Can markets function as learning arenas?
Feed-in tariffs, technological innovation systems and energy transition

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ABSTRACT This paper looks at the innovation implications of Feed-in tariffs (FITs), a widely used renewable energy deployment tool. Diffusion of new renewable energy technologies is hampered by low competitive ability. FITs circumvent this by incentivizing market introduction, and relying on market deployment to stimulate learning to achieve cost reductions. The paper argues the rationale of FITs to draw on ideas stemming from learning curve concepts. The core idea being that the market is to become a new learning arena. The analysis shows how FITs are designed to let industry do the "innovation effort" and public authorities prescribe the "learning pace". What is thought of being a demand side instrument hence in fact is one heavily reliant on supply side dynamics. In this loosely coupled principal-agent relationship there however exists little coordination of what industry is supposed to be doing other than reduce costs. FITs coordinate one central aspect of innovation processes - diffusion. From a systemic perspective, this however is only part of broader innovation processes, and there is little coordination of how industry might reap the benefits of technology diffusion. The paper looks at some of the challenges for solar PV with respect to building technological innovation systems to illustrate both how FITs have stimulated system growth and how increased coordination may become important for further development.

Introduction

Given the challenges of climate change, fossil fuel dependence and need for energy security, governments are concerned with how to stimulate increase of renewable energy and technological change. It is common to distinguish between demand and supply side instruments, the former often being argued to be more efficient because one avoids "picking winners". This paper illustrates how Feed-in tariffs (FITs), one of the most popular demand side deployment instruments, are as much a supply side instrument, heavily reliant on inducing technological change.

As a deployment tool, providing investors with substantial tariffs well above electricity market prices, FITs have lead to surges in investments in new renewable energy technologies (RET), raising their share in electricity generation from 4,7% in 1998 to 16% in 2009 (BMU 2010).

However, a prerequisite for FITs to be a *viable* long-term deployment tool is that learning takes place in production of low-carbon technologies. Technologies need to be available at lower prices to accommodate for reductions of tariffs over time. The paper argues FITs to be heavily inspired by learning curve models. This goes both for the idea that market stimulation affects learning and the prescription of learning rates in policy design. Applying learning curve models in policy implies assuming technological development trajectories ex ante. Hence, policy rests on profound assumptions of how technological change evolves. The paper argues that applying learning curve models does not reveal the processes that may foster or hamper innovation nor what makes technologies more competitive.

Such processes are highly uncertain and development trajectories are not intrinsically knowable. In fact, the large technological transitions that are sought to be policy induced are complex processes where policy is but one part of broader technological and social transformations (Geels 2002, Kemp et al 2007). If we understand innovation as systemic processes of continuous and cumulative improvements in which diffusion and feed-back mechanisms are intrinsic, understanding the role of FITs within a framework of emerging technological innovation systems (Jacobsson 2008, Bergek et al 2008) provides new insight into their potential as learning tools (particularly when it comes to identifying bottlenecks and systemic strengths and weaknesses). The paper argues that limiting the coordination of innovation efforts to tariffs and markets, much of the potential impacts of diffusion on innovation and competitiveness remain unchartered terrain.

The paper first briefly presents overall characteristics of feed-in tariffs, reviews relevant literature and points out the need to look at the underlying innovation dynamics. It then moves to present a framework for understanding the role of learning and innovation in development of new technologies. The focus here is on the constraints posed by technological regimes and their implications for diffusion and innovation systems. The paper then moves to analyse how innovation and competitiveness issues are dealt with in the case of FITs. Here the paper first discusses the perspectives on learning found in learning curve approaches followed by an assessment of how FIT policy is based on such a rationale. The second part of the paper outlines a systemic perspective on solar PV to illustrate how FITs have played a central role in system building and how increased coordination may become central to achieve further growth and development.

Feed-in tariffs to create markets as learning arenas

The focus of the paper is FIT implementation in Germany, which has long history with experimenting with this policy tool. To explore the notions of learning in the context of feed-in tariffs the paper takes the approach of a document analysis to look into the nature and argumentation underlying the implementation and use of FITs. Doing so the paper aims to analyse how policy makers frame and promote the core concepts of learning and innovation. The paper is based on analysis of law texts, underlying studies used in the design of feed-in tariff law and the German renewable energy law (Erneuerbaren-Energien Gesetz (EEG) in which FITs are central, as well as periodical reports assessing effects of FITs.

In Germany FITs have proven to be highly successful with regards to deployment, boasting impressive growth of renewable energy as a share of electricity generation from 4,7 % in 1998 to 16 % in 2009 (BMU 2010). The massive deployment effects have also spurred industrial growth in production of renewable energy technologies. Germany for instance is one of the world's largest producers of photovoltaic (PV) solar cells.

FITs allow investors to sell electricity produced from a selected set of renewable energy sources onto the grid and are awarded a set of additional payments (tariffs). These are normally well above electricity market price. In Germany the tariffs[1] for 2009 are set to:

- 12.67 ct/kWh for *hydropower* (New installations below 500kW. New larger installations below 5MW, as well as renewal of existing installations receive lower tariffs)
- 9.00 ct/ kWh for *landfill, sewage and mine gas* (Landfill gas installations below 500 kW. Sewage and mine gas receive lower tariffs. Bonus payment for installations above 5 MW)
- 11.67 ct/ kWh for *biomass* (Installations above 150 kW receive lower tariffs. Bonus payment for cultivated biomass)
- 16 ct/ kWh for *geotherma*l (Installations below 10MW. Additional bonus if installation produces heat.)
- 9.2 ct/ kWh for *onshore wind* (First 5 years from beginning of operation 5. Tariffs are then reduced towards 5.02 ct/ kWh).
- 13.00 ct/ kWh for *offshore wind* (2 ct/ kWh in addition if installation is set up before 31.12.2015).
- 43.01 ct/ kWh for *solar radiation* (for roof mounted installations below 30 kW. Larger installations, as well as freestanding facilities, receive lower tariffs).

Box 1: Feed-in tariff rates 2009 (Source: BMU 2008)

Some distinguishable traits of FITs (these hold for Germany and may differ for other countries) include: (a) FITs are not technology neutral (as opposed to tradable certificates, emission trading or carbon taxes), (b) FITs are aimed to promote immature technologies (c) FITs are an incentive based tool oriented towards *users* of RET (d) FITs oblige utilities to prioritise renewable energy before conventional power (when the grid is operating on full capacity conventional plants must reduce their load. Grid operators are also bound to extend grids to be able to receive electricity from renewable energy installations). The regulation of utilities to accommodate for new RET hence also is a vital part of creating markets by making it possible to sell electricity onto the grid.

Feed-in tariffs have received attention mainly in economic literature. A key issue is design of tariff systems with weight on designing efficient and "accurate" tariff levels in order to avoid too low (leading to ineffectiveness), or too high tariffs (leading to extra consumer costs) (del Rio & Gual 2007, Butler & Neuhoff 2008, Couture & Gagnon 2010). Overall costs and effectiveness is another central issue and are often discussed in comparison to other policy

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[1] Eurocents per kilowatt-hour.

[2] Concepts such as experiences curve, progress curve and improvement curve often refer to the same phenomena (Yelle 1979).

