WHAT ARE THE INNOVATION EFFECTS OF PILOT AND DEMONSTRATION PLANTS? THE CASE OF ADVANCED BIOFUELS IN THE TRANSPORT SECTOR

K. Bäckström
Economics Unit, Luleå University of Technology
SE-971 87 Luleå, Sweden
Phone: +46-920-492890
Fax: +46-920-492035
E-mail: kristoffer.backstrom@ltu.se

ABSTRACT: Pilot and demonstration plants (PDPs) may be important for fostering technological innovation. They constitute a bridge between basic knowledge generation and technological breakthroughs on the one hand, and industrial application and commercial adoption of new technology on the other. The aim of this paper is to examine the innovation impacts of publicly funded PDP activities in the empirical context of production technology for advanced biofuels. The study is conducted by employing patent data for eight European countries over the time period 1980-2011, and it is acknowledged that PDPs have two main objectives: testing and optimization of technology (experimental PDPs), and diffusion and commercialization of technology (exemplary PDPs). The results are overall robust to alternative model specifications, and indicate that: (a) PDP activities are overall positively correlated with biofuel patenting activity; (b) both experimental and exemplary PDPs encourage biofuel innovation although the impact of the former is more profound; and (c) development activities in experimental PDPs encourage innovation also indirectly through knowledge spillovers across countries.
Keywords: innovation, patent, pilot plant, demonstration plant.

1 INTRODUCTION

1.1 Background and contribution

The transport sector is currently facing a number of challenges such as its dependence on fossil fuels, local air pollution and its contribution to greenhouse gas emissions. On political agendas and in the media the issue of biofuels for transportation is becoming increasingly prevalent, a fact reflected in, e.g., the passing of the Renewable Energy Directive by the EU Commission in 2009 (Directive 2009/28/EC). The directive lays down a mandatory 10 percent minimum target for the share of biofuels and other renewables in road transport fuels to be achieved by all member states by 2020.

Production and use of biofuels provide several benefits, including de-carbonization of the transport sector and reduced local air pollution, and this is especially the case of so-called advanced biofuels (produced from non-edible feedstock). However, commercialization and large scale deployment of advanced biofuels are obstructed as the production technologies are not yet mature and still under development. While production processes have been tested and proven in lab scale, tests, re-development and demonstration at larger scale is necessary before the technologies can successfully be implemented commercially. In response to this, a number of companies around the world pursue projects to develop and deploy technologies for production of advanced biofuels by operating pilot and demonstration plants (PDPs) [1]. PDP activities are taking place along a number of trajectories which differ with respect to, e.g., the type of biofuel produced and the production process used. For instance, some PDPs produce synthetic natural gas (SNG) based on thermochemical conversion while others employ biochemical conversion processes to produce ethanol.

Using PDPs to test, develop and diffuse technology is not a unique feature of the biofuel sector, nor is it a new phenomenon in the energy sector. For instance, a number of PDPs are currently being operated or planned around the world to enable learning and reduce costs in the case of carbon capture and storage (CCS) technology [2]. Moreover, several wind power and solar photovoltaic (PV) PDPs have been operated in Europe, Japan and the US since the 1970s [3]. Still, PDPs have been used earlier than this – pilot experiments were for example conducted in the early 1940s by the pharmaceutical company Merck, which indicated that streptomycin was the answer to tuberculosis [4].

PDPs may be important for fostering technological development (i.e., innovation) as they constitute a bridge between basic knowledge generation on the one hand, and exploitation of new technology for commercial use on the other. For instance, so-called experimental PDPs offer opportunities for technology to be developed, fine-tuned and adjusted for commercial purposes in an industrially relevant scale [5]. Moreover, so-called exemplary PDPs can be important for the reduction of organizational, institutional and market related uncertainties which could otherwise hamper desirable diffusion and learning-by-doing (e.g., tacit knowledge acquired during manufacturing) [6] and [7]. It has also been suggested that development activities at PDPs may generate knowledge spillovers which are beneficial to society [8]. A lack of understanding of the importance of PDPs for technological innovation makes it difficult to design appropriate public support for such activities and to realize potentially generated social benefits.

The relationship between environmental policy and innovation has received increasingly more attention in the empirical research, and the overall findings suggest a positive correlation between the two [9]-[12]. Previous research efforts also indicate that technical innovation in the renewable energy sector can generally be induced by two main policy types: public R&D support, and production support schemes such as feed-in tariffs or renewable energy certificates, e.g., see [9] and [13]. Still, while the role of these policies for technology development has been fairly well investigated, the potential innovation impacts of publicly funded PDP activities have been largely overlooked [5] and [14].

In one of the few studies available, it is concluded that PDPs are important not only for technical development but also for market creation and network formation [15]. Other studies explicitly addressing the role of privately or publicly funded PDPs in socio-technical regime shifts and technology development include [6] and [16]-[19]. The existing research, however, consists of conceptual studies or retrospective case studies based entirely on qualitative or descriptive approaches [5] and [14]. Consequently, while the importance of PDPs for innovation has been confirmed in such studies, their role for technical development remains to be investigated also in a quantitative empirical setting.

1.2 Purpose and overall approach

Following the above, the specific purpose of this paper is to empirically assess the effects of publicly funded PDP activities on innovation in advanced biofuel production technology. In doing this it is acknowledged that PDPs have two main objectives: testing and optimization of technology in an industrially relevant scale (experimental PDPs), and diffusion and commercialization of technology and products (exemplary PDPs). Technical innovation is measured as counts of patents related to technology for producing advanced biofuels.

The empirical analysis builds on a panel data set of eight European countries over the time period 1980-2011. Regression models are specified in which the dependent variable, biofuel patent counts, is explained by PDP activities along with a selection of control variables (see further section 4.1). Based on the estimation results elasticities are computed reflecting changes in patenting activity with respect to (marginal) changes in the independent variables. Specifically, the paper analyzes: (a) the overall effect of PDPs on innovation in biofuel technology; (b) the innovation impacts of PDPs with different objectives; and (c) whether PDPs induce technical development also indirectly through knowledge spillovers.

1.3 Current status of advanced biofuels for transportation

In most parts of the world, the fastest growth in biofuel production has taken place since the 2000s and has generally been promoted by blending obligation schemes and tax incentives. Global production increased from 16 to 100 billion liters between 2000 and 2010 [20], and in the IEA member countries in Europe, biodiesel production grew from 717 to 9.765 kiloton during the same period [21]. In 2008 about 3 percent of the demand for road transport fuels was met with biofuels in the EU [20], and biodiesel constituted around 80 percent of these while the rest were primarily bioethanol, pure plant oil and biogas [22].

Still, the impressive increase in biofuel production has not been free of controversy. Their ability to displace fossil energy has been questioned along with their ability to de-carbonize the transport sector [23], and studies have linked their production to rising food prices and analyzed their potential contribution to deforestation, e.g., [24] and [25]. These discussions have prompted an increased interest in so-called advanced biofuels, a fact reflected in a recent proposal by the Energy Council of the EU limiting the support for conventional biofuels while encouraging member states to set minimum target levels for advanced biofuels (Proposal for a Directive COM(2012) 595). Advanced biofuels refers to: (a) 2nd generation biofuels (derived from non-food sources, e.g., wheat stalks, corn stover etc.); (b) 3rd generation biofuels (derived from algae); and (c) 4th generation biofuels (derived from modified micro-organisms) (1). Advanced biofuels enable greater reductions in greenhouse gas emissions and are less water and land intensive compared to conventional (1st generation) biofuels derived from edible feedstock, e.g., sugar or starch [26], [27] and [29].

2 THE ROLE OF PILOT AND DEMONSTRATION PLANTS IN TECHNOLOGICAL DEVELOPMENT

In recent decades the role of endogenous innovation and technological change has received increased attention in the economics literature on environmental policy and innovation, e.g., [11], [30] and [31]. Modeling endogenous innovation implies explicitly addressing the feedback mechanisms by which market signals and policy may change the direction of technological change towards cleaner (e.g., carbon-free) energy technology (2). Generally, policy-induced innovation is modeled as occurring through two main channels: basic knowledge generation, and learning-by-doing (e.g., tacit knowledge acquired during manufacturing). The former is supported by public R&D expenses which add up to a cumulative knowledge stock, e.g., [33] and [34]. The latter is encouraged by production support schemes resulting in capacity and production expansions [35]. Fig. 1 provides an illustration of the conceptual framework which draws heavily on [5].

