable energy sources was one major part of the Energy and Climate package agreed by the Council in December 2008. The promotion of renewable energy aims at (i) reducing CO2-emissions, (ii) diversifying the energy mix and thereby improving energy security, while at the same time (iii) contributing to the competitiveness and growth of the EU economy through technological development and the development of a new industry. In other words, this policy aims at addressing the externalities related to environmental damage, energy security risks, and knowledge spill-overs. The new Renewable Directive creates a regulatory framework for achieving a share of 20% renewable energy in EU energy consumption by 2020. It sets national renewable targets for Member States, taking account of different starting points and potentials, as well as differences in GDP.

The policy instruments applied to promote the introduction of renewable energy sources remain, however, the competence of Member States. This note focuses on these policy instruments, and in particular on the features of the most common systems, that is, feed-in tariffs, feed-in premiums and green certification/obligation systems. One objective of this paper is to assess the support levels in relation to the above-mentioned externalities. Another objective is to look at how these systems can be designed as efficiently as possible considering the ambitious renewable policy target. The note discusses various implementation issues related to these schemes, including the issue of harmonisation, compatibility with the internal electricity market as well as the sequencing of instruments.

The note is structured as follows. Section 2 presents the current state of play as regards the share of renewables and expected production cost developments. Section 3 describes the model and discusses the level of support schemes when considering the different externalities. Section 4 focuses on the design of support schemes and covers the issue of uncertainty, trade and the impact on the internal market. Finally, section 5 is an economic assessment of current support schemes in Member States, based on the considerations previously analysed. Section 6 concludes by recalling the main policy recommendations of the paper.

# 2 Market share and production cost developments

In 2007, the overall EU share of renewables in the energy mix was 7.8%, while nearly 17% of the EU electricity production originated from renewable energy sources[1].

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[1] The definition of renewable energy applied in EU energy statistics includes hydropower, wind energy, solar energy, biomass and wastes, and geothermal energy. The Renewable Directive (European Commission 2009*a*) defines it as "energy from renewable non-fossil sources, namely

Hydro power, a well-established mature technology, accounted for about 10% of electricity production in the EU. The potential for additional large-scale hydro power is close to exhaustion at the EU level, and the focus of this note is therefore on the new innovative renewable technologies. These technologies account for the remaining 7%, which is dominated by power production based on biomass (3%) and wind (3.1%). The new technologies have experienced a considerable growth in the last 10 years (see figure 1), starting from a very low level. The share of renewable sources in overall power production is expected to grow considerably not only as a result of climate and energy policies, but also in the business-as-usual (BAU) scenario due to existing policies as well as increasing fossil fuel prices over time. The projections for the implementation of the energy and climate policy estimate that renewable energy sources will account for 31% of electricity production in 2020 in the EU27. The corresponding figure for the BAU scenario is 20%[2].

The overall use of renewable energy varies considerably across Member States. The share of renewable energy in power production ranges from around 70% (Austria) to nil for Cyprus and Malta, or 1.4% for Estonia. The mix of production technologies also varies significantly. Figure 2 shows that large scale hydro dominates renewable electricity generation, but the share of wind electricity is also significant in Germany, Denmark and Spain. Small scale hydro is mainly applied in Austria, Germany, Spain, France and Italy, while solid biomass is applied in Finland, Germany, and Sweden. Biogas, on the other hand, plays a role in particular in Germany and the UK.

The generation cost of renewable electricity generally remains higher than that of conventional technologies. Figure 3 presents comparable costs for different technologies in 2007, as well as projections for 2020 and 2030 (see the detailed numbers presented in Annex 7.1). These projections represent expected learning curves, as further technology development and more deployment are expected to reduce production costs over time (European Commission 2008*a*). However, there is a question regarding the causation here, since lower costs would also induce more deployment. A policy that promotes early deployment could thus run the risk of resulting in lower than expected learning rates (Stern 2006).

Cost ranges are expressed in €(2005)/MWh, which allows for a comparison of the economic competitiveness during the life time of the power plant. The comparison is based on a state-of-the-art facility that is assumed to start operating in the relevant year. The reported ranges reflect variations in capital costs which depend on specific

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wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases"(Article 2a). Currently, there can be small discrepancies between the energy statistics and the coverage of the directive, in particular regarding the inclusion of the different types of heat pumps and the treatment of waste. Work is on going to improve the statistics on renewable energy.

[2] The figures notably assume an oil price of \$61/bbl (European Commission 2008*c*).

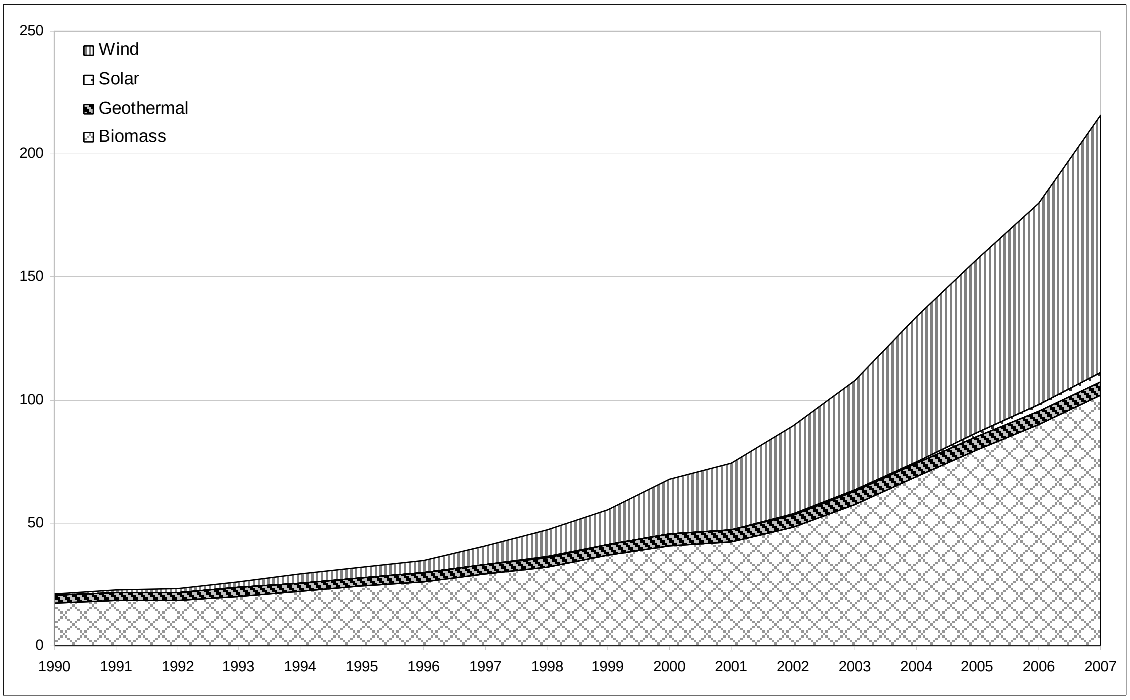

Figure 1: Renewable electricity generation in the 27 EU Member States, TWh per year (Source: Eurostat, hydropower excluded)

technology choices, plant location and market conditions across the EU[3].

It is clear that costs differ substantially depending on the site and local conditions of the investments, which will have a large impact on the competitiveness vis-à-vis conventional power technologies. Biogas, on-shore wind and small-scale hydro have the potential to compete with nuclear, gas and coal if local conditions are in their favour. Higher fuel prices would also benefit these technologies. Photovoltaic and off-shore wind farms have the largest potential to reduce costs.

As mentioned above, the cost of producing renewable electricity remains on average higher than that of conventional technologies, and high in relation to the average wholesale prices. However, these relative costs do not take account of all the negative externalities related to the use of conventional power production. Since 2005 the EU Emission Trading System (ETS), which covers fossil fuel based power generation, introduces an opportunity cost for power producers on the negative externality of CO2-emissions. Taking account of these costs improves the competitiveness of renewable electricity and creates a level playing field in this respect. Air pollution as

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[3] The variability related to fuel retail prices is, however, not included in the ranges, but based on an oil price assumption of \$54.5 per barrel (European Commission 2008*b*).

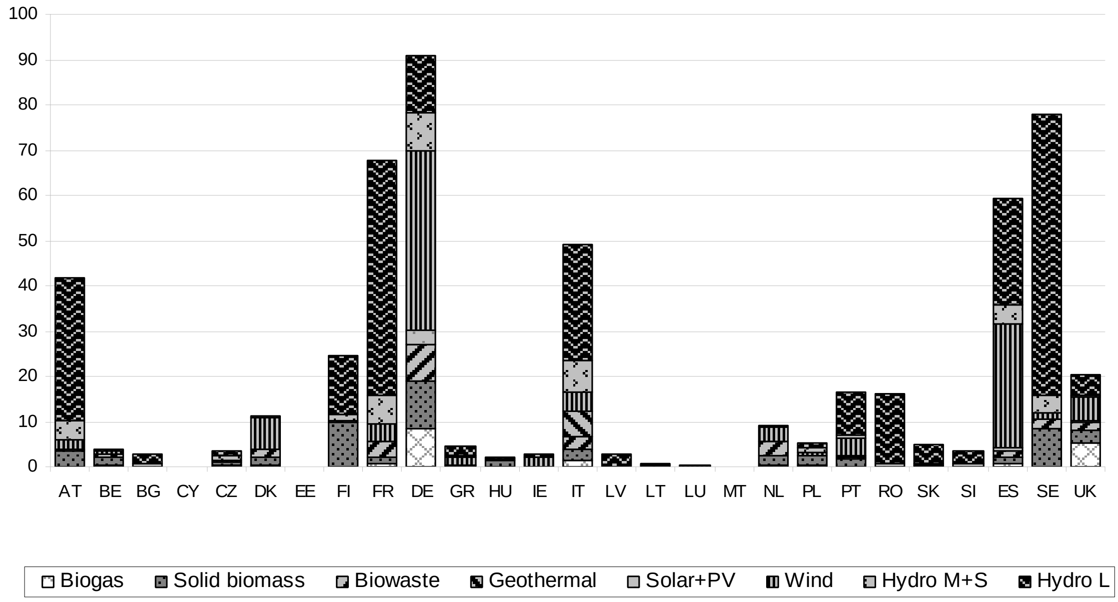

Figure 2: Renewable electricity generation in European Union in 2007, TWh (Source: Eurostat)

well as other environmental standards similarly add to the generation cost of conventional power. However, despite these rather recent efforts to internalise external costs, renewable electricity remains more costly than electricity produced with established technologies. Various forms of economic support schemes are therefore applied at national level to support the market introduction of renewable electricity technologies. The objective is to create economies of scale and allow for further technology development, which will reduce the costs of these technologies over time and render them competitive in the longer run. Further diversification of the fuel mix, in order to improve the security of supply, is another policy objective. The most common renewable electricity support schemes include feed-in tariffs, feed-in premiums and green certificates.

Feed-in tariffs provide the eligible renewable power producer with a guaranteed price for the power they feed into the grid. The preferential and technology-specific tariffs are regulated by the government and are normally guaranteed for a period of 10 - 20 years. The electricity is delivered to the grid, where the system operator will ensure the further distribution of the renewable electricity. Hence, the producers also face a rather secure demand for their renewable power. The feed-in tariffs thereby reduce both the price and market risk, and create certainty for the investor regarding the rate of return.

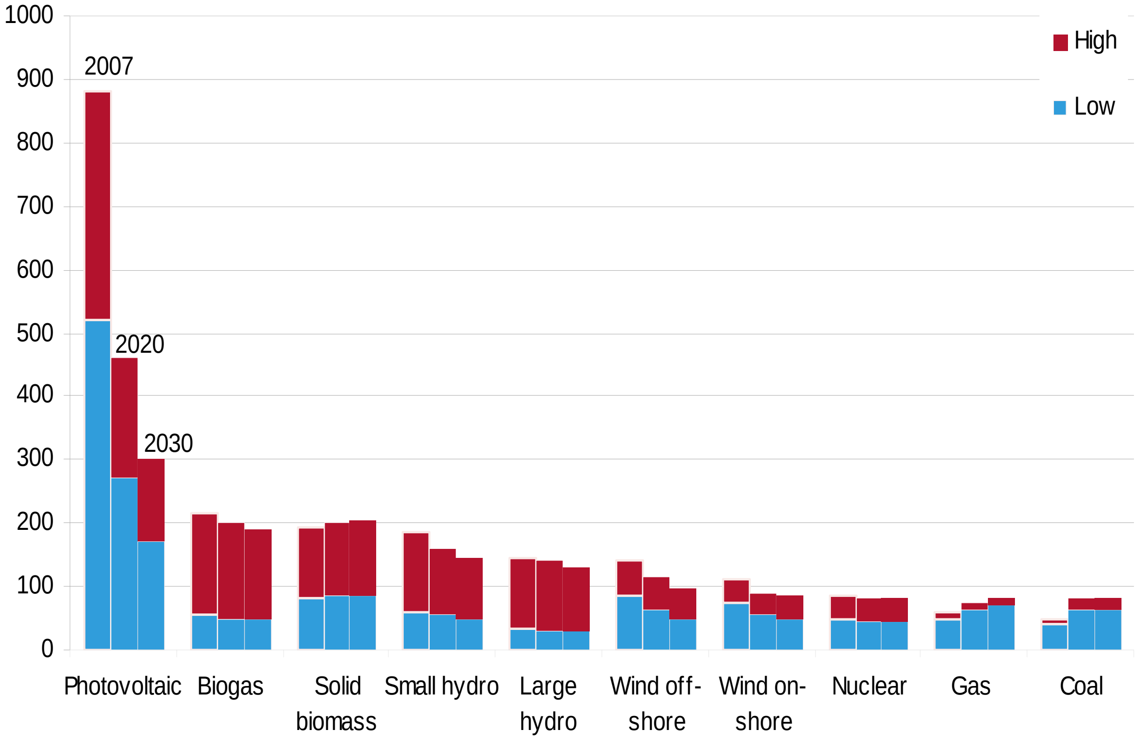

Figure 3: Production cost ranges for different electricity technologies, state of the art 2007, €(2005)/MWh (Source: European Commission, 2008a)

A feed-in premium provides the producer with a guaranteed premium in addition to the electricity market price. The preferential and technology-specific premiums are still determined by the government and the producer still benefits from a secure demand. However, in this case, the price faced by renewable electricity producers fluctuates according to the changes in the electricity market price.

Green certificates are normally based on a quota obligation. Hence, the government imposes an obligation on consumers or suppliers to have a certain percentage of the electricity sourced from renewable sources. The authorities issue certificates to producers corresponding to their production of renewable energy, which are sold separately from the electricity. The quota obligation on electricity suppliers ensures that there is a demand for certificates, as suppliers will need to buy certificates to fulfil their quotas. The main advantage of this system is that it allows competition between renewable producers as the certificate price will depend on demand and supply of green certificates.

Feed-in tariffs and premiums are currently used by 21 Member States. Six States apply green certificates, and a few countries are planning to do so in the future. Other instruments include tenders, grants and various fiscal support measures. However, these instruments are often applied as a complement to the other support systems. The features of feed-in tariffs, feed-in premiums and green certificates are discussed in the next sections on the basis of the externalities they address.

# 3 Considerations on the level of support schemes

## 3.1 The model

Consider the following stylised partial equilibrium model of the electricity sector, inspired by existing contributions (Fischer & Newell 2008, Lehmann 2009). The electricity sector encompasses two sub-sectors. One sector uses fossil fuels to generate electricity, which creates polluting emissions as a by-product. The other sector employs renewable energy sources. Both sectors are assumed to be competitive and produce an identical output, electricity.

The model has two periods and there is discounting at rate $\delta$ between periods. The fossil-fuel sector uses a technology based on fossil fuel and, to simplify, one unit of fossil fuel is necessary for one unit of production $x$. Production costs are increasing and convex and summarised by the following function: $C(x_t)$. Emissions are assumed to be fixed at rate $\mu$. To avoid excessive complications and without loss of generality, polluting emissions are limited to the first period. Total emissions from the emitting sector are: $E_1 = \mu x_1$. Polluting emissions produce damage to society, which depends on the overall level of emissions: $D_1(E_1)$. Damage is assumed to be increasing and convex. The renewable sector consists of $n$ identical firms, each one of them producing the same electricity output $q_t$ in period $t$. Individual production cost in period one is $G_1(q_1)$. Individual production cost in period two is a function of output in period two and the total level of learning, or experience, $L$ in period one, that is, $G_2(q_2, L)$ (Bläsi & Requate 2007). Total learning depends on the output of the firm under consideration and the output of all other identical firms in the sector: $L = q_{1j} + \rho \sum_{i=1,i\neq j}^{n} q_{1i}$, which can be simplified by $L = q_1 + \rho(n-1)q_1$ as firms are identical and produce the same output level. Note that the second part of this equation is considered as given by individual producers. The spillover rate $\rho$ indicates to which extent a firm can benefit from the experience made by other firms. Production costs in each period are increasing and convex. Production cost in period two is declining and convex in learning. Learning also reduces marginal production cost in period 2. Production cost in period 2 is assumed to be convex overall.[4]

Total output of the electricity sector in period $t$ is the sum of electricity generated in the fossil-fuel sector and the renewables sector: $Q_t = x_t + nq_t$. In equilibrium, electricity output equals electricity demand. The inverse demand function is given by $P_t = P_t(Q_t)$, with $P_t'(Q_t) < 0$. We assume that $P_t'(Q_{t)} + P_t''(Q_t)Q_t < 0$, implying that the inverse demand function is not too convex.