[3] The EEG progress report attributes the underlying cause for this to be high raw-material prices (but does not state how high) because of

measures such as carbon taxes, emission trading and green certificates (see for instance Menanteau et al (2003), Helm (2005), Kverndokk et al (2004), Midttun & Gautesen (2007), Frondel et al (2010)). Whilst Menanteau et al (2003) point out that FITs may be favourable in the long run based on a dynamic efficiency perspective, Helm (2005) and Kverndokk et al (2004) argue FITs to be picking winners and thereby distorting market mechanisms and rendering them ineffective. Frondel et al (2010) conclude that the net costs of tariffs for solar PV alone amount to 52.3 Bn € for installations set up between 2000-2009, having little impact on emission reduction, job creation and innovation. In a survey of FIT models Sijm (2002) points out how large increase of RET receiving support to produce significant shares of total electricity production may have serious impact on consumer electricity costs. The argument being that FIT support schemes may grow to become unsustainably costly.

The relation between FITs and innovation, is an issue which, although at the core of FIT policy, has received less attention. Shum & Watanabe (2010) call for analysis of network externalities coupled to FITs, hence broadening the perspective beyond cost issues. Johnstone et al (2010) use patent data to argue that FITs are successful at inducing innovation in less mature technologies such as solar energy. However, few studies address how FITs on the long run depend on learning and innovation. The need for analysing links between feed-in tariffs and innovation has to do with how they are not solely a deployment tool. FITs, on the long term, can only work if they promote large scale innovation efforts. A core trait of the tariff system is decreasing tariffs over time. To maintain deployment effects RETs need to be available at decreasing prices to sustain investments. We may think of FITs as innovation policy because it ultimately rests on its ability to stimulate learning and technological development. FITs hence relies on the co-evolution of diffusion and innovation, but are however only aimed at diffusion explicitly. Moreover, as shown in more detail below, the innovation efforts for RETs are delegated to industry, whilst public authorities prescribe the "learning pace". This is a loosely coupled principal-agent relation in which little coordination is taking place beyond the setting and reduction of tariff levels which signal the pace of cost reduction.

From an innovation perspective FITs are interesting because they differ from other RET policy measures in terms of the role of market mechanisms, regulation and governance. FITs, not being technology neutral, requires active decision making with regards to setting tariff levels for individual technology categories. Selection is not made by the market, but by policy makers who in turn are influenced by a broad set of stakeholders and experts. This is what makes FITs successful at stimulating deployment of less mature technologies. For instance, as shown in box 1, solar photovoltaics are rewarded with substantially higher support than other technologies. The key argument for doing so is that the market is to become a new learning arena for these types of technologies. Stimulating market introduction by applying FITs is intended to spur technological development (i.e. cost reductions). The core assumption hence is that deployment affects cost reductions. Once technologies are taken into use, production increases, which in turn is assumed to create virtuous circles (Smith 1776/2003).

Technological change and competitiveness

The fundamental challenge with regards to increase in the share of RET is that new technologies seldom compete well at early stages of development (Rosenberg 1972, Mowery & Rosenberg 1998, Smith 2009). There exist a range of low-carbon technologies which drastically reduce emissions. Few however compete well with dominant fossil or nuclear based means of energy production. Whilst solar energy technology for instance has several advantages, such as the ability to power remote installations which are not grid connected, the crucial issue for moving beyond such niches, although being important early learning arenas, is competitive ability. This implies (at least in most developed countries with well developed electricity grids) being able to compete with existing technologies on price and on the grid.

The literature on technological regimes (Freeman 1994, Kemp et al 1998) and paradigms (Dosi 1982) describes how barriers to entry of new and often alien technologies (into the market and energy systems) is due to incumbent technologies, industries and systems. New technologies seldom match existing socio-institutional frameworks (Freeman & Perez 1988). Technological regimes are characterised by path dependent processes, which points towards the fact that what is done in the future is determined by what is done (learned) in the past (David 1985, David 2007, Pavitt 2005). Smith (2009) points out that technological regimes are coupled to technological paths that over time may create lock-in situations towards inferior technologies. Innovation efforts hence are constrained within boundaries of existing regimes for which learning has taken place over long periods of time.

Diffusion

Regimes hence provide conditional factors, which hamper diffusion processes for new RETs beyond niche areas. The fact that new technologies diffuse slowly has been recognised repeatedly. Rosenberg (1972) pointed out that both overall slowness and wide variation in the rate of acceptance of new technologies are characteristic of diffusion processes.

Diffusion however is a pivotal part of innovation processes and may be described as the process of adoption of new technology. This process is not decoupled from the innovation process, it is an inherent part of it (Rosenberg 1972). In fact diffusion processes consist of vital learning process which continuously improve technologies through learning, imitation and feedback-loops (Hall 2005). The fact that new technologies seldom compete well in part has to do with lack of learning processes associated with broader markets and user bases. Georghiou et al (1986) discussed it as a process of post-innovation improvements, arguing that once an innovation has reached the market there usually is a long period of time where learning affects the performance of the technology. Similarly Kline & Rosenberg (1986) stressed that innovations usually evolve dramatically over time, with potential large effect on cost. Technologies therefore may experience long periods of improvements with large effects on cost. Lock-in to inferior technologies may therefore simply have a temporal explanation.

Learning as forming technological innovation systems

Whilst the concept of technological regimes provides explanatory power as to why new technologies do not compete well from a contextual point of departure, the problem of diffusion and competitiveness is one which also has intra-technological origins. A technology may not compete well because of lack of embeddedness within a system.

Innovation systems approaches are holistic approaches where learning is the core attribute of any such system. These focus on the dynamics amongst components within a system delineated at various geographic or technological levels, such as national (NIS) (Lundvall 1992, Nelson 1993), regional (RIS) (Asheim & Gertler 2005), sectoral (SIS) (Malerba 2005) and technological (TS) (Carlsson and Stankiewicz 1991, Hughes 1989, Carlsson et. al. 2002). The technological innovation system (TIS) focuses on explaining innovation processes linked to specific technologies or knowledge fields (Jacobsson 2008, Bergek et al 2008). The TIS approach originates from the works of Carlsson and Stankiewicz (1991) who define a technological systems as:

> "...a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology."(p. 94)

The structural components of an innovation system consist of organisations and networks which are guided by institutions. A main contribution of the innovation system approach is the acknowledgment of interaction amongst structural components in the generation and diffusion of innovation. There has nevertheless been a lack of a clear-cut focus on the processes that take place within systems, (i.e. traditional NIS approaches are mainly focused on structural setup of systems). Rather than viewing systems as static entities, the TIS approach to larger extent focuses on *processes* in addition to structural analysis, by applying a functional approach (Bergek et al 2008, Jacobsson 2008, Hekkert et al 2007). In fact the approach in many of its operationalisations is concerned with the evolution(s) of technologies in their systemic contexts using the concept of functions to refer to what goes on within a system as it moves through development phases. Functions hence are a set of processes needed for technologies to emerge and grow.

Linked to the competitiveness problem for RET, a general manifestation is no or little developed markets for new TIS (Carlsson & Stankiewicz 1991). There are a multitude of reasons for why markets do not exist. These go beyond the competitiveness issue and may for instance include poorly developed policy frameworks (Kemp et al 1998). Yet the obvious and main reason for under developed markets is that there exist dominant lower-price technologies with which new RET have low ability to compete. Hence the creation of markets is a core function linked to stimulation of growth of the TIS. Market creation as a function within TIS is nevertheless one amongst several functions that need to be in place for a system to form and grow. Whilst focusing on market creation the paper also briefly looks at the totality of system functions to illustrate how learning as a systemic phenomenon includes a complex set of dynamic processes.

