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Report on Work Package B-1 of the ETSAP Project "Integrating policy instruments into the TIMES Model"

The explicit modelling of support systems for renewable electricity in TIMES

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1. Introduction

Enhancing the use of renewable energy sources is considered as one of the major strategies in the combat against climate change. For the European Union, an ambitious goal of raising the share of renewable energies in gross final energy consumption to at least 20 % until 2020 has been established (cf. EC 2009). In this context, the electricity sector plays an essential role. According to the National Renewable Energy Action Plans, the contribution of renewables to total electricity generation should increase to 37 % by 2020 (cf. EC 2011). In order to reach this goal, by now some type of support system for renewable electricity has been implemented in every EU member state. As has already been highlighted in the *Report on Work Package A* of this project, a basic differentiation can be made between price-based (especially fixed feed-in tariffs (FIT)) and quantity-based measures (most importantly tradable green certificate schemes (TGC) and tendering procedures). In the European Union, a clear domination of feed-in tariffs or premiums is observable with 23 member countries using such a system. In Sweden, Poland and Romania quota obligations constitute the only promotion scheme for renewable electricity, while in the United Kingdom, Italy and Belgium both FIT and TGC systems are applied simultaneously (cf. de Jager et al. 2011, p. 28).

Support systems for renewable electricity have a significant impact on the long-term development of the energy system and should therefore be taken into account when conducting energy system analyses. The purpose of this report is to show how such systems can be explicitly integrated into the energy system model TIMES, such that their effects can be evaluated endogenously. Here, a focus is put on developing a methodology for the incorporation of feed-in tariffs, as these schemes are much more complex to model in an explicit manner than renewable quotas. In order to arrive at a modelling approach with high practical relevance, the German FIT system, which will be outlined in Chapter 2, is used as a basis. Chapter 3 then looks at the different steps of modelling FIT schemes, including the representation of the payment side, where both the basic approach to depict feed-in tariffs and special provisions of the German system are considered, and of the demand side, i.e. most importantly, the effects on end-use electricity prices and demand. In the following chapter, basic issues in the modelling of different types of quantity-based promotion systems for renewable electricity are highlighted.

On the basis of this methodological approach, various aspects regarding the promotion of renewable electricity can be examined. First of all, the most common support systems can be compared with respect to their impacts on the expansion of the different renewable energy sources in electricity production, on electricity prices, energy system costs etc. Apart from that, it can be analysed how changing scenario assumptions, for example on fossil energy prices or the role of nuclear energy, affect the development of renewable electricity under the different support systems. In addition, the flexible and explicit modelling approach provides the possibility to evaluate the interactions between different policy instruments, e.g. promotional measures for renewable electricity and emission trading systems.

2. Basis for the case study: The German feed-in tariff system

In Germany, a feed-in tariff scheme for renewable electricity, the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG), was introduced in the year 2000 with the aim to shift electricity generation on to a more sustainable pathway, to reduce the demand for fossil fuels as well as to foster renewable technologies. Basically, this system comprises three structural elements: (1) grid operators are obliged to connect any renewable generation unit to the grid and, if necessary, to strengthen and expand the existing grid system; (2) renewable electricity is to be granted priority purchase, transmission and distribution and (3) grid operators pay previously fixed tariffs to the renewable electricity producers.

These tariffs are set by the policymaker with regard to the development stage and the cost situation of the different renewable generation technologies. Thus, tariffs vary according to the source of renewable energy (hydro, wind, solar, biomass and geothermal energy), the capacity of the installation and, in the case of wind, the location of the project (cf. Table 2-1). For each installation, they are paid over a period of twenty years. In order to incentivise constant efforts to increase cost effectiveness, tariffs for newly installed plants are subject to an annual degression at a certain percentage. Major amendments to the FIT law have been conducted in 2004, 2009 and 2012 and were based on a scientific monitoring process. Their main objective consisted in adjusting the tariffs to the current competitive situation of the different renewable generation technologies and in avoiding situations of excess subsidisation. Most importantly, substantial cuts were executed in the case of solar photovoltaics with tariffs falling by more than half between 2009 and April of 2012.

With the last amendment at the beginning of 2012, efforts were also undertaken to increase the market orientation of the system. With the conventional system based on fixed tariffs remaining in place, renewable electricity producers can now choose alternatively a market premium, which they receive when selling the generated electricity directly to the market. This market premium is calculated as the difference between the fixed FITs for the respective installation and the average monthly wholesale electricity market price plus a so-called management fee which differs across the various forms of renewable energy. Even though this alternative scheme as enjoyed great demand in the first half of 2012, mainly for onshore wind farms, its future is uncertain, as more and more criticism is being voiced regarding the extra costs that especially the high management fees have caused (cf. Rostankowski et al. 2012).

The additional costs that transmission system operators incur due to the difference between FIT tariffs and wholesale electricity prices can be passed on to final electricity consumers. A special equalization scheme is laid down in the FIT law levelling the electricity generation and the costs under the FIT system between the four transmission grid operators in Germany. On this basis, the FIT surcharge, i.e. the additional levy on end-use electricity prices, is then calculated as (cf. Bode and Groscurth 2006):

*FIT surcharge = (Ø-FIT tariff – Ø-wholesale electricity price) * FIT quota*

Table 2-1: Tariffs of the German FIT system for 2012 (cf. Bundesgesetzblatt 2011)

	Tariffs (ct/kWh)	Bonus (ct/kWh)		Annual degression rate
Hydropower (including modernisation (≤ 5 MW) and extension of existing power plants)				
≤ 500 kW	12.7	-		1%
≤ 2 MW	8.3			
≤ 5 MW	6.3			
≤ 10 MW	5.5			
≤ 20 MW	5.3			
≤ 50 MW	4.2			
> 50 MW	3.4			
Landfill, sewage and mine gas				
≤ 500 kW_{el}	6.84 - 8.6	*Gas processing bonus* (upgrade to natural gas quality; ≤ 500 kW_{el}): 1 - 3 ct/kWh depending on rated output		1.5%
≤ 1 MW_{el}	5.89 - 6.84			
≤ 5 MW_{el}	4.93 - 5.89			
> 5 MW_{el}	3.98 (only mine gas)			
Biomass[a]				
		Substance tariff class I[b]	Substance tariff class II[b]	2% (only on basic tariffs and gas processing bonus)
≤ 150 kW_{el}	14.3	6	8	
≤ 500 kW_{el}	12.3		8 / 6[d]	
≤ 750 kW_{el}	11	5[c]		
≤ 5 MW_{el}		4[c]		
≤ 20 MW_{el}	6	-	-	
		Gas processing bonus (see above)		
Geothermal energy				
Independent of capacity	25	*Bonus for using petrothermal technology*: 5 ct/kWh		5%, starting in 2018
Wind power				
Onshore				
Initial tariff[e]	8.93	*System services bonus*[f] (until 2015): 0.48 ct/kWh; *Repowering bonus*[g]: 0.5 ct/kWh		1.5%
Basic tariff	4.87			
Offshore				
Initial tariff[h]	15	-		7%, starting in 2018
Basic tariff	3.5			
Photovoltaics[i]				
Rooftop installations				
≤ 10 kW	19.5	-		Flexible degression depending on market volume, ranging between -6% (if installed capacity in the previous year < 1000 MW) and 29% (if installed capacity in the previous year > 7500 MW)
≤ 40 kW[j]	18.5			
≤ 1 MW[j]	16.5			
≤ 10 MW	13.5			
Free-standing installations				
≤ 10 MW	13.5			

[a] Special tariffs are available for small manure installations (≤ 75 kW_{el}; 25 ct/kWh) and biow aste fermentation plants (16 ct/kWh if ≤ 500 kW_{el}; 14 ct/kWh if ≤ 20 Mw_{el}).

[b] Additional remuneration for substances listed in the Biomass Ordinance (BiomasseV) (cf. BMU 2011a)

[c] For plants w ith a capacity betw een 500 kW_{el} and 5 MW_{el} only 2.5 ct/kWh for electricity from bark or forest w aste w ood

[d] For plants w ith a capacity betw een 500 kW_{el} and 5 MW_{el} only 6 ct/kWh for electricity from manure

[e] The higher initial tariff is paid for the first five years. This period is extended by tw o months for each 0.75% by w hich the installation yield falls short of 150% of a previously defined reference yield.

[f] Bonus for w ind pow er plants that fulfill the requirements of the System Services Ordinance (cf. Bundesgesetzblatt 2009)

[g] Bonus for the replacement of existing w ind pow er plants (installed before 2002) on the same or an adjacent site

[h] The higher initial tariff is paid for the first 12 years. This period is extended by 0.5 months for each full nautical mile beyond 12 nautical miles that the installation is located from the shore and by 1.7 months for each full metre of w ater depth over 20 metres. Alternatively, operators of plants installed before 2018 can also opt for the "acceleration model", receiving a higher initial tariff of 19 ct/kWh for 8 years (plus the same extension based on the distance to shore and w ater depth as in the normal model).