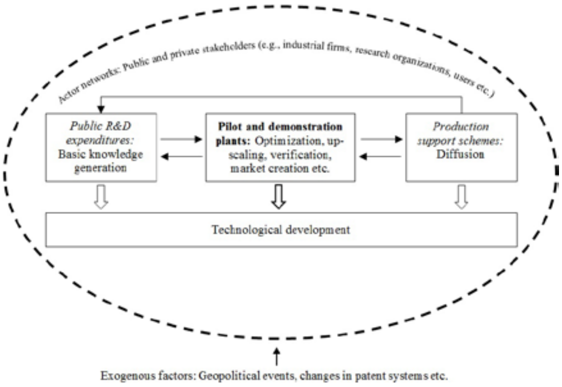

Figure 1: The role of pilot and demonstration plants in the process of technological development
Source: Adapted from [5].

The mid-part in Fig. 1 builds on the Schumpeterian notion of three stages in the process of technological development: invention, innovation and diffusion [36]. These constitute the conditions necessary for successful large scale deployment of a product or technology. Invention refers to development of a new product or process and innovation to the subsequent process in which technology is up-scaled, optimized and commercialized (these terms are often used synonymously in the literature). Diffusion refers to the gradual adoption of the new technology by firms. Still, this linear view of the technology development process needs to be developed in some important respects.

First, the technology development process is iterative and non-linear in the sense that none of the stages represent isolated activities. In practice there are feedback effects from the pilot and demonstration plant (PDP) phase to basic R&D and from the diffusion stage to PDP activities and basic R&D, e.g., [37] and [38]. For instance, when new technology is introduced future innovations will be affected (the re-development of a technology) through learning and vice versa. Second, innovation may be encouraged not only with R&D expenditures and production support schemes, but also with publicly funded PDP activities [3], [15] and [39]. Third, the process of technological progress is embedded in an actor network consisting of industrial firms, research organizations, users etc. [40]. These networks can shape the process by lobbying for political support, and they grow more complex as the system boundaries become wider as we move from the R&D stage towards deployment. Fourth, and finally, the technology development process is also influenced by exogenous factors, e.g., geopolitical events or changes in patent systems.

The innovative activities of firms are generally viewed as being profit-motivated, regardless if firms are perceived as rational agents who optimize their R&D investment activities, e.g., [41]. The R&D investment decisions are therefore essentially governed by their expected return as well as their costs. There are a number of factors which may determine the profitability of R&D and these include the size of the market, general scientific capacity and appropriability conditions [42]-[44]. Specifically, a larger market implies an increasing potential for firms to recoup their investments, and an increased general scientific capacity (i.e., scientific personnel, resources etc.) makes additional innovation less costly at a fixed level of demand. Moreover, know-how produced from R&D may benefit recipient firms that can imitate at a fraction of total costs incurred by the originator. The profitability of R&D and the propensity to engage in innovative activities and patenting are therefore also affected by legal conditions (i.e., patent rules and intellectual property rights). As legal conditions may differ across countries and over time, the propensity to patent will probably vary across countries and change over time within countries [45].

In this paper the relationship between publicly funded PDP activities and biofuel patent counts is examined. As suggested in the literature, PDPs can take on a number of important roles in the technology development process as they focus not solely on technical progress but on commercialization as well. This raises the question what is actually measured with patent counts. The indicator is generally taken as a measure of inventive performance in the economics literature on policy-induced innovation, which is also the case in this paper. Still, for an invention to be patented it must not only be novel and involve a non-obvious step – it must also be commercially viable [46]. Furthermore, most economically significant inventions have been patented [47] and [48], suggesting that the indicator may reflect the creation of new technology as well as its subsequent commercialization. While this question is important for the purpose of this paper, it has bearing for research based on patent counts in general. For a more thorough discussion on patent data, see section 5.1.

3 PILOT AND DEMONSTRATION PLANTS FOR ADVANCED BIOFUELS

This section provides an overview of pilot and demonstration plants (PDPs) producing advanced biofuels and/or fine-tuning conversion processes in the sample countries and over the time period 1980-2012 (the data sources are specified in section 5.2). No bench or lab scale plants have been considered for this study and only PDPs having received partial public funding are included. Moreover, PDPs exclusively working with biofuels from edible feedstock (conventional biofuels) have not been taken into consideration.

Table A1 in the Appendix provides an overview of the plants being, or have been, in operation. A PDP focusing primarily on technology optimization is classified as an experimental PDP, and a plant functioning mainly to diffuse a technology or product is categorized as an exemplary PDP. In summary, 15 PDPs have been in operation with the majority focusing on technology development and up-scaling issues and thus viewed as experimental plants. All sample countries have supported advanced biofuels by investing public funds in PDPs, although the number of plants supported varies across the countries. Public funding has been awarded to more than one plant only in Denmark (six PDPs), Germany (two PDPs) and Sweden (two PDPs).

Plant investments and installed output capacities vary considerably across PDPs. The highest investment, €56.18 million, has been made in the PDP in Babilafuente (Spain) and the lowest, €0.85 million, in the Maxifuel facility in Copenhagen (the figures reflect both private and public investment funds). Regarding output capacities, the biorefining plant in Oulu (Finland) can produce 5.000 tons per year of ethanol which is unmatched by the other PDPs with capacities from 4.300 tons per year of ethanol down to as little as 2 tons per year of hydro treated vegetable oil (HVO). Moreover, of the 15 PDPs covered only three produce biofuels based on thermochemical conversion, the remaining plants use biochemical processes. Finally, all PDPs work on 2nd generation biofuels, but some plats also work on 1st and 3rd generation fuels.

Counts of PDPs in operation are displayed in Fig. 2. As shown, there has been a steady increase in the number of operational PDPs. The experimental Pilot 1 facility in Fredericia (Denmark) started its operation in 2003 and was the first PDP on stream. During 2004-2012 a number of additional experimental PDPs came into operation resulting in ten facilities on stream by 2012. Work in two exemplary PDPs was started in 2010 and these were the Biorefinery Demo Plant in Örnsköldsvik (Sweden) and the Chempolis Biorefining Plant in Oulu (Finland). The third exemplary PDP, the Bio Base Europe Pilot Plant in Ghent (Belgium), became operational in 2011 (3).

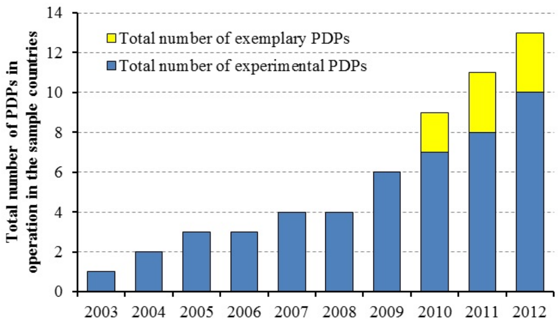

Figure 2: Total number of pilot and demonstration plants in operation in the sample countries
Sources: [1] and [49]-[51].

Another way of depicting PDP activities is to consider the investments made in each plant. Investments can result in the build-up a knowledge stock over time, and in this paper annual PDP investments are assumed to add to this stock with a time lag and knowledge is assumed to depreciate over time at a certain rate (see section 5.2). Fig. 3 depicts the development of two knowledge stocks based on investments in experimental and exemplary PDPs, respectively.

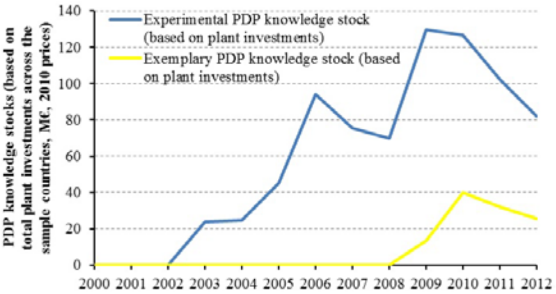

Figure 3: Pilot and demonstration plant based knowledge stocks constructed of total plant investments across the sample countries (1 year lag and 20 % depreciation rate)*
** One experimental PDP has not been considered due to missing data*.
Sources: [1], [50] and [51] and various plant specific sources.

The first investment in experimental plants was made in 2002 and has been followed by additional investments resulting in an ever larger experimental PDP knowledge stock. The exemplary stock also displays an overall positive trend, with the first investments being made in 2008. Notable is that the experimental stock is greater during 2000-2012.

4 METHODOLOGICAL APPROACH AND MODEL ESTIMATION ISSUES

4.1 Model specifications

In this paper it is hypothesized that biofuel innovation is explained by policy support, market factors, general scientific and technical advancements, and legal conditions. The innovation effects of pilot and demonstration plants (PDPs) are empirically investigated by using patent counts, and this approach necessitates the use of some count data modeling technique which has been developed for estimating the number of occurrences of an event, or event counts, e.g., [52] and [53]. An event count is formally defined as the realization of a non-negative integer-valued random variable. For this study, an event count corresponds to the number of biofuel patents in a given country and time period.