Learning curves and competitiveness

A related approach to learning and how technologies evolve from a cost competitiveness perspective is the concept of learning curves. This section looks at their underlying rationale. The concept of learning curves[2] describes how costs decline as production accumulates. It is used to understand how costs evolve over the long term. Learning curves state that production costs fall at a fixed percentage for each doubling of cumulative output (Yelle 1979, Liebermann 1987). The rate at which costs decline over time per unit of output is referred to as the progress ratio or learning rate. If a learning curve has a progress ratio of 80% this means that price is reduced to 0.80 of the initial price after each doubling of cumulative sales. Under such circumstances each doubling of sales reduces the price by 20% (IEA 2000 p. 12). Wright (1936) often is credited with creating foundations for thinking in terms of learning curves in his observation of decreasing labour costs as a result of increasing amounts of produced airframes. It first was observed as a correlation phenomenon, which later was supplemented by a number of empirical studies for many technologies and industries showing similar tendencies (Neij 1997).

Learning by doing and learning curves

Learning curves resonate with the concept of learning by doing. Acknowledging the shortcomings of neoclassical growth models and the importance of learning and knowledge accumulation for growth, Arrow (1962) attempted to model "learning by doing" as part of an aggregate production function. In doing so he proposed to further explain the residual (technical change). Arrow (1962) proposed that "...technical change in general can be ascribed to experience". The model attempted to explain technical change as a function of the effects of *learning by doing* operationalized as accumulated experience. The model uses cumulative gross investments rather than cumulative output (as opposed to what is used in most learning curve models) as an index of experience in the model. The proposed model is an aggregate one-sector model assuming learning to take place only in production of capital goods, excluding learning during use of capital goods. Arrow argues that "...each new machine produced and put into use is capable of changing the environment in which

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[2] Concepts such as experiences curve, progress curve and improvement curve often refer to the same phenomena (Yelle 1979).

production takes place (p. 157).” The model reduces technical change to be embodied in new capital goods (new capital goods are assumed to incorporate all available knowledge), excluding productivity increase in the aftermath of production of capital goods. Sheshinski (1967) argued cumulative investment to be a more reliable proxy than output.

Contrasting the aggregate work of Arrow (1962) where new capital goods was used as a proxy for learning, Lundberg (1961) and David (1973) approached the same matter focusing their work on empirical studies on the micro level analysing the “Horndahl effect” or “...learning by doing with fixed facilities” (David 1973, p. 131). The phenomenon in focus was productivity increase in absence of investments in new capital goods, hence discussing learning in use of technology on the micro level.

Whilst the conceptions above are not learning curve models per se, they possess similar traits to learning curves in how learning is studied as a phenomenon. Moreover they were central contributions in analysing technical change as experience or learning. Arrow`s conception of learning by doing as an opportunity for cost reductions provides the foundation for learning curve models in that these attempt to measure its effects. On the other hand the work of Arrow (1962), using it on an aggregate level, differs from what where the initial learning curve models; applying it to organisational domain of the firm or plant. The first learning curve studies where all micro level models (Wright 1936, Argote & Epple 1990, Boston Consulting Group 1972) discussing learning as an organisational phenomena where costs (labour) decline as output increases. Moreover the centre of attention in the approaches above is not learning in itself but productivity growth.

Learning curves and energy policy

One of the salient traits of the learning curve approach is the attempt to predict cost development. In fact, learning curves provide an exception within a broad literature on learning in attempting to quantitatively model and forecast learning. Moreover its implications for policy, and energy policy in particular, have become widespread. Learning or experience curves often are used to assess policy, yet as is shown below, the theoretical foundations are also used to design policy. Distinguishing between use of learning curves ex post or ex ante is essential as the latter is about technological forecasting, and hence may hold bold assumptions of developments in the future as opposed to assessing past development empirically. The attempt to apply learning curves in policy design is an attempt at using ex post data to model ex ante trajectories. Identifying past cost trends hence largely differs from applying these to model future cost trends. Using learning curves in policy design hence is a way of forecasting technological change, based on the existing development trajectory of a technology, or sets of technologies (such as in FIT design).

The core selling point of applying learning curves to policy stems from the idea that immature technologies still have a long way to travel along the learning curve (IEA 2000). A core aim is to promote the concept of learning curves to create deployment policy in order to "...bring the technologies to the market" (IEA 2000 p. 3). The argument is that investing in RET is a long term "project" with the potential of reaping rewards in the future as technologies attain cost competitiveness. A core argument for supporting immature technologies such as solar PV is that prices are expected to fall over time (IEA 2000 p. 10). It is argued that given large enough investments technologies will evolve through trajectories of learning curves. The market not only is viewed as a selection arena, it also is intended to become a learning arena.

In essence the theoretical argument for creating markets as learning arenas rests on the assumption that cost trends follow learning trajectories as proposed by learning curve analysis. Moreover the application of learning curves in policy design intends to tell policy makers something about the future potentials of cost reductions. The notion of learning in learning curves, using a black-box approach to argue that a certain amount of input results in a given amount of output, measured in cost reduction, may also be easily marketable towards policy makers as the simplicity of such a learning model may be appealing. It may however also be misleading.

The limitations of learning curves

There are several issues regarding application of learning curves in policy design that may prove to become problematic. These include; (a) predictability/uncertainty, (b) learning inputs (c) level of aggregation and (d) decoupling of price and cost.

Firstly a main problem related to use of a learning curve *ex ante* in design of policy, is the obvious fact that we do not know what the learning curve for a given technology might look like beforehand. In fact Alchian (1963) searching for factors affecting the learning curve found significant margins of errors when fitting the learning curve to aggregate past performance. Dutton et al (1984) surveyed a range of learning curve studies and found a high degree of variance in learning rates. Within the literature discussing technical change and innovation the learning curve approach provides an exception with regards to the attempt to predict or forecast technical change and learning rates. Whilst this is an observed empirical phenomenon for a range of technologies ex post, the question of the fruitfulness of use of an *ex ante* learning curve in design of policy remains. In the case of the FIT one assumes RET to be competitive with other energy technologies at some point along the learning curve (i.e. in the end prices are low enough to be competitive, without the support of FIT). Given that innovation by definition is highly uncertain (Freeman 1994, Kline & Rosenberg 1986) and spans across large periods of time (Rosenberg 1994, Fagerberg 2005) the likelihood that learning curves follow differing trajectories than those proposed in the FIT system also exists. In terms of learning rates these may for instance be more or less steep than projected. The main point however is that modelling learning trajectories includes high uncertainty levels because it relies on innovation processes which in themselves are uncertain, and do in themselves create uncertainty.

Secondly a learning curve does not tell us anything about which factors that influence learning. This point is at the core when it comes to design of policy. In the case of FITs we may argue that policy is designed on the assumption that deployment equals development (i.e. learning). There is no distinction between these two levels as use of a learning curve in design of policy does not tell us anything about which factors that influence learning other than increase in output and that time goes by. While such a display of learning may provide us with insight regarding a general tendency of cost development ex post, the underlying processes are "black boxed" to borrow the term from Rosenberg (1994). In fact, this point is expressed explicitly in the learning curve literature; "...it considers this system as a black box for which only input and output are observable" (IEA 2000, p 28). Applying such a learning model does not reveal any processes that might foster or hamper innovation processes. In other words, applying such a learning model, does not reveal any factors that make technologies more competitive. We may argue that learning curves are an assessment and, in the case if FITs, a prediction of quantitative growth and cost reductions. These challenges are sought addressed for instance by applying additional bottom-up approaches to identify some of the sources of cost reductions (see for instance Neij 2008). In itself a learning curve approach does not reveal any of the complex underlying dynamics of learning processes. In fact it may be argued that learning curves only are an assessment of the effects of learning on cost reduction, not of the qualitative aspects of learning. They are a projection of past learning processes onto the future.