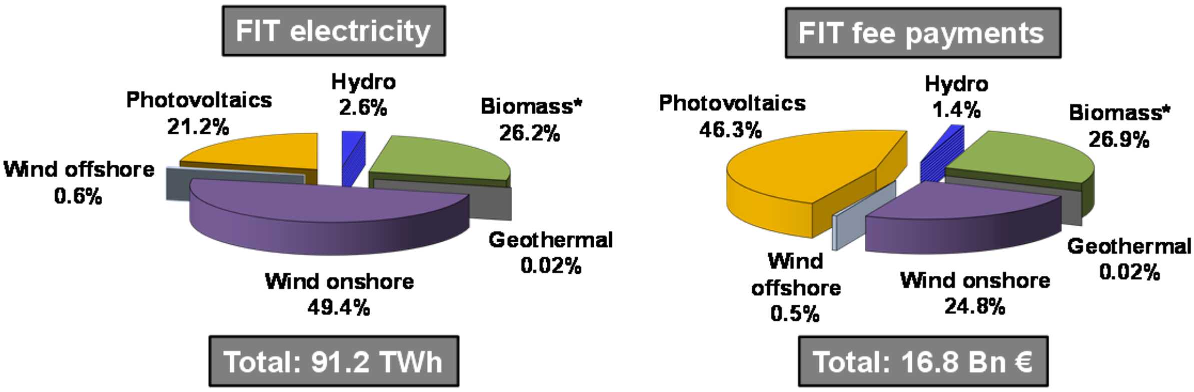
[i] Here, the tariffs according to the additional amendment on photovoltaics that have been decided in June 2012 and apply retroactively as of 1 April 2012 are reported (cf. BMU 2012a).

[j] For rooftop installations w ith a capacity betw een 10 kW and 1 MW a market integration model has been introduced: for these installations, only 90% of the electricity generated can be remunerated through the FIT system, w hile the rest must be used for ow n consumption or sold to the market.

Thus, the FIT surcharge in one year is obtained as the difference between the average FIT tariff (*Ø-FIT tariff*, across all renewable energy sources) and the average annual electricity price on the wholesale market (*Ø-wholesale electricity price*) multiplied by the *FIT quota*, i.e. the percentage share of electricity remunerated through the FIT system in total final electricity consumption.

Special provisions in form of a reduced FIT surcharge have been implemented for manufacturing enterprises and rail operators with comparatively high electricity consumption in order to prevent endangering their international or intermodal competitiveness. According to the amended FIT law, the following requirements need to be fulfilled in the case of manufacturing enterprises: (1) an electricity consumption of more than 1 GWh per annum, (2) a ratio of electricity costs to gross value added of more than 14 % and (3) a certified energy audit assessing energy consumption and the potentials for energy savings has been carried out. These companies then only pay the full FIT surcharge for the first GWh of consumption, 10 % of the regular charge for the consumption between 1 and 10 GWh, 1 % between 10 and 100 GWh and 0.05 ct/kWh for the share of electricity exceeding 100 GWh. Enterprises whose electricity demand is above 100 GWh and whose ratio of electricity costs to gross value added is more than 20 % only pay a FIT surcharge of 0.05 ct/kWh for their entire electricity consumption. The reduced surcharge of 0.05 ct/kWh also applies in the case of rail operators with an electricity demand of at least 10 GWh for the amount of electricity exceeding 10 % of the annual consumption. Apart from the rail operators, this regulation benefits mainly parts of the chemical, the paper, the iron and steel as well as the non-ferrous metal industry in Germany. In total, 73 TWh of final electricity consumption have been excluded from the regular FIT surcharge in 2011 (cf. BMU 2011b).

With the help of the feed-in tariffs, the share of renewable energies in the gross electricity consumption of Germany has increased from 6 % in 2000 to 20 % (122 TWh) in 2011 (cf. BMU 2012b). Within the FIT system, 91 TWh of renewable electricity have been remunerated in 2011 with fee payments amounting to 16.8 billion € and average tariffs ranging between 9.2 and 40.2 ct/kWh (cf. Figure 2-1). Given the wide spread in tariffs, considerable differences can be observed with respect to the contribution of the various renewable energy sources and the costs they entail for the system: while the share of solar photovoltaics in the total generation from FIT installations amounted to 21 % in 2011, almost half of the entire FIT payments went to solar photovoltaics. In contrast, onshore wind farms only accounted for a quarter of FIT payments while producing almost half of the electricity in the FIT system. The FIT surcharge has risen substantially in recent years from 0.2 ct/kWh in 2000 to 2.05 ct/kWh in 2010 and 3.59 ct/kWh in 2012. For the future, ambitious goals have been set regarding the expansion of renewable electricity generation in Germany. The aim is to increase the contribution of renewable energy to gross electricity consumption to 35 % in 2020, 50 % in 2030 and 80 % in 2050 (cf. BMU and BMWi 2011).



Average tariffs (ct/kWh)					
Wind onshore	9.2	Wind offshore	15.0	Geothermal	20.7
Hydro	9.6	Biomass*	18.9	Photovoltaics	40.2

*incl. gas from landfills, mines and sewage treatment plants

Figure 2-1: FIT electricity generation, fee payments and average tariffs in Germany in 2011 (own illustration based on ÜNB 2012)

3. Modelling of feed-in tariffs in TIMES

In the following chapter, a methodological approach on how to represent feed-in tariff systems for renewable electricity in the energy system model TIMES will be described. In former energy system analyses, the effects of feed-in tariffs have often only been taken into account in an indirect way by exogenously setting minimum volumes for the electricity produced from the different types of renewable energies through user constraints (cf. UBA (2009) and IER et al. (2010)). This, however, clearly reduces the flexibility of the model, as generally no changes in the electricity generation from renewable sources will occur when the scenario assumptions are altered. Moreover, the interaction with other types of policy instruments, as for example the European Emissions Trading Scheme (ETS), cannot be evaluated. Apart from that, the impact of the feed-in tariffs on retail electricity prices, as the additional costs of the tariff system are passed down to final consumers, is neglected when exogenously fixing the minimum generation from renewable energy.

Therefore, the aim of the methodology used in this report is to explicitly integrate the tariff system into TIMES. In this way, the competitive position of the various types of renewable energy technologies can be evaluated within the model and the development of electricity generation based on renewable energies is endogenously determined. In addition, the impact of the feed-in tariff system on electricity prices and electricity demand is taken into consideration by integrating the FIT surcharge into the model framework. Accordingly, the modelling approach is split up into two parts: firstly, it will be shown how the payment side (i.e. the tariffs) can be introduced into the model and secondly, the representation of the demand side (i.e. the FIT surcharge) will be outlined.

3.1. The payment side (1): The tariffs

It is often highlighted that FIT systems cannot be characterized as subsidies in the strict sense, due to the fact that they do not involve any payments from government units (cf. OECD 2007). From the point of view of the renewable plant operator, however, the tariffs can be understood as a subsidy, as they constitute a compensation for the renewable electricity generation above the market price. Hence, in the modelling approach the TIMES parameters which are already available to represent subsidies are used. In TIMES, subsidies are treated as payments from outside the system and therefore enter the objective function with a negative sign. In the case of feed-in tariffs, which can be interpreted as subsidies on the amount of electricity generated, the parameter *FLO_SUB*, describing a subsidy on a process flow, would be most appropriate.

At this point, however, attention needs to be called to a number of special features that the German FIT system exhibits and that have to be accounted for in the modelling approach:

- The tariffs are paid over a limited period of time (usually 20 years). As the technical lifetime of some renewable generation technologies exceeds this time span, the limitation of the payment period has to be explicitly specified within the model framework.

- According to the legal stipulations, the tariffs remain constant in nominal terms during the payment period resulting in a gradual decline in real terms. In the model, real monetary values are applied such that the reduction of tariffs due to inflation has to be considered when fixing the tariffs in the model.
- While the tariff level for a particular plant stays nominally constant throughout the payment period, each year tariffs are reduced for newly installed plants according to the degression rates in the FIT law. Thus, tariffs for new plants depend on their vintage year.

These characteristics are not specific to the German system, but are applied in most FIT systems throughout the European Union (cf. Ragwitz et al. 2012). The impact of the feed-in tariffs on the competitiveness of renewable generation technologies depends substantially on these features such that taking them into consideration in the model is essential for a realistic representation of the FIT system.

In order to integrate the annual degression of tariffs, the characteristics of the processes describing the different renewable electricity technologies need to be defined as dependent on their vintage year. In the default settings of TIMES, all process parameters are tied to the current model year, but by assigning the set *PRC_VINT* to a specific process all its parameters, including the tariffs, can be vintaged. It has to be mentioned, however, that using the vintaging option clearly increases the model size.

The representation of the other two important features, the limitation of the payment period and the tariff reductions caused by inflation, can be accomplished with the help of a *SHAPE* curve. This TIMES parameter establishes user-defined multiplication factors which are applied to age-dependent process parameters. Hence, for a specific renewable electricity plant built in a certain year the tariff would be paid in full height in the first year after construction (i.e. multiplication factor = 1). In the second year, tariffs (in real terms) are reduced by the annual inflation rate (i.e. multiplication factor = 1/1.023 with an annual inflation rate of 2.3 %). Thereby, inflation can be accounted for in each year of the payment period. The assumption on the future inflation rate can have significant implications on the development of the feed-in tariffs. This is highlighted in Figure 3-1 showing the *SHAPE* curve for different inflation rates. It becomes apparent that when assuming an average inflation rate of 2.3 %, after 20 years in real terms the tariffs only amount to about 65 % of the initial value stipulated in the FIT law. Consequently, tariffs do not only decrease on a year to year basis for newly installed plants because of degression, but tariffs also decline considerably for one specific plant due to inflation.