Five models, hereafter denoted S1-S5, are specified which differ concerning how PDP activities are operationalized. In all specifications the dependent variable, biofuel patent counts (*BIOPAT*), is assumed to be explained by PDP activities (*PDP*) along with a selection of control variables: biofuel blending obligations (*BLEND*), fossil diesel prices (*PRICE*) and total counts of patent applications for all technology areas (*TOTPAT*). The following reduced-form model can thus be specified:

$$BIOPAT_{i,t} = \beta_0 + \beta_1(PDP_{i,t}) + \beta_2(BLEND_{i,t}) + \beta_3(PRICE_{i,t}) + \beta_4(TOTPAT_{i,t}) + \sum_{i=1}^{n-1} \beta_{4+i} D_i + \varepsilon_{i,t}$$

where i indexes the cross-sectional unit (i.e., country) and t indexes time. Country-specific dummy variables (D) have been included to control for fixed effects attributed to unobserved factors such as regulatory and institutional framework etc. Finally, all residual variation is captured by the additive error term ($\varepsilon_{i,t}$).

Biofuel blending obligation schemes (*BLEND*) are basically requirements on fuel distributors to supply certain amounts of biofuels in relation to total sales of fossil fuels. Blending schemes are included since demand-pull production support should incentivize biofuel patenting activity by establishing a larger market and thus an increased potential for firms to recoup their investments. Furthermore, the commercial viability of biofuels is largely dependent on their price relative to the price of substitutes such as automotive diesel fuel. Increases in fossil diesel prices (*PRICE*) should imply increasing commercial viability of biofuels and thus increasing incentives to innovate in their production technology. Finally, total counts of patent applications related to all sorts of technologies (*TOTPAT*) are included to control for variations in scientific capacity and the overall propensity to patent over time and across countries.

In the first and second specification (S1 and S2), it is assumed that biofuel patent counts are explained by the build-up of a PDP based knowledge stock over time. Specifically, annual investments in PDPs are assumed to add to this stock with a time lag, and it is also assumed that knowledge depreciates over time at a certain rate, e.g., [13], [54] and [55]. In S1, the knowledge stock (*ALLSTOCK*) is based on total investments in experimental and exemplary PDPs. In S2, these investments are disaggregated by experimental PDPs (*EXPSTOCK*) and exemplary PDPs (*EXEMSTOCK*). Section 5.2 covers the details of these variable specifications.

Since this is the first explicit attempt to quantitatively examine the innovation effects of PDPs, an alternative way of measuring PDP activities is considered in the third specification (S3). Here the PDP investment based knowledge stocks have been replaced with a measure of installed output capacity in exemplary PDPs accumulated over time in each respective sample country (*EXEMOUTCAP*). Increases in cumulative output capacity reflect intensive PDP activities and should thus be positively correlated with biofuel patenting. A similar measure for experimental PDPs is not tested since these plants are operated mainly for technology optimization and development and seldom for continuous production.

The fourth and fifth specifications (S4 and S5) are based on the measure of PDP activities as investment based knowledge stocks. In S4, it is tested whether marginal increases in the experimental PDP knowledge stock have a higher innovation effect when there are more than one experimental PDP in operation in a given country and year (see further section 5.2). Specifically, a slope dummy variable (*INTEREXPSTOCK*) is included to test this notion. In S5, it is tested whether biofuel innovation activities in a given country are influenced by domestic as well as foreign PDP knowledge stocks (*FEXPSTOCK* and *FEXEMSTOCK*). In other words, biofuel patenting in, e.g., Sweden could be affected not only by domestic PDP knowledge stocks but also by PDP investments in other European countries adding up to foreign knowledge stocks. With this modeling approach the innovation effects of country-level knowledge spillovers are thus tested, e.g., [56]-[58].

In summary, the empirical analysis is based on five model specifications which differ concerning how PDP activities are operationalized: (S1) PDP activities measured as a knowledge stock based on total PDP investments; (S2) knowledge stocks based on investments in experimental and exemplary PDPs, respectively; (S3) exemplary PDP activities measured as cumulative output capacity; (S4) PDP knowledge stocks and a slope dummy variable for increases in the knowledge stock and when there are more than one PDP in operation; and (S5) domestic and foreign PDP investment based knowledge stocks.

4.2 Econometric issues

The count nature of the dependent variable studied necessitates the use of some count data estimator such as a negative binomial (NB) or Poisson estimator. Since patent count data are generally overdispersed, meaning that the variance exceeds the mean, a NB estimator is used for this study since it can accommodate this issue, e.g., [59] and [60]. A NB estimator is also used in other related work, e.g., [9] and [61].

A number of different NB models have been developed and those most commonly used are the so-called NB1 and NB2 models [53]. Their performance has been analyzed in a panel count data setting, and it has been found that the conditional NB1 model does not control for fixed effects unless a very specific set of suppositions are met, e.g., [62] and [63]. However, the unconditional NB2 model, a conventional NB2 model with dummy variables to address the fixed effects, performs well although the standard errors are biased downwards. Thus, the unconditional NB2 model is used for this study, and bootstrapped standard errors are computed to adjust for potential bias in the standard error estimates.

All model specifications are estimated using Stata 12 and a modified Newton-Raphson algorithm (i.e., the default setting when employing maximum likelihood estimation). To avoid perfect collinearity, the country-specific dummy variable for Germany is omitted from the estimations. Hence, Germany is the reference country in all regressions that follow.

5 DATA SOURCES AND DEFINITIONS

The econometric analysis in this paper is based on an unbalanced panel data set comprising eight European countries over the time period 1980-2011. Specifically this includes Austria, Belgium, Denmark, Finland, France, Germany, Spain and Sweden. Among these, prominent biofuel producers are included (e.g., Germany and France) as well as relatively small producers (e.g., Austria, Denmark and Finland). Due to delays in the publishing of patent information, the rate of applications decrease in recent years (2012-2015) and the panel data set is thus limited to 2011.

5.1 The dependent variable: biofuel patent counts

To measure biofuel innovations (the dependent variable), counts of patent families have been used related to technologies for pre-treatment and conversion of biomass to advanced liquid and gaseous biofuels for transportation. This includes conversion by thermochemical (e.g., gasification), chemical (e.g., hydro treatment) and biochemical methods (e.g., enzymatic hydrolysis) (4). A patent family is a set of patents or applications recorded at various patent offices around the world usually protecting the same invention [46]. In this paper, counts of Derwent World Patents Index (DWPI) families are used as a proxy for innovation activity, and due to their strict family definition they are generally deemed representative of single inventions, e.g., see [64] and [65]. Specifically, the only DWPI families considered are those containing (at least) an application filed through the Patent Cooperation Treaty (PCT) and/or to the European Patent Office (EPO). These families, referred to as ‘transnational patents’, are especially suitable to employ for up-to-date policy studies [66]. Furthermore, by imposing the condition above, only families protecting inventions with high economic value are covered (only patents with high expected value are filed through the relatively costly supranational procedures). Because of the same condition, all families considered must comply with PCT and/or EPO formality requirements and the data are thus largely free from patent comparability issues caused by differences in patent rules and practices across countries. In line with recommendations in [46], the data are sorted by inventor country of residence and earliest priority date, and the data are rounded to the nearest integer (patents specifying multiple inventor countries were partly attributed to each country by the use of fractional counts).

The data were compiled and provided by Thomson Reuters based on their Derwent World Patents Index (DWPI) database, see [67]. To avoid inclusion of irrelevant patents and exclusion of relevant patents, the data collection was based on combinations of key terms, International Patent Classification (IPC) codes and Derwent Manual codes. Patent collection based solely on IPC codes is associated with relatively poor validity in the case of biofuel technology [68].

To identify relevant and suitable indexing codes as well as key terms and phrases in the technical area, initial searches were conducted to acquire a small sample of high relevance. The sample was reviewed by using text mining, and indexing codes were tested for appropriateness. The search strategies developed were eventually applied to the database in an iterative procedure meaning that they were tested and re-tested as new key terms and classification codes were identified. In this way, a well-balanced and substantive overview of the technical area was assembled while avoiding high noise levels [65].

Patent counts are one of the most frequently used indicators of technological innovation, e.g., [9], [13] and [69]. Moreover, since patents are outputs of innovation activities as opposed to other potential indicators such as R&D expenditures, they are generally viewed as a more suitable proxy. Patents also have a close link to inventions and they can be disaggregated to specific technologies due to their detailed information content. Still, using patent counts to measure innovation is associated with a number of problems: (a) not all inventions are patented; (b) the value distribution of patents is highly skewed; and (c) there are differences in patent regimes and patent propensity across countries and over time [45], [46] and [70]. It is reasonable to assume that patent counts are positively correlated with non-patented inventive activity [71], and this mitigates the issue outlined in (a). Moreover, measuring innovations with counts of transnational patents limits the issues outlined in (b) and (c), and differences in patent propensity across countries and over time can be controlled for by the inclusion of country fixed effects and a variable reflecting national patenting activity across all technical areas.