In the context of this model, energy security is also a source of externality. There exists an energy mix, which consists of an optimal share s* of renewable-based electricity, that would minimise the risk of energy insecurity. Any other energy mix induces the chance of a positive and increasing damage $S_1(x_1, nq_1)$. Again, to limit excessive complications and to facilitate comparisons, the energy security issue is limited to the first period.

Total welfare includes consumer surplus, electricity producers' profits and damage induced by polluting emissions and energy insecurity.

$$(1) \qquad W = \int_0^{Q_1} P_1(Q_1) - C(x_1) - nG_1(q_1) - S_1(nq_1, x_1) - D_1(E_1)$$
$$+\delta(\int_0^{Q_2} P_2(Q_2) - C(x_2) - nG_2(q_2, L))$$

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[4] It would be possible to further account for the vertical structure of the renewable power industry by considering an upstream industry of oligopolistic renewable power equipment producers engaged in learning by doing (Reichenbach & Requate 2009). This would also require making a distinction between learning-by-doing in the renewable energy equipment industry or in renewable electricity production. The main differences originate from effects on international trade, since the output of the machinery and equipment sector is intensively traded on international markets unlike renewable electricity (Schumacher & Kohlhaas 2007). However, this extension is considered unnecessary in this simplified context.

### 3.1.1 The social optimum

Welfare is optimised with respect to the level of production for the fossil-fuel sector and for the renewable sector for the two periods when:[5]

$$\begin{aligned}
&(2) \qquad & P_1 &= C'(x_1) + D_1'(E_1)\mu + \frac{\partial S_1}{\partial x_1} \\
&(3) \qquad & P_1 &= G_1'(q_1) + \delta[\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1} + \rho(n-1)\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1}] + \frac{\partial S_1}{\partial q_1} \\
&(4) \qquad & P_2 &= C'(x_2) \\
&(5) \qquad & P_2 &= G_2'(q_2)
\end{aligned}$$

where $D_1'(E_1)$ is the derivative of the environmental damage function with respect to environmental emissions and $\partial S_1/\partial x_1$ is the partial derivative of the energy security damage function with respect to the production of fossil-fuel based electricity. Other derivatives adopt the same conventions.

These equations present the conditions for a socially optimal allocation of resources. Welfare is optimised when the price of electricity, or the consumers' marginal willingness to pay, is equal to its marginal cost. The marginal cost of electricity is measured as the marginal private production cost plus any marginal social cost associated with the production of electricity. This holds both true for the fossil-fuel based electricity sub-sector as well as for the renewable-energy based electricity sub-sector.

### 3.1.2 Introducing feed-in tariffs

The design of feed-in tariffs deviates from that of a traditional subsidy in some respects. First, it takes the form of a guaranteed price as producers of electricity receive a fixed feed-in tariff $\sigma$ per unit of electricity produced in period 1. Unlike traditional subsidies, the tariff is not funded through the government budget but by the system operators through an add-on $\varphi_1$ to the electricity price in period one. The add-on is determined endogenously and amounts to the feed-in tariff times the share of renewable electricity in total electricity supply.

$$\varphi_1 = \frac{\sigma n q_1}{Q_1} \tag{6}$$

In a competitive market, electricity producers take this add-on as given.

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[5] We made the necessary assumption on demand and cost curves to ensure that the problem was globally convex, that is second order conditions are always satisfied.

### 3.1.3 Introducing tradable green certificates

Tradable green certificates set a target for the share of renewables in the overall consumption of electricity. The producers of green energy have the right to issue green certificates. The market for green certificates determines their price. Let $\alpha$ be the share of renewables in the overall consumption. Let $\beta_1$ denote the market clearing price of certificates. The add-on $\psi_1$ to the electricity price paid by consumers is then:

$$\psi_1 = \beta_1 \alpha \tag{7}$$

Under perfect information, the two policies bring identical results, that is, we must have: $\varphi_1 = \psi_1$, and more specifically $\sigma = \beta_1$ and $\frac{nq_1}{Q_1} = \alpha$. The only difference between the two policies is that in the case of a feed-in tariff, the share of renewables (quantity, i.e. $\alpha$) is endogenous whereas in the case of green certificates, the add-on price is endogenous.

The remainder of this section focuses on the determination of optimal feed-in tariffs. Similar results could be derived for green certificates. Different scenarios are considered, according to assumptions made on the number of externalities that the regulator faces, as well as on the number of available policy instruments. The objective of this approach is to introduce gradually the treatment of the different externalities.

## 3.2 Pollution

### 3.2.1 Using renewable support schemes to address an environmental externality

Let us consider first that the only externality that needs to be internalised by the regulator is the pollution one. Standard environmental economics theory states that a Pigovian tax would in this context be optimal, that is, an environmental tax on polluting emissions whose rate would be equal to the marginal social damage of emissions. Here, it is considered that a renewable support scheme is used to address the environmental externality. In this scenario, welfare is:[6]

$$W_{Poll} = \int_0^{Q_1} P_1(Q_1) - C(x_1) - nG_1(q_1) - D_1(E_1) \tag{8}$$

---

[6] Note that there is no need to consider the second period as, under this set of assumptions, there are no possible interactions between the two periods.

The optimal feed-in tariff is determined by backward induction, that is, first by determining optimal production levels given the tariff and then by solving the regulator's welfare maximisation problem. Details of the calculations, for this subsection as well as for the other ones, are provided in Annex 8.1. The optimal feed-in tariff under this scenario is:

$$\sigma^*_{Poll} = P_1 - D_1'(E_1)\mu \frac{\frac{dx_1}{d\sigma}}{n\frac{dq_1}{d\sigma}} \tag{9}$$

This equation simply states that the optimal tariff should be equal to the price of electricity plus a mark-up. Recall that $\frac{dx_1}{d\sigma} < 0$ and therefore, the second part of the right-hand side of this equation is positive. This mark-up consists of the marginal social damage of polluting emissions times the impact of a change in the feed-in tariff on the relative levels of electricity production. The following proposition summarises the results.

**Proposition 1** *An optimal feed-in tariff internalising a pollution externality should be chosen above the electricity market price. The optimal mark-up is lower than the marginal damage of emissions.*

*Proof:* under our assumptions on the demand curve and the production cost function, we necessarily have: $0 < -\frac{\frac{dx_1}{d\sigma}}{n\frac{dq_1}{d\sigma}} < 1$

Two major considerations can be derived from this result. First, the regulator uses the feed-in tariff to modify polluters' behaviour. The only way to do so is to choose a feed-in tariff above the electricity market price so as to increase the share of renewables and decrease production by fossil-fuel based electricity producers. The problem with this approach is that such a renewable support scheme would not give the right incentives to the renewables sector. In this specific example, we have considered that the renewables sector creates no specific externality. Thus, there is no reason to distort the price faced by renewable electricity producers. What is optimal for the fossil-fuel sector is not optimal for the renewables sector. Hence, it is more efficient to directly address the emissions in the fossil-fuel sector than subsidising the renewables energy sector so as to indirectly influence, via a change in the market price, firms using fossil fuel sources. It is more efficient to address an externality as close as possible to its source.

Second, one could question whether such a feed-in tariff would be sufficient to promote renewable electricity production, given the important differences in production costs between conventional and renewable energy sources. This is discussed in more detail below.

### 3.2.2 External costs and the competitiveness of renewable electricity

The CASES research project (CASES 2009) provides estimates for several types of environmental externalities, and provides data on production costs, including external costs, for various technologies. This project aims to identify the full costs of electricity generation. Although some of the assumptions made could be challenged, the range of results remains of the same magnitude as the costs presented in section 2 and offers a good basis for discussion. Figure 4 summarises the results of the project (see as well Figure 9 in Annex 7.1).

The results for the current period (2005-2010) show that renewable electricity produced with on-shore wind technology is close to being competitive as compared to electricity produced with fossil-fuel sources, while hydropower is slightly more expensive, provided that externalities are taken into account. Note that this is to a large extent explained by the high cost associated with GHG emissions (measured in the CASES project by the marginal abatement cost of GHG emissions)[7]. Other renewable energy sources are, on the other hand, not yet competitive vis-à-vis conventional energy sources. This also means that a support scheme only internalising the environmental externality would not be sufficient to cover the costs of most renewable energy sources. In other words, the environmental externality only cannot justify current support schemes. The following policy conclusion summarizes our results.

**Policy conclusion 1** *Policies that solely aim to internalise environmental externalities are unlikely to make renewable power technologies competitive. Furthermore, it is more efficient to apply the policy instruments directly at the emission source rather than to support alternative clean technologies. Other considerations are therefore needed to justify policies supporting renewable energy production.*

## 3.3 Energy security

With both energy consumption and dependence on oil and gas imports growing, the risk of supply failures is rising, setting a shadow price on some energy sources. The EU has decided to promote a broad mix of energy sources. Renewable energy sources have a role to play in this regard as they can contribute to a more diversified energy supply. When only considering the energy security externality, welfare is:

$$W_{ES} = \int_0^{Q_1} P_1(Q_1) - C(x_1) - nG_1(q_1) - S_1(nq_1, x_1) \tag{10}$$

---

[7] Combined heat and power production based on biomass is also competitive, but excluded from this discussion as it requires a demand and a distribution network for the heat.

| COSTS OF ELECTRICITY GENERATION IN EU (Ec/kWh) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2005-2010 | | | 2020 | | | 2030 | | |
| Technology | Full costs | Private costs | External costs | Full costs | Private costs | External costs | Full costs | Private costs | External costs |
| biomass (woodchips) CHP with an extraction condensing turbine | **1,79** | 1,13 | 0,66 | **1,80** | 0,98 | 0,82 | **1,97** | 0,98 | 0,99 |
| nuclear power plant | **3,32** | 3,10 | 0,22 | **2,76** | 2,62 | 0,14 | **2,40** | 2,28 | 0,12 |
| hard coal CHP with backpressure turbine | **3,88** | 0,89 | 2,99 | **4,19** | 0,91 | 3,28 | **5,25** | 1,04 | 4,21 |
| hard coal CHP with extraction condensing turbine without CO2 capture | **4,07** | 1,31 | 2,76 | **4,31** | 1,34 | 2,97 | **5,21** | 1,39 | 3,82 |
| hard coal CHP with extraction condensing turbine with CO2 capture | **4,07** | 1,31 | 2,76 | **4,26** | 3,12 | 1,14 | **4,48** | 3,09 | 1,39 |
| biomass (straw) CHP with an extraction condensing turbine | **4,61** | 2,59 | 2,02 | **4,37** | 2,18 | 2,19 | **4,80** | 2,18 | 2,62 |
| lignite IGCC without CO2 capture | **5,38** | 3,00 | 2,38 | **4,96** | 2,83 | 2,13 | **5,68** | 2,77 | 2,91 |
| lignite IGCC with CO2 capture | **5,38** | 3,00 | 2,38 | **4,15** | 3,39 | 0,76 | **4,28** | 3,34 | 0,94 |
| natural gas CHP with extraction condensing turbine without CO2 capture | **5,39** | 4,12 | 1,27 | **5,72** | 4,37 | 1,35 | **6,17** | 4,40 | 1,77 |
| natural gas CHP with extraction condensing turbine with CO2 capture | **5,39** | 4,12 | 1,27 | **7,22** | 6,37 | 0,85 | **7,36** | 6,32 | 1,04 |
| lignite condensing power plant | **5,65** | 2,68 | 2,97 | **5,15** | 2,18 | 2,97 | **6,07** | 2,14 | 3,93 |
| natural gas combined cycle CHP with backpressure turbine | **5,71** | 4,31 | 1,40 | **5,83** | 4,27 | 1,56 | **6,31** | 4,24 | 2,07 |
| natural gas combined cycle without CO2 capture | **6,20** | 4,81 | 1,39 | **6,04** | 4,58 | 1,46 | **6,43** | 4,54 | 1,89 |
| natural gas combined cycle with CO2 capture | **6,20** | 4,81 | 1,39 | **6,90** | 5,98 | 0,92 | **7,03** | 5,91 | 1,12 |
| wind, on-shore | **6,21** | 6,11 | 0,10 | **6,09** | 6,02 | 0,07 | **6,03** | 5,96 | 0,07 |
| wind, off-shore | **6,46** | 6,36 | 0,10 | **6,21** | 6,14 | 0,07 | **5,88** | 5,81 | 0,07 |
| hard coal condensing power plant | **6,47** | 3,33 | 3,14 | **6,52** | 3,23 | 3,29 | **7,30** | 3,16 | 4,14 |
| hard coal IGCC without CO2 capture | **6,61** | 3,91 | 2,70 | **6,03** | 3,54 | 2,49 | **6,77** | 3,50 | 3,27 |
| hard coal IGCC with CO2 capture | **6,61** | 3,91 | 2,70 | **5,66** | 4,20 | 1,46 | **5,95** | 4,16 | 1,79 |
| hydropower, run of river >100MW | **6,85** | 6,81 | 0,04 | **6,85** | 6,80 | 0,05 | **6,86** | 6,80 | 0,06 |
| hydropower, run of river 10MW | **7,90** | 7,83 | 0,07 | **7,91** | 7,83 | 0,08 | **7,92** | 7,83 | 0,09 |
| hydropower, run of river <100MW | **7,98** | 7,93 | 0,05 | **7,99** | 7,93 | 0,06 | **8,00** | 7,93 | 0,07 |
| natural gas, gas turbine | **8,66** | 6,58 | 2,08 | **8,89** | 6,60 | 2,29 | **9,48** | 6,53 | 2,95 |
| heavy oil condensing power plant | **8,96** | 6,57 | 2,39 | **10,19** | 7,19 | 3,00 | **11,10** | 7,46 | 3,64 |
| hydropower, pump storage | **11,10** | 11,04 | 0,06 | **11,11** | 11,04 | 0,07 | **11,13** | 11,04 | 0,09 |
| hydropower, dam (reservoir) | **11,12** | 11,04 | 0,08 | **11,13** | 11,04 | 0,09 | **11,15** | 11,04 | 0,11 |
| light oil gas turbine | **12,34** | 9,87 | 2,47 | **13,01** | 10,08 | 2,93 | **14,03** | 10,34 | 3,69 |
| solar thermal, parabolic trough | **12,88** | 12,76 | 0,12 | **10,41** | 10,30 | 0,11 | **9,61** | 9,50 | 0,11 |
| MCFC (biogas) | **35,21** | 31,88 | 3,33 | **17,26** | 13,23 | 4,03 | **10,75** | 6,36 | 4,39 |
| MCFC (natural gas) | **35,55** | 33,55 | 2,00 | **15,77** | 13,34 | 2,43 | **9,91** | 7,26 | 2,65 |
| solar PV, open space | **36,80** | 35,91 | 0,89 | **21,65** | 20,83 | 0,82 | **17,51** | 16,58 | 0,93 |
| solar PV, roof | **45,63** | 44,76 | 0,87 | **25,94** | 25,14 | 0,80 | **24,39** | 23,48 | 0,91 |
| SOFC (natural gas) | **47,73** | 46,80 | 0,93 | **12,54** | 11,55 | 0,99 | **8,25** | 7,02 | 1,23 |

Figure 4: Summary of CASES results. (Source: CASES (2009))

Using the same methodology as in the previous section, the optimal feed-in tariff becomes:

$$\sigma^*_{ES} = P_1 - \frac{\partial S_1}{\partial q_1} - \frac{\partial S_1}{\partial x_1} \frac{\frac{dx_1}{d\sigma}}{n\frac{dq_1}{d\sigma}} \tag{11}$$

**Proposition 2** *An optimal feed-in tariff internalising an energy security risk is higher (resp. lower) than the electricity price if the production of renewable electricity is initially too low (resp. too high) compared to the optimal level.*

It is therefore technically possible to internalise an energy security externality by using a feed-in tariff or tradable green certificates if we know what the optimal energy-mix is. The feed-in tariff will be higher or lower than the price faced by fossil-fuel based power producers, depending on whether the regulator considers that there is too much or too little renewable electricity produced. However, this requires first to clearly understand what the energy security risk covers and to be able to measure it.

Diversity can be discussed in terms of balance, variety and disparity of the energy system (Stirling 2009). Variety is the number of different energy sources and technologies that are used in the energy system. Balance is a function of the distribution between these sources and technologies. Disparity refers to the degree to which these sources and technologies are related. Therefore, when discussing diversity, the presence of various energy sources is not sufficient. The relative share of each source also matters. Disparity is also relevant because some sources present similar characteristics and face similar challenges; for example the prices of oil and gas are highly related. It results from this analysis that no simple criterion can be used to measure the energy security risk reduction due to the presence of renewables.