Apart from that, the *SHAPE* curve is also applied to include the limitation of the payment period into the model. If the lifetime of a plant exceeds 20 years, the *SHAPE* parameter is set to zero from the 21st year onwards. Furthermore, shaping of process parameters also makes it possible to model other changes in the tariff structure of one specific installation. For onshore and offshore wind energy, a differentiation is made between a high initial tariff, which is paid over a specific number of years, and a lower basic tariff for the rest of the payment period. In other cases, a certain bonus is only provided for a limited number of years. This drop in remuneration can be reflected in the *SHAPE* curve by using the ratio of the basic tariff (or the tariff without bonus) to the initial tariff (or the tariff with bonus) as multiplication factor.

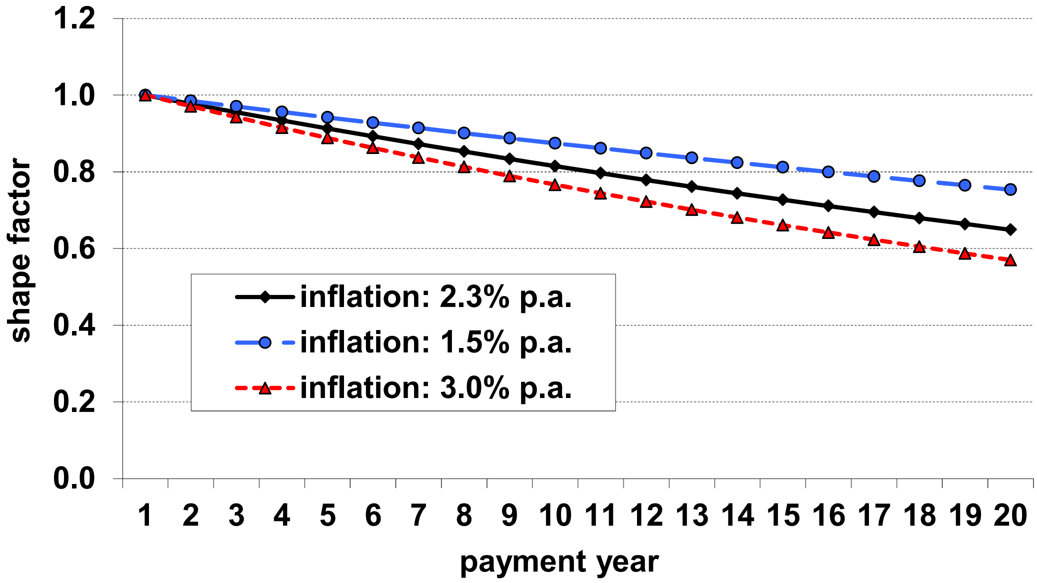


Figure 3-1: Development of the feed-in tariffs in real terms for one specific installation as a function of the inflation rate

Yet, introducing the TIMES parameter *SHAPE* also complicates the modelling process further. At the time that this methodology was developed, the *SHAPE* parameter could not be used in combination with the parameter *FLO_SUB*. To assign a *SHAPE* curve to *FLO_SUB*, the parameter *FLO_SUBX* would be necessary which would have to be established in the TIMES model code. Therefore, an alternative approach is created based on the parameter *NCAP_FSUB*. This parameter specifies a subsidy on the installed capacity of a process and can be used in combination with *NCAP_FSUBX*, whose parameter value is a discrete number indicating which *SHAPE* curve should be applied to the tariffs defined in *NCAP_FSUB*. This requires converting the assessment basis of the feed-in tariffs from the amount of electricity generated (ct/kWh) to the installed capacity (ct/kW) based on the availability factors laid down in the input data. Moreover, to avoid additional capacity being installed (to receive the subsidies) without it being used for electricity production, the availability is laid down as fixed (instead of using an upper bound). At the same time, using fixed availability factors seems to reproduce the situation in reality quite well, as with the fixed tariffs the electricity supply from renewables is usually not oriented on the market situation but on the availability of renewable sources.

So on the whole, with the help of the parameter *NCAP_FSUB* in combination with *PRC_VINT* and *SHAPE* a modelling technique can be developed to integrate feed-in tariffs explicitly into the framework of the energy system model TIMES. A general example of the implementation in the TIMES modelling language is given in the Annex. To illustrate how the tariffs affect energy system costs, a simple representation of the objective function, including the subsidies on the installed capacity of renewable technologies, is given in the following[1]:

$$
Min!\sum_{t=1}^{T}\beta_t\cdot\left[\begin{array}{ll}
\sum_{p}\sum_{s\in prc\_ts_{r,p,s}} cst\_act_{r,t,p}\cdot d_t\cdot ACT_{r.t,p,s} & \rightarrow \text{Variable operation costs}\\
+\sum_{p}\left(cst\_fom_{r,t,p}\cdot d_t\cdot\left(cap\_pasti_{r,t,p}+\sum_{v\in vint_{r,t,p}} NCAP_{r,v,p}+NCAP_{r,t,p}\right)\right) & \rightarrow \text{Fixed operation costs}\\
-\sum_{p\in fit_p}\left(\boldsymbol{sub\_fom_{r,t,p}\cdot d_t\cdot NCAP_{r,t,p}}\right) & \rightarrow \textbf{Subsidies on capacity}\\
+\sum_{p}\left(\sum_{v\in vint_{r,t,p}} cst\_inv_{r,v,p}\cdot NCAP_{r,v,p}+cst\_inv_{r,t,p}\cdot NCAP_{r,t,p}\right) & \rightarrow \text{Investment costs}\\
+\sum_{(r,p,c)\in imp_{r,p,c}}\sum_{s\in prc\_ts_{r,p,s}} price_{r,t,p,c,s}\cdot d_t\cdot IMP_{r,t,p,c,s} & \rightarrow \text{Import costs}\\
-\sum_{(r,p,c)\in exp_{r,p,c}}\sum_{s\in prc\_ts_{r,p,s}} price_{r,t,p,c,s}\cdot d_t\cdot EXP_{r,t,p,c,s} & \rightarrow \text{Export revenues}\\
+\sum_{p\in out_{r,p,c}\cup p\in in_{r,p,c}}\sum_{s\in prc\_ts_{r,p,s}} cst\_flo_{r,t,p,c,s}\cdot d_t\cdot FLO_{r,t,p,c,s} & \rightarrow \text{Flow costs}
\end{array}\right] \qquad (1)
$$

With:

$\boldsymbol{c}$	commodity index,
$\boldsymbol{exp}_{r,p,c}$	index for export processes *p* of commodity *c* to region *r*,
$\boldsymbol{fit}_{p}$	index for processes *p* in the feed-in tariff system,
$\boldsymbol{imp}_{r,p,c}$	index for import processes *p* of commodity *c* from region *r*,
$\boldsymbol{in}_{r,p,c}$	index for process *p* with commodity *c* as input,
$\boldsymbol{out}_{r,p,c}$	index for process *p* with commodity *c* as output,
$\boldsymbol{p}$	process index,
$\boldsymbol{r}$	region index,
$\boldsymbol{t}$	index for the current time period from 1,..,*T*,
$\boldsymbol{s}$	time-slice index,
$\boldsymbol{v}$	index for the vintage year,
$\boldsymbol{vint}_{r,t,p}$	index for vintage periods of processes *p* that have been installed in a previous period *v* but still exist in time period *t*,
$\boldsymbol{ACT}_{r,t,p,s}$	activity variable,
$\boldsymbol{cap\_pasti}_{r,t,p}$	past capacity,
$\boldsymbol{cst\_act}_{r,t,p}$	specific variable operation cost,
$\boldsymbol{cst\_flo}_{r,t,p,c,s}$	specific flow cost,
$\boldsymbol{cst\_fom}_{r,t,p}$	specific fixed operation and maintenance cost,
$\boldsymbol{cst\_inv}_{r,t,p}$	specific investment cost,
$\boldsymbol{cst\_inv}_{r,v,p}$	specific investment cost,
$\boldsymbol{d}_{t}$	duration of time period *t*,
$\boldsymbol{EXP}_{r,t,p,c,s}$	export variable (for export process *p* of commodity *c* to region *r* in time period *t* and time slice *s*),

[1] The description of variables used for the objective function can be found in the List of Variables at the beginning of this report.

$\boldsymbol{FLO_{r,t,p,c,s}}$	flow variable,
$\boldsymbol{IMP_{r,t,p,c,s}}$	import variable (for import process *p* of commodity *c* from region *r* in time period *t* and time slice *s*),
$\boldsymbol{NCAP_{r,t,p}}$	new investment variable (of process *p* in time period *t*),
$\boldsymbol{NCAP_{r,v,p}}$	new investment variable (of process *p* in vintage period *v*),
$\boldsymbol{prc\_ts_{r,p,s}}$	time slices *s* of process *p*,
$\boldsymbol{price_{r,t,p,c,s}}$	specific import and export cost (for process *p* and commodity *c* from/to region *r* in time period *t* and time slice *s*),
$\boldsymbol{sub\_fom_{r,t,p}}$	specific subsidy on installed capacity and
$\boldsymbol{\beta_t}$	discount rate in time period *t* to the base year.