Third, a macro/meso level conception of learning is now increasingly entering the field of learning curves, by using learning curves on the meso and macro level to say something about cost trends across technologies, industries and sectors. This shortcoming is acknowledged within the literature (van der Zwaan & Seebregts 2004, Ferioli et al 2009) arguing that assessment of non-standardised products increases uncertainty in the outcome of learning curve analysis. In the construction of FIT levels, assessment about learning rates are made on the basis of learning curve analysis of several technologies including the one receiving support. The problem with doing this is first and foremost firm and technological heterogeneity. Given both inter- and intra differences with respect to production technologies, learning rates may not necessarily follow similar trajectories. Hence using learning curves in cross technology contexts may contribute to increased variation and uncertainty.

Fourth, methodological choices may have impact on policy design. A typical learning curve assessment on a micro level (for instance on firm level) assesses the relation between output and production *cost*. However, due to lack of producer cost data, the literature on learning curves accepts the use of *price* data as an alternative measure (Neij 2008). Within a policy framework such as FITs, measuring price rather than cost may prove to become problematic as prices and costs are increasingly decoupled. A core question regarding FITs as a stimuli system hence is to what extent prices align with tariff levels. Can prices increase or be upheld even if production costs decrease? In the case of solar PV, innovation and cost reduction measures such as the reductions of Silicon use have not been ”… passed on to customers as price reductions, but have increased profit margins (doubling of average profit margins from 15% in 2004 to 30% in 2006)” (Staiss, Schmidt & Musiol: 261). Raw-material usage has been reduced, but prices have risen on the short term. In fact, in the period 2004-2006 solar cell prices rose 5-10% despite reductions of tariffs.[3] Hence we may argue that cost and price

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[3] The EEG progress report attributes the underlying cause for this to be high raw-material prices (but does not state how high) because of lack of sufficient amounts of high-grade Silicon used in the production of most solar cells. This factor is seen as a main cause for withstanding high prices for PV. It must nevertheless be mentioned that the issue of accessibility and high prices of raw-materials has been bottleneck for the PV industry since its emergence, and is not an issue that solely characterises the period 2004-2006.

are decoupled which in turn may be due to tariff levels. There hence arise unintended dynamics with regards to how firms attain profit margins on the basis of tariff levels that are not well aligned with production costs. There exist arguments saying that this may spur innovation, for instance by enabling firms to increase R&D budgets. This argument however rests on the assumption that firms actually do so and to what extent such measures actually lead to overall cost reduction.

There hence are a range of challenges that face the learning curve approach both on a theoretical level, in addition to its application in design of policy. They all relate to the fact that what is measured is not learning in itself but the effects of learning on cost. Using such an analysis to project future cost trends is highly uncertain as it does not account for any learning inputs that may disrupt learning trajectories. Neither does the approach take account for any changes in cost trends if the measurements rely on price data. Moreover uncertainty is increased by measuring non-standardized products in addition to using cross-technology data to create tariffs and tariff reduction rates. There hence exists a large degree of uncertainty when it comes to learning, which is the nature of technological change, that are not accounted for using learning curves.

Feed-in tariffs as learning curves

FITs have generated a surge in new RET installations, including less mature technologies such as solar photovoltaic (PV), which conforms to the core objective; increasing the RET share. However, supporting RETs by means of tariff is nevertheless impossible or viewed as ideal in a long term perspective:

> ”… renewable energy should attain competitiveness on the energy markets on the medium to long-term. Only when renewable energy is competitive without financial support it is possible to play an important part on energy markets” (Deutscher Bundestag 2008: 26) (Authors translation)

The main purpose alongside increasing the RET share hence is to stimulate competitiveness of RET over the medium to long term. The rationale is that technologies will evolve to become competitive during this policy supported “transitional” phase. The underlying assumption of FIT policy is that tariffs are a sufficiently strong tool to stimulate competitiveness through cost reductions;

> ”At the same time the EEG (Erneuerbare-Energien-Gesetz – Law for renewable energies) fulfills an important function with regards to industry policy. The reduction of production costs for electricity from renewable energy sources through technological innovations and learning effects induced by the EEG, strengthens the already strong competitive position of the German renewable energy industry” (Deutscher Bundestag 2008: 26) (Authors translation)

Cost reduction hence is argued to be driven by innovation and learning processes induced by FITs. As discussed above, the fact that FITs support immature technologies does entail expectations towards learning. The core objective of FITs hence resonates with objectives commonly associated with innovation and research policy; induce learning. In essence it is assumed that deployment will stimulate development. It is explicitly stated that RETs offer large cost cut potential, and that these are not attained using R&D stimuli alone. Market introduction stimulation is needed:

> “The realisation that renewable technologies offer considerable potential for cutting costs is a main reason for the provision of state support. That potential cannot, however, be mobilised exclusively by means of R+D. It is essential that, in parallel, dynamic market growth is triggered and maintained over a longer period, in order that the production-side learning effects can be mobilised under real-world conditions, i.e. through quantitative growth at a sufficiently high level.”(Nitsch 2008: 101)

In order to ensure cost cuts market introduction stimulation is needed to achieve learning in what is referred to as the “production-side”. This development is in turn reliant on industry which is assumed to be the instrument that through innovation and learning effects reduces technology and production costs.

Despite being a user oriented tool, FITs do in effect target learning in industry and production of capital goods. This becomes evident looking at how tariffs are structured. An installation receives a fixed rate over 20 years. Yearly degression of rates applies only to newly installed projects. The tariff level depends on which year the installation is set up. A plant set up in 2008 receives lower rates than a similar plant set up in 2007. Roof mounted solar cells for instance receive the highest tariffs and are currently degressed 5% each year. Such an installation set up in 2004 receives 57,40 Eurocent per kilowatt-hour for 20 years, whilst the same installation set up in 2008 receives 46,75 Eurocents for 20 years (BMU 2007a). In effect there are expectations towards cost decrease of 5 % (for solar photovoltaics) annually. Hence incentives both go for investments themselves but also to invest as early as possible to receive the highest tariffs. The long-term learning curve applied for FITs is mainly coupled to production of technologies, as the feed-in tariff rates are set flat over 20 years, and is subject to yearly degression only for new installations. By applying fixed rates there is little weight put on learning and cost reduction after installations are set up. Tariff reduction in turn may be viewed a formally institutionalised relation amongst public and private actors signalling future market conditions, which is intended to create long-term stability. Hence the focus in German FIT policy when it comes to learning is on industry, whereupon policy makers in effect will have to rely to achieve the future goal of competitiveness for RET.

How is learning approached in the white papers and FIT models? In essence the model treats learning as a quantitatively measurable phenomenon. In fact it is argued that:

> "...this cost development is calculable over the long term, in contrast to a resource-based energy supply system, as it is influenced *only by technological developments* and the capital inputs required for these…" (Nitsch 2008: 103) (Author`s itallics).

The trajectory of cost reductions hence is one that is assumed to be determined by technological developments, given that energy resources are free of cost for most RETs- There is an explicit notion of learning curves as a way of understanding cost cuts for RETs over time as technological development. The lead study for 2008 makes use of the so-called ARES (Ausbau regenerativer Energiesysteme – expansion of renewable energy systems) model. It is argued that this model:

> "…captures these technology-specific learning effects in learning curves, with the specific learning factors being derived from the (previous) development of other technologies, but also from the development of renewable technologies themselves, some of which have a history spanning more than a decade." (Nitsch 2008: 101).