Most of the literature seems to follow an approach consisting of building indices measuring the degree of diversity in energy sources. These indices try to include as many dimensions as possible but often fail to induce consistent choices across dimensions (Kruyt et al. 2009). It is not clear how these results can be used to determine the optimal level of support to renewable power production. In fact, the optimal level of policy intervention derived above assumes implicitly that both the optimal level of diversification as well as the damage induced by energy insecurity is known. The above-mentioned indices, on the other hand, are potentially able to rank Member States in terms of the exposure to energy security risk but do not permit to measure the externality associated with this energy insecurity. At this stage, the only policy recommendation that could be derived is that higher levels of support schemes could be justified for Member States with a high energy security index.

An alternative approach would be to measure the direct costs associated with energy insecurity (De Joode et al. 2004). A cost-benefit analysis of various measures to improve the security of energy supply in the Netherlands is provided. On electricity markets, the authors consider that the key risks refer to the ability of the power sector to meet demand at all times, and the threat of execution of market power by producers. The creation of capacity markets, reserve contracts and capacity payments could give power producers additional incentives to invest in peak capacity. The implementation of these measures incurs relatively high costs. Hence, the policy options are not efficient in preventing price spikes, as the welfare costs of price spikes are lower than the costs of the policy options (unless price spikes occur with an implausibly high frequency).

A final approach could consist of measuring the difference between the production costs of a natural gas combined cycle power plant and of renewable power technologies, adjusted for environmental externalities. This approach would offer an estimate of the externality needed to justify the policy. A natural gas combined cycle power plant is considered as the reference technology, as it is the likely choice for new investments in conventional power production in the EU. Using results of the CASES project (see Figure 4), one can see that the energy security risk would have to represent a cost of €0.01 cent/kWh to justify producing electricity with on-shore wind energy instead of a natural gas combined cycle. For all other renewable technologies, a higher energy security cost would be necessary to justify the change in technologies. Note also that the difference between natural gas combined cycle without CO2 capture and on-shore wind will increase slightly by 2020-2030.

Renewable energy sources have so far only been presented as reducing energy security risk. However, the opposite could be true in some cases. First, energy security issues are often the results of imperfectly competitive markets. In this respect, competition between renewable energy technology suppliers needs to be fostered in order to avoid market power on the supplier side and to limit unjustified price fluctuations. For instance, according to the International Energy Agency, learning effects have induced decreasing wind turbine costs by a factor of four since the 1980s. However, since 2004, they have increased by 20-80%, due to tight supply of turbines and components and high commodity prices (International Energy Agency 2008). Second, intermittency is the greatest obstacle to the seamless integration of wind and solar generated power into electricity grids. Diversification between both different renewable energy sources and other sources and the promotion of grid interconnections will reduce the problem with intermittency as well as the risk of extreme weather events disabling electricity infrastructures.

**Policy conclusion 2** *Based on currently available evidence, the benefits of increased energy security seem to be quite modest. Besides, renewable sources can also, in certain cases, contribute to an increase in the energy security risk. This implies that apart from on-shore wind, it is difficult to justify costly support measures with energy security benefits.*

## 3.4 Knowledge spillovers and learning-by doing

As mentioned in Section 2, production cost in the renewable energy sector is expected to decrease over time. Cumulative learning is an important determinant of future production costs. In the renewables sector, total learning depends on individual output levels, but also on the output of all other firms in the sector. The spillover effect is not considered by individual firms when choosing their optimal level of investment, which creates an externality and the need for public intervention. With only knowledge spillovers, welfare is:

$$W_{LBD} = \int_0^{Q_1} P_1(Q_1) - C(x_1) - nG_1(q_1) + \delta(\int_0^{Q_2} P_2(Q_2) - C(x_2) - nG_2(q_2, L))$$

In this context, a feed-in tariff is only justified in period 1. However, this will have consequences in period 2, because production costs and thus optimal production levels will change for renewable-based electricity producers. Annex 8.1.2 provides the necessary steps that allow us to conclude that the optimal feed-in tariff is:

$$\sigma^*_{LBD} = P_1 - \delta \frac{\partial G_2}{\partial L} \rho(n-1) \tag{12}$$

The optimal feed-in tariff has to be set equal to the sum of the market price for electricity and the discounted marginal gains from period-one learning spillovers in period two. Note that without learning spillovers, there is no justification for distorting the electricity market. The optimal share of renewables is also implicitly defined by this condition as it gives the optimal output level for firms in the renewables sector.

This equation also reveals that if renewable technologies differ with respect to marginal gains from learning in period two and/or the spillover rate, or the number of adopting firms, a differentiation of feed-in tariffs can be justified on efficiency grounds. However, no distinction needs to be made in the choice of the feed-in tariff to take account of initial differences in production costs. Therefore, it is not so much the initial situation but rather the learning rate that justifies differences in feed-in tariffs between renewable technologies.

**Proposition 3** *An optimal feed-in tariff considering learning-by doing would always be higher than the electricity price. If renewable technologies differ with respect to (1) marginal gains from learning in period two, (2) the spillover rate, or (3) the number of adopting firms, a differentiation of feed-in tariffs can be justified on efficiency grounds.*

The risk with uniform support schemes is that more mature, close to market, renewable energy technologies, for instance wind, will dominate the market. Even if there is room for a certain degree of specialisation, too much specialisation could result in a new form of energy dependence on a limited set of technologies. Furthermore, within the wind power sector, there is a need to carefully design the time development of the tariff levels. Increases in the feed-in tariff for wind power promote diffusion of wind capacity, which in turn encourages learning and generates cost reductions. However, there exists also a direct negative effect of feed-in tariff increases on learning. They induce wind power producers to select high-cost sites, for example locations with expensive grid connections and/or poor wind conditions and discourage the competitive pressure from other energy sources, and – as a result – innovation activities become less attractive (Söderholm & Klaassen 2007).

As explained above, one of the main rationale for technology-specific support schemes is based on variations in learning rates. However, there is no easy way to measure learning rates. Differences in the return on private and public investments in R&D could be used as a proxy for the spillover rate, but no data exist yet for this sector. Another approach would consist of making a distinction between the social and private progress ratios, which measure the learning rate of a technology by considering the cost decline for every doubling of capacity. However, current studies seem to concentrate on determining the progress ratio at the sector level, without making a distinction between private and social learning rates. The estimation of these ratios usually varies between 0.75 and 0.95, depending on the studies and the technologies considered (Van Benthem et al. 2008, Papineau 2006). One policy conclusion is that it is extremely difficult to measure the spillover rate, even though it is a key element for the determination of optimal support schemes and their levels. The proxy used in the literature is the progress ratio, and differences in progress ratios are used to justify technology specific support schemes.

One advantage of technology-specific feed-in tariffs is that they allow a simultaneous development of various technologies. On the contrary, green certificates normally cover all eligible technologies without distinguishing between them, which favours the most advanced technologies while providing too small incentives for less advanced ones. Unfortunately, a potential differentiation of green certificates by technology would reduce the scope of exchanges and negatively influence the liquidity of these markets. Thus, tradable green certificates need to be complemented with other instruments in order to promote the development of a diversified mix of renewable energy technologies.

When all learning effects are assimilated, it is not necessary anymore to support renewables technologies. Thus, support schemes need to be phased out when learning spillovers disappear. This implies that if the evaluation of the spillover rate is incorrect and support measures are badly adjusted, rents risk emerging for renewable producers as they could benefit from too high support levels for too long. At this stage, the phasing out of support schemes depends on the level of development for each renewable technology.

**Policy conclusion 3** *Learning rates and spillovers justify the presence of support schemes, but measuring spillover rates adequately is a major challenge. Optimal support levels vary across technologies and Member States, and should be reduced regularly to provide incentives for technology development.*

## 3.5 Combining learning-by doing and pollution

This scenario assumes that the regulator faces two externalities: pollution and learning spillovers. Welfare is then:

$$\begin{aligned} W_{Poll+LBD} &= \int_0^{Q_1} P_1(Q_1) - C(x_1) - nG_1(q_1) - D_1(E_1) \\ &\quad +\delta(\int_0^{Q_2} P_2(Q_2) - C(x_2) - nG_2(q_2, L)) \end{aligned} \tag{13}$$

A first-best outcome is achievable through the combination of two instruments. For instance, the regulator can use an environmental tax and a feed-in tariff to address the two externalities. In this case, we have:

$$\tau^* = D_1'(E_1) \tag{14}$$

$$\sigma^* = P_1 - \delta \frac{\partial G_2}{\partial L} \frac{\partial L}{\partial q_1} \rho(n-1) \tag{15}$$

where $\tau$ is the pollution tax rate per unit of emissions. The optimal pollution tax is the Pigovian one, equal to the marginal social damage of emissions. Renewable support schemes can be entirely dedicated to addressing the spillover externality.

Considering now that the regulator has to use the renewable support scheme to address both externalities, welfare is optimised when:

$$\frac{dW_{Poll+LBD}}{d\sigma} = 0 \Leftrightarrow -D_1'(E_1)\mu \frac{dx_1}{d\sigma} + n[P_1(Q_1) - \sigma - \delta\rho(n-1) \frac{\partial G_2}{\partial L} \frac{\partial L}{\partial q_1}] \frac{dq_1}{d\sigma} = 0 \tag{16}$$

which gives,

$$\sigma^*_{Poll+LBD} = P_1 - \delta \frac{\partial G_2}{\partial L} \frac{\partial L}{\partial q_1} \rho(n-1) - D_1'(E_1) \frac{\mu \frac{dx_1}{d\sigma}}{n \frac{dq_1}{d\sigma}} \tag{17}$$

A feed-in tariff addressing both the environmental and the learning externalities would be set higher than the one obtained in the context of an optimal policy mix. This is because the regulator must increase the incentives to produce renewable-based electricity so as to indirectly affect the production of fossil-fuel based electricity. First-best welfare is not achievable as the same instrument has to be used to modify two variables, that is, renewable-based and fossil-fuel based electricity production.

## 3.6 Combining learning-by doing and energy security

Here, welfare is:

$$\begin{aligned} (18) \qquad W_{Poll+ES} &= \int_0^{Q_1} P_1(Q_1) - C(x_1) - nG_1(q_1) - S_1(nq_1, x_1) \\ &\quad + \delta\left(\int_0^{Q_2} P_2(Q_2) - C(x_2) - nG_2(q_2, L)\right) \end{aligned}$$

If the regulator can use two instruments, then an optimal policy-mix would be the combination of a tax $\upsilon$ on each unit of fossil-fuel based electricity production and a feed-in tariff for renewable-based electricity producers, which gives:

$$\begin{aligned} (19) \qquad \nu^* &= \frac{\partial S_1}{\partial x_1} \\ (20) \qquad \sigma^* &= P_1 - \delta \frac{\partial G_2}{\partial L} \frac{\partial L}{\partial q_1} \rho(n-1) - \frac{\partial S_1}{\partial q_1} \end{aligned}$$

The regulator may have to address both the knowledge spillovers and the energy security externality through the choice of a single renewable energy policy. The first-best solution is not achievable as the same instrument has to be used to influence in two different ways two distinct maximisation production decisions. In other words, the optimal feed-in tariff should be different for fossil-fuel based producers, to address efficiently energy security issues, than for renewable-based electricity producers, to address energy security and learning spillovers. Thus, the optimal policy will be the result of a trade-off between the two externalities. The second-best optimal feed-in tariff is:

$$(21) \qquad \sigma_{Poll+ES} = P_1 - \delta \frac{\partial G_2}{\partial L} \rho(n-1) - \frac{\partial S_1}{\partial q_1} - \frac{\partial S_1}{\partial x_1} \frac{\frac{dx_1}{d\sigma}}{n\frac{dq_1}{d\sigma}}$$

An optimal feed-in tariff regulating both learning effects and an energy security externality will be higher (resp. lower) than the feed-in tariff only focusing on learning spillovers if the initial level of renewables is less (resp. more) than the optimal level.

### 3.7 Combining all three externalities

Finally, let us consider the general case where the regulator needs to address all three externalities simultaneously. Welfare in this context is given by Equation (1). The social optimum in period 1 is given by Equations (2) and (3). Assuming that the regulator can use as many instruments as she wants, one can show that only two instruments are necessary to perfectly internalise these externalities. The main intuition for this result is that these three externalities are associated with only two production decisions. Therefore, only two instruments are necessary to influence the two production decisions. Using a tax rate $\vartheta$ on each unit of fossil-fuel based electricity produced and a feed-in tariff, the regulator can address all three externalities and enforce the first-best outcome. Optimal policy levels are given by:

$$\vartheta^* = D_1'(E_1)\mu + \frac{\partial S_1}{\partial x_1} \tag{22}$$

$$\sigma^* = P_1(Q_1) - \delta\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1}\rho(n-1) - \frac{\partial S_1}{\partial q_1} \tag{23}$$

However, in the context of this study, the relevant case is when only the renewable support scheme is used to address all three externalities simultaneously. As one instrument cannot adequately influence two separate production decisions, first-best outcomes are not achievable anymore. The second-best tariff is then the result of a trade-off between the different externalities.

$$\sigma = P_1 - \delta\frac{\partial G_2}{\partial L}\rho(n-1) - \frac{\partial S_1}{\partial q_1} - [\frac{\partial S_1}{\partial x_1} + D_1'(E_1)\mu]\frac{\frac{dx_1}{d\sigma}}{n\frac{dq_1}{d\sigma}} \tag{24}$$

As stated in introduction, the renewable energy policy has three main objectives (i) reducing environmental pollution, (ii) diversifying the energy mix and thereby improving energy security, while at the same time (iii) contributing to the competitiveness and growth of the EU economy through technological development and the development of a new industry. If this is the case, then optimal support schemes should be determined based on the elements emphasized in Equation (24). We have seen in this section that accurate measurement of these externalities is not straightforward. The following sections refine this analysis and present an economic assessment of current policies.

Annex 8.2 provides a numerical illustration of the main results of the model. Some sensitivity analysis is provided so as to discuss the impact of the main parameters of the model on optimal support schemes. It is also a way to illustrate

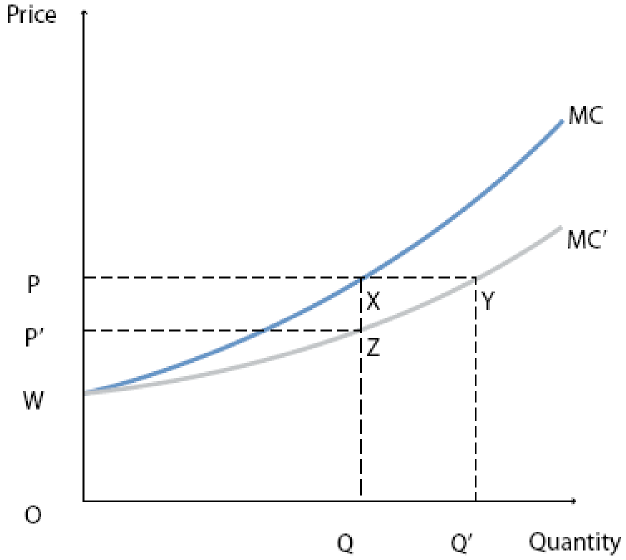

Figure 5: Cost-effectiveness and cost for consumers: feed-in tariffs vs. tradable quotas with lower-than-expected marginal costs of producing renewable electricity (Source: Finon, 2007)

how only using renewable policies to regulate three distinct externalities reduces the economy's overall welfare.

# 4 Considerations on the design of support schemes

## 4.1 Introducing uncertainty

The discussion on the level of support schemes has so far not considered any uncertainties in cost development. One of the consequences is that in a situation with perfect information both instruments have similar effects. However, if this condition is relaxed, then the relative impact of feed-in tariffs and green certificates will differ (Finon 2007).

Consider the situation in Figure 5 where, contrary to expectations, the marginal cost curve turns out to be MC' instead of MC. In case feed-in tariffs are the policy instruments, renewable electricity production will be Q', the cost for consumers is OQ'YP and producers' surplus is WYP. In case a tradable green certificate system is the instrument, output reaches the expected level Q, the price of renewable electricity is P', cost for consumers is OQZP', and producers' surplus is WZP'. All in all, when the marginal cost of renewable electricity turns out to be lower than expected by policy makers, feed-in tariffs deliver a higher output at the pre-determined price P whereas a tradable green certificate system delivers the targeted output at a lower price. Thus, in case regulators overestimate the cost of producing renewable technologies, a tradable system is more cost-effective than a feed-in tariff as it limits the risk of an excessively high output and burden on consumers. Tradable green certificates will, in this case, limit the burden on consumers by automatically adjusting the price of certificates. This also underlines that in the presence of learning rates, feed-in tariffs need to be frequently reviewed so as to adjust to the latest available information.