Hence, energy system costs are reduced when adding the subsidies for renewable electricity. Further insights on how the modelling approach functions can be gained by looking at a simplified version of the dual equation of the activity variable of a renewable electricity generation process (assuming that the activity is defined as the electricity output) (cf. Remme 2006, pp. 136f):

$$ACT_{r,v,t,p,s}: \quad act\_\mathrm{cost}\_d_{r,t,p,s} + \frac{1}{\eta_{r,t,p,s}} \cdot combal_{r,t,FUEL,s} + \boldsymbol{capact_{r,v,t,p,s}} - \zeta_{r,v,t,p,FW,UP,s} \cdot floshrup_{r,v,t,p,FW,s} - actup_{r,t,p,s} \geq combal_{r,t,ELC,s} \quad (2)$$

With:

$\boldsymbol{act\_cost\_d_{r,t,p,s}}$	discounted variable operation cost (without fuel cost),
$\boldsymbol{actup_{r,t,p,s}}$	dual variable of an upper bound on the activity variable (economic rent),
$\boldsymbol{capact_{r,v,t,p,s}}$	dual variable of the capacity-activity constraint,
$\boldsymbol{combal_{r,t,ELC,s}}$	dual variable of the commodity balance of the output electricity (*ELC*),
$\boldsymbol{combal_{r,t,FUEL,s}}$	dual variable of the commodity balance of the fuel input (*FUEL*),
$\boldsymbol{floshrup_{r,v,t,p,FW,s}}$	for CHP plants: dual variable of the constraint on the maximum share of heat generation in total electricity and heat generation,
$\boldsymbol{\eta_{r,t,p,s}}$	activity-based efficiency of converting the input flow (*FUEL*) into the output flow (*ELC*) and
$\boldsymbol{\zeta_{r,v,t,p,FW,UP,s}}$	for CHP plants: maximum share of heat generation in total electricity and heat generation.

The dual equation of the activity of an electricity generation process contains all cost components which need to be covered by the electricity price. The electricity price (right-hand side of equation (2)) is calculated as the dual variable (i.e. the shadow price) of the commodity balance of electricity output. Thus, when the left-hand side of equation (2) is larger than the electricity price, the technology is not competitive and the activity of the process will be zero. For an activity level above zero, the left-hand and right-hand side of equation (2) need to be equal, meaning that the electricity price covers all cost components of the activity of the process. For example, if generation costs (represented by the first three terms in equation (2)) of a renewable technology are lower than the electricity price, this technology will be applied up to its full potential for the respective model period. In this example, the potential is limited by an upper bound on the activity of the process. Hence, the shadow price of this constraint (negative value) represents the economic rent associated with electricity generation with this technology.

When modelling the FIT system with *NCAP_FSUB*, the fixed operation and maintenance costs of the respective installations are lowered, rendering them more competitive when compared to conventional generation technologies. In equation (2) this is reflected in a decrease in the capacity related cost which are included in the variable $capact_{r,v,t,p,s}$, representing the dual variable of the capacity-activity constraint, i.e. in the case of a power plant the part of the electricity price that is needed to cover fixed operation and investments costs (cf. Remme et al. 2009). Consequently, it is decided endogenously through the optimization mechanism which processes for electricity production will be invested in.

However, the modelling approach with *NCAP_FSUB* also has its limitations. The conversion of tariffs from *FLO_SUB* to *NCAP_FSUB* is based on the condition that there is a fixed ratio between electricity generated and installed capacity. This is the case for electricity-only plants and combined heat and power (CHP) plants for which the ratio between heat and power generation is fixed. The conversion is not possible, though, for CHP installations with a flexible power to heat ratio. Consequently, for this type of CHP technology it is unavoidable to put the subsidy directly on electricity generation with the help of *FLO_SUB*. Yet, this makes it impossible to integrate the annual degression of tariffs, the tariff reduction due to inflation and the limitation of the payment period with the help of the parameters *PRC_VINT* and *SHAPE*. In order to still guarantee a realistic representation of the FIT system, it is therefore necessary to introduce for each renewable CHP technology with flexible power to heat ratio one process for each model period that can only be installed in the respective model period. This process then receives the average tariff (in real terms) for each model period for the following 20 years, taking into account the annual degression and inflation rates. It is apparent that this technique entails the implementation of a large number of additional processes, such that its application is limited to CHP plants with a flexible heat to power ratio. As an overview, the modelling approaches for different types of electricity generation technologies are outlined in Figure 3-4.

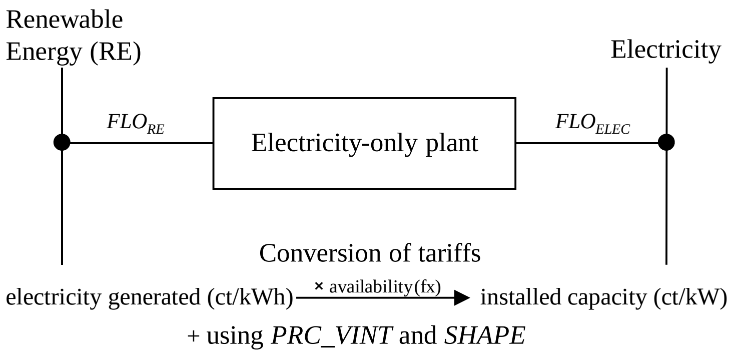


Figure 3-2: Modelling approach to integrate feed-in tariffs in TIMES in the case of an electricity-only plant

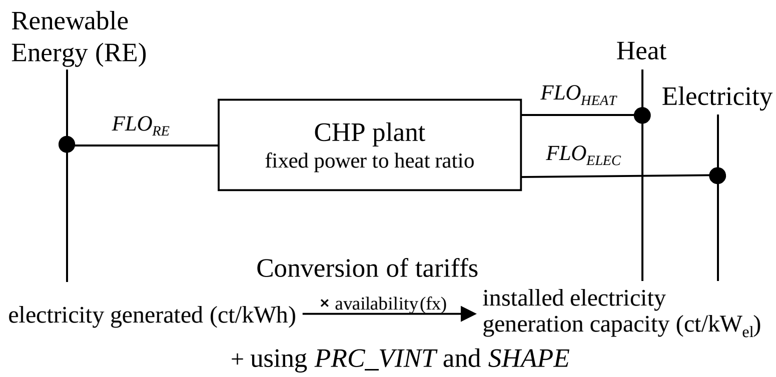


Figure 3-3: Modelling approach to integrate feed-in tariffs in TIMES in the case of a CHP plant with fixed power to heat ratio

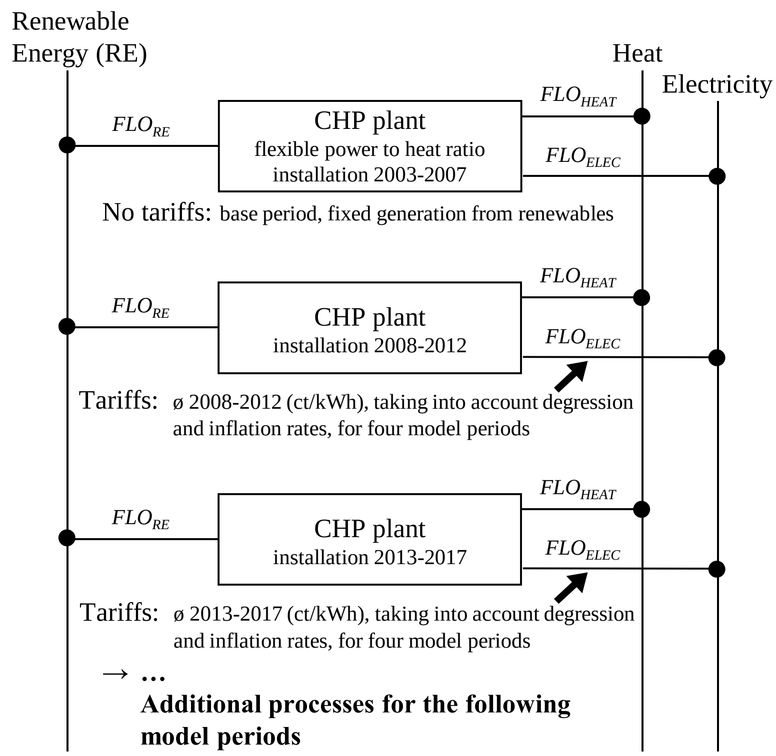


Figure 3-4: Modelling approach to integrate feed-in tariffs in TIMES in the case of a CHP plant with flexible power to heat ratio

3.2. The payment side (2): Special provisions in the German FIT system

Apart from the regular tariffs for new installations, FIT systems usually contain a number of special provisions that need to be taken into account in the modelling approach. In the case of the German FIT law, this concerns the modernization of existing hydropower plants, the re-powering of onshore wind farms and the flexible degression scheme for solar photovoltaics. Moreover, when trying to evaluate the impacts of feed-in tariffs on the energy system, other factors that might influence the expansion of renewable electricity generation should be taken into consideration. In the analysis at hand, the focus is laid on tax incentives for solar PV rooftop installations.