Fig. 4 illustrates the patent data for the sample countries in terms of counts of transnational patents related to advanced biofuels, and their share of the total number of applications filed under the PCT (across all technical areas).

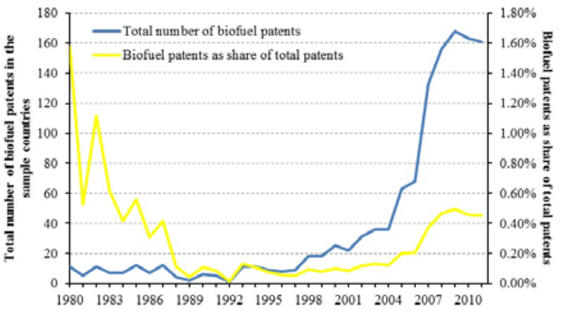

Figure 4: Biofuel patent families (transnational patents) in the sample countries
Source: [67] and [72].

Biofuel patenting activity remained stable on a relatively low level during the first half of the time period studied, and after 1997 it increased rapidly but tailed off after 2009. Biofuel patents as share of total patents exhibit a U-shape pattern. Between 1980 and around 1995 there were relatively small differences with respect to biofuel patenting across the sample countries. Still, in the end of the 1990s Germany saw its biofuel patent applications increase significantly, and France saw its applications increase rapidly since 2004. These developments have made Germany and France the most prominent in biofuel patenting among the sample countries in recent years. The remaining sample countries saw their applications increase in the beginning of the 2000s, although they did not experience a take-off of the same magnitude. Among these, Denmark, Finland and Sweden stand out with the highest number of applications while the figures for Austria, Belgium and Spain display more modest trends.

5.2 The independent variables

The independent variables in the model specifications tested can be divided into two main categories: pilot and demonstration plant (PDP) variables, and control variables. To measure PDP activities, two principal approaches are tested where the first is based on total (public and private) plant investments and the second on cumulative output capacity. In this paper it is assumed that PDP investments (in total or categorized for each PDP type) add up to an investment based knowledge stock:

$$ALLSTOCK_{i,t} = (1 - \delta)ALLSTOCK_{i,t-1} + PDPINVEST_{i,t-x}$$

where i indexes the sample country and t indexes time. *ALLSTOCK* is the (aggregate) PDP investment based knowledge stock for biofuels in country i and time period t, *PDPINVEST* are the annual investments in both PDP types, x is the number of years it takes before investments add to the knowledge stock, and δ is the annual depreciation rate of the knowledge stock ($0 \leq \delta \leq 1$). Hence, the formulation suggests that: (a) PDP investments do not have an instantaneous effect on the generation of new knowledge, but will only lead to tangible results after some time has lapsed; and (b) knowledge depreciates in that the effects of previous investments gradually become outdated, e.g., see [73]. The same formulation is applied to the PDP type specific knowledge stocks (*EXPSTOCK* and *EXEMSTOCK*), which are based on plant investments disaggregated by experimental and exemplary plants, respectively.

To construct the knowledge stock variables a time lag of one year ($x = 1$) and a depreciation rate of 20 percent ($\delta = 0.20$) is assumed. This suggests a relatively high rate of knowledge depreciation [55], [73] and [74], but this is reflected in the relatively intensive development of production technology for advanced biofuels during the recent decades. Though, given the uncertainties inherent in these parameter assumptions, the consequences of using alternative depreciation rates and times lags are examined in a sensitivity analysis.

The knowledge stock variables have been constructed based on PDP investment data in [1], [50], [51] and various plant specific sources. The investment figures were taken as nominal currency for the year of the publication or legislation and were deflated to 2010 prices by using a consumer price index. The figures were also converted to EUR when necessary by using market exchange rates. All PDPs covered in this study have been erected during the 2000s and PDP investment figures were thus equal to zero in 1980 (the starting year of the time period covered in this study). These figures represent the initial conditions when constructing the PDP investment based knowledge stocks. For example, the knowledge stock reported in 2005 for a given country is a function of the annual investments in biofuel PDPs during the time period 1980-2004, and with the above depreciation rate attached to the stock. The data sources mentioned above were also used to construct: (a) the second and alternative measure of PDP activities (*EXEMOUTCAP*) based on cumulative output capacity (tons/year), and to this end, data on PDP specific output capacities were also extracted from [49]; (b) the interaction variable (*INTEREXPSTOCK*) investigating whether increases in the knowledge stock based on experimental PDP investments are more innovation-promoting when there are more than one experimental PDP in operation; and (c) the foreign knowledge stocks (*FEXPSTOCK* and *FEXEMSTOCK*) based on PDP investments in n - i sample countries (constructed by adding national knowledge stocks across the sample countries in each year). The focus on experimental PDPs in the case of the interaction variable depends on the lack of observations in the data set where there is more than one exemplary plant in operation (or where both types are in operation simultaneously).

All model specifications (S1-S5) include three control variables: biofuel blending obligation schemes (*BLEND*), fossil diesel prices (*PRICE*) and total patent applications (*TOTPAT*). In the case of *BLEND*, policy stringency is measured as the required biofuel share of total fossil fuel sales of individual fuel distributors in terms of energy content, and the data were taken from [75], [76] and various country-specific sources. *PRICE* is based on an industry end-user price index obtained from [77], and the index reflects automotive diesel fuel prices including taxes. Prices of petrol were not considered in the empirical analysis since the data suffered from missing observations in several official databases. Still, petrol and diesel prices are likely to be highly correlated, and the European market for automotive fuels is generally considered to be heavily 'dieselized', e.g., [78] and [79]. Finally, *TOTPAT* reflects total patent applications filed under the Patent Cooperation Treaty (PCT) regardless of technological area. The data were obtained from [72] and are sorted by inventor country of residence and priority date.

The variables employed in the empirical analysis are summarized in Table I. Due to some missing observations in *BLEND*, the S3 model is fitted using 251 observations. S1, S2 and S4 use 240 observations because of some additional missing observations in *EXPSTOCK*. S5 use 219 observations due to the missing observations mentioned above and since Austria is excluded from the regression (see further section 6.1). The descriptive statistics presented in the table are based on the 240 observations used to estimate S1, S2 and S4.

6 EMPIRICAL RESULTS AND DISCUSSION

6.1 Model estimation results

Table II presents the regression results of the five model specifications using a negative binomial model (NB2) with bootstrapped standard errors stratified by country and country-specific fixed effects (5). For all model specifications, the Newton-Raphson algorithm converged to a maximum after relatively few iterations and a concave (i.e., marginally declining) convergence path could be observed (6-9 iterations were required for fitting each specification). In other words, all five log-likelihood functions seem to be well-behaved [80]. All models are statistically significant according to the *p*-values associated with the Wald x^2-statistics, thus rejecting the null hypothesis that all of the estimated coefficients are equal to zero. Finally, overdispersion tests suggest that a NB distribution and estimator is better suited than a Poisson for the biofuel patent data, e.g., [53]. Likelihood-ratio tests and Wald tests were conducted and both reject the null hypothesis of equidispersion (i.e., that the overdispersion parameter is equal to zero), except for S4 and S5 where the Wald test could not reject the null hypothesis. Although the tests yield conflicting results for S4 and S5, a NB estimator is still regarded as preferable over a Poisson since it can accommodate overdispersion parameters close to zero as well as overdispersion. Nevertheless, the flexibility of a NB estimator comes at the price of larger standard errors than those produced by a Poisson estimator [59].

According to Table II, biofuel technology innovations are (partly) driven by increasing pilot and demonstration plant (PDP) investments (6). Specifically, increasing PDP investment based knowledge stocks explains variation in biofuel innovation – regardless if the investments are broken down by PDP type (*EXPSTOCK* and *EXEMSTOCK*) or not (*ALLSTOCK*). The alternative measure of PDP activities, cumulative output capacity of exemplary plants (*EXEMOUTCAP*), is statistically insignificant – possibly due to few non-zero observations and thus low variation in the variable. S4 tests whether marginal increases in the experimental PDP knowledge stock (*INTEREXPSTOCK*) are more innovation-promoting when there is more than one such PDP in operation in a given country and year (ceteris paribus). The econometric results, however, do not support such a notion. Moreover, the foreign knowledge stock based on investments in experimental PDPs (*FEXPSTOCK*) is found to be important for biofuel patenting in a country. Concerning the coefficients for the control variables, all are statistically significant and positive across the specifications. Increasing biofuel blending targets (*BLEND*) seem to induce biofuel patents, which is also the case of higher diesel prices (*PRICE*). The overall propensity to patent (*TOTPAT*) also explains some of the variations in biofuel innovation (7).