From the firm's point of view, another distinction needs to be made between the two instruments. Under imperfect information, there is uncertainty on the value of the endogenous variable, that is, quantity with feed-in tariffs and price with certificates. The difference is that in the case of a feed-in tariff the quantity produced only depends on the renewable electricity producer's decision. Given its cost structure, a producer determines its optimal level of production. Conversely, with green certificates, the price at which certificates are sold is not only influenced by the firm's cost structure but also by its competitors'. Hence, firms that are risk-averse are less willing to invest as their expected return on investment not only depends on their cost structure but also on competitors'.

Hence, one element of best practice for national support schemes is to provide stability, such as through the setting of targets or other objectives and the creation of long-term support schemes. By guaranteeing the price and providing a secure demand, feed-in tariffs reduce both the price and market risks, and create certainty for the investor regarding the rate of return. This seems to be one of the main explanations for the popularity of feed-in tariffs, and their success in generating investment. Conversely, uncertainty about the current and future price of tradable green certificates can increase the financial risks faced by developers and can have a negative impact on their willingness to invest in renewable energy technologies. Furthermore, producers have to sell green electricity as two products, electricity and green certificates, and the risk on the green certificates market is added to the risk on the wholesale electricity market. Thus, so far, certificates have generally generated fewer investments than feed-in tariffs and higher costs for consumers. The risks associated with a feed-in premium will be between those of the other two systems. The premium provides a secure additional return for producers, while exposing them to the electricity price risk.

**Policy conclusion 4** *By effectively guaranteeing the price and providing a secure demand, feed-in tariffs create certainty for the investor regarding the rate of return. However, they also risk inducing a high burden on consumers when production cost estimates are incorrect. Hence, they should be time-limited to keep rents and the overall costs for consumers down, and frequently reviewed to adjust the system to* *the latest available information. This is also valid for a feed-in premium. Certificates should in theory limit the costs to consumers as the level of support is determined on the market. However, this feature also induces a market risk for producers, which has proved not to be conducive to investments in new capacity.*

## 4.2 Harmonisation of support schemes and trade

The issue of a Community framework for support schemes was already raised in the Directive 2001/77/EC on promotion of renewable energy sources in the internal electricity market. The directive called for a report on support schemes by 2005, which could be accompanied with a proposal on a Community framework (European Commission 2005). Such an EU-wide scheme would be cost-efficient and reduce costs as it would allocate renewable electricity production where it is most favourable, that is, have lowest costs. A related issue is its better compatibility with the internal electricity market, as the support scheme needs to be conducive to trade in electricity on the internal market. The subsequent discussion has focused on a common green certificate system, as this would fulfil these criteria.

The main advantage of a common certificate system is its potential to foster a cost-effective development of renewable electricity production across the EU. This would provide a least-cost production of the targeted amount of renewable electricity, a common price of green certificates, and the equalisation of marginal costs of producing renewable electricity across the EU. However, two conditions need to be fulfilled for this to be feasible: (i) a well-integrated European electricity market with a common electricity price, and (ii) a harmonised institutional and regulatory framework for the green certificate market. A competitive electricity market is required in order to ensure an optimal allocation of renewable electricity production due to the fact that it is the sum of the certificate and electricity prices that determines the allocation of renewable electricity production. Hence, imperfect integration of the electricity market may result in different marginal costs for renewable electricity production across the EU and a less than optimal allocation of production, despite a common European price for certificates.

Harmonisation based on a common certification system has also been criticised by some authors on several grounds. First, there is a risk that harmonisation will not favour the development of a broad range of technologies, as it will tend to support the most mature technologies, which might inhibit the development of a broad range of renewable energy technologies and the related industries in Europe. Second, one argument has been that harmonisation will not take account of local environmental and regional development objectives. For instance, political objectives such as reducing local air pollution or creating local job opportunities in the renewable sector risk not being realised with a harmonised system. These effects would translate into different external costs and benefits associated with the renewable energy production. Third, concerns have been expressed regarding the functioning of both the electricity market (see above) as well as the certificate market. Finally, harmonisation risks creating large rents as the level of support will be determined by the marginal cost of the last technology supported (Del Rio 2005, Jacobsson et al. 2009).

Directive 2009/28/EC (European Commission 2009*a*)[8] sets targets at national level for the overall share of renewable energy in the Member States' fuel mix. Targets are based on a flat rate increase in the share of renewables weighted by GDP and modulated to take account of earlier development of these resources. Thus, they are not solely based on the national renewable resource potential. Trade in renewable energy would therefore be very useful at the Member State level. This would mitigate differences in the resource potential and other factors and thereby differences in costs between countries. As a result, trade would reduce the overall cost of the policy.

The Renewable Energy Directive introduces the possibility to trade through flexibility measures under the control of Member States. The aim is to facilitate cross-border exchange without affecting national support schemes. Hence, the Directive includes provisions for "statistical transfers" between Member States in order to allow for a more cost-effective distribution of renewable energy production. These measures can also take the form of joint projects between Member States and joint support schemes. The Renewable Directive thereby allows for voluntary and bilateral harmonisation of marginal generation costs of renewable energy sources between Member States, while safeguarding national control over the various systems. In particular, flexible mechanisms should allow Member States to reap benefits from favourable conditions in some countries that are not yet fully exploited. However, it remains to be seen to which extent this possibility will be utilised by Member States. No clear indication has been given yet on the implementation of these measures.

**Policy conclusion 5** *Harmonisation of support schemes would equalise marginal production costs and thereby minimise the cost of the policy as production would be allocated efficiently across the EU. However, harmonisation based on a common certificate system would run the risk of mainly supporting mature technologies. Another concern is that local environmental and regional development benefits will not*

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[8] The Commission report from 2005 stayed short of proposing a common framework as it advocated co-operation between countries and optimisation of the impact on national schemes (European Commission 2005). At that time, it was seen as too early to harmonise the systems due to the limited experience with the various systems. The follow-up report in 2008 also found it to be inappropriate to harmonise the support schemes, mainly due to the fact that it remained unclear which of the system was more efficient (European Commission 2008*d*). The new Renewable Directive does not explicitly aim at harmonisation of support schemes. However, the Commission is to present an analysis and action plan on, inter alia, better co-ordination of Community and national funding and other forms of support. (Article 23(7).)

*accrue to the country granting the support. Finally, an optimal allocation of renewable power production is dependent on well-functioning and competitive electricity and certificate markets.*

## 4.3 Interactions with the internal market

One issue that requires attention is to which extent the support system is compatible with and supports a competitive and well-integrated internal electricity market. It is estimated that renewable energy sources will account for around 31% of electricity production in 2020. As mentioned earlier, at present the share amounts to 17%, while the support schemes can be assumed to cover around 7% (excluding hydropower). Considerable growth is expected to take place in the new renewable technologies during the next 20 years, while the EU will continue to pursue its efforts to create a competitive well-functioning internal electricity market. It is therefore vital that the support schemes applied are conducive to trade and support the creation of the internal market, in particular as the share of renewable electricity grows.

A recent contribution discusses the potential efficiency gains in the longer term of exposing renewable power producers, and in particular wind producers, to more market signals (Hiroux & Saguan 2009). This implies that wind producers should participate in the day-ahead/intraday market, the balancing market and be exposed to congestion pricing. Hence, by exposing wind producers to market signals, improvements could be achieved concerning (i) a better selection of wind sites in relation to temporal generation patterns (for example peak loads), (ii) an optimal selection of sites in relation to congestion costs and losses, (iii) maintenance planning, (iv) technology combinations and portfolios, (v) intermittency issues, through innovation, and (vi) forecasting and system balancing efficiency.

Feed-in tariffs are problematic in these respects as they risk distorting the wholesale market. Feed-in tariffs include a (feed-in) obligation on the system operator and/or distributor to buy the renewable electricity at a fixed price. This implies that renewable power produced under the feed-in tariff regime remains outside the trade on the wholesale service exchange, that is, the day-ahead and intraday markets. If there is no obligation for balancing[9], the producers are not taking part on the balancing market either[10]. Hence, in practice, the system reduces liquidity on

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[9] Balancing responsible parties is defined as having an obligation to submit day ahead generation schedules (modifiable up to closing time before delivery) and to bear financial responsibility for any deviation from this schedule (Klessmann et al. 1987) .

[10] Provisions regarding balancing differ across countries. In Germany balancing is done at the level of the transmission system operator. Hence, producers are not exposed to market signals. Wind producers applying the feed-in tariff in Spain, on the other hand, are exposed to imbalance prices, but are provided with wider tolerance margins than other electricity producers. The producers applying the premium are furthermore fully responsible for balancing like any other market participant (Klessmann et al. 1987).

the wholesale exchange, which has negative implications for the overall functioning of the market.

Both a feed-in premium and a certificate system are, on the other hand, more compatible with well-functioning electricity wholesale markets. A premium system, which provides a fixed support on top of the underlying electricity price, has the advantage of allowing all electricity to be traded and priced on the wholesale market. By exposing producers to the electricity market price, feed-in premiums should provide the necessary incentives to achieve the improvements mentioned above, while limiting the risk exposure imposed by a certificate system.

However, neither feed-in tariffs nor premiums facilitate trade in the "green" property of the electricity as does a certificate. The fact that the support is provided at the point of the delivery to the grid, that is, at the "feed-in", implies that these schemes in fact – nearly by definition – are limited to domestic producers. Hence, the support is granted to the producers in the appropriate jurisdiction. In practice, this depends on the detailed construction of the system. Ireland is the only EU country that currently applies feed-in tariffs and allows other EU-producers to be eligible for the tariff under certain conditions[11]. In this case the guaranteed feed-in tariff is granted to the supplier, who will buy the electricity from different producers. However, it is assumed that these bilateral trades, possibly with foreign producers, will take place outside the market place. In the German case, on the other hand, it appears difficult to extend the system to foreign suppliers as it is the grid operator that provides the guaranteed tariff, and the costs are subsequently transferred to the transmission operator and later on to the suppliers/consumers. Thus, in practice, all but one feed-in system apply only to domestic producers. This distorts competition, in particular in a situation where electricity markets are being increasingly integrated. The Member States that apply certificates normally also limit their eligibility to domestic producers. The exception in this case is Italy, which acknowledges certificates of origin from other Member States as well as on the basis of bilateral agreements with Albania and Switzerland. It is easy to facilitate international trade in certificates by allowing them to be credited against the quota obligation. However, in order to gain the full advantages of trade and avoid distortions, harmonisation of eligible technologies and other rules governing certificates might prove necessary.

**Policy conclusion 6** *In order to limit internal market distortions, feed-in premiums should be preferred over feed-in tariffs. However, when possible, tradable green*

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[11] A certificate of origin or a supplementary document needs to prove that the electricity was generated from renewable energy sources and that it does not contribute to the achievement of the Member State's energy goals for a period of 15 years. Furthermore, the construction of the plant generating renewable energy needs to be authorised according to the provisions of the respective Member State.

*certificates should be used, as they limit internal market distortions and facilitate trade in the green property of electricity.*

## 4.4 Combination or sequencing of instruments?

From the analysis presented above, it does not seem to exist one optimal instrument that could be used for any kind of renewable energy technology and in any circumstances. On the one hand, by effectively guaranteeing the price and providing a secure demand, feed-in tariffs create certainty for the investor regarding the rate of return. On the other hand, feed-in tariffs risk distorting the wholesale market, whereas a premium system has the advantage of allowing all electricity to be traded and priced on the wholesale market.

Certificates can be regarded as an even more suitable instrument once the technology is close to being competitive. At that stage, a certificate system would expose producers to market forces and provide a more competitive environment, while still providing support. The system is more compatible with the Internal Market which is important when volumes grow, and trade could potentially be allowed across the EU. Another advantage is the fact that the support will be automatically phased out once the technology manages to compete. A potential problem is that the market might be rather limited if this is based on one or a few technologies; application at the EU level might address this issue. It has also been shown that broad-based policies, such as tradable energy certificates, are more likely to induce innovation in technologies that are close to being competitive with fossil fuels (Johnstone et al. 2009). More targeted subsidies, such as feed-in premiums, are on the other hand more suitable to induce innovation in more costly energy technologies.

Overall, an option to consider would then be to combine feed-in premiums and tradable certificates. Tradable green certificates would be used as a general support scheme for all renewable electricity. The certificate price would provide support in addition to the electricity price. Meanwhile, specific technologies, for instance photovoltaic energy, would benefit from a guaranteed feed-in premium in addition to the electricity and green certificate equilibrium prices. Such a combination of instruments should in theory address specific learning effects for less mature renewable technologies, while at the same time providing efficient support for more mature technologies.

Figure 6 considers the potential impact of such a policy on the market for green certificates. First, an exogenous number $Q^*$ of green certificates is fixed by the regulator. It is the only support scheme. The supply curve $S$ is the sum of individual supply curves from renewable-based electricity producers. Let us consider that there are two types of producers, wind-based and photovoltaic-based electricity producers, and that wind-based electricity is cheaper than photovoltaic-based electricity. From the analysis above, we know that green certificates tend to favour the cheapest

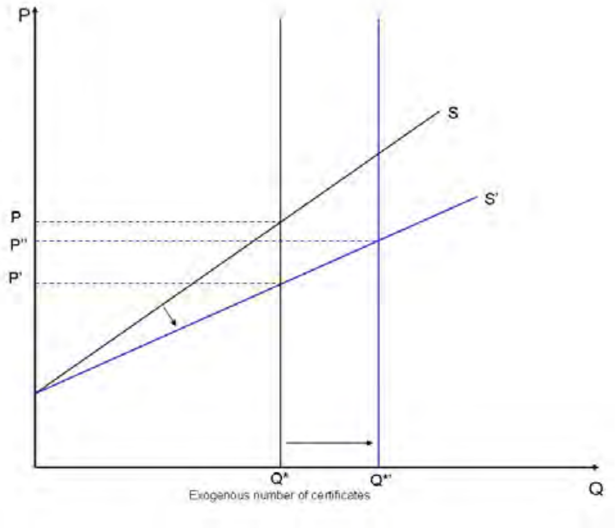

Figure 6: Effect of a combination of instruments on the market for green certificates

technology, and it is likely that most of the green electricity produced in the baseline scenario comes from wind-mills.

Second, the regulator decides to introduce feed-in premiums for photovoltaic-based power producers. This subsidy induces a shift to the right in the individual supply curves of photovoltaic-based power producers, which translates into a new overall supply curve $S'$. The share of renewable production is exogenously given by the quota obligation determined by the regulatory agency. Thus, increasing production of photovoltaic-based electricity would come at the expense of wind-based electricity generation, creating crowding-out effects between renewable technologies. In addition, this drives downward the equilibrium price of green certificates, which has a non-ambiguous negative effect on wind-based power producers' profits. The impact on photovoltaic-based power producers' profits depends on the price-supply elasticity for green certificates. When production costs are quadratic the supply is inelastic enough to increase photovoltaic-based power producers' profits[12]. This does not have to be the case in a more general context. Furthermore, the indirect impact on the price for electricity would also have to be taken into account.

Of course, the regulator could decide to increase the quota for green electricity. This would translate into a shift to the right in the demand for green electricity, in blue on Figure 6, and an increase in the price for green certificates from $P'$ to

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[12] For instance when $c(x_s) = sx_s^2$ and $c(x_w) = wx_w^2$, where $x_s$ is the production of photovoltaic-based electricity and $x_w$ the production of wind-based electricity, with $s > w$, the presence of a feed-in premium would result in a less than proportional change in $P$.

$P''$. This would reduce crowding-out effects and could potentially increase profits for both types of renewable-based power producers. However, a simpler signal would be sent to renewable-based power producers by using a sequencing of instruments instead of a combination of instruments.

When implementing a sequencing of instruments, it would be decided ex ante which technologies benefit from feed-in premiums, and which technologies use tradable green certificates. The decision would be based on the maturity of the technology and the need for stable support to promote investments and economies of scale. The choice of instruments should be reviewed on a regular basis. This would limit the risk of crowding-out effects without jeopardising the overall cost-effectiveness of the system, since the other characteristics of the combination of instruments would be maintained. The only risk is that the market for green certificates would be too thin but this could potentially be addressed by facilitating international trade in certificates.

**Policy conclusion 7** *Support schemes should fit the level of development of the technology. The solution may be to sequence instruments according to the maturity of the technology. Feed-in premiums can be used for technologies at the early stage of market deployment. Once the volumes start to have an impact on the internal market and the technology approaches competitiveness, tradable green certificates would be a more suitable support instrument.*

# 5 Economic assessment of current policies

## 5.1 Assessment of current features of support schemes

Based on the Renewable Energy Progress Report (European Commission 2009*b*), the following Box summarises the choices made on the design of support schemes by Member States.