Modernization of hydropower plants

Hydropower has been utilized for electricity production in Germany for several decades and the potential has already been exploited almost entirely. Furthermore, stringent ecological requirements have to be met when installing new hydropower plants (Kaltschmitt et al. 2006). Therefore, more attention is put on the modernization and reactivation of existing power plants and since 2004, the German FIT scheme contains special tariffs for modernized hydropower installations. According to the amended FIT law from 2012, existing hydropower plants are entitled to tariff payments (at the same level as new installations) if the installed or potential capacity is raised or if technical facilities to reduce output by remote means are implemented. In the case of an installed capacity of up to 5 MW, total electricity generation is remunerated, while for installations with more than 5 MW tariffs are only paid for the share of electricity that can be attributed to the increase in capacity. The costs of modernization are set at 1000 €/kW (cf. Kaltschmitt et al. 2006; Staiß et al. 2007) and it is assumed that the modernization entails an increment in installed capacity of 5 % (cf. BMU 2011c).

When integrating this special tariff rule into the model, it has to be kept in mind that operators of existing hydropower plants have two options: either to keep operating in the same manner - thereby avoiding additional costs but also forfeiting tariff payments - or to carry out modernization activities and enter the FIT system. In TIMES, the modernization option is introduced with the help of an additional process subsequent to the original process representing the existing hydropower plant (cf. Figure 3-5).

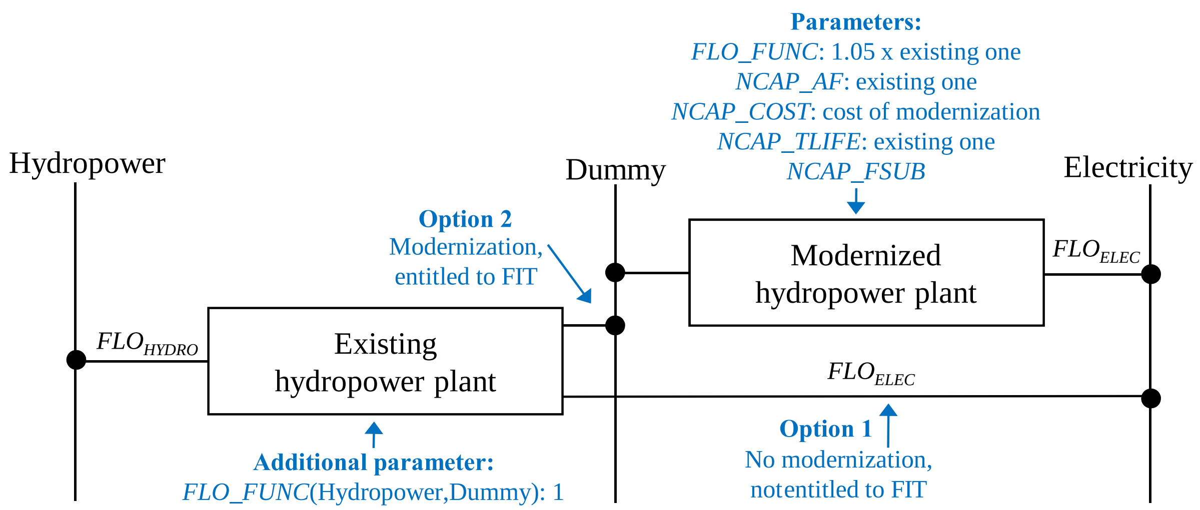


Figure 3-5: Modelling approach for modernized hydropower plants in TIMES

This process contains the cost of modernization as well as the feed-in tariffs (using *NCAP_FSUB*). As the modernization process is bound to the existing power plant through its output, the increase in installed capacity is modelled with the help of the parameter *FLO_FUNC*, usually used to specify the efficiency of a process. In general, for hydropower plants *FLO_FUNC* (describing the relation between hydropower input and electricity output) is fixed to 1. When setting *FLO_FUNC* to 1.05 in the case of the modernization process and defining the activity through the process output, the capacity (and activity) of the process is automatically raised by 5 %. The availability factor (parameter *NCAP_AF*) and the technical lifetime (parameter *NCAP_TLIFE*) for the modernization process are taken from the existing hydropower plant.

Repowering of onshore wind farms

Besides the regulations for the modernization of hydropower plants, the German FIT law contains another special provision related to existing installations of a renewable generation technology: the repowering bonus for onshore wind power plants. Hence, a similar procedure is chosen to incorporate this tariff option into the model.

Repowering describes the replacement of older and smaller wind turbines with new and more powerful ones. Especially in areas with favorable wind conditions near the coast the potential for electricity generation from onshore wind has already been exhausted to a great extent, such that the repowering option will play a crucial role in further increasing the wind power capacity in Germany. Apart from that, the impact on the landscape is reduced, as a smaller number of wind turbines is needed for the same amount of electricity generation, and improvements in terms of grid integration are expected (cf. BMU 2007).

Therefore, in the German FIT law from 2012 a bonus of 0.5 ct/kWh in addition to the higher initial tariff for onshore wind power is provided for repowering installations if they satisfy the following conditions: (1) the replaced turbines were commissioned before 2002 and (2) the installed capacity of the repowering plants is at least twice the capacity of the replaced ones. In the model, the relatively conservative assumption is chosen that repowering leads to a doubling of installed capacity (in accordance with BMU (2007) and Rehfeldt and Gerdes (2005)). With respect to the investment costs of repowering plants, it has to be taken into account that these plants can make use of the already existing infrastructure of the replaced installations. Thus, it is assumed that in the case of repowering, the infrastructure related costs (site development, foundations, grid connection, etc.) only amount to 20 % of the investment costs of the actual wind turbine, as compared to 30 % for wind power plants in previously undeveloped locations (cf. Rehfeldt and Gerdes 2005).

As it was the case for the modernization of hydropower plants, the modelling procedure for the representation of repowering is based on the different courses of action the operator of the existing onshore wind power plant can choose. His first option would be to operate the existing plant until the end of its lifetime without replacing it. Alternatively, he could replace it before the end of its lifetime with a more powerful, new turbine. Here, the residual value of the existing installation plus the expected revenues (minus operating costs) for the remaining lifetime need to be taken into consideration. If the plant was installed after 1999, this includes FIT payments. A third option consists in a replacement at the end of the lifetime of the existing turbine. It has to be noted that while the modernization of hydropower plants constituted an alteration to an existing plant which keeps operating, repowering implies the definite replacement of an existing installation. This renders the modelling approach more complex. The different steps that are necessary to integrate repowering of onshore wind power plants into the model are illustrated in Figure 3-6.

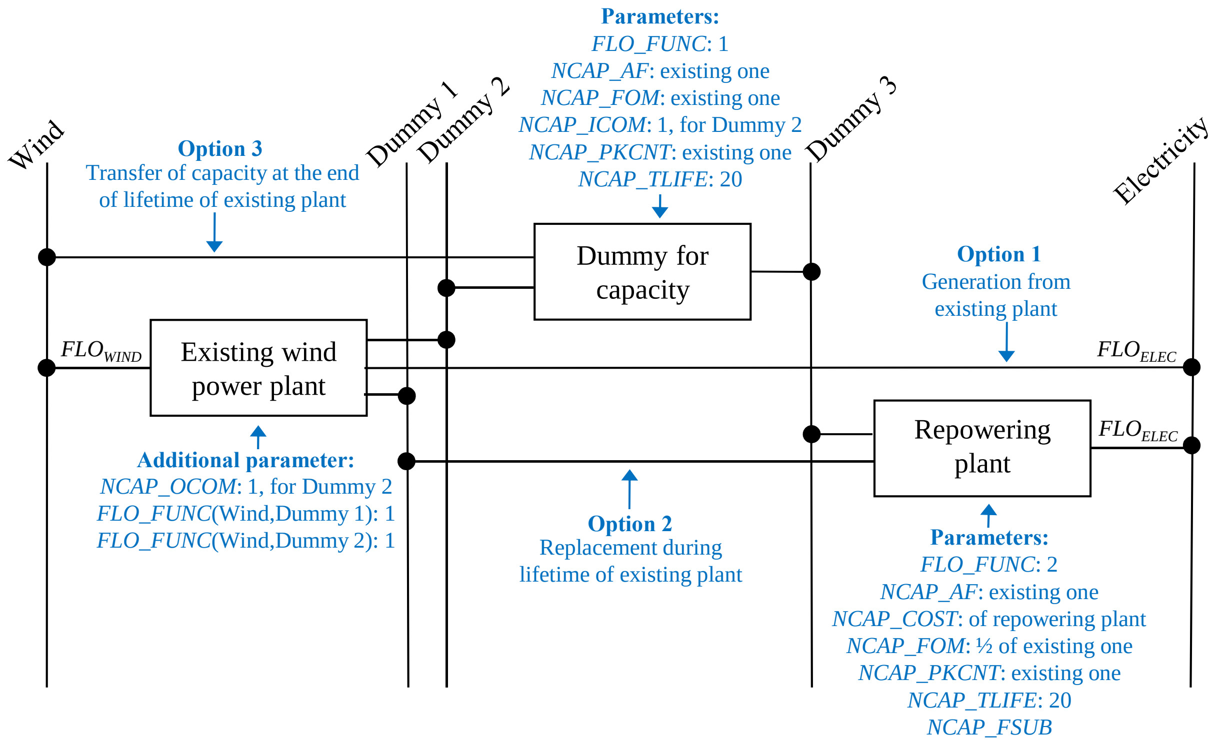


Figure 3-6: Modelling approach for the repowering of existing onshore wind farms in TIMES

