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Financing energy innovation

The role of financing constraints for directed technical change from fossil-fuel to renewable innovation

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The role of financing constraints for directed technical change from fossil-fuel to renewable innovation

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Non-Technical Summary

Addressing both the challenge of climate change and the world's growing energy needs will only be possible by achieving a breakthrough in clean technologies in order to deliver safe, clean and sustainable energy for future generations. Such a large-scale technological transition will require massive investments in research and development (R&D) of clean energy production. Within the sector of electricity generation, renewable (REN) energy technologies, such as solar, wind or geothermal energy, can provide a clean alternative to electricity produced from carbon-intensive fossil-fuels (FF). Nonetheless, private firms' investments in advancing innovation for renewable energy technologies face important challenges.

The first challenge relates to the intrinsic properties of the R&D process in general, which makes it difficult to finance via external funds. As the majority of R&D expenditures concerns wages of R&D workers, banks cannot claim collateral in return for R&D investment. Also, R&D is by definition an uncertain process - and so is its financial return - subject to market failures such as asymmetric information. Hence, financial frictions are particularly important for firms investing in innovation activities.

The second challenge relates to the specific nature of REN technologies. Within the energy sector, REN investments tend to have an unattractive risk/return profile compared to investments in the incumbent FF technologies. This is because REN technologies still heavily depend on public policy support and the risk that policies supporting clean energy are subject to change makes it challenging for investors. Second, REN technologies also present higher technological risks than traditional FF ones: they usually require higher upfront capital investments and are still in an early stage of development with high failure rates. Finally, the renewable energy sector is mainly composed of small firms, which tend to be more financially constrained than large mature firms.

The purpose of this study is to examine the impact of firms' financing constraints on innovation activities in renewable vs. fossil-fuel technologies. In particular, we study whether firms specialized in REN innovation are more likely to face financing frictions than firms conducting FF innovation. We also look at the financing constraints faced by so-called 'mixed firms', i.e. large incumbent firms which invest in both technologies, although predominantly in fossil-fuels technologies. Due to the specific challenges of investing in REN innovation, our central hypothesis is that firms specializing in REN innovation are more financially constrained than either FF or mixed firms.

Our empirical methodology relies on the construction of a firm-level dataset for 1,300 European firms over the 1995-2009 period combining balance-sheet information linked with patenting activities in REN and FF technologies. Following the economic literature on low-carbon innovations, we extract patents filed at the European Patent Office and at 17 other national patent offices in Europe and related to REN and FF technologies, identified using International Patent Classification codes. REN patents include patents in wind, solar, hydro, marine, biomass, geothermal and waste energy technologies while FF patents include patents related to production of fuel gases by carbureting air, steam engine plants, gas turbine plants, hot-gas or combustion-product positive displacement engine, steam generation, combustion apparatus, furnaces and improved compressed-ignition engines. Using unique firm's identifiers provided in the Orbis database linked to PATSTAT, we match information about each firm's sources of financing (e.g. cash flow, long-term debt, and stock issues) and other firms' characteristics (such as age, number of employees, sales). We also include variables controlling for the market developments of REN and FF technologies in Europe borrowing data from the International Energy Agency.

Our descriptive analysis shows some important distinctive features between firms specialized in REN innovation, firms specialized in FF innovation and firms that mix both types of innovation in their patent portfolio. First, firms specializing in REN innovation tend to be small and young occasional innovators. Yet, the new entry of these firms since the mid-1990s explains the recent surge in patenting activities in renewable technologies in Europe. These firms appear thus as key actors in driving the electricity generation sector towards renewable technologies. Second, firms specializing in FF technologies are relatively older and larger than REN firms but they also only innovate occasionally. Finally, other important actors are large incumbent firms which tend to conduct innovation in both REN and FF technologies (`mixed firms'), although their patent portfolio appears to be predominantly dominated by FF technologies. These firms are much older and larger than other firms and are more persistent innovators. Regarding the types of financing of these firms, we find that cash flows and cash holdings are an important source of funding for all firms, while debt and stock issues appear less relevant. Firms specialized in REN innovation tend to have relatively higher levels of stock issues, possibly because these are younger and stock issues are used primarily in the early stage of the firm's life cycle.