The learning curve analysis is based upon the previous development of other technologies as well as development of RETs as key variables. Using cross-technology data on non-standardised products is, as mentioned, contributing to making learning curves more prone to estimate errors. These data are however used to generate technology specific learning rates. For solar PV an estimated cost reduction of 10% annually is assumed using the ARES model:

> "In the ARES programme a learning factor of 0,80 is assumed until 2020. This implies cost degressions of 10%/a under 25%/a growth rates…(Nitsch et al 2005: 17) (Authors translation)

This estimate is based on the assumption of a 20% learning rate equalling cost reduction to 0.80 of initial cost per cumulative doubling of production. Under the assumption of 25% annual growth in deployment rates, this translates into 10% annual cost reduction. The nature of the learning curve approach makes the analysis dependent on high deployment rates to uphold annual cost reduction. According to this model the pace of cost reductions is dependent on how fast industry is able to increase production. There hence is an explicit notion of how deployment and production increase does affect cost reduction (learning) estimated into annual rates of cost reduction. As mentioned above, this technical calculation of the potential *effects* of learning does not state anything about which processes and dynamics that need to take place in order for the cost cuts to take place. The learning curve approach underlying FIT policy presented above is a straightforward adaptation of the theoretical models in the learning curve literature, described below. FITs assume that learning in RET take place, further that the rate at which learning takes place may be calculated and then put in to a tariff reduction system.

What is the underlying supporting material upon which FIT policy and tariff reduction is based? The foundation for the degression of tariffs is based on factors such as historical price data, amount of installations, estimates for future prices and technological efficiency. Reports on specific technologies are produced regularly on commission of the German government. These are used as underlying material for setting tariffs as well as providing the underlying reasoning for use of FITs. The reports are produced by sets of research environments and expert groups within the respective technological fields. Nevertheless the reports that are supposed to provide the basis for policy are to some extent inconsistent, partially because these types of estimates are characterised by uncertainty but also because the underlying material lacks sufficient data (see for example Renewable Energy Sources Act (EEG) Progress Report 2007). In the case of solar cells, industry data such as raw-material costs are not included in the reports. For solar cells raw materials can account for up to 25% of production costs (Sarti & Einhaus 2002: 31). As pointed out in more detail below, raw-materials are in themselves subject to vital learning dynamics with potential effects on other production areas within solar PV. Moreover raw-materials are a key factor related to cost reductions for PV (Nemet 2006). Hence the lack of including central issues, such as raw-material dynamics, may lead to inconsistencies in the analysis and therefore also in the setting of tariff levels.

System building as learning

Thus far we have explored how FITs are heavily reliant on theoretical assumptions about technological change. In this section the paper explores the systemic nature of such processes using examples from solar PV. Why does this matter, and why do we need more understanding of how learning processes take place when FITs seem as an effective deployment tool?

The key point is that we know little about how the diffusion effects of FITs impact the development processes on which the policy tool relies on the long term. If we one is to take the aspect of technological change seriously it is necessary to look at it. Understanding the development of competitiveness for RETs as a process of system building implies policy and diffusion being parts of broader and complex dynamics. These hence are endogenous to a broader set of processes which are not coordinated and not well understood. Understanding the potentials and challenges of such dynamics may therefore help reap their associated benefits.

FITs assume to stimulate "production side learning effects". A starting point is to ask what the production side learning arenas for new energy technologies are? As previously argued, learning may be viewed as a complex phenomenon as opposed to black boxing learning to consist of mere input/output measures used in learning curve models. It may be viewed as a systemic phenomenon in which complex sets of process occur. This section looks at some of the structural and functional dynamics within the technological innovation system (TIS) for solar PV. It mainly focuses on the emergence of specialised suppliers. The core objective of doing this is to point out the importance of knowledge flows stemming from sectors originally external to solar PV, such as the role of the process industry with regards to development of Silicon feedstock. It does so to illustrate how disruptive changes may originate even from outside of initial system boundaries. The production of solar PV technology is highly complex and consists of numerous steps[4], the production of suitable raw-material being one important component. The paper analyses feedstock production in particular as this points out the importance of interaction amongst system components which in turn includes coupling knowledge sources from differing industries.

Structures in the solar energy TIS in Germany

Figure 2 provides an overview of the structural complexity of the PV industry in Germany. It displays the distribution of PV producers (cell, module and feedstock) as well as R&D undertakings in addition to central policy measures and amounts of PV capacity and electricity production.

The figure shows a wide range of PV-producers with a focus on cell and module production (measured in MWp). There also exist many thin-film (2nd generation PV) producers, yet these have a lower output than standard mono- and polycrystalline cells and modules. The German PV TIS is also characterised by a large amount of PV equipment producers. These stand behind half the world's production equipment. In particular a large number of producers of automation equipment exist. Additionally a wide range of research and development (R&D) is invested in PV. These R&D efforts are mainly industry driven (83% of total R&D investments in PV). R&D efforts are mainly focused on next generation PV (thin films and organic cells) as well as process and production technology. Fewer focus on dominant technologies such as wafer based technology and Silicon feedstock.

The distribution of firm size is characterised mostly by small to medium sized firms in international comparison. In the European context German firms dominate with seven companies within the list of the top ten producers. Additionally the German company Q-cells was the world's largest producers of solar cells in 2007 (Jäger-Waldau 2008). We may use Q-cells as an example of production plant size expansion. What started with a 12 MW

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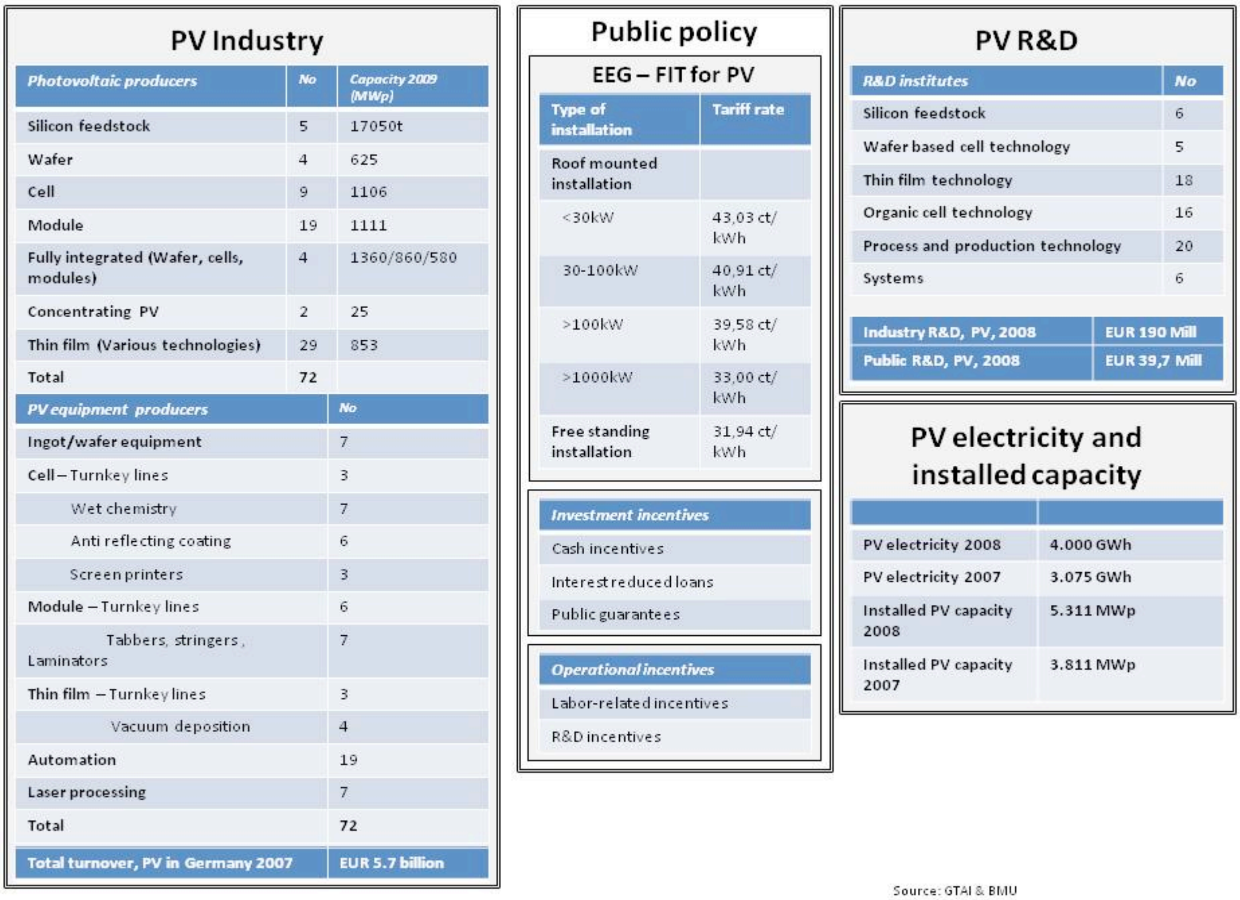
[4] The production of solar energy technology may be categorised in three broad steps; feedstock production (most commonly Silicon), wafer production and module production. Feedstock production includes refining of raw-material and production of ingots (blocks of refined raw-material). Wafer production includes cutting as thin as possible slices (wafers) off ingots in addition to chemically treating the slices to become cells. Module production consists of wiring cells and assembling them onto durable frames.