First of all, a process representing the repowering plant needs to be added comprising the investment and operating costs as well as the feed-in tariffs (including the repowering bonus). This process is coupled with the existing wind power plant through a dummy commodity ("Dummy 1"). The doubling of installed capacity is again defined via the parameter *FLO_FUNC*. Other specifications, like the availability factor and the amount of capacity contributing to the peak (parameter *NCAP_PKCNT*), are adopted from the existing plant and the lifetime is fixed to 20 years (as is the case with all wind turbines in the model). Hence, with this configuration the replacement of the existing turbine during its lifetime can be modelled. It has to be pointed out that in the model the process for the existing plant will still be used giving rise to fixed operating and maintenance costs such that on the repowering process (which has double capacity) only half of the specific operating cost is put to keep the total amount correct. However, with only "Dummy 1" as input the repowering plant would no longer function once the existing plant reaches the end of its lifetime. Therefore, an additional process ("Dummy for capacity") is introduced which provides the input commodity ("Dummy 3") for the repowering plant after the existing one has been put out of operation. This process has wind power as an input so it can operate independently of the existing plant. Most importantly, the capacity of this process is bound to the decommissioned capacity of the existing wind turbine. This is achieved with the help of the parameters *NCAP_OCOM* and *NCAP_ICOM*. By assigning *NCAP_OCOM* to the existing wind turbine process, it specifies the amount of a commodity (here "Dummy 2") which is released during the decommissioning of the process. This commodity is then required to install capacity of the process "Dummy for capacity" to which *NCAP_ICOM* is allocated. In this way, the capacity of the dummy process (and also of the repowering plant) is limited by the capacity of the existing plants that go out of operation. Thus, also the third option - replacement at the end of lifetime – can be accounted for in the modelling approach.

Flexible degression for solar photovoltaics

Photovoltaic systems have experienced a period of very dynamic growth in recent years in Germany with an increase in installed capacity from 76 MW_p in 2000 to 24.8 GW_p in 2011 (cf. BMU 2012b). This was fuelled by relatively high feed-in tariffs and a significant drop in investment costs for PV modules (cf. BSW-Solar 2012). Consequently, in addition to a number of substantial tariff cuts, the German government has introduced in 2010 a flexible degression scheme for solar photovoltaics where the annual decline in tariffs depends on the actual market growth. In the current version of the FIT law (including the additional amendment from June 2012), an extension of the solar PV capacity between 2500 and 3500 MW_p per annum has been established as the target value which is associated with a monthly degression rate of 1 % (resulting in 11.4 % p.a.). If the actual annual investments fall below or exceed this "extension corridor", the degression rate is adjusted accordingly resulting in potential rates between -6.2 % and 28.9 % per year (cf. Table 3-1). Furthermore, it has been decided that the total amount of solar PV capacity that will be remunerated through the FIT system is limited to 52 GW_p.

This flexible tariff scheme can be taken into account in the model by implementing one process for each of the degression steps. These processes all represent the same type of photovoltaic system (i.e. have the same economic and technical features), but they receive different tariffs depending on the degression rate. With the help of user constraints, the increase in installed capacity per model period is then restricted to the corresponding maximum value for the respective degression step. In addition, one more PV process is added which is not included in the FIT system. In this way, an additional user constraint can be put on the other PV processes participating in the tariff system (10 per type of solar PV system) in order to limit the total amount of capacity that is entitled to funding to 52 GW_p. This modelling approach exhibits one slight drawback. While in reality there is only one tariff level for all photovoltaic installations, in the model in each time period the capacity limits for each process would be exhausted consecutively according to their degression rate. This issue can, however, be rectified within the iterative process of several successive model runs, which will be necessary anyway for the calculation of the FIT surcharge (cf. Chapter 3.3). In the first model run, the different degression steps will be taken into account resulting in investments in new PV installations at different degression levels (provided that photovoltaic systems are competitive in the FIT system). In the second model run, the highest degression level that is reached in each model period will be applied to all solar PV processes.

Table 3-1: Flexible degression rates for solar photovoltaics according to the German FIT law from 2012 (own illustration based on BMU 2012a)

Annual extension	Monthly degression	Annual degression
> 7500 MW_p	2.8 %	28.9 %
> 6500 MW_p	2.5 %	26.2 %
> 5500 MW_p	2.2 %	23.4 %
> 4500 MW_p	1.8 %	19.6 %
> 3500 MW_p	1.4 %	15.6 %
Extension corridor: 2500 – 3500 MW	**1 %**	**11.4 %**
< 2500 MW_p	0.75 %	8.6 %
< 2000 MW_p	0.5 %	5.8 %
< 1500 MW_p	0 %	0 %
< 1000 MW_p	-0.5 %	-6.2 %

Tax incentives for solar PV rooftop installations

While it is certain that the substantial growth rates for solar photovoltaics can be mainly attributed to the high tariff level, other factors that might have influenced investments should be taken into consideration. In this context, the case of solar PV systems is of particular interest as the typical investor differs clearly when compared with the other renewable energy sources. It can be observed that photovoltaic rooftop systems in Germany are usually installed by private households, farmers or small businesses. These investors benefit from a number of incentives which are generally not available to large-scale investors.

First of all, for the financing of photovoltaic installations, soft loans, currently with interest rates between 1 % and 6 %, are available through the government-owned bank *Kreditanstalt für Wiederaufbau* (cf. KfW 2012). In the model, this is captured by applying a lower discount rate of 5 % to PV rooftop systems, as compared to 7 % for all other renewable electricity generation technologies.

Moreover, the German Income Tax Act (EStG, cf. Bundesgesetzblatt 2009b) contains a number of special rules concerning the depreciation of photovoltaic installations. Generally, solar PV systems are written off on a straight-line basis over a period of 20 years. Private tax payers and small businesses (with operating assets of up to 235000 €) then have the option to use an investment deduction (cf. § 7g (1) EStG) allowing them to depreciate off the balance sheet a maximum of 40 % of the planned acquisition costs. In addition, on the residual value a special depreciation of in total 20 % in the year of the installation and the following four years can be applied (cf. § 7g (5) EStG). Hence, on the whole it is possible to depreciate up to 55 % of the investment costs of a photovoltaic system in the year it is installed.

In order to be able to incorporate these special depreciation rules in the modelling approach, the effect such tax incentives might have on the investment decision needs to be analysed.

The benefit of an accelerated depreciation can be found in the tax deferral effect, as taxable income in the first year(s) is reduced at the price of a higher taxable income in future years. Due to the time value of money, this results in a positive interest effect (cf. Ostertag et al. 2000). For the case at hand, this can be illustrated by calculating and comparing the net present value of future tax savings for the following two cases: (1) the solar PV installation (assumed value of 50000 €) is depreciated on a straight-line basis only; (2) in addition to the straight-line basis depreciation, the investment deduction of 40 % and the special depreciation of 20 % are applied in the first year (to the same solar PV installation). In the first case, the net present value of the annual depreciation amounts adds up to 32700 €, as compared to 42200 € in the second case (calculated with a discount rate of 5 %). Assuming an average income tax rate of 25 %, the respective net present values of future tax savings then amount to 8200 € and 10600 €. Thus, in the present example, making use of special depreciation options can increase the net present value of tax savings by 2400 €, i.e. almost 5 % of the assumed installation price of 50000 €. This percentage share increases slightly in the case of a cheaper installation price, and vice versa.

Integrating such fiscal incentives into an energy system model is fairly difficult as repercussions on the income situation of households and other economic agents, which might influence their investment decisions, cannot be taken into consideration. In the methodological approach at hand, the effect is approximated by assuming a reduction in investment costs for solar PV rooftop installations by 5 %.

3.3. The demand side: The FIT surcharge

Given the fact that renewable electricity generation technologies are generally not yet competitive when compared to conventional technologies, feed-in tariffs need to be significantly higher than current wholesale electricity prices entailing additional costs in electricity generation and changes in electricity prices. A differentiation needs to be made between the impact of FIT systems on wholesale and on retail electricity prices.

As far as wholesale electricity prices are concerned, it has been observed that promoting renewable electricity can have a dampening effect on the price level – referred to as the merit-order effect (cf. Sensfuß et al. 2008). This mechanism is illustrated in Figure 3-7. The wholesale electricity price is determined as the intersection between the electricity demand and supply curve (also called merit-order curve). This means that the price is set by the (variable) generation costs of the marginal unit which is needed to cover demand. With increased support for renewable electricity, which exhibits low variable generation costs, the most costly part of the conventional generation is driven out of the market. This entails a movement of the merit-order curve to the right and a reduction in wholesale electricity prices.