To operationalize our test of higher financial frictions for firms specialized in REN innovation, we estimate the importance of the different types of financing (e.g. cash flow, long-term debt, and stock issues) on firms' patenting activities for the different samples of firms. We use count estimation techniques (negative binomial and Poisson models) commonly used for models with patent data and control for a large set of firm-specific controls and market developments in REN and FF technologies. We also control for the change in firm-level stocks of cash (and cash equivalents) to capture the possibility for firms to "smooth R&D" over time, as it has been established that failing to control for the change in cash stocks may lead us to underestimate the relationship between innovation and financial constraints. We expect to find a stronger link between the financial variables and R&D in the groups of firms most likely to be financially constrained, i.e. small firms specialized in REN innovation.

Our results confirm our hypothesis as we find evidence for a positive impact of internal finance on patenting activities for the sample of firms specialized in REN innovation, while we find no evidence of this link for other firms, such as firms conducting FF innovation or large mixed firms conducting both REN and FF innovation. Hence, financing constraints matter for firms specialized in REN innovation but not for other firms. Results from a two-stage count model, in which we estimate the impact of financial variables on 1) the decision to enter innovation (extensive margin) and 2) conditional on entry, the firm's level of innovation (intensive margin) confirm that financing constraints are particularly relevant for REN firms' decision to start innovating.

Our results have important implications for policymaking. First, the results emphasize that small innovative newcomers in the field of renewable energy are particularly vulnerable to financing constraints, not solely because they are younger and less mature than other established firms, but mainly because they focus on new clean technologies that are still perceived as more risky by investors than the incumbent technologies based on fossil-fuel electricity generation. Government and policymakers should thus pay particular attention to ease financing constraints of start-up companies into renewable energy. Some options for policymaking include providing venture capital for REN start-up firms or providing specific R&D subsidies for small innovating firms in renewable energy. Our results highlight thus the need for sector specific subsidies (rather than generic policies for all firms) and for the need to configure investment policies to steer investments towards clean technologies, for instance in the form of specific capital grants, venture and equity funds or low-interest loans for starters in clean energy. Public regulators can also more actively use the option to lend directly to the renewable energy sector via public investment banks on terms more favourable than those of the market.

1. Introduction

Addressing both the challenge of climate change and the world's growing energy needs will only be possible by achieving a breakthrough in clean technologies in order to deliver safe, clean and sustainable energy for future generations. Such a large-scale technological transition will require massive investments in research and development (R&D) of clean energy production. Within the sector of electricity generation, renewable (REN) energy technologies, such as solar, wind or geothermal energy, can provide a clean alternative to electricity produced from carbon-intensive fossil-fuels (FF). Although a few renewable technologies, in particular solar energy, are developing at a rapid pace, renewable electricity production only accounts for 22% of worldwide electricity's production and is projected to reach 26% by 2020 (OCDE, 2015).

To achieve the Paris climate agreements goal to limit global temperature rise below 2 degrees Celsius, the world will need to invest $12.1 trillion investment in new renewable power globally over the next 25 years (Ceres, Bloomberg New Energy Finance, & Locklin, 2015). This investment surge will require the development of investment vehicles supporting clean energy, including bonds, asset-back securities that capital market players or institutional investors can take advantage of. Besides fostering the deployment of renewables, massive investments will also be required in advancing innovation in renewable energy. During the climate change meetings in Paris, 20 countries, including the UK, US, China and India, pledged to double their public investment in low-carbon energy innovation and 28 key investment players, including Bill Gates, Richard Branson and Mark Zuckenberg, announced their commitments to a new private investment fund, the Breakthrough Energy Coalition, to invest in novel clean technologies including renewable energy. Such large support for investment in clean R&D is critical, as firms find it difficult to attract investors to finance innovation in renewable energy, as these technologies are still perceived as less mature and more risky than incumbent technologies based on fossil-fuels electricity generation.