production line in 2001 has evolved into a capacity of 630 MW in 2008 (Jäger-Waldau 2008: 115). In addition tight networks exist between firms and research organisations, which for instance is manifested in joint ventures and shareholding both within Germany and across borders.



PV Industry

Photovoltaic producers	*No*	*Capacity 2009 (MWp)*
Silicon feedstock	5	17050t
Wafer	4	625
Cell	9	1106
Module	19	1111
Fully integrated (Wafer, cells, modules)	4	1360/860/580
Concentrating PV	2	25
Thin film (Various technologies)	29	853
Total	72	

PV equipment producers	*No*
Ingot/wafer equipment	7
Cell – Turnkey lines	3
Wet chemistry	7
Anti reflecting coating	6
Screen printers	3
Module – Turnkey lines	6
Tabbers, stringers, Laminators	7
Thin film – Turnkey lines	3
Vacuum deposition	4
Automation	19
Laser processing	7
Total	72
Total turnover, PV in Germany 2007	**EUR 5.7 billion**

Public policy

EEG – FIT for PV

Type of installation	Tariff rate
Roof mounted installation	
<30kW	43,03 ct/ kWh
30-100kW	40,91 ct/ kWh
>100kW	39,58 ct/ kWh
>1000kW	33,00 ct/ kWh
Free standing installation	31,94 ct/ kWh

Investment incentives
Cash incentives
Interest reduced loans
Public guarantees

Operational incentives
Labor-related incentives
R&D incentives

PV R&D

R&D institutes	*No*
Silicon feedstock	6
Wafer based cell technology	5
Thin film technology	18
Organic cell technology	16
Process and production technology	20
Systems	6

Industry R&D, PV, 2008	**EUR 190 Mill**
Public R&D, PV, 2008	**EUR 39,7 Mill**

PV electricity and installed capacity

PV electricity 2008	4.000 GWh
PV electricity 2007	3.075 GWh
Installed PV capacity 2008	5.311 MWp
Installed PV capacity 2007	3.811 MWp

Source: GTAI & BMU

Figure 2: PV TIS Germany (Source: GTAI 2009a GTAI 2009b and BMU)

Functions in the solar photovoltaic TIS in Germany

Functions of technological innovation systems may be viewed as processes occurring within a system as it forms and grows. Bergek et al (2008) propose a set of seven key functions presented in box 2.

- *Market formation*
- *Influence on the direction of search*
- *Entrepreneurial experimentation*
- *Resource mobilization*
- *Legitimation*
- *Positive externalities*
- *Knowledge development and diffusion*

Box 2: Functions of a technological innovation system (source Bergek et al 2008)

We start by looking at the function *Market formation.* Due to low price competitiveness amongst others, markets often do not exist in early phases of development for a TIS. Creation of markets often is dependent on institutional change. For PV this is influenced directly by FIT policy. By providing tariffs that are well above grid electricity prices, policy creates incentives for investments, which in turn leads to expansion of markets. This relates to how FITs operate as a deployment tool targeting users of technology. However, as previously argued, the long-term viability of FITs rests on the ability of producers of capital goods to innovate. Such producers also operate under the market conditions created by FITs. Policy hence is highly influential in affecting the institutionalised framework under which both public and private actors operate. Public authorities depend on industry to reduce costs and sell goods at decreasing prices. Private actors depend on tariff levels, which allow markets to function in order to sell goods. Tariffs and tariff reductions hence are central in determining market formation and conditions for both users and producers.

Influence on the direction of search relates to how growth of a TIS is dependent on the entering, and incentives for entering, of new organisations as these bring new knowledge into the system. Growth potentials, visions and regulatory environments for instance play a central role. This function is strongly affected by how the FIT system is designed. Policy triggered market formation does play a key role in influencing the direction of search with regards to entry into TISs, for instance PV. FITs provides strong incentives for investment in PV projects and subsequently entering of new firms in production of capital goods. This function is however just partly influenced by policy as there are few guiding factors influencing the direction of search *within* TISs. Beyond stimulating entry into PV, there exist no governing mechanisms attempting to structure or guide activities within TISs. For instance regarding which types of technologies firms and research organisations choose, often from a heterogeneous set of technologies. FITs do not address such intra-technology issues.,

Within a systemic perspectives there are however other actors and institutions that may govern the influence of search. In addition to the influence of regulatory measures, advocacy organisations such as interest organisations and industry associations play a central role regarding promoting industry interests as well as promoting the image of the PV TIS. Solarwirtschaft (the interest group of the German solar energy industry) and the EPIA (European Photovoltaic Industry Association) are key player in the PV TIS as regards promotion of PV technology and trends, as their assessment of growth and growth estimates are influential to both public and private actors[5]. In the EPIA market outlook (2009) the compound annual growth rate is estimated to 32% (17% using a moderate scenario) for the period 2008-2013. This comes in the aftermath of periods with high growth rates (40-80% from 2003 (Jäger-Waldau 2009). The high growth numbers and estimates contribute to a perception of a booming PV TIS. This in turn provides an additional influence on the direction of search as it influences the entering of new firms. A result may be argued to be expansion of the TIS both in terms of number of producers of PV technology (broadening of the TIS), but also with regards to entering of new down- and upstream suppliers (i.e. deepening of the TIS). The structural assessment above showed at least 142 firms active within the PV TIS in Germany (including producers of PV technology and equipment producers), in addition to a range of R&D organisations.

As we discuss in greater detail below the entering of downstream suppliers gives rise to new dynamics within the TIS. The fact that large incumbents such as Wacker Chemie, Hemlock and Elkem choose to enter the PV TIS producing raw-materials specifically to the PV-industry indicates a perception of the PV TIS as large enough for investments to be viable. Hence the influence on the direction of search for these large incumbents may be argued to be influenced by public policy through the tariff system. Financial risks and investment decisions are however also dependent on policy in the sense that uncertainty in policy frameworks also may influence decision making processes negatively.

Entrepreneurial experimentation relates to the functions above in the sense that new entrants experiment with various technologies and production techniques. In order for a TIS to

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[5] EPIA estimates are often used in public and private reports on PV industry.

develop experimenting with new designs and technologies. Such processes are inherently uncertain as many will fail and some succeed. Entrepreneurial experimentation within the PV TIS may be identified with regards to heterogeneity in both technologies and production techniques.