Although the coefficients provide useful information about the sign of the innovation impacts of the explanatory variables, the economic significance (i.e., size) of these impacts is difficult to interpret. Formally, the coefficients are expressed as the difference between the natural logarithms of expected counts [59]. To examine the size of the impacts of the independent variables, elasticities are computed as $\varepsilon = b_j\bar{x}_j$ which is a measure of the elasticity of $E[y|\boldsymbol{x}]$ with respect to x_j (i.e., the j^{th} regressor) [53]. The elasticities are presented in Table II (as 'E: …') and are interpreted as the percentage change in biofuel patenting following a one percentage change in a given explanatory variable.

The estimated elasticities suggest that all control variables are positively correlated with biofuel innovation activity, but also that their economic significance differs considerably. A one percent increase in biofuel blending targets or total patent applications (ceteris paribus) induces a 0.032-0.063 or 0.072-0.105 percent increase in biofuel patents (depending on the model specification), respectively. These impacts are not particularly strong compared to the innovation effect of increasing diesel prices. If the prices increase by one percent (ceteris paribus), patent counts increase by 2.686-4.020 percent.

The elasticities confirm an overall positive (lagged) innovation effect of PDP investments adding up to investment based knowledge stocks (8). The elasticity is positive and equal to 0.068 in the S1 model where the knowledge stock is based on investments in both PDP types. When categorizing the investments as related to experimental or exemplary plants, as done in S2, the estimated elasticities are positive and equal to 0.058 and 0.013, respectively. Thus, the results suggest that experimental PDPs have been more innovation-promoting than exemplary plants. This finding is confirmed by S4 where the corresponding elasticities are equal to 0.075 for experimental PDPs and 0.013 for exemplary PDPs. In S5 one of the foreign knowledge stocks is found to be positively correlated with biofuel innovation. The elasticity for the experimental PDP investment based knowledge stock is equal to 0.184, suggesting a 0.184 percent increase in biofuel patents in a given country following a one percent increase in the foreign knowledge stock associated with experimental

Table I: Variable definitions and descriptive statistics

Variables	Description and units	Mean	S.D.	Min	Max
Dependent variable					
BIOPAT	Total number of biofuel patent families (counts)	4.346	8.783	0	59
Independent variables					
BLEND	Annual blending obligation targets for biofuels (% of total sales of fossil fuels in terms of energy content)	0.292	1.193	0	7
PRICE	Price index for automotive diesel fuel (2010 = base year)	75.227	16.813	34.461	111.953
TOTPAT	Total PCT patent filings (count in thousands)	1.95	3.501	0	18.492
ALLSTOCK	PDP investment based knowledge stock (million EUR in 2010 prices, see section 5.2 for detailed definitions of the stock variables)	3.087	9.895	0	68.246
EXPSTOCK	Knowledge stock based on investments in experimental PDPs (million EUR in 2010 prices)	2.881	9.71	0	68.246
EXEMSTOCK	Knowledge stock based on investments in exemplary PDPs (million EUR in 2010 prices)	0.207	1.72	0	20.243
EXEMOUTCAP	Cumulative output capacity of exemplary PDPs (tons/year)	22.333	323.114	0	5000
INTEREXPSTOCK	*EXPSTOCK* multiplied with a dummy variable taking the value one (1) if there are more than one experimental PDP in operation, 0 otherwise	1.041	6.816	0	68.246
FEXPSTOCK	Foreign knowledge stock based on investments in experimental PDPs in n - i sample countries (million EUR in 2010 prices)	16.766	33.504	0	129.439
FEXEMSTOCK	Foreign knowledge stock based on investments in exemplary PDPs in n - i sample countries (million EUR in 2010 prices)	2.016	7.576	0	39.813

PDP activities. Hence, development activities in experimental plants appear to induce technical innovation also indirectly through country-level knowledge spillovers. The results indicate a negative and statistically significant innovation effect of the other foreign knowledge stock based on investments in exemplary plants. On the one hand this finding is unexpected given the focus of exemplary plants on commercialization and technology diffusion, activities which can be assumed to be positively correlated with knowledge spillovers and which can encourage innovation in turn. On the other hand, the spillovers may concern primarily how to create customer awareness instead of spreading technology learning as such. Still, this reasoning does not explain the negative innovation impact of the knowledge stock.

6.2 Discussion

This section provides a discussion of the empirical results, and contrasts these to the findings of other studies. Overall the results suggest that renewable energy patents are influenced by general propensity to patent as well as variation in fossil fuel prices. These findings are in line with other work, e.g., [9], [81] and [82]. Nevertheless, while this paper reports a statistically significant and positive innovation impact of demand-pull production support measured as biofuel blending targets, [82] along with [83] and [84] cannot reject the null hypothesis that this impact is non-existent. Possible explanations for the divergent results include that policy stringency is measured as annual targets in this paper while [83] include a dummy variable set to unity for the years when biofuel blending obligations are in force. In [82], on the other hand, patents are considered not only related to biofuel conversion processes but also to technology used for feedstock production as well as for ethanol combustion in automotive engines. In [84], patents related to advanced biofuel technology are considered and biofuel blending schemes are measured in the same way as in this paper, although the policy variable is lagged with one year. Nevertheless, the relation between ethanol innovation and market characteristics in Brazil is examined in [85], and the findings suggest that there is a demand-pull effect between ethanol consumption and innovation, thus providing some support for the above finding in this paper.

The results indicate a positive biofuel innovation impact of total PDP investments as well as investments in experimental and exemplary PDPs, respectively. This finding is consistent with qualitative research suggesting that PDPs facilitate technology learning and that they hold an important role in the process of technological development, e.g., [5], [15] and [86]. Moreover, a positive correlation between innovation and exemplary PDP investments confirms that such plants focus not only on market creation and diffusion, but on technology development as well, as suggested in [8]. Still, the results suggest that experimental PDPs are more

Table II: Estimation results from the negative binomial models with fixed effects

	S1	**S2**	**S3**	**S4**	**S5**[a]
Control variables					
BLEND	0.140** (0.015) E: 0.041	0.127** (0.022) E: 0.037	0.164*** (0.001) E: 0.063	0.123** (0.034) E: 0.036	0.101* (0.065) E: 0.032
PRICE	0.047*** (0.000) E: 3.536	0.046*** (0.000) E: 3.460	0.053*** (0.000) E: 4.020	0.046*** (0.000) E: 3.460	0.036*** (0.000) E: 2.686
TOTPAT	0.050** (0.011) E: 0.098	0.054*** (0.002) E: 0.105	0.041** (0.040) E: 0.079	0.054*** (0.002) E: 0.105	0.034** (0.038) E: 0.072
PDP variables					
ALLSTOCK	0.022*** (0.000) E: 0.068	------	------	------	------
EXPSTOCK	------	0.020*** (0.000) E: 0.058	------	0.026*** (0.001) E: 0.075	0.023*** (0.000) E: 0.073
EXEMSTOCK	------	0.063*** (0.000) E: 0.013	------	0.063*** (0.000) E: 0.013	0.046 (0.161) E: 0.010
EXEMOUTCAP	------	------	0.000 (0.853) E: 0.004	------	------
INTEREXPSTOCK	------	------	------	-0.010 (0.311) E: -0.010	------
FEXPSTOCK	------	------	------	------	0.011*** (0.000) E: 0.184
FEXEMSTOCK	------	------	------	------	-0.024*** (0.003) E: -0.048
Log-likelihood (NB)	-421.761	-419.772	-456.926	-419.153	-387.928
Log-likelihood (Poisson)	-484.956	-471.621	-519.230	-471.140	-399.235
Overdispersion parameter (α)	0.226 (s.e. 0.082)	0.206 (s.e. 0.073)	0.253 (s.e. 0.075)	0.203 (s.e. 0.236)	0.098 (s.e. 0.189)
Wald x^2	489.00	555.67	577.89	507.40	653.68
$p > x^2$	0.000	0.000	0.000	0.000	0.000
N	240	240	251	240	219

Note: *p*-values in parentheses (based on bootstrapped standard errors stratified by country); * $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$. Stata automatically provides the log-likelihood of fitting a Poisson model (the statistic is necessary for the likelihood-ratio overdispersion test).

[a] Due to missing information concerning the level of PDP investments in Austria, the country was dropped before estimation. The foreign knowledge stocks were constructed by adding national stocks across the sample countries and the inclusion of Austria in the analysis would thus underestimate the size of the foreign knowledge stocks (since Austria's investment levels would implicitly be treated as equal to zero).

innovation-promoting than exemplary plants. Experimental PDPs focus primarily on technology testing and optimization and have low visibility since creating customer awareness is of low priority. Exemplary PDPs, on the other hand, have high visibility and functions mainly to create markets by spreading information about an innovation to potential adopters. This indicates that technology development efforts have been more effective when conducted away from pressure of customers and provides quantitative support for this argument made in [8]. They argue that avoiding such pressure makes it easier to pursue enduring and iterative development efforts.