The purpose of this paper is to examine the role of firms' financing constraints on the direction of technological change in the electricity generation sector. We examine the impact of firms' balance sheet health on firms' incentives to invest in renewable vs. fossil-fuel technologies. In particular, we study whether firms specialized in REN innovation are more likely to face financing frictions than firms conducting FF innovation. We also look at the financing constraints faced by so-called 'mixed firms', i.e. large incumbent firms which invest in both technologies, although predominantly in fossil-fuels technologies. Combining balance-sheet data with data on firm-level patents in renewable and fossil-fuel energy technologies for a sample of 1,300 European firms over the period 1995-2009, we estimate the importance of different types of financing (e.g. cash flow, long-term debt, and stock issues) on firms' innovation in renewable versus fossil-fuel technologies. We estimate the model using negative binomial estimation techniques, controlling for a large set of firm-specific controls and market developments in REN and FF technologies. Our results confirm our hypothesis that small specialized REN firms tend to rely more on cash flow to finance R&D, suggesting that they find it difficult to finance R&D through external sources. We find evidence for a positive impact of internal finance on patenting activities for the sample of firms specialized in REN innovation, while we find no evidence of this link for other firms, such as firms conducting FF innovation or large mixed firms conducting both REN and FF innovation.

Our study relates to two different strands of literature. First, by its focus on innovation in the electricity generation sector, our work relates to the literature investigating the determinants of green R&D at the country and firm level. Several studies have found a positive impact of energy prices, market developments and environmental policies (Johnstone et al 2009)(Dechezleprêtre & Glachant, 2014) on the number of patents in green technologies. So far, only few studies have considered the impact of financial constraints on green innovation. Brunnschweiler (2010) looks at the impact of financial sector development on installed capacity of renewables in panel data estimations for 119 non-OECD countries for 1980-2006, but does not consider innovation by firms. Nanda et al (2015) find a relationship between the rising share of patenting by startups in the early 2000s and the surge in venture capital finance for renewable technologies.

In recent years, the literature on technical change and the environment has been concerned with how to affect the direction of technological change at the industry or firm-level, by inducing a shift away from dirty towards clean innovation (Acemoglu, Aghion, Bursztyn, & Hemous, 2012). Aghion et al. (2016) find evidence for path-dependency in innovation in the automobile industry. Firms that have innovated a lot in dirty innovation (e.g. internal combustion engines) in the past have incentives to continue innovating in dirty rather than in clean technologies (e.g. hybrid and electric engines). They find that firms tend to innovate relatively more in clean technologies when they face higher tax-inclusive fuel prices. Noailly and Smeets 2015) study the factors affecting directed technical change in the electricity generation sector and find that there are important differences between small and large innovating firms. In particular, they find that in recent years the reduction in the aggregate technology gap between FF and REN patenting activities in the electricity generation sector has been induced mainly by increased entry of small firms specialized in REN innovation. However, innovation by large firms patenting in both REN and FF technologies has remained largely concentrated in FF technologies, with only a moderate shift towards REN technologies. Their estimation results confirm the role of path-dependency and suggest that the entry of small firms into renewable technologies is central to a technological transition away from fossil-fuels. The present study aims to add new insights to this literature by investigating how firms' balance sheet health may affect the direction of innovation, either towards REN or FF technologies.

Second, our work also relates to the literature in corporate finance studying the role of finance for innovation. This literature generally argues that debt and external financing are a disfavored source of finance for R&D investment. This is due to the fact that R&D has intrinsic properties that make it difficult to finance externally (Hall and Lerner, 2010). Empirical evidence tends to confirm the theoretical arguments, with the nuance that European firms tend to be less constrained than US firms (Bond et al. 2005), (Brown and Petersen 2009). The literature also explores how financing constraints vary between small and large firms ((Robb & Robinson, 2014). Compared to this literature, we offer two new insights: First, we shed light on the impact of financial frictions on the direction of technological change. So far, there is only anecdotal evidence on how financing may affect the direction of innovation. For instance, Abraham (2011) argues that the pharmaceutical industry has become locked into innovation in drugs which are less complex and provide easier returns than other areas of research (such as diagnostics or life-style remedies). Second, we look specifically at the case of innovation in electricity generation, a sector which has not yet been studied in the finance and innovation literature, and which is crucial to policymaking aiming to address climate change.

Our study is structured as follows. Section 2 provides a review of the literature and describes the main theoretical hypotheses to be tested in the analysis. Section 3 gives a description of the data sources and our empirical framework. Section 4 presents our estimation results. Section 5 concludes.

2. Related literature and main hypotheses

Our work relates to several strands of existing literature. First, Section 2.1 describes how it relates to the literature linking corporate financing and innovation. Second, Section 2.2 discusses the specific case of financing REN versus FF innovation. Finally, Section 2.3 describes our main hypotheses.

2.1 Corporate financing and innovation

The theoretical literature in corporate finance predicts that innovation has intrinsic properties that make it difficult to finance externally (Hall and Lerner, 2010). This is explained by several factors.