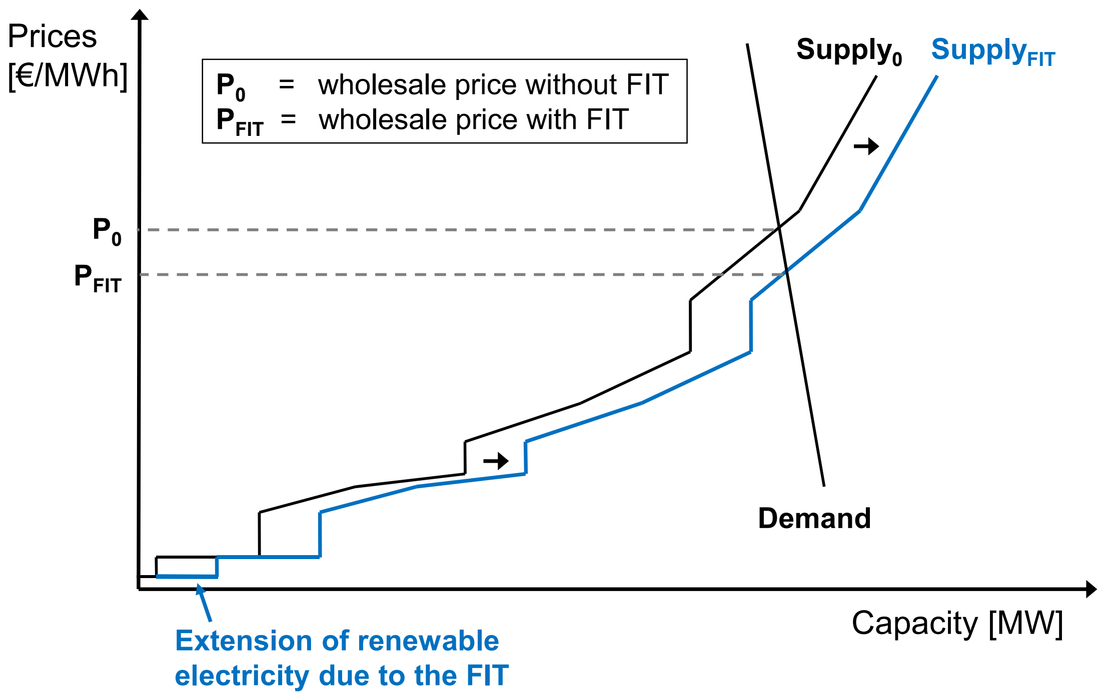


Figure 3-7: Illustration of the merit-order effect of renewable electricity generation (own illustration based on Teske and Schmidt 2008)

A clearly different picture arises for retail electricity prices. They can be expected to increase after the introduction of an FIT system, as grid operators are allowed to pass on the additional costs of the system to final electricity consumer via the FIT surcharge. Rising electricity prices are likely to lead to adjustment reactions in the end-use sectors – either in the form of a decline in demand for electricity services, the purchase of more efficient appliances or the substitution with alternative energy carriers (e.g. less heating with electricity, changes in manufacturing processes). These effects need to be taken into account in the modelling approach by incorporating the FIT surcharge into the model. When using the parameters *NCAP_FSUB* and *FLO_SUB* to model the feed-in tariffs, the source of funding lies outside of the system boundaries of the model. Hence, energy system costs are even reduced in comparison to a scenario without FIT scheme in place.

The FIT surcharge can be calculated according to the equation on page 2 as the difference between the average FIT tariff and the average wholesale electricity price multiplied by the share of FIT electricity in total electricity consumption. Once this term is established, it can be assigned to final electricity consumption in the model with the help of the parameter *FLO_COST*. However, at this stage of the modelling approach, a number of problems arise. First of all, it is apparent that the various components of the FIT surcharge depend themselves on the model results. The aggregate sum of tariff payments can be directly determined within the model by adding an additional output commodity to all FIT processes whose output equals the total amount of FIT payments made for this process (modelled with the parameters *FLO_FUNC*, *FLO_FUNCX* and the same *SHAPE* curves that have been used for the tariffs). There is, though, no linear relationship between the total sum of tariff payments and electricity consumption that would allow to directly link them within the model. Furthermore, it has to be kept in mind that the optimization approach of energy system models always conducts a simultaneous cost minimization over the entire system. Consequently, if tariff payments and the FIT surcharge are directly coupled in the model, they offset each other and the expansion of renewable electricity generation based on the FIT system ceases completely.

That is why an alternative approach to integrate the FIT surcharge into the model is chosen. This comprises a number of consecutive model runs (cf. Figure 3-8). In the first model run, only the payment side, i.e. the tariffs, are introduced into the model and the development of electricity generation based on renewables is determined endogenously. From the results of this model run, the FIT surcharge can be calculated and incorporated in the model. Here, the difference in FIT surcharge between “normal” and “privileged” (electricity-intensive manufacturing enterprises and rail operators) end-users is also accounted for. Thus, in the second model run, both the effects on the payment side and the demand side are represented making it possible to evaluate the impacts of the FIT surcharge on electricity prices and consumption.

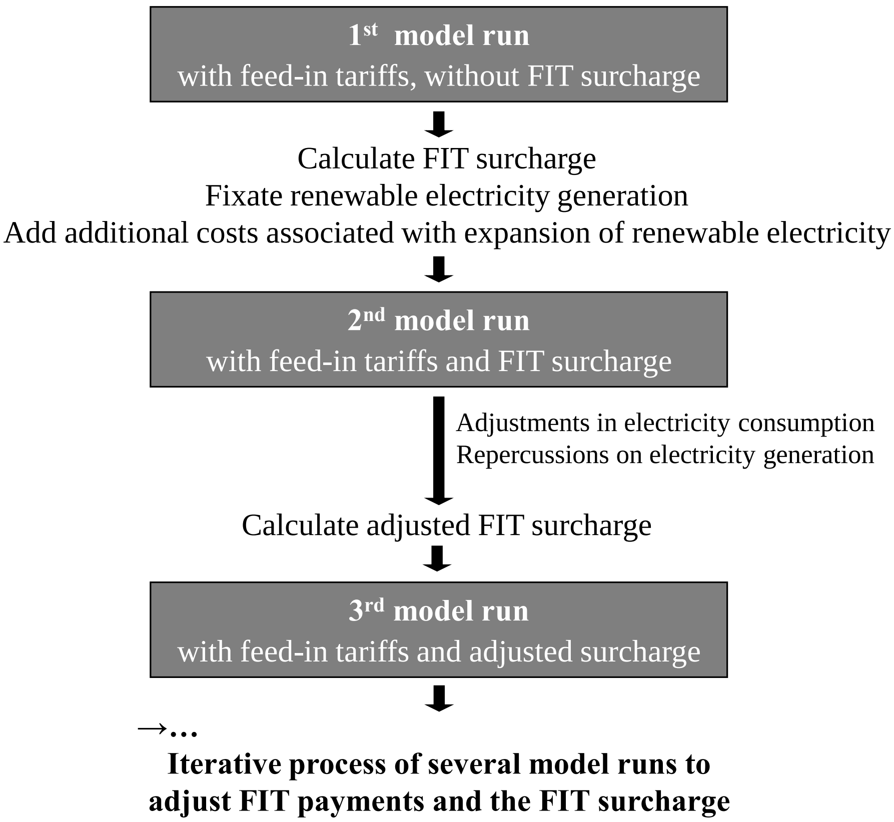


Figure 3-8: Modelling approach to integrate the FIT surcharge in TIMES

In addition, in this model run electricity generation from renewables is fixated, as changes on the demand side should have no effect on renewable electricity generation when receiving fixed tariffs. An added advantage of using subsequent model runs consists in the possibility of implementing additional cost terms in the model that should not influence the extension of renewable electricity. For example, the costs for grid expansion, which will be necessary as more and more decentralised renewable technologies enter the market, should be included in the model. At the same time, these costs should not affect the development of renewable electricity generation, since in reality they do not play any role in the investment decision of renewable plant operators. Therefore, grid expansion costs are only added to the model after the generation from renewable sources is fixated.

Now it has to be taken into consideration that introducing the FIT surcharge in the second model run clearly modifies the model results in terms of electricity consumption as well as electricity generation. Hence, the components of the FIT surcharge themselves will change. As a consequence, an iterative process of several model runs is required in order to adjust the FIT payments and the FIT surcharge to one another. The iteration is ended when the surcharge (in ct/kWh) no longer changes in its second decimal place from one model run to the other.

In addition, it has to be pointed out that after calculating the FIT surcharge from the model, some additional factors are accounted for before reporting the actual development of the surcharge. First of all, the option of direct marketing is considered which is expected to reduce the FIT surcharge in the long-term. Instead of choosing the feed-in tariffs, plant operators may also sell the generated electricity directly to the market with the possibility of entering and exiting the FIT scheme on a monthly basis. When computing the FIT surcharge, it is assumed that the direct marketing option is chosen if wholesale electricity prices exceed the tariff level for a specific plant (calculated on the seasonal level). Apart from that, in the model the FIT system is only implemented from 2008 onwards, whereas when the actual FIT surcharge is calculated the payments for plants that have been installed between the years 2000 and 2007 need to be incorporated. Here, an extrapolation of the statistical values based on ÜNB (2009) has been carried out.

4. Modelling of quantity-based support schemes in TIMES

Tradable green certificate schemes

In the discussion on the optimal way of promoting renewable energy sources in electricity generation, feed-in tariff systems are usually contrasted with tradable green certificate schemes (TGC). Here, electricity utilities or grid operators are obliged to cover a certain quota of electricity generation or capacity with renewable energies. In addition, a market for green certificates, representing a certain amount of renewable electricity generation or capacity, is implemented where renewable producers can sell certificates to the obligated electricity suppliers. Thus, while FIT systems establish the price for renewable electricity, TGC schemes address the quantity of renewable generation.