Nevertheless, it is important that protection of innovation does not come at the price of too weak competition from other technologies [86]. If protection is too generous, technology developers are not forced to handle negative side effects associated with applications of a new technology on a large scale. This also calls for policy makers to support PDP activities focusing on multiple technological trajectories [19], and this is perhaps most important for achieving radical technology shifts [87]. Moreover, publicly funded PDP activities need to be complemented and followed up with market creation activities through market-pull support. This issue is stressed in [88] which analyze policy challenges in moving gasified biomass from the demonstration phase to large scale diffusion. It is argued that the creation of initial markets is critical for the evolution of new industries and subsequent technology development since they provide income streams for investors.

Turning to the role of knowledge spillovers resulting from PDP activities, the findings presented in this paper indicate that innovation in a country is driven not only by domestic investments in experimental PDPs but also by similar investments in other countries. This is consistent with theoretical reasoning in [6] and [8] suggesting that PDPs may generate significant knowledge spillovers. However, some empirical evidence has been presented which suggests that domestic R&D funding has no effect on foreign innovation, see [57]. Nevertheless, empirical studies on R&D spillovers support the notion of a positive spillover effect, e.g., [89].

While the results indicate the existence and importance of PDP induced country-level knowledge spillovers in Europe, there could be significant spillovers on a national and regional level as well [90]. Still, while these positive externalities are beneficial to society, they constitute a mixed blessing since they are in conflict with the interests of commercial actors involved in PDP development efforts [3] and [5]. The externalities benefit outside competitors who can imitate technology development efforts at a fraction of total costs, and this reduces the incentives for commercial actors to contribute to the learning processes in the first place [91]. This issue must be properly addressed when designing public support to PDP activities.

7 CONCLUSIONS AND AVENUES FOR FUTURE RESEARCH

This paper examines the impacts of publicly funded pilot and demonstration plant (PDP) activities on innovation in biofuel production technology. The results seem robust to alternative model specifications and indicate that: (a) PDP activities are overall positively correlated with biofuel patenting activity; (b) both experimental and exemplary PDPs encourage biofuel innovation even though the impact of the former is more profound; and (c) development activities in experimental PDPs encourage innovation also indirectly through knowledge spillovers across countries.

Overall these results suggest that innovations are endogenously determined in the renewable energy technology field, and they provide quantitative support of the notion that PDPs facilitate technology learning and hold an important role in the process of technology development. While the economics literature on policy-induced innovation stresses the importance of public R&D support and production support schemes, we must also acknowledge the role of PDPs in technical progress and address how public support to these activities can and should be properly designed.

There are a number of issues that deserve attention in future research. First, while this paper identifies important innovation impacts of publicly funded PDPs, greater understanding of how to properly design public support to these activities would be beneficial for policy making. Second, the kind of learning taking place in PDPs is dependent on the constellation of stakeholders involved [18], and this suggests that the magnitude of the innovation impacts of PDPs can be explained by the involvement of certain key actors, e.g., end users. This issue deserves more in-depth empirical research. Third, and finally, while the findings in this paper indicate the importance of PDPs for biofuel innovation, their innovation impacts may be less pronounced in the case of more mature technologies such as solar PV as well as over time as less-developed technologies mature. A greater understanding of such differential impacts is important information for policy making.

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9 NOTES

(1) Guiding the distinction with respect to feedstock type is in line with, e.g., [26]-[28].

(2) A change in the relative prices of two production factors will spur innovations to economize the use of the factor which has become relatively more expensive [32].

(3) Table A1 in the Appendix indicates that all exemplary PDPs came on stream in 2010. However, if startup of normal operation in a given facility occurs on or between 1 July and 31 December in year *t*, startup has been attributed to year *t + 1* in Fig. 2 and in the regressions that follow (if startup occurs before 1 July it has been attributed to year *t*). The idea is that PDP activities occurring before 1 July in year *t* are attributed to this year since they can explain more than half of all patent counts in year *t* (given that patent activities are uniformly distributed over a calendar year). If a PDP is taken into operation on or after 1 July it can explain less than (or exactly) half of all patenting activities in the current year. For instance, the approach avoids the situation where patent counts in January-November in year *t* are to be explained by PDP activities starting in, e.g., December in year *t*.

(4) The data set excludes patents and applications related to collection of feedstock and composition of biofuels. In addition, patents covering technologies for 1st generation biofuels have been excluded, except when they also describe non-food feedstock processing.

(5) 200 bootstrap replications are generally sufficient for estimates of standard errors [53]. Hence, all models (S1-S5) were fitted using 200 replications.

(6) PDP investments can possibly be endogenously

determined meaning that biofuel patenting explains variations in PDP investment based knowledge stocks. The knowledge stocks are, however, lagged which limits this issue (biofuel patents in year *t* would have to explain changes in knowledge stocks in year *t-1*).

(7) Biofuel innovation is supposedly also affected by public R&D support. However, R&D expenditure data provided in official databases covered biofuels on an aggregate level by including not only transportation fuels but also solid biofuels for instance (used for heat or electricity production). Inclusion of this variable in the regressions is thus questionable. As a robustness check R&D expenditures were included in S1 and S3, but the associated coefficient was statistically insignificant and the inclusion of this variable had negligible effects on the remaining parameter estimates.

(8) The PDP investment based knowledge stocks are based on a one year time lag and a depreciation rate of 20 percent. Since these are uncertain parameters, a sensitivity analysis was conducted in which alternative time lags and depreciation rates were tested. The results appeared to be overall robust with respect to different depreciation rates (15 and 30 percent) and time lags (two years). The knowledge stock coefficients remained positive and significantly different from zero in all cases except when a two year lag was assumed. The changes in the remaining coefficients were overall minor. Finally, a similar sensitivity analysis was also conducted for S4 and S5, with minor changes in the results.

10 REFERENCES

[1] D. Bacovsky, L. Ludwiczek, M. Ognissanto, and M. Wörgetter, Status of Advanced Biofuels Demonstration Facilities in 2012, (2013), a Report to IEA Bioenergy Task 39, No. T39-P1b, Bioenergy2020+, Graz.

[2] R. Haszeldine, Carbon Capture and Storage: How Green Can Black Be?, (2009), *Science*, vol. 325, pag. 1647.

[3] C. Hendry, P. Harborne, and J. Brown, So what do innovating companies really get from publicly funded demonstration projects and trials? Innovation lessons from solar photovoltaics and wind, (2010), *Energy Policy*, vol. 38, pag. 4507.

[4] W. Kingston, Antibiotics, invention and innovation, (2000), *Research Policy*, vol. 29, pag. 679.

[5] J. Frishammar, P. Söderholm, K. Bäckström, H. Hellsmark, and H. Ylinenpää, The role of pilot and demonstration plants in technological development: synthesis and directions for future research, (2015), *Technology Analysis & Strategic Management*, vol. 27, pag. 1.

[6] S. Lefevre, Using Demonstration Projects to Advance Innovation in Energy, (1984), *Public Administration Review*, vol. 44, pag. 483.

[7] K. Magill and E. Rogers, Federally Sponsored Demonstrations of Technological Innovations, (1981), *Knowledge: Creation, Diffusion, Utilization*, vol. 3, pag. 23.

[8] C. Hendry, P. Harborne, and J. Brown, The Uncertain Middle: Innovation lessons for low carbon energy technology from demonstration projects and trials, (2010), Advanced Institute of Management Research (AIM), London.

[9] N. Johnstone, I. Haščič, and D. Popp, Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts, (2010), *Environmental and Resource Economics*, vol. 45, pag. 133.

[10] J. Noailly and S. Batrakova, Stimulating energy-efficient innovations in the Dutch building sector: Empirical evidence from patent counts and policy lessons, (2010), *Energy Policy*, vol. 38, pag. 7803.

[11] S. Brunnermeier and A. Cohen, Determinants of environmental innovation in US manufacturing industries, (2003), *Journal of Environmental Economics and Management*, vol. 45, pag. 278.

[12] D. Popp, Induced Innovation and Energy Prices, (2002), *The American Economic Review*, vol. 92, pag. 160.

[13] K. Bäckström, R. Lundmark, and P. Söderholm, Public Policies and Solar PV Innovation: An Empirical Study Based on Patent Data, (2014), Paper presented at the IAEE International Conference: Energy & the Economy, New York, June 15-18.

[14] A. Klitkou, L. Coenen, P. Dannemand Andersen, A. Fevolden, and T. Hansen, Role of demonstration projects in innovation: Transition to sustainable energy and transport, (2013), Paper presented at the 4th International Conference on Sustainability Transitions, Zürich, June 18-21.

[15] M. Karlström and B. Sandén, Selecting and assessing demonstration projects for technology assessment: The case of fuel cells and hydrogen systems in Sweden, (2004), *Innovation: Management, Policy & Practice*, vol. 6, pag. 286.