A core issue related to the "cost problem" for PV is material constraints often resulting in high production costs. This is a core bottleneck both in terms of volumes and price. The effects of learning arising from raw-material shortage are multiple. We may divide them into two broad categories. The first relates to handling raw-material shortage in the production of wafers and solar cells. As a reaction to high raw-material costs, an up weighing tendency has been the usage of less Silicon per energy unit. During the period 2004-2006 Silicon use decreased from 13 g_{Si}/W to10, 5 g_{Si}/W (Staiss, Schmidt & Musiol 2007: 261). Ways in which Silicon use can be reduced is for instance through cutting thinner wafers, achieving less Silicon waste in the cutting process or by recycling Silicon. Thin-film solar cells are also a way of using less raw-materials. This goes for Silicon as well as other materials. This depicts the general development of handling the raw-material bottleneck in the production of solar cells. This has resulted in a range of experiments both related to reduction of material usage in new types of products (for instance thin films) and using less raw-material in traditional SI wafers (new types of wafer sawing and recycling) as well as production of raw-materials. The large number (29) of thin film producers in Germany indicates experimentation with a technology that may challenge the dominant wafer based design over time.

The second, and more central issue, relates to setting up dedicated raw-material supply. The increased efficiency of production of solar cells is an important development but not sufficient when it comes to establishing viable access to raw materials. A withstanding paradox therefore is why raw material production has not grown more rapidly since demand is high and growing. Raw-material shortage and cost constituted the largest bottleneck for PV. Despite high long term growth the solar cell industry has depended on raw materials from the semiconductor industry. This dependency has been viewed as problematic as prices are high and fluctuant. Additionally the PV and semiconductor industries experience differing growth patterns, which in turn give rise to differing dynamics affecting raw-material price. Nevertheless experimentation with production of raw materials for the solar cell industry has been ongoing for decades and now seems to manifest in actual production. As we point out in Hanson (2008) and Hanson (2011), we can identify growth of producers of Silicon dedicated for the Solar cell industry. In Germany we find Wacker Chemie which are the worlds second largest producer of solar grade Silicon (next to Hemlock and Renewable Energy Corporation (REC)) (BMU 2007b: 6). Internationally a range of firms are experimenting with various process. Norwegian firms, such as Elkem Solar, are for instance experimenting with upgrading processes traditionally used in the production of FerroSilicon. These apply various production techniques which are incremental changes of well known processes (for instance upgrading metallurgical Si, or new versions of well established gasification processes). These producers are mainly traditional producers of Silicon materials (or have tight links to the process, polysilicon and/or semiconductor industry) that are moving onto catering the solar cell industry. Hence we can identify new entering of new organisations bringing with them new knowledge into system. In that sense we may argue that the raw-material bottleneck also has contributed to creating dynamic learning processes regarding Silicon production and supply. As pointed out in Hanson (2011) the learning processes on which firms embark are both complex and spanning long time periods.

The emergence of new raw-material suppliers is a central development, yet amounts are insufficient to cater high demand. The establishment of Silicon production are long term processes that are characterised by high uncertainty, as they are highly capital intensive, which may explain the reluctance to establish production at an earlier point in time. The late entry of firms within raw-material supply has provided a major bottleneck for the PV TIS globally. This has led to undersupply of raw-materials and high prices. Hence the lack of entrepreneurial experimentation and entering of firms producing raw-materials has had negative impacts on growth of the PV TIS hitherto.

Although being only a component within the system for solar PV raw-material production has undergone complex developments and learning processes. Such processes are not being captured in learning curves, but may have substantial impacts on both on the overall functioning of the PV TIS both in terms of structure and functioning as well as cost development over time.

We may argue that FITs are strong enough to spur investments in PV installations, as well as downstream levels of the value chain, but to a lesser extent in upstream raw-material production. We may therefore argue that the TIS for PV so far has failed to stimulate sufficient growth of upstream suppliers, whilst the system has managed to expand to include suppliers of production technology on downstream levels. This has to do with the uncertainty of entrepreneurial experimentation and the financial magnitude of investments in development of raw-material supply. The question being if FITs are able to reduce uncertainty sufficiently for this part of the value chain. On the short term shortage leads to developments not intended such as increase of price. On the long term, as upstream production is increased, effects such as reductions in production cost and decrease in price of Silicon may be expected[6].

Resource mobilisation relates to the ability to raise financial and human capital in order to facilitate growth of the TIS. Globally, new PV investments surpassed bio energy in 2008, second only to wind with 33, 5 billion US $, up 49% from 2007 (UNEP 2009). Given the strong surge in German markets based on FIT, large shares of this total are located here. The high investment level also gives rise to employment increase. UNEP (2008) estimates the global number of jobs in PV to be 170,000 in 2008. In Germany the total employment within PV was estimated to 57,000 for 2008 (BMU 2009). As regards human capital a survey concerning employment issued by the BMU[7] indicated lack of sufficiently trained personnel for all industries within the renewable energy sector. Within PV 30% of the surveyed firms reported lack of sufficiently trained personnel (Lehr et al 2008). Hence, although Germany traditionally has an attractive engineering workforce this is not sufficient to cater the large demand from rapidly growing renewable energy industries. Although companies in the survey were optimistic about future growth and recruitment, a negative development of this function could provide challenges to further growth.

Legitimation has to do with gaining acceptance and aligning with relevant institutions. It is a central function to emerging and growing TISs as these are challenged with “being new” and often competing with more mature technologies. Gaining legitimacy is associated with gaining acceptance amongst relevant actors in order to succeed with mobilising resources and forming markets. Moreover the process of gaining legitimacy is one of gaining political influence. In Germany this was the key to succeeding with FIT policy implementation, and for PV it was about ensuring that tariffs would be large enough to spur investments. This was a long term process involving numerous actors and institutions in broad parts of society.

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[6] Industry analysts have anticipated Silicon price reductions regularly, but actual reductions have as of yet been marginal. (price for Silicon for solar cells has been 75$/kg Si on average. Peak spot prices peaked with up to 450-500$/kg in 2008 (source: interview).

[7] 1100 german renewable energy companies were asked to report on issues related to employment and workforce.

As deployment of new RET includes vast economic impacts and high uncertainty the need to create, increase and *maintain* legitimacy is pivotal. One of the key arguments of the German government for introduction of FITs are the extended effects associated with industry growth locally. Creating jobs and new industries hence is assumed to give the public reason to accept higher electricity prices due to tariffs. The German government therefore puts pressure on local industry to be able to cater local demand (Scheer 2004). Again the interdependence of private and public actors becomes central. The legitimacy of FITs is dependent on these extended effects to be sufficient. This includes both substantial growth in industry, but also the reduction of production cost and price.

The development of this function may also have impact on other functions such as influence on the direction of search or entrepreneurial experimentation. If FITs loose legitimacy due to increased consumer costs, if capital goods prices are not reduced sufficiently do meet what is proposed in the learning curve, of if local industry does not grow sufficiently this may have impact not only on the legitimacy of FITs but also the systems where they are an inherent component. Given the high dependence on FITs within systems, the uncertainties associated with entrepreneurial activities may therefore negatively affected by decrease of legitimacy.

The development of *positive externalities* is linked to how the evolving TIS is influenced by new entrants through the effects on other system functions. The function is therefore not independent of the others, but rather has impact on functions such as influence on the direction of search, knowledge development, legitimation and market creation. New entrants may affect uncertainty as well as give rise to knowledge spillovers which may be beneficial for other firms and organisations. This may arise for instance in the form of pooled labour markets, the emergence of specialised suppliers and co-location.