First, the majority of R&D expenditures concerns wages of R&D workers, rather than capital investment. This implies that banks often cannot claim collateral in return for R&D investment. First-time innovators will also often lack a valuable asset that can serve as collateral. As a result, the availability of external (debt) finance is either limit or very costly. Second, due to the highly uncertain nature of the outcome of the innovation process, so is its financial return. The high degree of uncertainty around innovation makes it always difficult to know in advance whether a firm will be successful at innovating or not. As a result, the risk premium charged on external sources of finance is often prohibitively high. Finally, market failures affecting investments also play a role for R&D investment. There exists asymmetric information between the provider of finance and the innovator, since the latter tends to have more information about potential success or failure. As a result, the high-success firms will tend to exit the market as they cannot signal their quality to financiers. Further, moral hazard may induce innovators to spend money on more risky projects than agreed upon *ex-ante* with the financier. Anticipating such behavior, financiers could limit the availability of external financing, or offer it at higher cost.

Taken together, these problems imply that external (to the firm) financing of innovation can be quite costly. This creates a hierarchy in the corporate financing of innovation (Hall & Lerner, 2010b): firms will typically first deplete their internal cash flow (and possibly part of their cash stocks) before turning to external sources of financing. A corollary of this result is that firms that are relatively cash-constrained will be more sensitive to shocks in both the internal and external supply of financing, relative to their cash-replete counterparts. Indeed, a number of studies have demonstrated that in particular small, young, and high-tech firms' R&D activities are sensitive to internal and external (equity) cash constraints, unlike large and mature firms (Brown, Fazzari, & Petersen, 2009; Brown, Martinsson, & Petersen, 2012; Himmelberg & Petersen, 1994).

Another insight of the same literature is that, when resorting to external sources of finance, equity financing trumps debt financing (Brown et al., 2012). Two important reasons for this are that, first, equity financing does not require collateral, and second, unlike providers of debt, equity investors share in the upside of the investment. This makes external equity cheaper than external debt. Indeed, Brown, et al. (2009), Brown and Petersen (2009, 2011), and Brown, Martinsson, and Petersen (2012) all demonstrate the sensitivity of small, young, and technology-intensive firms' R&D to external equity financing constraints. Given that large and mature firms typically do not rely on external equity for their marginal innovation financing needs, their R&D does not exhibit a significant elasticity with respect to such constraints.

However, there are a number of caveats to these established insights that are important for the purposes of the current study. First, the majority of the studies on the corporate financing of innovation are undertaken for US firms. It is not completely clear that their results translate one-to-one to the European context, given the substantial differences in the structure of capital markets. In particular, EIB (2015) quotes Mario Draghi as saying that "in the United States 80% of credit intermediation goes via the capital markets […]. In the European situation it is the other way around; 80% of financial intermediation goes through the banking system" (p.110). This suggests that the importance of equity markets (vs. debt markets) may not be as prevalent in Europe as it is in the US. This in turn may have specific implications for the (external) financing hierarchy of innovation alluded to above.

It should be noted that Brown et al. (2012) do study R&D and financing constraint in a number of European countries. However, their study is particular in the sense that they only study publicly listed firms. This constitutes the second caveat to the established literature in this field, which mostly focuses on samples of publicly traded firms. In this context, the typical definition of a small firm is one with less than 500 employees, whereas a young firm is one whose IPO took place less than 15 years ago. These are hardly the small start-up firms that one might typically think of in the context of our study.

In an implicit acknowledgement of these limitations, a more recent literature has developed that explicitly considers the importance of non-equity external financing for truly small (start-up) firms (Kerr & Nanda, 2015). One important insight from this literature is that for many small firms, debt financing is an important resource for innovation. Partly, this is due to the fact that innovation sometimes does produce some valuable collateral, such as patents (Sudheer, Nanda, & Xiao, 2015), as well as the increased willingness and ability of (US) banks to monitor small and innovative corporate borrowers (Chava, Oettl, Subramanian, & Subramanian, 2013; Cornaggia, Mao, Tian, & Wolfe, 2015). Yet in other part, it is also due to costs associated with being a publicly listed firm undertaking R&D that were not previously acknowledged. Risk-averse managers of public corporations, who recognize the highly skewed returns of innovation, as well as its stochastic failure, will not innovate or only engage in incremental innovation when confronted with short-term oriented stockholders. In this line of thinking, there is little symbiosis between public equity and innovation.