[16] W. Baer, L. Johnson, and E. Merrow, Analysis of federally funded demonstration projects: Final report, (1976), Rand Corporation, Santa Monica.

[17] S. Myers, The demonstration project as a procedure for accelerating the application of new technology, (1978), United States Department of Energy, Washington, DC.

[18] P. Harborne and C. Hendry, Pathways to commercial wind power in the US, Europe and Japan: The role of demonstration projects and field trials in the innovation process, (2009), *Energy Policy*, vol. 37, pag. 3580.

[19] H. Hellsmark, Unfolding of the formative phase of gasified biomass in the European Union: The role of system builders in realising the potential of second-generation transportation fuels from biomass, (2010), PhD diss., Chalmers University of Technology, Gothenburg.

[20] International Energy Agency (IEA), Technology Roadmap – Biofuels for Transport, (2011), OECD, Paris.

[21] International Energy Agency (IEA), OECD - Renewables supply and consumption, (2014), OECD, Paris.

[22] L. Pelkmans, L. Govaerts, and K. Kessels, Inventory of biofuel policy measures and their impact on the market, (2008), Report D2.1 of ELOBIO subtasks 2.1-2.2, Intelligent Energy Europe, Brussels.

[23] T. Searchinger, R. Heimlich, R. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes,

and T. Yu, Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land use change, (2008), *Science*, vol. 319, pag. 1157.
[24] G. Timilsina, J. Beghin, S. Mevel, and D. van der Mensbrugghe, The Impacts of Biofuel Targets on Land-Use Change and Food Supply: A Global CGE Assessment, (2010), Policy Research Working Paper No. 5513, the World Bank, Washington, DC.
[25] D. Mitchell, A Note on Rising Food Prices, (2008), Policy Research Working Paper No. 4682, the World Bank, Washington, DC.
[26] M. Carriquiry, X. Du, and G. Timilsina, Second generation biofuels: Economics and policies, (2011), *Energy Policy*, vol. 39, pag. 4222.
[27] United Nations Environment Program (UNEP), Towards sustainable production and use of resources: Assessing biofuels, (2009), UNEP Division of Technology, Industry and Economics (DTIE), Paris.
[28] Organization for Economic Cooperation and Development (OECD)/International Energy Agency (IEA), Energy Technology Perspectives: Scenarios and Strategies to 2050, (2008), OECD, Paris.
[29] J. Scharlemann and W. Laurance, How Green Are Biofuels?, (2008), *Science*, vol. 319, pag. 43.
[30] J. Lanjouw and A. Mody, Innovation and the international diffusion of environmentally responsive technology, (1996), *Research Policy*, vol. 25, pag. 549.
[31] K. Gillingham, R. Newell, and W. Pizer, Modeling Endogenous Technological Change for Climate Policy Analysis, (2008), *Energy Economics*, vol. 30, pag. 2734.
[32] J. Hicks, *The Theory of Wages*, (1932), Macmillan, London.
[33] I. Sue Wing, Representing Induced Technological Change in Models for Climate Policy Analysis, (2006), *Energy Economics*, vol. 28, pag. 539.
[34] A. Löschel, Technological Change in Economic Models of Environmental Policy: A Survey, (2002), *Ecological Economics*, vol. 43, pag. 105.
[35] M. Grubb, J. Köhler, and D. Anderson, Induced Technical Change in Energy and Environmental Modelling: Analytical Approaches and Policy Implications, (2002), *Annual Review of Energy and the Environment*, vol. 27, pag. 271.
[36] J. Schumpeter, The theory of economic development, (1934), Cambridge, MA: Harvard University Press.
[37] S. Kline and N. Rosenberg, An overview of innovation, (1986), In R. Landau and N. Rosenberg (Eds.), The positive sum strategy: Harnessing technology for economic growth, Washington, DC: National Academy Press.
[38] A. Sagar and B. van der Zwaan, Technological innovation in the energy sector: R&D, deployment, and learning-by-doing, (2006), *Energy Policy*, vol. 34, pag. 2601.
[39] S. Macey and M. Brown, Demonstrations as a Policy Instrument with Energy Technology Examples, (1990), *Science Communication*, vol. 11, pag. 219.
[40] B. Carlsson and R. Stankiewicz, On the nature, function and composition of technological systems, (1991), *Journal of Evolutionary Economics*, vol. 1, pag. 93.
[41] A. Jaffe, R. Newell, and R. Stavins, Environmental Policy and Technological Change, (2002), *Environmental and Resource Economics*, vol. 22, pag. 41.
[42] J. Schmookler, Invention and Economic Growth, (1966), Harvard University Press, Cambridge.
[43] N. Rosenberg, Inside the Black Box, (1982), Cambridge University Press, Cambridge.
[44] A. Jaffe, Demand and Supply Influences in R&D Intensity and Productivity Growth, (1988), *Review of Economics and Statistics*, vol. 70, pag. 431.
[45] F. Jaumotte and N. Pain, From Ideas to Development: The Determinants of R&D and Patenting, (2005), OECD Economics Department Working Paper No. 457, OECD, Paris.
[46] Organization for Economic Cooperation and Development (OECD), OECD Patent Statistics Manual, (2009), OECD Publishing, Paris.
[47] H. Dernis, D. Guellec, and B. van Pottelsberghe, Using Patent Counts for Cross-country Comparisons of Technology Output, (2001), STI Review No. 27, OECD, Paris.
[48] H. Dernis and M. Kahn, Triadic Patent Families Methodology, (2004), STI Working Paper 2004/2, OECD, Paris.
[49] Biofuels Digest, SuperData Global Biofuels Plant list, (2014), Ascension Publishing, Miami.
[50] BIOMAP, Time-enabled Mapping and Dissemination Tool for Biofuel Projects, (2014), European Commission, Brussels.
[51] International Energy Agency (IEA), Status of 2nd Generation Biofuels Demonstration Facilities, (2014), IEA Bioenergy Task 39, Paris.
[52] G. Maddala, Limited-Dependent and Qualitative Variables in Econometrics, (1983), Cambridge University Press, Cambridge.
[53] A. Cameron and P. Trivedi, Regression Analysis of Count Data, (1998), Cambridge University Press, New York.
[54] P. Söderholm and G. Klaassen, Wind Power in Europe: A Simultaneous Innovation-Diffusion Model, (2007), *Environmental and Resource Economics*, vol. 36, pag. 163.
[55] G. Klaassen, A. Miketa, K. Larsen, and T. Sundqvist, The Impact of R&D on Innovation for Wind Energy in Denmark, Germany and the United Kingdom, (2005), *Ecological Economics*, vol. 54, pag. 227.
[56] J. Grafström, International knowledge spillovers in the wind power industry – Evidence from Europe, (2014), Paper presented at the IAEE International Conference: Energy & the Economy, New York, June 15-18.
[57] M. Peters, M. Schneider, T. Griesshaber, and V. Hoffmann, The impact of technology-push and demand-pull policies on technical change – Does the locus of policies matter?, (2012), *Research Policy*, vol. 41, pag. 1296.
[58] E. Verdolini and M. Galeotti, At Home and Abroad: An Empirical Analysis of Innovation and Diffusion in Energy Technologies, (2011), *Journal of Environmental Economics and Management*, vol. 61, pag. 119.
[59] J. Hilbe, Negative Binomial Regression, (2011), Cambridge University Press, New York.