That is why modelling such quota-based schemes in energy system models is much more straightforward than it was the case with fixed feed-in tariffs. Target values for relative shares of renewable energies in electricity generation can be easily integrated in the model with the help of user-defined constraints (making use of the parameter *UC_FLO* in the case of a quota on electricity generation). As it would be the case in the trading system for green certificates, in the optimization process the cheapest generation options to fulfil the quota are chosen. The shadow price of such a user constraint is equivalent to the difference between the generation costs of the technologies covered by the quota and the market price and can therefore be interpreted as the certificate price in the trading system. The effect of the TGC system on electricity generation cost can be illustrated by looking at the dual equation of the activity variable of both a renewable (cf. equation (3)) and a conventional (cf. equation (4)) generation process. It becomes apparent that generation costs of conventional plants (outside of the quota) increase by the costs that arise from the purchase of green certificates (cost term equal to the certificate price multiplied by the quota), while generation costs of renewable plants decrease through the selling of certificates (cost term equal to the certificate price multiplied by the factor 1-quota).

$$
\begin{aligned}
ACT_{r,v,t,p,s}: \quad & act\_\mathrm{cost}\_d_{r,t,p,s} + \frac{1}{\eta_{r,t,p,s}} \cdot combal_{r,t,FUEL,s} + capact_{r,v,t,p,s} - \\
& \zeta_{r,v,t,p,FW,UP,s} \cdot floshrup_{r,v,t,p,FW,s} - actup_{r,t,p,s} - \boldsymbol{q_{r,t}} \cdot \left(\boldsymbol{1 - quota_{r,t}}\right) \geq combal_{r,t,ELC,s}
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
ACT_{r,v,t,p,s}: \quad & act\_\mathrm{cost}\_d_{r,t,p,s} + \frac{1}{\eta_{r,t,p,s}} \cdot combal_{r,t,FUEL,s} + capact_{r,v,t,p,s} - \\
& \zeta_{r,v,t,p,FW,UP,s} \cdot floshrup_{r,v,t,p,FW,s} - actup_{r,t,p,s} + \boldsymbol{q_{r,t}} \cdot \boldsymbol{quota_{r,t}} \geq combal_{r,t,ELC,s}
\end{aligned} \tag{4}
$$

With:

$\boldsymbol{q_{r,t}}$	dual variable of the quota on renewable electricity generation (equal to the certificate price in the TGC system)
$\boldsymbol{quota_{r,t}}$	quota for the electricity generation from renewable energies

In this context, an important difference between using relative and absolute bounds to model the expansion of renewable electricity needs to be highlighted. When generation from renewable energies is forced into the model by specifying absolute minimum quantities, the dual variable of such a constraint enters the dual equation of the activity variable of the renewable generation process (cf. equation (5)) to reduce the left-hand side such that it is fulfilled with equality (cf. Remme et al. 2009). This shadow price can be interpreted as the subsidy that would be needed to make the respective technology competitive. Consequently, electricity prices are not affected in this case, as the additional costs of renewable technologies are accounted for by the shadow price of the constraint. Energy system costs would still rise due to the higher generation cost in renewable plants, but it is assumed that the required subsidies are funded from outside the energy system and therefore do not raise the electricity price. In contrast, when fixing a relative quota for the renewable share in electricity generation, the additional costs are directly reflected in an increase in the electricity price (cf. Remme 2006, pp. 131ff). Hence, by using relative bounds to model a TGC system, the effect on electricity prices is directly included in the model.

$$ACT_{r,v,t,p,s}: \quad act\_\mathrm{cost}\_d_{r,t,p,s} + \frac{1}{\eta_{r,t,p,s}} \cdot combal_{r,t,FUEL,s} + capact_{r,v,t,p,s} - \zeta_{r,v,t,p,FW,UP,s} \cdot floshrup_{r,v,t,p,FW,s} - actup_{r,t,p,s} - \boldsymbol{actlo_{r,t,p,s}} \geq combal_{r,t,ELC,s} \tag{5}$$

With:

$\boldsymbol{actlo_{r,t,p,s}}$ dual variable of a lower bound on the activity variable (reduced cost),

Different types of quota systems can be evaluated with this modelling approach. Here, the most important differentiation can be made between technology-unspecific systems, where a uniform certificate price for all types of renewable energies is established, and technology-specific systems, where for each renewable energy carrier a separate quota is defined resulting in reduced trading possibilities and distinct certificate prices.

Tendering procedures

Another important promotional instrument for renewable electricity are tendering procedures, assigning previously specified quantities of renewable capacity to producers through a bidding process. The generators with the lowest prices then receive long-term contracts to supply electricity at the established bidding price. Such systems have been applied in some European countries, like for example France, Ireland, Denmark and the United Kingdom, for large-scale projects mainly in the area of wind energy. Usually, tendering schemes are technology- or even project-specific.

When modelling tendering procedures it needs to be taken into consideration that the determination of the quantity of renewable capacity that is to be allotted through the bidding process is based entirely on a political decision. Hence, the minimum quantities for the respective model periods can be specified exogenously and put in the model by way of user constraints. Furthermore, differentiations in the modelling approach arise when specifying the source of financing for the difference between the bidding price and the wholesale electricity price. Generally, two options can be distinguished: the extra costs are either covered by a levy on end-use electricity prices or through general government funds.

In the first case, the use of relative bounds on the capacity of renewable generation processes would be convenient to model the tendering scheme. In this way, the effect on end-use electricity prices would be directly captured in the model. Just as it was the case with TGC schemes, the shadow price of the relative constraint can be interpreted as the difference between the bidding price determined in the tendering procedure and the wholesale electricity price. Thus, the generation costs of the renewable technologies covered by the tender decrease by this price difference multiplied with (1-quota) (cf. equation (3)), while the generation costs of generation processes outside of the quota increase by the difference between the bidding and the wholesale electricity price multiplied by the quota (cf. equation (4)).

If the funding for the tendering schemes is provided through general government funds, i.e. from outside the energy system, the modelling approach can be based on absolute lower bounds on the different types of renewable capacity. The shadow price of such a constraint reflects the subsidy that would be needed to induce an additional unit of investment in the respective technology. Here, generation costs of processes not included in the tender are not affected by the tendering scheme and therefore the additional costs of the support system are not funded through end-use electricity prices.

5. Conclusion

After ambitious goals for the expansion of renewable energies have been set in Europe, an intense debate regarding the optimal way of reaching these targets has emerged. In electricity generation, usually two main instruments are contrasted – fixed feed-in tariffs and tradable green certificate schemes, while currently less emphasis is put on tendering procedures. Energy system models like TIMES provide the possibility to evaluate the impacts of such policy instruments on the development of the energy system in a quantitative way taking into consideration all repercussions both on the supply and the demand side.

In this report, a methodological approach to explicitly model different types of support systems for renewable electricity in TIMES has been developed. Given the fact that price-based measures like feed-in tariffs are much more complex to represent, the main emphasis of this study lay on the integration of FIT schemes into the modelling framework. In this context, it is of particular importance to account both for the effects on the payment side and the demand side. On the payment side, the feed-in tariffs need to be implemented with the help of model parameters for subsidies such that the actual regulations are reflected in a realistic manner and the extension of renewable electricity generation can be determined endogenously within the model. Furthermore, most FIT laws contain a number of special provisions, e.g. for the modernization or replacement of existing plants, that should also be included in the modelling approach. On the demand side, the FIT surcharge needs to be model in order to be able to analyse the impacts of the FIT system on electricity prices and electricity demand. Finally, an iterative process is needed to adjust the effects on the payment and demand side to one another. In comparison, the modelling of TGC schemes and tenders is much less complicated based on the application of user constraints to specify relative bounds on the renewable share in electricity generation.

The main advantage of modelling instruments for the promotion of renewable electricity in an explicit manner can be found in the greater flexibility. As the development of renewable generation and all feedbacks within the energy system are calculated endogenously, this methodology allows to evaluate the impact of changing scenario settings on the increase in renewable electricity as well as to examine the interactions with other policy instruments. On the whole it needs to be pointed out that for a realistic representation of the future trends in renewable electricity generation the model itself has to fulfil certain requirements, including: (1) a large variety of renewable technologies, with realistic assumptions on their technical and economic development and potentials, should be incorporated; (2) other technological changes that substantial growth rates in renewable electricity generation entail should be taken into account, like the required extension of the electricity grid or the need for storage capacity in the case of intermittent energy sources; (3) the model should feature a relatively high time resolution and (4) to adequately capture the effect on electricity consumption, the partial equilibrium approach with price elastic demands should be chosen.

6. Literature

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7. Annex

General example on the implementation of feed-in tariffs in the TIMES modelling language

```
SET PRC_VINT(REG,PRC) (indicates vintaging for renewable generation process P)
/
WEST      .P
/;

NCAP_FSUB(R,datayear,P,CUR) =  tariff;  (tariffs on installed capacity in real terms of the base year)
NCAP_FSUB(R,datayear,P,CUR) =  tariff;  (taking into account annual degression rate)
NCAP_FSUB(R,datayear,P,CUR) =  tariff;
…

NCAP_FSUBX(R,T,P) = 1; (indicates selection of shape curve 1)

PARAMETER SHAPE(J,AGE) (specifies shape curve)
/
1.1          1.000
1.2          0.978 (values include inflation rate of 2.3% p.a.)
1.3          0.956
1.4          0.934
…
1.20         0.649
1.21         EPS (if technical lifetime of process exceeds the usual FIT payment period of 20 years)
1.22         EPS
…                (until the end of the technical lifetime of the process)
/;
```