In a survey on the capital structure decision of new US firms, (Robb & Robinson, 2014) further uncover some interesting stylized facts of small-firm debt financing. Although their study is not specifically aimed at innovative or high-tech firms, the underlying survey is biased towards such firms. Two results stand out in particular: First, newly founded businesses rely heavily on formal outside debt financing, in the form of bank loans and business credit lines. This even holds for the relatively small number of start-ups that have access to (private) equity (such as venture capital, or angel investment). Second, many small entrepreneurs overcome the lack of corporate collateral by leveraging their personal assets as collateral or guarantees for bank financing.

Taken together, these findings cast some doubt on the traditional notion of a financing hierarchy for innovation. This is particularly important in the context of our study because our empirical analysis is limited to European firms only. As documented in (EIB, 2015), European capital markets are still heavily tilted towards debt. The report documents in particular that "smaller firms have a more restricted direct access to capital markets due to relatively high fixed costs, leading them to rely largely on bank finance" (p.84). More generally, debt accounts for +/- 40% of the corporate liability structure, followed by listed equity (25%) and other equity, such as private equity or venture capital (35%). Within the category of corporate debt, short and long-term bank loans make up the majority of financing, far outpacing short and long-term debt securities.

2.2. Financing renewable technologies

While the previous section has established that financial frictions are particularly relevant for R&D, the nature of the problem may also differ across technologies. Energy technologies for instance present specific characteristics that make them largely dependent on external finance: they are highly capital-intensive, require large upfront investments, and these investments are often irreversible. This explains why investments in energy exhibit very different risk profiles than investments in other sectors (such as IT).

Within the energy sector, REN and FF technologies also present distinct risk profiles, as investments in renewable energy face specific challenges. First, REN technologies still largely rely on policy support. Government intervention is justified in this sector by the environmental externality. Since firms do not pay for pollution, they have little incentives to invest in clean technologies. Yet, the risk that policies supporting clean energy are subject to change makes it challenging for investors, especially for private equity investors who might hold an investment under successive governments. Looking at the determinants of venture capital financing in the renewable energy sector using data on deals in the "clean tech" industry for 26 countries over the period 2005-2010, Criscuolo and Menon (2014) find that national policies designed with a long-term perspective (e.g. feed-in tariffs) are associated with higher investment levels compared to more short term fiscal policies (e.g. tax incentives, rebates).

Second, REN technologies present higher technological risks than traditional FF ones. Renewables usually require higher upfront capital investments. Nelson and Shrimali (2014) estimate that upfront capital costs represent 84-93% of total project costs for wind, solar and hydro energy (compared to 66-69% for coal and 24-37% for gas). More importantly, most of these technologies are still in an early stage of development, and failure rates are still high. Gosh and Nanda (2010) and Nanda et al. (2013) discuss how entrepreneurs in renewables need risk capital, not only in early stages, but also later on to demonstrate that the technology can work at scale. This is less of a problem for FF technologies that are well-established in the sector.

Finally, firms active in renewables tend to be relatively small, both in the R&D and deployment stage (Noailly and Smeets, 2015; Donovan 2015). As a consequence, projects are often small (compared to nuclear or gas for instance) and small companies do not have an institutional track record to secure debt financing. Incumbents, by contrast, are large companies that often remain specialized in FF technologies. For such firms, shifting to REN often implies cannibalizing their core business. As a result, energy producing firms and utilities are far from active in acquiring promising clean energy startups, thus limiting the available exit options for such firms (Gosh and Nanda 2010).

Altogether, these factors explain why REN investments have an unattractive risk/return profile compared to FF investments.[2] In the realm of REN innovation, this implies a "double squeeze": First, compared to FF innovation, REN innovation is more uncertain, making debt financing more difficult. Second, REN innovation is typically undertaken by small and young firms, which only have limited internal funds. Furthermore, given the limited importance of equity markets in (continental) Europe (vis-à-vis the US), equity financing is not likely to be a viable substitute.

2.3 Hypotheses

From this literature review, it follows that there are several primary inhibiting factors driving the financing of innovation: (1) the nature of the innovation process (lack of collateral, uncertainty, asymmetric information); (2) the characteristics of the innovating firm (size, age, and/or technology intensity); (3) the risk profile of one technology relative to another.