- 18 countries (Austria, Bulgaria, Czech Republic, Denmark, Germany, Greece, France, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, the Netherlands, Portugal, Slovak Republic, Slovenia, Spain) use differentiated feed-in tariffs or premiums.
  - In most cases, feed-in tariffs are time-limited, except for Spain (lower fixed rate after 15-25 years) and Latvia (solar energy). The time limitation can take different forms, for instance in Hungary the period is determined by the Energy Office.
  - Austria, Spain and Slovenia apply reduced rates after a specified number of years.
- Cyprus and Estonia (for 12 years) use uniform feed-in tariffs.
- Premiums are used in Denmark (for 10 years) and in the Netherlands. Czech Republic, Estonia, Slovenia and Spain offer the choice between feed-in tariffs and premiums.
- Green certificates are used in Belgium, Italy, Poland, Romania, Sweden and the UK.
  - Programs are time-limited except for Poland.
  - Belgium sets minimum prices (which vary across regions), Poland imposes a price (average market price of the previous year) and in Romania prices must fall between 24-42 euro up to 2012. Only Sweden and the UK do not guarantee prices.
  - Lithuania is committed to using green certificates beyond 2020.
- Denmark (offshore wind farms), France (wind, biomass and biogas), Latvia (wind over 0.25 MW) and Portugal (wind and biomass) also use tenders.
- Malta offers grants.

The vast majority of Member States (21 out of 27) use feed-in tariffs or premiums to promote renewable energy sources. 18 countries use differentiated feed-in tariffs, which facilitates the development of a portfolio of various renewable power technologies. In most countries, the differentiation according to technology is significant, for example the support to photovoltaic is often 5 to 10 times the level provided for small hydro. This reflects varying production costs across technologies as well as the expected externalities that support schemes help to internalise (see Figure 3).

A few countries, for example Estonia and Cyprus, apply, however, a common feed-in tariff across technologies. In such a system, technologies will be in competition with each other for the support, which will favour the lowest cost, that is, the most competitive technologies. A non-differentiated feed-in tariff will, like a certificate system, promote cost-efficiency at the expense of technology differentiation.

Feed-in tariffs are in most cases time-limited, which should facilitate the phasing-out of the support and keep the costs down for consumers. This also limits windfall rents to producers once the investment is recovered. In other cases, for example in Spain, the overall cost of the system is limited through a maximum support by installed capacity according to technology and year. However, the fact that the support is provided for the entire time of the operation of installations in Spain risks providing producers with the above mentioned windfall rents.

Most countries update their support levels rather regularly in order to take account of developments in electricity and other markets. For example both Bulgaria and Hungary revise their tariffs annually for all installations with references to inflation and electricity price developments. Latvia adjusts the tariffs to take account of exchange rate and gas price developments. However, it is less clear how regularly and systematically support levels are updated to reflect changes in production costs as well as to incentivise progress in technology development. The German system can be seen as best practice in this respect. It explicitly addresses this issue by reducing feed-in tariffs gradually by a prescribed percentage with the aim to provide incentives for future technology development.

Only Denmark and the Netherlands offer premiums as their only price instrument, which makes their systems more compatible with liberalised electricity markets. A premium is provided in addition to the market price of electricity. In Denmark a statutory maximum is set for the sum of the market price and the premium. The maximum puts a cap on the overall return for producers and thereby limits overall costs for consumers. The statutory maximum depends on the plant's date of connection, the energy source, and the technology. The premium granted in the Netherlands is determined yearly. In contrast with the Danish case, this is directly financed from the public budget, which also puts an overall cap on the cost of the system. If demand for premiums exceeds the allocated budget, the subsidy will be granted according to the order of the submission of applications. This system was only implemented in 2008, so the experience so far is limited. It appears that this approach could create a problem of continuity and certainty for investors, if the demand for the support is greater than the allocated funds.

Spain, the Czech Republic, Estonia and Slovenia have introduced the possibility to choose between feed-in tariffs and premiums. The flexibility and coverage of the systems differ. In the Czech Republic, the choice can be reversed at the earliest after a year. In Spain, large installations above 50MW are only entitled to the premium, with the exception of photovoltaic systems, which are covered exclusively by the fixed feed-in tariff. Other Spanish producers can choose yearly whether to apply the premium or the tariff, and whether these should be fixed or variable.

To allow producers to choose between tariffs and premiums provides them with the possibility to take advantage of years with higher electricity prices, while limiting the exposure to falling or low prices. These hybrid systems allow producers to take on greater price risk, using the guaranteed feed-in tariffs as a price floor. Combining feed-in tariffs and premiums can be regarded as a transition phase, as the introduction of a premium makes the system more market-oriented and exposes producers to more risk. However, to make the system compatible with a well-functioning electricity market, the premium should be the preferred instrument.

Six countries are currently using green certificates. In this case, both the certificate and the electricity can be traded on the market. It can be noted that both the UK and Sweden, which liberalised their electricity markets relatively early, have opted for certificate systems. On these markets, the penalty fee paid by electricity producers in case of non respect of the quota plays de facto the role of a price ceiling. The main aim of the fee is to constitute a sanction for the electricity retailers who have failed to fulfil the quota. In Sweden the fee is set at 150% of the average certificate price in the obligation period (normally the corresponding year). However, the degree of compliance to the quota obligation has been consistently above 99% since 2004 (the first year of full operation of the system), and as a result the fee is scarcely applied.[13] Another objective of a penalty fee is to limit the overall costs of the support system and its impact on consumers. In the UK, suppliers may satisfy their obligation by paying a so-called buy-out price to the regulatory authority. In 2007-2008, 36% of the renewable quota was not met and suppliers chose to pay the buy-out price instead. This represented a total of £307M. These funds are later channelled back to those suppliers that have fulfilled their quotas (Ofgem 2009). Poland has explicitly introduced a fee, which acts as a substitute to purchasing a certificate. This fee is lower than the penalty charge for non-compliance with the quota. Generally, if the sanction should act as a deterrent it should be set high, while if the aim is to provide a safety valve it should probably be set at a lower price level.

In addition, half of the countries using certificates complement their policy with some form of more direct price control. Romania, for instance, defines an interval for the transaction value of the certificate for the 2008-2014 period (thereafter a penalty will act as a price ceiling), while Belgium guarantees a minimum price for the certificates. The purpose of a price floor is generally to ensure a minimum level of support, and thereby return for the producers of renewable energy. It is a non-negligible risk that the quota will be set at such a level that either the price ceiling or the price floor will determine the price. This will imply that the certificate system translates into a price regulation, that is, a semi-fixed feed-in tariff, thereby limiting

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[13] In 2003 and 2004, there was a cap on the penalty fee (175SEK and 240SEK per missing certificate). However, the cap was removed in 2005 since it acted as a price ceiling on the certificate market and thereby directly influenced price formation (Swedish Energy Agency 2009)

the advantages of this quantity instrument. Hence, the market is not allowed to determine the required level of support, which in turn will inhibit the possibility to achieve the targeted level of renewable power production.

Few countries offer both feed-in tariffs and certificates. In Italy, electricity generated from renewable energy sources is mainly promoted through a quota system. As an alternative, small plants and expensive technologies like photovoltaics generation can make use of price regulation in the form of feed-in tariffs. This targeted support on specific technologies might be more cost-efficient than participation in the general certificate system. Even though this combination of instruments is not consistently used across the EU, it could be regarded as a first example of a sequencing of support schemes according to the maturity of the technology.

Finally, well-adapted support schemes are only a necessary condition for the development of renewable energy sources. Simplifying administrative procedures and ensuring grid access can also influence investor decisions. In most Member States, administrative procedures continue to be complicated, with multiple authorities requiring consultation. Indicators have been deployed to monitor progress made by Member States, such as the average number of authorities involved in the building permission procedure or the average lead time for overall authorisation procedure and grid connection. It is also evident that broad support in the society for the development of renewable energy sources has proved to be important for the market up-take of renewable technologies, as it has translated into a greater acceptance of these technologies.

**Policy conclusion 8** *Most Member States have chosen feed-in tariffs over tradable green certificates. Latest developments in the design of feed-in tariffs tend to reduce the overall cost of the policies and make them more compatible with the internal market. In the meantime, the introduction of various price control mechanisms tends to bring the characteristics of tradable green certificates closer to those of a price instrument, that is, a feed-in tariff.*

## 5.2 Assessment of current levels of support schemes

Figure 7 describes, focusing on feed-in tariffs, Member States' choices in terms of level of support schemes. The diagrams denote the range of support levels for different technologies, that is, power production based on off- and onshore wind, small hydro, photovoltaic, solid and liquid biomass, biogas, and geothermal energy. When a range is provided, the level of support will for example depend on the size of the installation, the location, and/or the duration of the support. Annex 7.2 presents the same information, but in a table, and introduces as well a second table with average support levels[14]. Figure 8 presents, for countries using feed-in

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[14] It is very difficult to aggregate and compare the information regarding support scheme levels, as conditions are both location and technology specific. In addition, the level and design of support

premiums, Member States' current support levels.

Following the methodology presented in section 4, feed-in tariffs should be introduced so as to optimally internalise all externalities associated with the production of renewables. There are not any significant differences among renewables technologies in the way they internalise environmental externalities[15], which calls for a uniform treatment of pollution issues to determine optimal support levels. The energy security risk is managed by supporting the development of a balanced, diversified and economically viable mix of energy technologies. Support schemes would then have to consider the individual contribution of each renewable technology to reducing the energy security risk. This may justify higher support levels for less developed and less competitive technologies. Finally, differences in learning rates could explain different average levels of feed-in tariffs. It is for instance the case between on-shore and off-shore wind, due to earlier development of on-shore wind technologies.

Overall, Figure 7 shows significant differences from Member State to Member State in the relative support level given to various technologies. Although general conclusion should be derived with caution, it seems very difficult to justify these differences by cost-efficient internalisation of externalities at the Member State level. In other words, although externalities are hard to measure, it is equally difficult to consider that they greatly differ from Member State to Member State.

Let us now consider support levels by technology. As regards wind energy, the market deployment of this technology is such that it can be qualified as relatively mature. At current cost levels, the feed-in tariffs range from 2.3 to 13 €cents/kWh, with an average of 8.5 €cents/kWh. This average rate would guarantee a rent of about 2 €cents, compared with production costs as given in the CASES project, for each kWh of on-shore wind produced. As seen with Figures 3 and 4, expected learning rates are modest beyond 2020. Considering that energy security risks are marginal compared to learning rates, support is probably too high for on-shore wind and would need to be fully phased out by 2020.

Expected learning rates appear to be rather low for both the biogas and solid biomass technology, as the production cost ranges are expected to fall slightly or even increase for biomass up to 2030. The feed-in tariff rates for these technologies range from 6 to 23 €cent/kWh, with averages around 10€cent for biomass and 11€cent for biogas. These rates can be assumed to internalise and compensate for the expected learning rates over time, in particular beyond 2030. However, it remains vital to ensure that learning by doing results in reduced production costs in

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schemes evolve rapidly. Thus, general conclusions should be derived with caution. In 2010, Member States will have to provide national renewable action plans, and as of 2011 they will report biannually on the promotion and progress in the use of renewable energy. This process

[15] The only difference could come from the environmental externalities they themselves generate but, according to the CASES project, this difference represents less than 0.1€cent/kWh.

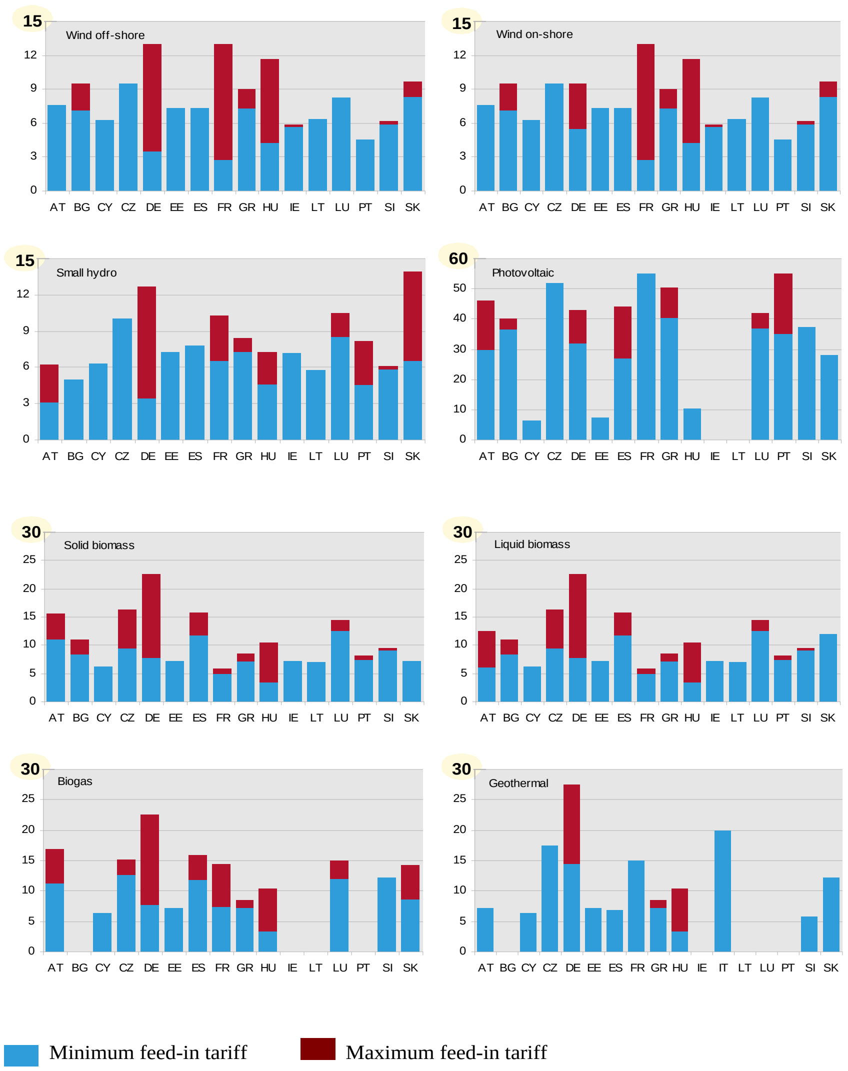

Figure 7: Feed-in tariffs in the EU per technology, €cent/kWh. (Source: European Commission (2009b) and http://res-legal.de)

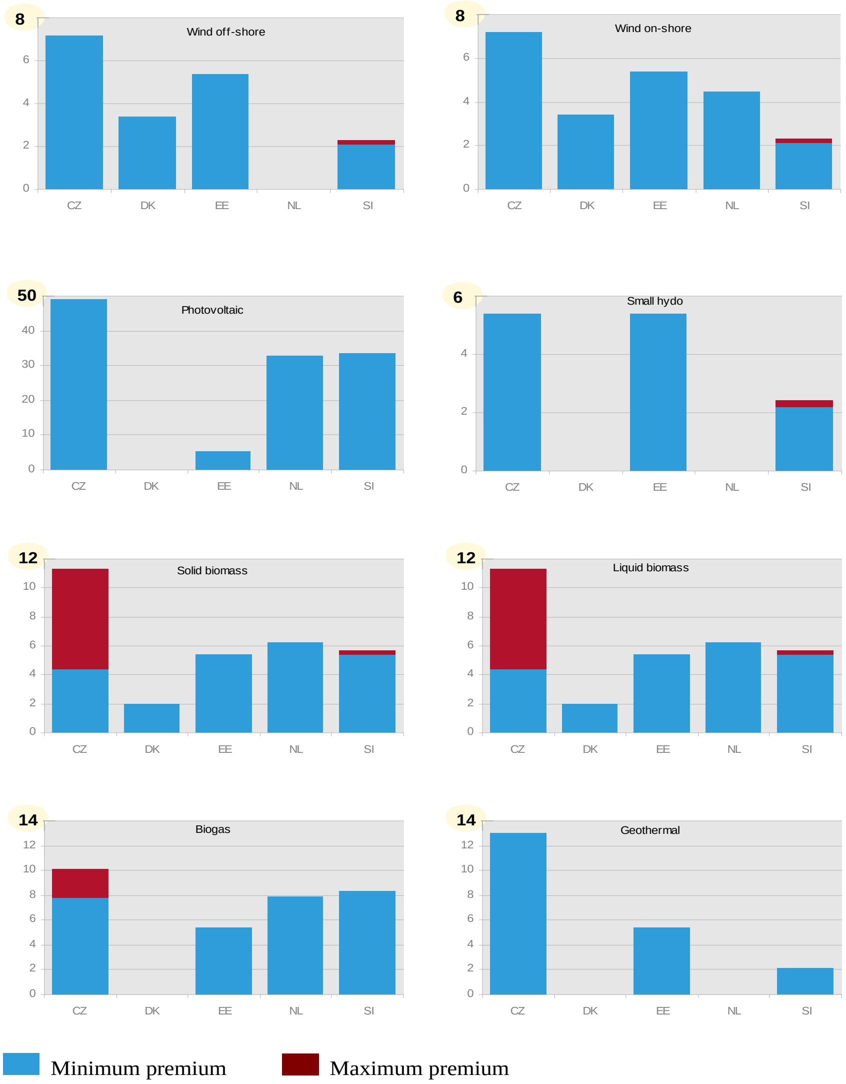

Figure 8: Premiums in the EU per technology, €cent/kWh. (Source: European Commission (2009b) and http://res-legal.de)

the longer term so that these technologies can reach market maturity in the future.