[60] W. Greene, Functional forms for the negative binomial model for count data, (2008), *Economic Letters*, vol. 99, pag. 585.
[61] D. Rübbelke and P. Weiss, Environmental Regulations, Market Structure and Technological Progress in Renewable Energy Technology – A Panel Data Study on Wind Turbines, (2011), FEEM Working Paper No. 581.2011, Fondazione Eni Enrico Mattei (FEEM), Milan.
[62] P. Allison and R. Waterman, Fixed-Effects Negative Binomial Regression Models, (2002), *Sociological Methodology*, vol. 32, pag. 247.
[63] P. Guimarães, The Fixed Effects Negative Binomial Model Revisited, (2008), *Economics Letters*, vol. 99, pag. 63.
[64] C. Martinez, Insight Into Different Types of Patent Families, (2010), STI Working Paper 2010/2, CSIC – Institute of Public Goods and Policies, Madrid.
[65] Thomson Reuters, Phone and e-mail communication with personnel working with IP Consulting and Services, (2014).
[66] R. Frietsch and U. Schmoch, Transnational patents and international markets, (2010), *Scientometrics*, vol. 82, pag. 185.
[67] Thomson Reuters, Derwent World Patents Index (DWPI) database, (2014), IP Consulting and Services, New York.
[68] V. Costantini, F. Crespi, and Y. Curci, A keyword selection method for mapping technological knowledge in specific sectors through patent data: the case of biofuels sector, (2014), SEEDS Working Paper 17/2014, Sustainability Environmental Economics and Dynamic Studies (SEEDS), Ferrara.
[69] R. Lundmark and K. Bäckström, Bioenergy innovation and energy policy, (2015), *Economics of Innovation and New Technology*, article in press.
[70] M. Schankerman, How Valuable is Patent Protection? Estimates by Technology Field, (1998), *RAND Journal of Economics*, vol. 29, pag. 77.
[71] U. Schmoch, Indicators and the relations between science and technology, (1997), *Scientometrics*, vol. 38, pag. 103.
[72] Organization for Economic Cooperation and Development (OECD), Patents by Main Technology and by International Patent Classification (IPC), (2014), OECD Patent Database, Paris.
[73] Z. Griliches, R&D and Productivity: Econometric Results and Measurement Issues, (1995), In P. Stoneman (Ed.), Handbook of Economics on Innovation and Technological Change, Blackwell, Oxford.
[74] W. Nordhaus, Modeling Induced Innovation in Climate-Change Policy, (2002), In A. Grubler, N. Nakicenovic, and W. Nordhaus (Eds.), Technological Change and the Environment, Resources for the Future Press, Washington, DC.
[75] International Energy Agency (IEA), Renewable Energy – Market and Policy Trends in IEA Countries, (2004), OECD, Paris.
[76] International Energy Agency (IEA), Policies and Measures Databases, (2014), OECD, Paris.
[77] International Energy Agency (IEA), Energy Prices and Taxes Statistics, (2014), OECD, Paris.
[78] M. Kojima, D. Mitchell, and W. Ward, Considering Trade Policies for Liquid Biofuels, (2007), the World Bank, Washington DC.
[79] International Energy Agency (IEA), IEA Energy Policy Review – The European Union, (2008), OECD, Paris.
[80] W. Gould, J. Pitblado, and W. Sribney, Maximum Likelihood Estimation with Stata (3^{rd} edition), (2006), Stata Press, College Station.
[81] J. Brolund and R. Lundmark, Bioenergy Innovations and Their Determinants: A Negative Binominal Count Data Analysis, (2014), *Drewno*, vol. 57, pag. 41.
[82] H. Jang and X. Du, Price- and Policy-Induced Innovations: The Case of U.S. Biofuel, (2013), *Journal of Agricultural and Resource Economics*, vol. 38, pag. 299.
[83] R. Karmarkar-Deshmukh and C. Pray, Private Sector Innovation in Biofuels in the United States: Induced by Prices or Policies?, (2009), *AgBioForum*, vol. 12, pag. 141.
[84] V. Costantini, F. Crespi, C. Martini, and L. Pennacchio, Demand-pull and technology-push public support for eco-innovation: The case of the biofuels sector, (2015), *Research Policy*, vol. 44, pag. 577.
[85] L. De Freitas and S. Kaneko, Is there a causal relation between ethanol innovation and the market characteristics of fuels in Brazil?, (2012), *Ecological Economics*, vol. 74, pag. 161.
[86] R. Kemp, J. Schot, and R. Hoogma, Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management, (1998), *Technology Analysis & Strategic Management*, vol. 10, pag. 175.
[87] P. Harborne, C. Hendry, and J. Brown, The development and diffusion of radical technological innovation: The role of bus demonstration projects in commercializing fuel cell technology, (2007), *Technology Analysis & Strategic Management*, vol. 19, pag. 167.
[88] H. Hellsmark and S. Jacobsson, Realising the potential of gasified biomass in the European Union – Policy challenges in moving from demonstration plants to a larger scale diffusion, (2012), *Energy Policy*, vol. 41, pag. 507.
[89] Z. Griliches, The Search for R&D Spillovers, (1992), NBER Working Paper Series No. 3768, National Bureau of Economic Research, Cambridge.
[90] A. Jaffe, M. Trajtenberg, and R. Henderson, Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations, (1993), *Quarterly Journal of Economics*, vol. 108, pag. 577.
[91] D. Mowery, R. Nelson, and B. Martin, Technology policy and global warming: Why new policy models are needed (or why putting new wine in old bottles won't work), (2010), *Research Policy*, vol. 39, pag. 1011.

11 APPENDIX

Table A1: Publicly funded pilot and demonstration plants producing advanced biofuels (1980-2012)

Plant	Location	Operator	Operating period	Type	Plant investment[a] (EUR, 2010 prices)	Conversion process	Product	Feedstock	Generation	Output capacity (t/y)
Experimental PDPs										
SNG demo	Güssing, Austria	Conzepte Technik Umwelt AG (2009); Biomassekraftwerk Güssing (2010-2012)	2009-	Demo	N/A	Thermochemical	Synthetic naturalgas (SNG)	Lignocellulo-sics; syngas from gasifier	2G	576 (SNG)
BornBioFuel 1	Ballerup, Denmark	BioGasol	2009-2010	Pilot	8 430 000	Biochemical	Ethanol	Corn fiber; corn stover; grasses; garden waste; straw	1G; 2G	28 (ethanol)
BornBioFuels Optimiz-ation	Bornholm, Denmark	BioGasol	2009-	Pilot	1 620 000	Biochemical	Ethanol; biogas	Wheat straw; cocksfoot grass	2G	11 (ethanol)
Maxifuel	Copenhagen, Denmark	BioGasol	2007-2008	Pilot	850 000	Biochemical	Ethanol; biogas; lignin	Lignocellulo-sics; wheat straw; corn fiber	1G; 2G	28 (ethanol)
Pilot 1	Fredericia, Denmark	Elsam (2003-2005); Inbicon (DONG Energy) (2006-2012)	2003-	Pilot	5 720 000	Biochemical	Ethanol; c5 molasses; lignin bio-pellets	Lignocellulo-sics; straw	2G	N/A
Pilot 2	Fredericia, Denmark	Elsam (2005); Inbicon (DONG Energy) (2006-2012)	2005-	Pilot	16 970 000	Biochemical	Ethanol; c5 molasses; lignin bio-pellets	Maize silage; sugar cane bagasse; municipal solid waste	2G	Several tons per hour
Demo	Kalundborg, Denmark	Inbicon (DONG Energy)	2009-	Demo	51 040 000	Biochemical	Ethanol; c5 molasses; lignin bio-pellets	Lignocellulo-sics; wheat straw	2G	4 300 (ethanol)
Futurol Project	Pomacle, France	Procethol 2G	2011-	Pilot	29 470 000	Biochemical	Ethanol	Wood wastes; agricultural and forest residues; energy crops	2G	2 700 (ethanol)

[a] Figures reflect both public and private investments.

Table A1: Publicly funded pilot and demonstration plants producing advanced biofuels (1980-2012) (continued)

Plant	Location	Operator	Operating period	Type	Plant investment (EUR, 2010 prices)	Conversion process	Product	Feedstock	Generation	Output capacity (t/y)
Experimental PDPs										
STS-plant	Oberhausen, Germany	Fraunhofer UMSICHT (2011); Greasoline (2012)	2011-	Pilot	3 030 000	Thermochemical	Diesel-type hydrocarbon (i.e., hydrotreated vegetable oil (HVO))	Waste fats; energy crop oil; algae oil; fatty acids; grease trap contents	2G; 3G	2 (diesel-type hydrocarbon)
Hohenhe-im Pilot	Stuttgart, Germany	University of Hohenheim; Butalco	2010-	Pilot	1 220 000	Biochemical	Ethanol	Grass; corn stover; starch	1G; 2G	N/A
Demo	Babilafuente, Spain	Abengoa Bioenergy	2009-	Demo	56 180 000	Biochemical	Ethanol	Cereal straw (mostly barley and wheat)	2G	4 000 (ethanol)
BioDME	Piteå, Sweden	Chemrec	2011-	Pilot	23 920 000	Thermochemical	Di-Methyl-Ether (DME)	Forest residues through black liquor gasification	2G	1 800 (DME)
Biorefin-ery Demo Plant*	Örnsköldsvi-k, Sweden	SEKAB E-technology	2004-	Pilot	28 860 000	Biochemical	Ethanol	Wood chips; sugarcane bagasse; wheat; corn stover; energy grass	1G; 2G	120 (ethanol)
Exemplary PDPs										
Bio Base Europe Pilot Plant	Ghent, Belgium	Bio Base Europe	2010-	Com-merci-al	13 280 000	Biochemical	Ethanol; fine chemicals; food ingredients; bioplastics	Wheat straw; corncobs; wood chips; Jatropha; algae	2G; 3G	Kg to multi-ton scale
Chempol-is Biorefini-ng Plant	Oulu, Finland	Chempolis	2010-	Demo	20 240 000	Biochemical	Ethanol; biochemicals; pulp and paper fibers	Straw; reed; bagasse; corn stalks; wood residues; paper waste	2G	5 000 (ethanol)

* Categorized as an experimental PDP in 2004-2009, after this period it is viewed as an exemplary PDP.