As we discussed above, the traditional literature on the corporate financing of innovation sketches a financing hierarchy: First internal cash flow is depleted, followed by external equity financing, possibly followed by external debt financing. Moreover, the literature in this field has also firmly established that small, young, and technology-intensive firms are more sensitive to *both* internal and external equity constraints than large and mature firms.

[2] The specificities of the REN sector explain why project financing is so popular, compared to other sources of financing (Alonso, 2015). Project financing is mainly used for the deployment stage (i.e. construction of REN generating facilities, such as solar or wind turbines) and is less suited for R&D investment, which is why we abstract from project financing in this paper. This form of financing provides a fixed-income which relies solely on the ability of the project cash flows to repay the amounts borrowed; it typically involves the creation of a project company (Special Purpose Vehicle) which is the legal owner of the project assets and which has contractual agreements with a number of other parties that include off takers, operators, suppliers, insurers and so on. About 30% of the total new investment deployed into large scale REN projects over the 2003-2013 period was financed by project finance debt (Alonso, 2014).

As we will demonstrate empirically below, there is a clear and systematic distinction between the three types of firms in our sample: Firms that specialize in REN innovation (henceforth: "REN firms"), firms that specialize in FF innovation (henceforth: "FF firms"), and firms that mix both types of innovation (henceforth: "mixed firms").

On average, REN firms are smaller and younger than FF firms, which in turn are smaller and younger than mixed firms. This means that REN firms should be expected to have the most limited internal financing capacities, so that our first hypothesis is that REN firms' innovation will be facing more binding financial constraints than other firms, due to their small size and because they conduct innovation on REN technologies that are perceived as more risky by investors. If financing constraints matter for firms specialized in REN innovation we should observe a higher sensitivity of their patenting activities to internal cash flows and external equity.

The situation for FF firms most likely resembles that of specialized REN firms discussed above, even though in terms of (average) age and size, they fall in between REN and mixed firms. Also, given the lower degree of uncertainty regarding the return on FF innovation, the cost of external capital is likely lower for these firms than for REN firms. This may imply a reduced sensitivity to both internal and external financing constraints relative to REN firms. This constitutes our second hypothesis.

Mixed firms by definition carry out two types of innovation, REN and FF. Even though, through complementarities and economies of scope, the innovation financing needs of mixed firms are presumably not double those of specialized firms, they are likely still more extensive. It is therefore not unlikely that the marginal source of financing will be external for (some) mixed firms too. The question is which type of innovation will be (mostly) affected. As discussed, an important drawback of financing R&D in general is the high degree of uncertainty regarding its outcome. In the context of our study, REN (compared to FF) innovation is characterized by a higher degree of uncertainty still, implying that the risk premium, and hence the interest rate, will be higher as well. Therefore, in order to minimize the *total* cost of innovation financing, mixed firms may prefer to use internal cash flow to finance REN innovation (at constant cost of capital), and resort to external sources for its marginal financing needs of FF innovation. To summarize, our main hypothesis regarding mixed firms is that we expect to find no evidence of financing constraints for these large mature firms. More specifically, we should find no evidence that patenting activities of mixed firms are sensitive to increases in internal cash flows. This is particularly true for FF innovation activities, while there might be some weak evidence that internal finance matters for REN innovation activities by mixed firms (although to much lower extent than for REN firms).

3. Data and descriptive statistics

3.1. Patents data

We measure innovation in REN and FF technologies using patent data, following the literature on low-carbon innovation (Popp, 2002; Johnstone et al, 2009). There are several advantages and limitations to working with patent data, which have been discussed at length in the literature.[3] We extract patents from the Orbis dataset provided by Bureau van Dijk, which has recently been linked to the European Patent Office's (EPO) PATSTAT dataset. The main advantage of using the Orbis-PATSTAT dataset to extract relevant patents is that it provides us with an unique firm's identifier that will allow us to match firm-level patents to balance sheet and income statement data at a later stage.

We extract data on firms' patenting activities in REN and FF technologies using International Patent Classification (IPC) codes to select patents in REN and FF technologies. REN patents include patents in wind, solar, hydro, marine, biomass, geothermal and waste energy technologies (Johnstone et al, 2010), while FF patents include patents related to production of fuel gases by carbureting air, steam engine plants, gas turbine plants, hot-gas or combustion-product positive displacement engine, steam generation, combustion apparatus, furnaces and improved compressed-ignition engines (Lanzi et al 2011).