Furthermore, photovoltaic energy currently benefits from very high support levels due to high learning rates. These learning rates are expected to be high for this technology in the next 20 years as production costs are expected to come down to a third of current levels. However, according to Figures 3 and 4, solar energy produced by photovoltaics will still have high relative costs and be far from competitive in 2030. One concern in this context is whether support to market deployment generates these learning effects in the most cost efficient way, or if other instruments which support technology development more directly, for example research grants, would be more efficient in order to internalise the spill-over effects. The security of supply externality would be another basis for the support of photovoltaic energy. However, the few empirical results attempting to measure energy security risks do not allow concluding that the promotion of photovoltaic energy is a cost-efficient policy.

Concerning feed-in premiums, their level should be set so that they compensate for the externalities of the individual technologies in addition to the electricity price. In those countries that apply both a feed-in tariff and a feed-in premium, the difference between the two instruments should be the average expected electricity price. This appears to hold for most countries. However, the treatment of wind energy in the Czech Republic seems to be an exception, as the premium appears rather generous vis-à-vis both other technologies and other Member States. Overall, the same analysis applies for the premiums as for the feed-in tariffs. As wind energy approaches maturity, it should be possible to phase out the premiums by 2020. Moreover, it is not evident that support to market deployment through feed-in premiums is the most cost-efficient way to promote photovoltaic energy.

The importance of keeping the overall costs down is vital in order to maintain both political and public acceptance of the support schemes. Examples from Denmark[16] and the Netherlands demonstrate that systems that are considered as too generous and costly run the risk of being overhauled, which in turn risks having a detrimental impact on the stability of and the confidence in the system and thereby reduce investments.

**Policy conclusion 9** *Differences in support levels must be justified by differences in each technology's contribution to energy security or in each technology's learning rate. Overall, these considerations do not seem to be the main explanation for observed variations in support levels across Member States. As regards wind energy, support levels are probably too high. In addition, the current promotion of photo-*

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[16] Denmark shifted to FIT premiums in 2001 and support to R&D activities was cut. However, the premium was set rather low, and as a consequence the pace of investment in the wind sector slowed down.

*voltaics could possibly be more cost-efficient if it targeted technology development more directly.*

# 6 Conclusion

Major barriers in the growth and integration of renewable electricity remain. By adopting well-adapted instruments and combining different types of support measures, Member States can continue to improve their efforts to support renewable energy with the ambition to reach the agreed targets in an efficient way. However, greater clarity on issues relating to design and implementation of the support schemes could be useful in order to improve efficiency. In that context, the following conclusions have been derived:

- Given relative production and external costs, policies that solely aim to internalise environmental externalities are unlikely to make the renewable power technologies competitive. Besides, the costs of energy security are unlikely to motivate, by themselves, ambitious renewable policies. Hence, it is the combination of all three externalities, pollution, energy security and learning effects, that would justify a strong policy intervention. In designing appropriate support schemes, the main challenge is to measure adequately these externalities, and in particular spill-over rates, in order to determine optimal intervention levels.

- By guaranteeing the price and providing a secure demand, feed-in tariffs create certainty for the investor regarding the rate of return. However, they also risk inducing a high burden on consumers when production cost estimates are incorrect. Hence, they should be time-limited to keep rents and the overall costs for consumers down, and frequently reviewed to adjust the system to the latest available information. Certificates should in theory limit the costs on consumers as the level of support is determined on the market. However, this feature also induces a market risk for producers, which has proved not to be conducive to investments in new capacity.

- To limit internal market distortions, feed-in premiums should be preferred over feed-in tariffs.

- The support scheme should fit the level of development of the technology. A solution may be to sequence instruments according to the maturity of the technology. Feed-in premiums can be used for technologies at the early stage of market deployment. Once the volumes start to have an impact on the internal market and the technology approaches competitiveness, tradable green certificates would be a more suitable support instrument.

- Harmonisation of support schemes would equalise marginal production costs across the EU and thereby minimise the cost of the policy. However, harmonisation based on a common certificate system would run the risk of mainly supporting mature technologies, unless it is limited to technologies with similar levels of development. Another concern is that local environmental and regional development benefits will not accrue to the country granting the support. Finally, an optimal allocation of renewable power production is dependent on well-functioning and competitive electricity and certificate markets.

- Most Member States have chosen feed-in tariffs over tradable green certificates. Latest developments in the design of feed-in tariffs tend to reduce the overall cost of the policies and make them more compatible with the internal market, for example through applying a feed-in premium. In the meantime, the introduction of price controls tends to bring the characteristics of tradable green certificates closer to those of a price instrument.

- Differences in support levels must be justified by differences in each technology's contribution to energy security and/or in each technology's learning rate. Overall, it does not seem to be the main explanation for observed variations in support levels across Member States. As regards wind energy, the available estimates of externalities suggest that support levels are probably too high in many countries. In addition, the current promotion of photovoltaics could possibly be more cost-efficient if it targeted technology development more directly.

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# 7 Non-technical annex

## 7.1 Production cost for different electricity technologies

| **Technology** | **€2005/MWh 2007** | **€2005/MWh 2020** | **€2005/MWh 2030** |
|---|---|---|---|
| Biogas | 55 – 215 | 50 – 200 | 50 - 190 |
| Solid biomass | 80 – 195 | 85 – 200 | 85 - 205 |
| Photovoltaic | 520 - 880 | 270 – 460 | 170 - 300 |
| Wind on-shore farm | 75 – 110 | 55 – 90 | 50 - 85 |
| Wind off-shore farm | 85 – 140 | 65 – 115 | 50 - 95 |
| Small scale hydro | 60 – 185 | 55 – 160 | 50 - 145 |
| Large scale hydro | 35 – 145 | 30 – 140 | 30 - 130 |
| Nuclear | 50 – 85 | 45 – 80 | 45 - 80 |
| Gas (Combined cycle gas turbine) | 50 – 60 | 65 – 75 | 70 - 80 |
| Coal (Pulverised Coal Combustion) | 40 – 50 | 65 – 80 | 65 - 80 |
| Electricity prices, wholesale | 51-74 | | |

Source: European Commission (2008*a)*

## 7.2 Feed-in tariffs in the EU per technology

Figure 10 presents current levels of support schemes per Member State and per technology. Figure 11 presents the results of our estimates of average levels of support schemes by technologies and by Member States. These averages have simply been determined by calculating the average support level per technology and per Member State. Hence, on average, the level of feed-in tariffs offered by Member States to promote renewable technologies goes from 7 ct€/kWh for landfill gas to 31.8 ct€/kWh for photovoltaics. There exists a difference in the average level of support between wind on-shore and wind off-shore. There is also a slight difference between biomass technologies. Small hydro receives relatively low support whereas biogas and, to some extent, geothermal receive relatively high supports.

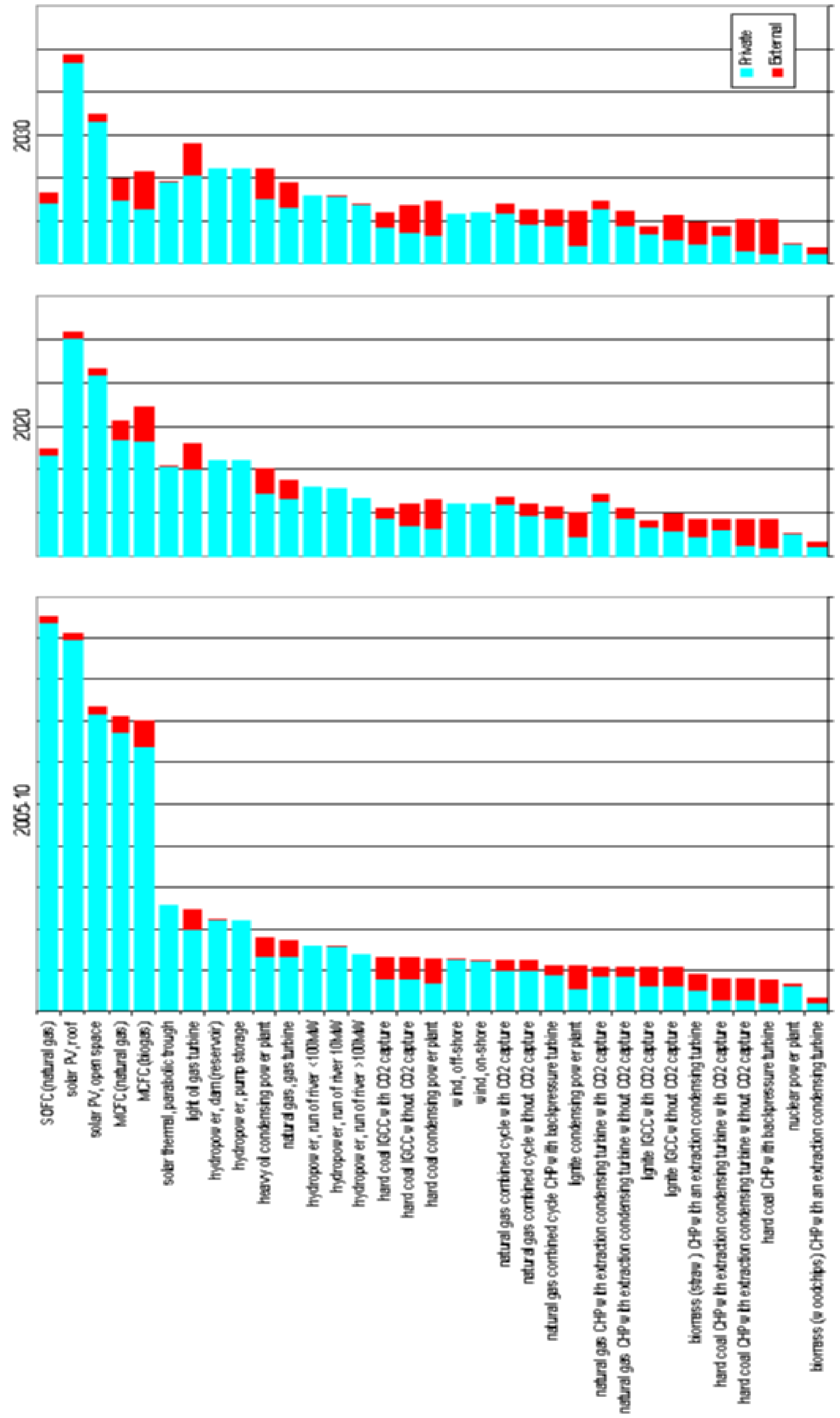


Figure 9: Private and external production costs of electricity generation by technology, eurocents/kWh (Source: CASES, 2009)

| | off shore | on shore | Solid Biomass | Liquid Bomass | Biogas | Landfill gas | Geothermal | PV | Small hydro |
|---|---|---|---|---|---|---|---|---|---|
| **Austria** | 7,6 | | 11,1-15,65 | 6-12,50 | 11,3-16,95 | 1,05-5,95 | 7,3 | 30-46 | 3,15-6,25 |
| **Belgium (min prices, fed state)** | 9-10,7 | 5,0 | 2,0 | | | | | 15,0 | 5,0 |
| **Bulgaria** | 7,15-9,5 | | 8,4-11 | | | | | 36,7-40 | 5,0 |
| **Cyprus** | 6,3 | | | | | | | | |
| **Czech Republic (FIT)** | 9,5 | | 9,4-16,3 | | 12,7-15,1 | | 17,4 | 52,0 | 10,0 |
| ***Czech Republic (premium)*** | *7,2* | | *4,4-11,3* | | *7,8-10,1* | | *13,0* | *48,9* | *5,4* |
| ***Denmark (bonus)*** | *1,3* | *3,4* | *2,0* | *2,0* | | | | | |
| **Denmark (max payment)** | 7,0-8,4 | | | | 10,0 | 8,1 | 8,1 | 8,1 | 8,1 |
| **Estonia (FIT)** | 7,3 | | | | | | | | |
| ***Estonia (bonus)*** | *5,4* | | | | | | | | |
| **Germany** | 3,5-13 | 5,5-9,5 | 7,79-22,67 | | | 7,16-11 | 14,5-27,5 | 31,94-43,01 | 3,5-12,67 |
| **Greece** | 7,3-9 | | 7,3-8,46 | | | | | 40,3-50,3 | 7,3-8,46 |
| **Spain (fixed price)** | 7,3 | | 11,8-15,8 | | | | 6,9 | 26,9-44,0 | 7,8 |
| **Finland** | | | subsidies or tax refunds, feed-in tariffs for electricity produced from peat, but formula anavailable | | | | | | |
| **France** | 2,8-13 | | 4,9-5,9 | | 7,5-14,5 | | 42339,0 | 55,0 | 6,6-10,3 |
| **Hungary** | 4,27-11,69 | | 3,41-10,47 | | | | | 10,5 | 4,65-7,27 |
| **Ireland** | 5,7-5,9 | | 7,2 | | | 7,0 | | | 7,2 |
| **Italy, mainly certificates, but:** | 30,0 | | 22-30 | | 18-30 | | 20,0 | 36-49 | 22,0 |
| **Lithuania** | 6,4 | | 7,0 | | | | | | 5,8 |
| **Latvia** | according to formulas prescribed by the regulation | | | | | | | | |
| **Luxemburg** | 8,3 | | 12,5-14,5 | | 12,0-15,0 | | | 37-42 | 8,5-10,5 |
| **Malta** | grants | | | | | | | | |
| ***Netherlands (bonus)*** | | *4,5* | *6,2* | | *7,9* | | | *33,0* | |
| **Poland: mainly green certificates, but:** | mean electricity price of the previous year | | | | | | | | |
| **Portugal** | 4,6 | | 7,5-8,2 | | | | | 35-55 | 4,5-8,2 |
| **Romania** | tradable green certificate trading schemes with Price floor: 2,4 and Price cap: 4,2 | | | | | | | | |
| **Sweden** | tradable green certificates | | | | | | | | |
| **Slovenia (FIT)** | 5,9-6,2 | | 9,1-9,4 | | 12,1 | | 5,8 | 37,4 | 5,9-6,1 |
| ***Slovenia (premium)*** | *2,1-2,3* | | *5,4-5,7* | | *8,3* | | *2,1* | *33,7* | *2,2-2,4* |
| **Slovak Republic** | 8,4-9,7 | | 7,3 | 11,9 | 8,7-14,3 | | 12,2 | 27,9 | 6,6-13,9 |
| **United Kingdom** | tradable green certificates | | | | | | | | |

Figure 10: 2009 level of support schemes in Member States. Source: European Commission (2009b) and http://res-legal.d

|  | off shore | on shore | Solid Biomass | Liquid Bomass | Biogas | Landfill gas | Geothermal | PV | Small hydro |
|---|---|---|---|---|---|---|---|---|---|
| **Austria** | 7,6 | 7,6 | 13,4 | 9,3 | 14,1 | 3,5 | 7,3 | 38,0 | 4,7 |
| **Belgium (min prices, fed state)** | 9,9 | 5,0 | 2,0 | 2,0 | 2,0 | 2,0 | 2,0 | 15,0 | 5,0 |
| **Bulgaria** | 8,3 | 8,3 | 9,7 | 9,7 |  |  |  | 38,4 | 5,0 |
| **Cyprus** | 6,3 | 6,3 | 6,3 | 6,3 | 6,3 | 6,3 | 6,3 | 6,3 | 6,3 |
| **Czech Republic (FIT)** | 9,5 | 9,5 | 12,9 | 12,9 | 13,9 |  | 17,4 | 52,0 | 10,0 |
| **Czech Republic (premium)** | 7,2 | 7,2 | 7,9 | 7,9 | 9,0 |  | 13,0 | 48,9 | 5,4 |
| **Denmark (bonus)** | 3,4 | 3,4 | 2,0 | 2,0 |  |  |  |  |  |
| **Denmark (max payment)** | 7,7 |  |  |  | 10,0 | 8,1 | 8,1 | 8,1 | 8,1 |
| **Estonia (FIT)** | 7,3 | 7,3 | 7,3 | 7,3 | 7,3 | 7,3 | 7,3 | 7,3 | 7,3 |
| **Estonia (bonus)** | 5,4 | 5,4 | 5,4 | 5,4 | 5,4 | 5,4 | 5,4 | 5,4 | 5,4 |
| **Germany** | 8,3 | 7,5 | 15,2 | 15,2 | 15,2 | 9,1 | 21,0 | 37,5 | 8,1 |
| **Greece** | 8,2 | 8,2 | 7,9 | 7,9 | 7,9 | 7,9 | 7,9 | 45,3 | 7,9 |
| **Spain (fixed price)** | 7,3 | 7,3 | 13,8 | 13,8 | 13,8 |  | 6,9 | 35,5 | 7,8 |
| **Finland** |  |  | subsidies or tax refunds, feed-in tariffs for electricity produced from peat, but formula anavailable |  |  |  |  |  |  |
| **France** | 7,9 | 7,9 | 5,4 | 5,4 | 11,0 |  | 15,0 | 55,0 | 8,5 |
| **Hungary** | 8,0 | 8,0 | 6,9 | 6,9 | 6,9 | 6,9 | 6,9 | 10,5 | 6,0 |
| **Ireland** | 5,8 | 5,8 | 7,2 | 7,2 |  | 7,0 |  |  | 7,2 |
| **Italy, mainly certificates, but:** | 30,0 | 30,0 | 26,0 | 26,0 | 24,0 |  | 20,0 | 42,5 | 22,0 |
| **Lithuania** | 6,4 | 6,4 | 7,0 |  |  |  |  |  | 5,8 |
| **Latvia** | according to formulas prescribed by the regulation |  |  |  |  |  |  |  |  |
| **Luxemburg** | 8,3 | 8,3 | 13,5 | 13,5 | 13,5 |  |  | 39,5 | 9,5 |
| **Malta** | grants |  |  |  |  |  |  |  |  |
| **Netherlands (bonus)** |  | 4,5 | 6,2 |  | 7,9 |  |  | 33,0 |  |
| **Poland: mainly green certificates, but:** | mean electricity price of the previous year |  |  |  |  |  |  |  |  |
| **Portugal** | 4,6 | 4,6 | 7,9 | 7,9 |  |  |  | 45,0 | 6,4 |
| **Romania** | tradable green certificate trading schemes with Price floor: 2,4 and Price cap: 4,2 |  |  |  |  |  |  |  |  |
| **Sweden** | tradable green certificates |  |  |  |  |  |  |  |  |
| **Slovenia (FIT)** | 6,1 | 6,1 | 9,3 | 9,3 | 12,1 | 12,1 | 5,8 | 37,4 | 6,0 |
| **Slovenia (premium)** | 2,2 | 2,2 | 5,6 | 5,6 | 8,3 | 8,3 | 2,1 | 33,7 | 2,3 |
| **Slovak Republic** | 9,1 | 9,1 | 7,3 | 11,9 | 11,5 |  | 12,2 | 27,9 | 10,3 |
| **United Kingdom** | tradable green certificates |  |  |  |  |  |  |  |  |
| **Average FIT** | **8,8** | **8,5** | **9,9** | **10,1** | **11,3** | **7,0** | **10,3** | **31,8** | **8,0** |
| **Average premium** | **4,6** | **4,5** | **5,4** | **5,2** | **7,6** | **6,9** | **6,8** | **30,3** | **4,4** |