The entering of a specialised suppliers of various production equipment may be used as an example. For the solar cell TIS the entering of firms with competencies and knowledge within the fields of automation and robotics for instance has effects on how solar cell factories are constructed and operated. The use of robotics and automated production lines for instance affects productivity in plants. How solar cells are produced is hence affected by the entering of production equipment firms. For this function the entering of new raw-material suppliers also provides positive externalities as this may affect the raw-material constraints under which firms have operated. The new knowledge brought into the TIS by incumbents within raw-materials, robotics and production equipment therefore may provide positive externalities for other firms residing within the solar cell TIS.

Knowledge development and diffusion is at the core of a developing TIS and all the functions above contribute. It relates to the (evolving) knowledge base and the types of knowledge that characterise the TIS. As a quantitative portrayal of knowledge diffusion we may use patent data[8]. Figure 3 shows a steady increase in patenting activity, and a peak for 2000 and onwards. The data show yearly patenting and although only indicative, portray a positive trend concerning knowledge development and diffusion in the form of patenting. Patenting data need to be treated with caution, as low shares of patents actually are implemented as products or processes, and is here only used as a mere indicator of this specific function. The increasing patenting numbers may be linked to R&D support. In Germany PV public R&D support has remained steadily between 30-40 million Euros since the early eighties with a peak in the early nineties and a drop in the mid nineties.

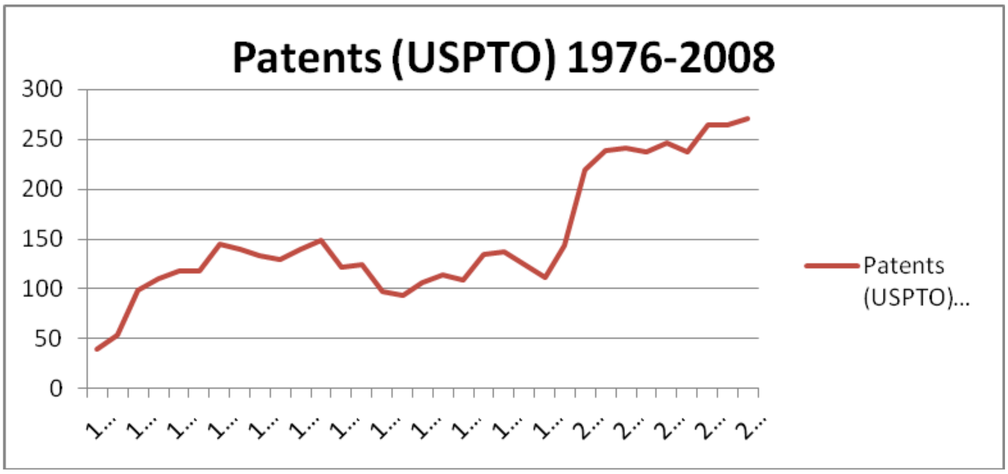

Figure 3: PV patents 1976-2008 (Source: USPTO)

Policy endogeneity

The analysis above shows that FIT policy plays a central role in the formation of a technological innovation system (TIS) such as PV. FITs hence are intrinsically embedded in systems as both structural components and functions are policy dependent. At the same time FITs rest on the ability of systems to grow and become increasingly competitive. Hence, there exists a reciprocal relation, which is best understood seeing innovation as a systemic

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[8] Data were obtained for the period 1976-2008 (data from 1975 and back are not searchable with keywords in title or abstract) from the US patent and trademark office. Keywords; ‘photovoltaic’ and ‘solar cell’.

phenomenon. In fact the literature on systems transitions highlights the point that transitions in fact are dependent on broad changes in socio-technical systems, where policy is but one part (Geels 2002, Kemp et al 2007). We may view policy as an endogenous element of systems.

The design and underlying line of thought for FIT may prove to create challenges for system performance on the long run, using learning curves as the underlying foundation for FIT as the main policy tool stimulating large parts of the world markets for instance for solar PV (Germany as the largest and driving market, in addition to emerging FIT stimulated markets in Spain, Italy and others). This in turn relates to how FITs are in fact linked to what may described as one of the key objectives of innovation and science/research policy; stimulating industry to take part in learning and innovation processes and thereby increase competitiveness. Nevertheless this principal-agent relation has weak links to what is the ultimate goal; namely increased competitiveness through cost reductions in industry. Using the design of a learning curve in a policy tool that formally is aimed at *users* of technology but in reality rests on the ability of *producers* of technology to reduce costs and price may prove to become the main challenge for FIT in the future. We therefore can identify strong but little coordinated interdependencies between policy and industry as the policy in reality rests on the ability of industry to reduce costs and prices and in that the industry relies on the FIT system to grow.

A remaining question therefore is to what extent the system is reliant on public policy to achieve formation and system growth, and to what extent it is resilient to withstand declines in public policy support. If FITs for instance prove to loose legitimacy, coupled to short run price increases or too low cost decrease on the long run, this potentially could have serious impact on the system as a whole.

Conclusions

In conclusion we may argue from a systemic perspective that FITs stimulate one central function of TISs – market formation. Diffusion hence is stimulated by user incentives. However, other central systemic functions may be argued to be stimulated loosely and not directly by FITs, but by its extended effects. What this paper has shown is that market deployment has stimulated various processes in the PV TIS. There are however critical blocks that have been and still are problematic for further growth, and raw-materials is one such issue.

An initial conclusion is that markets in themselves do not function as learning arenas. Markets may however provide firms and organisations with learning opportunities. Whether or not these embark on “learning ventures” to the extent that is prescribed in FIT policy is however uncertain. It depends on the structure and functions of the system where market creation is one amongst many processes that need to be in place in order for a system to grow. Moreover, the potential learning trajectories (or curves) do not necessarily develop in accordance with what is “prescribed” in learning curves. The dynamics occurring within a TIS, such as the one for solar PV, are highly complex and are reliant on a broad set of factors, not solely policy. Market creation is one amongst many factors that may influence to what extent a system is able to develop and learn over time. What may be argued is that FITs have been, one amongst many, driving forces within this system. FITs hence are not solely a demand side instrument, they are heavily reliant on stimulating technological change. Hence, whilst FITs have proven to be a strong deployment tool its role as an innovation tool is highly dependent on a range of external factors, which are not directly coordinated by policy. Using learning curves as an underlying rationale for does however not lead to an increased understanding of how these linkages are at work, nor how they will evolve.

From the discussion above three issues become central. First the increasing size, complexity and heterogeneity of support receiving systems is little understood and not coordinated by policy. With regards to policy design, an understanding of how learning dynamics evolve, are of importance to stimulate a more rapid evolution of RETs. Second, increasing costs due to the increase in supported technologies may challenge both FITs and systems, and the viability of TIS with reduced public support is highly uncertain. Understanding how learning takes place also becomes increasingly important in the long run as FITs support increasing shares of RET, and may come to a point where upholding FIT support is increasingly challenging. Third, PV and many other RET are still in a development phase with large-scale innovation efforts needed to become more competitive on the grid. Moreover, the contribution of new RETs in the energy mix in Germany is still small. For further growth, the understanding of innovation dynamics, for instance with regards to widening of system boundaries, internalising new knowledge, firms and organisations, may become increasingly pivotal.

Hence understanding and assessing the complexity of such systems by means of TIS analysis, may be a way of creation for a foundation for increased coordination of policy as an integral part of TIS. Applying such analysis may be a mapping and assessing issues with need for coordination and therefore also a way of strengthening the basis for flexibility of setting tariff levels. The coordination problem hence may be supported by both applying TIS analysis as well as using TIS approaches to inform flexibility in tariff level setting.

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