Figure 11: 2009 average levels of support schemes in Member States (Source: own calculations)

# 8 Technical annex

## 8.1 Determination of optimal renewable policies

### 8.1.1 Scenario 1: environmental externality only

The optimal feed-in tariff is determined by backward induction, that is, first by determining optimal production levels given the tariff and then by solving the regulator's welfare maximisation decision. Given the support scheme policy, firms in the renewable sector maximise the following profit function:

$$Max\pi^R = \sigma q_1 - G_1(q_1) \tag{25}$$

First order conditions of profit maximisation are, for both periods:

$$\sigma = G_1'(q_1) \tag{26}$$

Firms in the fossil fuel sector maximise the following profit function:

$$Max\pi^F = P_1 x_1 + (P_1 - \sigma) n q_1 - C(x_1) \tag{27}$$

They consider the electricity price and the add-on cost due to the support scheme as given. However, as the price of electricity is endogenous, fossil-fuel based power producers will be affected. First order conditions of profit maximisation are, for both periods:

$$P_1 = C'(x_1) \tag{28}$$

Second order conditions are always satisfied. Totally differentiating first order conditions of profit maximisation for both types of firms, we get:

$$\frac{dq_1}{d\sigma} = \frac{1}{G_1''(q_1)} > 0 \tag{29}$$

$$\frac{dx_1}{d\sigma} = \frac{-nP_1'(Q_1)}{G_1''(q_1)(P_1'(Q_1) - C''(x_1))} < 0 \tag{30}$$

In other words, an increase in the feed-in tariff will increase the renewable-based electricity production and decrease the fossil-fuel based electricity production. Maximising welfare with respect to the feed-in tariff gives:

$$(31)\quad \frac{dW_{Poll}}{d\sigma} = 0 \Leftrightarrow (P_1(Q_1) - C'(x_1) - D_1'(E_1)\mu)\frac{dx_1}{d\sigma} + n(P_1(Q_1) - G_1'(q_1))\frac{dq_1}{d\sigma} = 0$$

which, using first order conditions of profit maximisation, can be rearranged to give the optimal policy level.

### 8.1.2 Scenario 3: learning-by doing only

The profit maximisation problem for firms in the renewables sector is:

$$(32)\quad Max\pi^R = \sigma q_1 - G_1(q_1) + \delta[p_2 q_2 - G_2(q_2, L)]$$

First order conditions of profit maximisation are:

$$(33)\quad \sigma = G_1'(q_1) + \delta \frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1}$$

$$(34)\quad p_2 = \frac{\partial G_2}{\partial q_2}$$

Recall that firms in the renewable sector only consider their own impact on learning, not the one provided by production levels of the other firms in the sector. So, spillover aspects are not considered when firms maximise their profits. First-order conditions of profit maximisation in the fossil-fuel based sector are as usual. Note that the feed-in tariff affects prices in period 1 and 2 and therefore production decisions in both periods. Comparative statics are implicitly given by the following conditions:

$$\frac{dx_1}{d\sigma} = \frac{-nP_1'(Q_1)}{P_1'(Q_1) - C''(x_1)}\frac{dq_1}{d\sigma}$$

$$\frac{dx_2}{d\sigma} = \frac{-nP_2'(Q_2)}{P_2'(Q_2) - C''(x_2)}\frac{dq_2}{d\sigma}$$

$$\frac{dq_1}{d\sigma} = \frac{1 - \delta \frac{\partial G_2^2}{\partial L \partial q_2}\frac{dq_2}{d\sigma}}{G_1''(q_1) + \delta \frac{\partial G_2^2}{\partial L^2}}$$

$$\frac{dq_2}{d\sigma} = \frac{P_2'(Q_2)\frac{dx_2}{d\sigma} - \frac{\partial G_2^2}{\partial L \partial q_2}\frac{dq_1}{d\sigma}}{\frac{\partial G_2^2}{\partial q_2^2} - nP_2'(Q_2)}$$

Maximising welfare with respect to the feed-in tariff is given by:

$$\begin{aligned}(35)\qquad \frac{dW_{LBD}}{d\sigma} = 0 \Leftrightarrow (P_1(Q_1) - C'(x_1))\frac{dx_1}{d\sigma} + \delta(P_2(Q_2) - C'(x_2))\frac{dx_2}{d\sigma} \\ +n[P_1(Q_1) - G_1'(q_1) - \delta\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1} - \delta\rho(n-1)\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1}]\frac{dq_1}{d\sigma} \\ +\delta n(P_2(Q_2) - \frac{\partial G_2}{\partial q_2})\frac{dq_2}{d\sigma} = 0\end{aligned}$$

which, using the envelope theorem, can be simplified to obtain the optimal feed-in tariff.

### 8.1.3 Scenario 4: combining pollution and learning-by doing

Firms in the fossil-fuel based electricity sector maximise the following profit function:

$$(36)\qquad Max\pi^F = P_1x_1 + (P_1 - \sigma)nq_1 - C(x_1) - \tau\mu x_1$$

The first-order condition of profit maximisation is:

$$(37)\qquad P_1 = C'(x_1) + \tau$$

Maximising welfare with respect to the pollution tax supposes that:

$$\begin{aligned}(38)\qquad \frac{dW_{Poll+LBD}}{d\tau} = 0 \Leftrightarrow (P_1(Q_1) - C'(x_1) - D_1'(E_1)\mu)\frac{dx_1}{d\tau} \\ +\delta(P_2(Q_2) - C'(x_2))\frac{dx_2}{d\tau} + n[P_1(Q_1) - G_1'(q_1) - \delta\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1} - \delta\rho(n-1)\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1}]\frac{dq_1}{d\tau} \\ +\delta n(P_2(Q_2) - \frac{\partial G_2}{\partial q_2})\frac{dq_2}{d\tau} = 0\end{aligned}$$

Using the envelope theorem, we have:

$$\begin{aligned}(39)\qquad \frac{dW_{Poll+LBD}}{d\tau} = 0 \Leftrightarrow \mu(\tau - D_1'(E_1))\frac{dx_1}{d\tau} \\ +n[P_1(Q_1) - \sigma - \delta\rho(n-1)\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1}]\frac{dq_1}{d\tau} = 0\end{aligned}$$

Applying the same approach for the feed-in tariff, we have:

$$\frac{dW_{Poll+LBD}}{d\sigma} = 0 \tag{40}$$

$$\Leftrightarrow \mu(\tau - D_1'(E_1))\frac{dx_1}{d\sigma} + n[P_1(Q_1) - \sigma - \delta\rho(n-1)\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1}]\frac{dq_1}{d\sigma} = 0$$

The solution to this system of equations is to set equal to zero each one of the two terms in both equations. This gives the optimal levels of policy intervention.

### 8.1.4 Scenario 5: Combining learning-by doing and energy security

Welfare optimisation conditions would be:

$$\frac{dW_{ES+LBD}}{d\upsilon} = 0 \Leftrightarrow (P_1(Q_1) - C'(x_1) - \frac{\partial S_1}{\partial x_1})\frac{dx_1}{d\upsilon} \tag{41}$$

$$+\delta(P_2(Q_2) - C'(x_2))\frac{dx_2}{d\upsilon} + n[P_1(Q_1) - G_1'(q_1) - \delta\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1} - \delta\rho(n-1)\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1} - \frac{\partial S_1}{\partial q_1}]\frac{dq_1}{d\upsilon}$$

$$+\delta n(P_2(Q_2) - \frac{\partial G_2}{\partial q_2})\frac{dq_2}{d\upsilon} = 0$$

Using the envelope theorem, we have:

$$\frac{dW_{ES+LBD}}{d\upsilon} = 0 \tag{42}$$

$$\Leftrightarrow (\upsilon - \frac{\partial S_1}{\partial x_1})\frac{dx_1}{d\upsilon} + n[P_1(Q_1) - \sigma - \delta\rho(n-1)\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1} - \frac{\partial S_1}{\partial q_1}]\frac{dq_1}{d\upsilon} = 0$$

Applying the same approach for the feed-in tariff, we have:

$$\frac{dW_{ES+LBD}}{d\sigma} = 0 \tag{43}$$

$$\Leftrightarrow (\upsilon - \frac{\partial S_1}{\partial x_1})\frac{dx_1}{d\sigma} + n[P_1(Q_1) - \sigma - \delta\rho(n-1)\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1}]\frac{dq_1}{d\sigma} = 0$$

### 8.1.5 Scenario 6: Combining all three externalities

Using a tax rate on fossil fuel based electricity producers and a feed-in tariff, welfare optimisation conditions are given by:

(44) $$\frac{dW}{d\vartheta} = 0 \Leftrightarrow (P_1(Q_1) - C'(x_1) - D_1'(E_1)\mu - \frac{\partial S_1}{\partial x_1})\frac{dx_1}{d\vartheta}$$
$$+\delta(P_2(Q_2) - C'(x_2))\frac{dx_2}{d\vartheta} + n[P_1(Q_1) - G_1'(q_1) - \delta\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1} - \delta\rho(n-1)\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1} - \frac{\partial S_1}{\partial q_1}]\frac{dq_1}{d\vartheta}$$
$$+\delta n(P_2(Q_2) - \frac{\partial G_2}{\partial q_2})\frac{dq_2}{d\vartheta} = 0$$

Using the envelope theorem, we have:

(45)
$$\frac{dW_1}{d\vartheta} = 0 \Leftrightarrow (\vartheta - D_1'(E_1)\mu - \frac{\partial S_1}{\partial x_1})\frac{dx_1}{d\vartheta} + n[P_1(Q_1) - \sigma - \delta\rho(n-1)\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1} - \frac{\partial S_1}{\partial q_1}]\frac{dq_1}{d\vartheta} = 0$$

Applying the same approach for the feed-in tariff, we have:

(46) $$\frac{dW}{d\sigma} = 0 \Leftrightarrow (\vartheta - D_1'(E_1)\mu - \frac{\partial S_1}{\partial x_1})\frac{dx_1}{d\sigma} + n[P_1(Q_1) - \sigma - \delta\rho(n-1)\frac{\partial G_2}{\partial L}\frac{\partial L}{\partial q_1}]\frac{dq_1}{d\sigma} = 0$$

## 8.2 Numerical illustration

The objective of this section is to illustrate with a simple example the main theoretical results identified in section 3. Due to the overall simplicity of the approach, it cannot be used as an attempt to calibrate the model. In this section, any demand effect is ruled out. We assume that at the market price, electricity producers can sell as much electricity as they want, and that the feed-in tariff only implies a transfer between producers and consumers and thus there is no net effect on welfare. This has an important consequence: because the price of electricity (before feed-in tariffs) is exogenous, feed-in tariffs cannot influence the production decisions of fossil-fuel based power producers. Thus, in this case, no feed-in tariff can internalise the environmental externality. Therefore, we can directly move to the consideration of an optimal feed-in tariff in presence of learning by doing.

### 8.2.1 Determining optimal feed-in tariffs in presence of learning by doing

**Equations defining the model** First, let us introduce specific production cost functions, while recalling the learning rate equation: $C_1 = c\frac{x_1^2}{2}$, $C_2 = c\frac{x_2^2}{2}$, $G_1 = q_1^2$, $G_2 = \frac{q_2^2}{2} + \frac{1}{2}(q_2 - \frac{L}{\theta})^2$ and $L = q_1 + \rho(n-1)q_1$. Based on these production cost functions, and recalling that the underlying price of electricity is now exogenously given and equal to $m$, production levels of the fossil fuel sector are easily determined: $x_1 = \frac{m}{c}$ and $x_2 = \frac{m}{c}$. Production levels for the renewable sector are the following:

$$q_2 = \frac{m + \frac{L}{\theta}}{2} \tag{47}$$

$$q_1 = \frac{4\theta^2\sigma + m\theta\delta}{\delta + 8\theta^2 - \delta\rho + n\delta\rho} \tag{48}$$

Overall production levels are then given as follows: $Q_1 = x_1 + nq_1$ and $Q_2 = x_2 + nq_2$. The optimal welfare, taking account of the two periods, is such that:

$$W = mQ_1 - C_1 - nG_1 + \delta(mQ_2 - C_2 - nG_2) \tag{49}$$

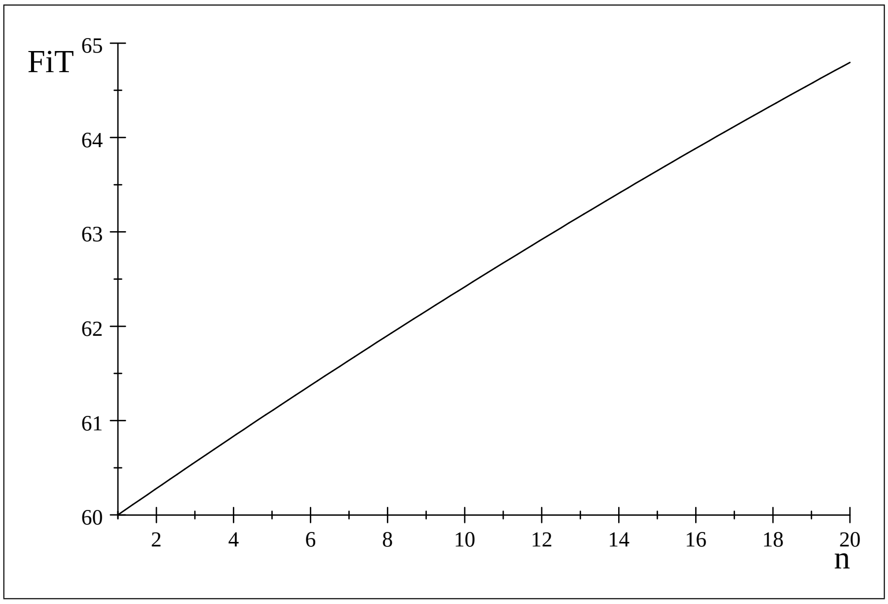
Welfare is optimised when the first derivative with respect to the feed in tariff $\sigma$ is equal to zero. In this context, the solution is:

$$\sigma_{LBD} = \frac{m\delta + 4m\theta^2 - m\delta\rho + mn\delta\rho - 2m\theta\delta\rho + 2mn\theta\delta\rho}{\delta + 4\theta^2 - 2\delta\rho + \delta\rho^2 + n^2\delta\rho^2 + 2n\delta\rho - 2n\delta\rho^2} \tag{50}$$

The optimal feed-in tariff depends on the electricity price, on the number of firms, on the discount parameter, on the influence of learning on future costs, and on the spillover rate. We note as well that the optimal feed-in tariff does not depend on production costs in the fossil-fuel based electricity sector. Some sensitivity analysis can be performed in order to check the robustness of the results.

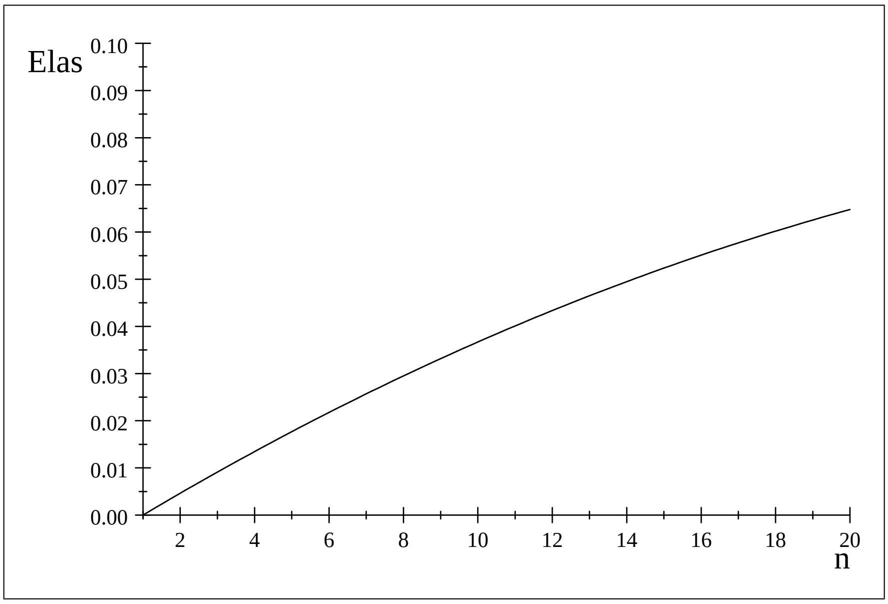
**Sensitivity analysis** By default, the following specific values are given to the parameters: $n = 10$, $c = 48$, $m = 60$, $\rho = 0.5$, $\theta = 50$ and $\delta = 0.95$. Given these parameter values, the optimal feed-in tariff is equal to: 62.418.

**Sensitivity as regards the number of renewable firms** $n$ The optimal tariff as a function of $n$ is presented in the following graph.



Optimal feed-in tariff as a function of the number of firms

If there is only one firm in the renewable industry, all learning effects are internalised and so there is no need for policy intervention. Thus, the optimal tariff is equal to the electricity price. As the number of firms increases, the spillover effects become more important and so the optimal tariff increases. The following graph presents the elasticity of the feed-in tariff to a change in the number of firms.

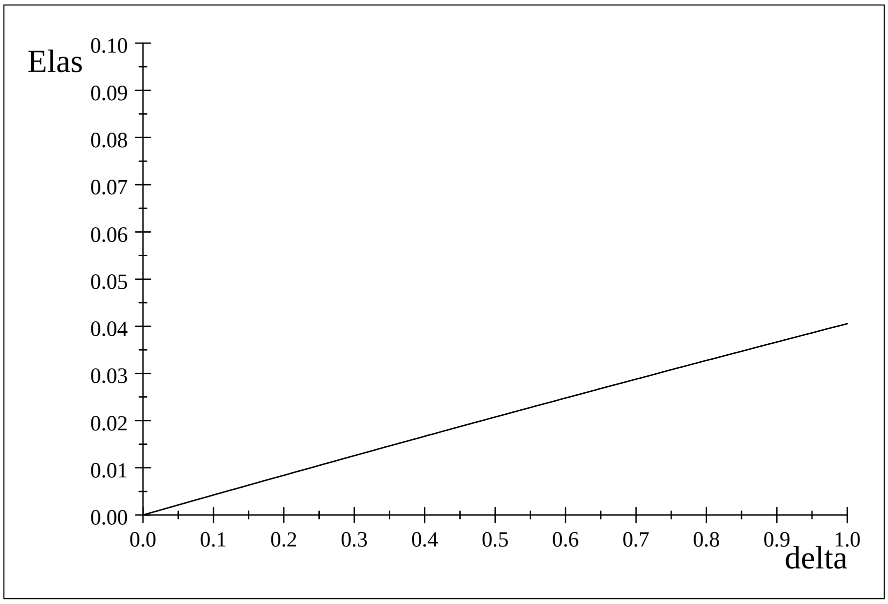


Elasticity of feed-in tariff to a change in the number of firms

As the number of firms increases, the optimal feed-in tariff becomes more elastic to a change in $n$. Intuitively, as $n$ increases, spillover effects become major issues, which forces the regulator to adjust all the more the optimal tariff to any change in $n$.

**Sensitivity as regards the spillover rate, $\rho$** Similar interpretations can be conducted as regards the spillover rate. Optimal feed-in tariffs increase with the spill-over rate, so as to increase the incentives for cost reductions. The variation in the elasticity of the feed-in tariff to a change in the spillover rate has the same shape than in the case of $n$. The intuition is identical to the one associated with a change in $n$.

**Sensitivity as regards the discount rate $\delta$** Similar results are obtained when looking at the influence of a change in $\delta$. The more the regulator also considers welfare in period 2, the higher the incentives to increase the feed-in tariff. The following graph indicates however that the optimal tariff is less sensitive to a change in $\delta$ than to a change in the other parameters of the model.



Elasticity of the feed-in tariff to a change in the discount rate

### 8.2.2 Determining optimal feed-in tariffs in presence of an energy security externality

**Equations defining the model** Most of the equations used in the previous simulations apply here. The only difference is the absence of learning-by doing but the presence of an energy security externality. To keep things comparable, we consider that there is no energy security risk in the second period. The energy security damage function is modelled as follows:

$$s_1 = \gamma(s - nq_1)^2 \tag{51}$$

where $s$ is an optimal volume of renewables exogenously given and $\gamma$ is the probability (or frequency) of the energy security damage. $\gamma = 0$ would signify that a sub-optimal level of renewables would not induce any energy security cost. $\gamma = 1$ would on the other hand create an energy security cost with certainty. The production level in the first period is given by the following equation: $q_1 = \frac{\sigma}{2}$. In the second period, it is equal to the electricity price. Welfare is given by the following equation:

$$W = mQ_1 - C_1 - nG_1 - s_1 + \delta(mQ_2 - C_2 - nG_2) \tag{52}$$

Welfare is optimised when the first derivative with respect to $\sigma$ is equal to zero. The solution is:

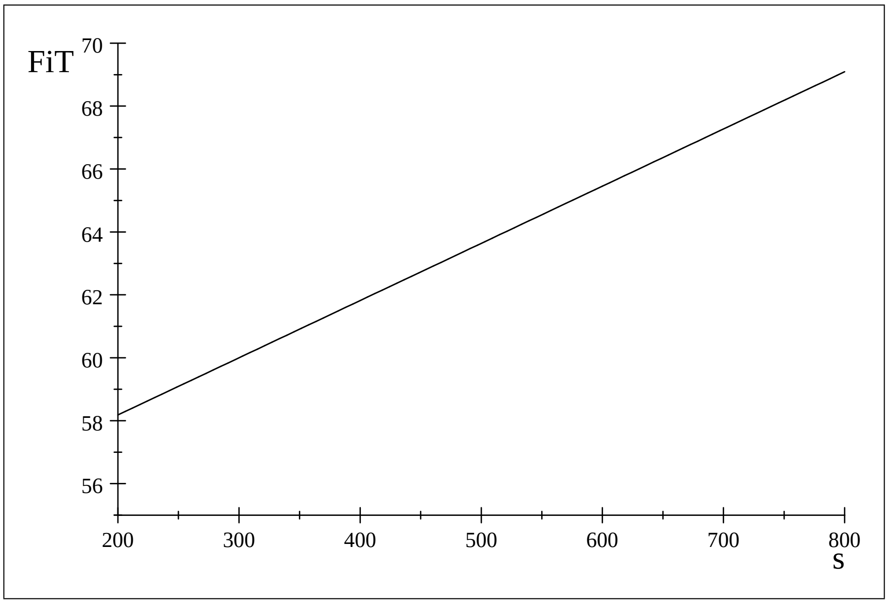
$$\sigma_{ES} = \frac{1}{n\gamma + 1}(m + 2s\gamma) \tag{53}$$

In the context of this model, the optimal feed-in tariff is equal to the electricity price when the optimal level of renewable production is 300. For an optimal level of renewables lower than this value, the optimal feed-in tariff will fall short of the electricity price, so as to reduce renewable energy production, and conversely. Assuming $\gamma = 0.01$ and $s = 400$, the optimal feed-in tariff is then equal to: 61.818

**Comparative statics** A change in $\gamma$ can increase or decrease the optimal feed-in tariffs, depending on the optimal level of renewable electricity. If the level of renewable electricity produced at the electricity market price is too low (resp. high) compared to the optimal level of renewables, then the optimal feed-in tariffs increases (resp. decreases) in $\gamma$. This is explained by the fact that the optimal feed-in tariff is higher (resp. lower) than the electricity price if the level of renewable electricity produced is initially too low (resp. high).

Clearly, an increase in the optimal level of renewable energy production has a non-ambiguous positive impact on the optimal feed-in tariff. The following graph presents the variation in the tariff as a function of $s$. This graph is determined assuming that $\gamma = 0.01$, that is, that the probability of an energy security damage is 1%.

$\sigma = \frac{1}{n\gamma+1}(m + 2s\gamma)$



Optimal feed-in tariff as a function of the optimal level of renewables

### 8.2.3 Determining optimal tariffs in presence of learning-by doing as well as energy security risk

**Optimal tariff** Welfare in this context takes account of learning-by doing effects in the renewable energy industry as well as the energy security issue. Welfare is optimised when the first derivative with respect to the control variable is equal to zero. The optimal tariff is then:

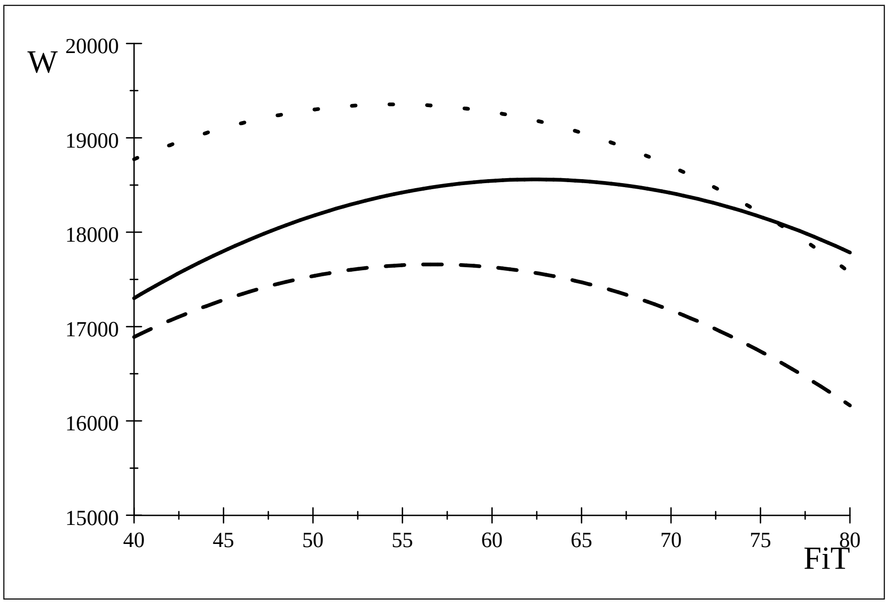
$$(54)\quad \sigma_{LBD+ES} = \frac{m\delta + 4m\theta^2 - m\delta\rho + 2s\gamma\delta + 8s\theta^2\gamma + mn\delta\rho}{\delta + 4\theta^2 - 2\delta\rho + \delta\rho^2 + n^2\delta\rho^2 + 2n\delta\rho + 4n\theta^2\gamma - 2n\delta\rho^2} - \frac{2m\theta\delta\rho + 2s\gamma\delta\rho + 2mn\theta\gamma\delta - 2mn\theta\delta\rho - 2ns\gamma\delta\rho}{\delta + 4\theta^2 - 2\delta\rho + \delta\rho^2 + n^2\delta\rho^2 + 2n\delta\rho + 4n\theta^2\gamma - 2n\delta\rho^2}$$

The comparative statics are not significantly modified compared to the situation where there was only one externality considered. Using the same parameter values as in the previous two sections, the optimal feed-in tariff is: 63.963. The two externalities reinforce each other, which increases the optimal feed-in tariff. In other words, if the regulator was to consider only one of these externalities, the production of renewables would be too low.

**Welfare comparison** The following graphs present the welfare considered previously for various optimal values $s$ of renewable electricity production. The dotted lines represent welfare when there is only an energy security externality, the black solid lines represent welfare in the presence of learning-by doing and the dashed lines represent welfare when combining the two externalities.

The black solid lines are clearly not affected by a change in $s$. It is shown however that in the other two scenarios, the optimal tariff increases as $s$ increases. Initially, the feed-in tariff had to be set relatively low so as to avoid too much production of renewables. As $s$ increases, renewable electricity is more and more valued, from an energy security point of view, and therefore the optimal tariff increases. Note that the optimal tariff in the presence of both externalities is always higher than the tariff with only the energy security externality. It is because all else being equal, there is always an incentive to push for a higher production of renewables in the first period so as to decrease production costs in the second period.

Finally, it is also important to note that whatever the context, welfare in the presence of two externalities and only one instrument to regulate them is always lower than welfare in the presence of a single externality. Even though it is not discussed here, the presence of a single externality may mean that the other externalities are already regulated by other policy instruments. In this case, this reinforces the argument for a combination of instruments in order to regulate the renewable-based electricity sector. Support schemes alone cannot optimally control for energy security risk, learning curve effects, as well as environmental damage.



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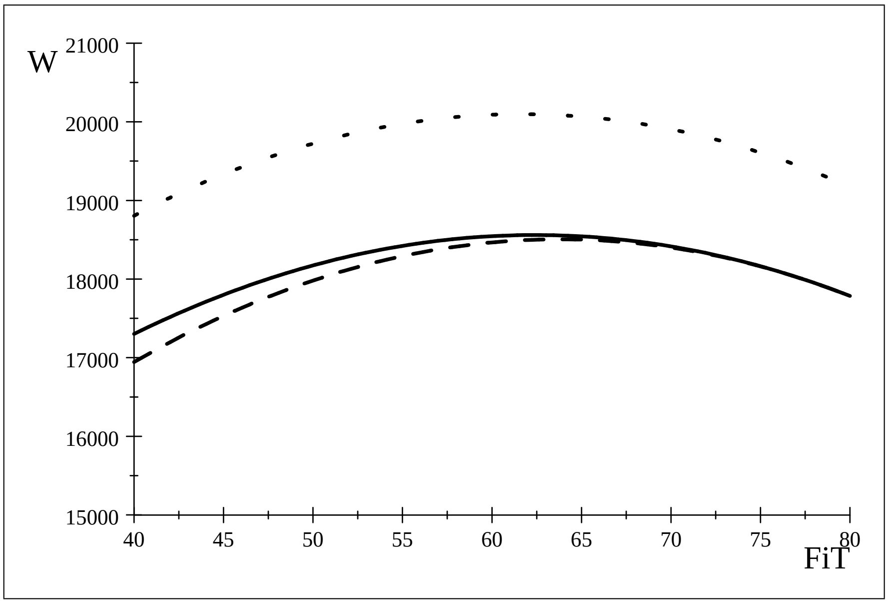
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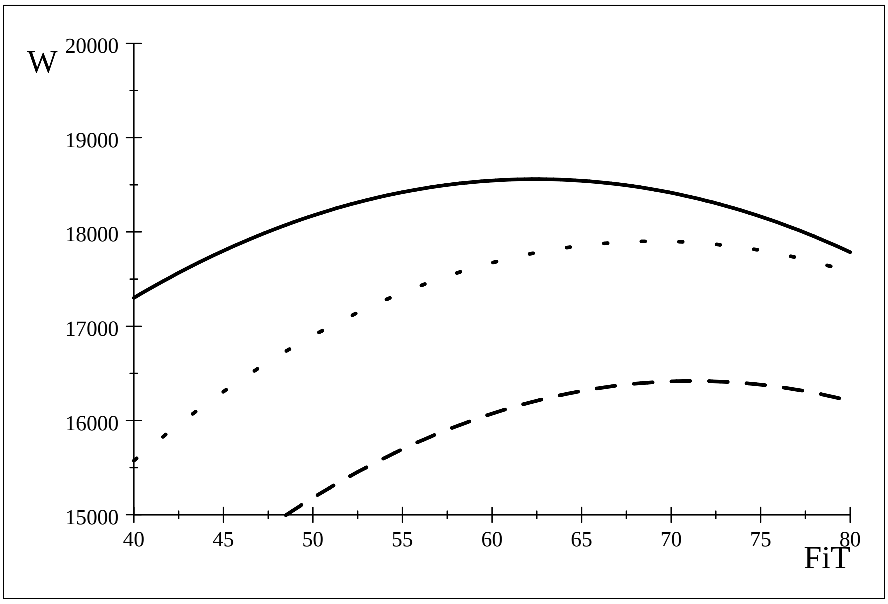
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