Just as in Noailly and Smeets (2015), we focus on firms that have been granted at least one REN or FF patent at the EPO and 17 national patent offices (EU-15, Switzerland and Norway). Compared to Noailly and Smeets (2015)'s study which covers the period 1976-2006, we update the patent sample to the period 1980-20094. We count the number of granted patents per firm per year, including only priority patents and excluding equivalent patent filings. The fact that we focus on granted patents of firms' registered in Orbis implies that our sample is not likely to include the lowest quality patents (such as non-successful applications). We use the application year of priority patents, as this is closer to the year of the inventive idea than the year in which the patent was granted. We compute the annual count of REN and FF patents per firm as well as firm-specific REN and/or FF knowledge stocks, which are the cumulated number of patent counts over the period.[5]

The firms in our sample have been granted a total of 21,487 patents during the period 1980-2009. 16,854 (78%) of these apply to FF innovations, whereas the remaining 4,633 (22%) apply to REN

[3] A main caveat of working with patents is that not all inventions are patented, as for strategic reasons firms may prefer not to disclose valuable information. The value of patents is also very heterogeneous: only a few patents will lead to successful commercial applications. Despite these limitations, the link between patents and inventions has been clearly established in the literature (Griliches, 1990) as patents are correlated with other indicators of innovative activity, such as R&D expenditures or new product introductions. For our purpose, the main advantage of patent data is that they are highly disaggregated and are available at the firm and technology level.

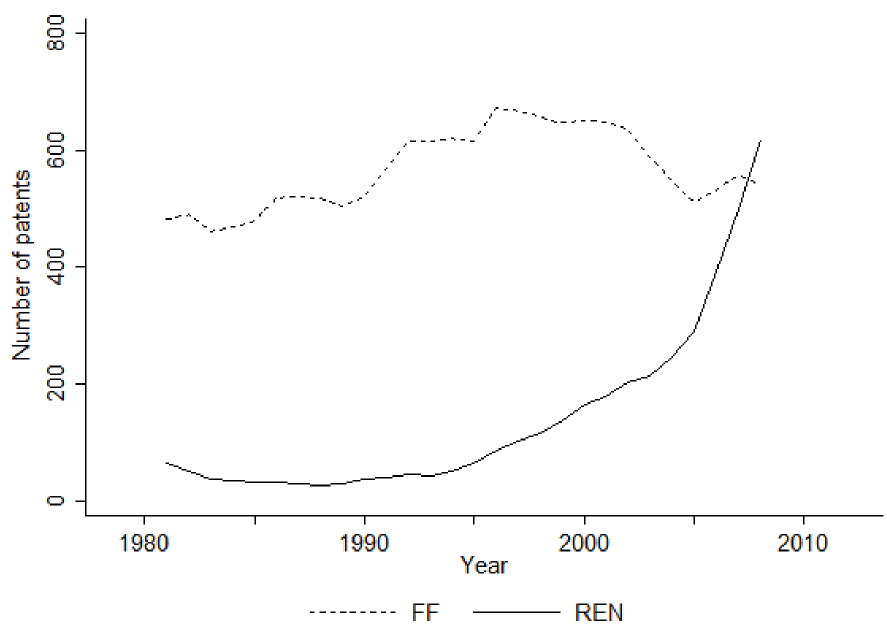
[4] Note that we observe a large truncation problem after 2009 in terms of number of patents in Orbis (since we look at granted patents and the examination time to grant patents takes several years).

[5] Knowledge stocks are calculated using the perpetual inventory method, assuming an annual depreciation rate of 15%.

innovations. In the econometric analyses below, we restrict the sample period to 1995-2009, given the limited availability of firm-level financial data. The total patent count in this period is 12,377, with 8,384 (68%) allocated to FF innovation and 3,953 (32%) to REN innovation.

The strong bias towards FF innovation in the sample as a whole masks the fact that REN innovation has caught up with FF innovation spectacularly since the second half of the 1990s, as witnessed in Figure 1. Whereas the average gap between FF and REN innovation before 1995 was around 500 patents, by 2009 the total number of granted REN patents has actually overtaken the number of granted FF patents.

FIGURE 1: The development in FF and REN patents (3-year moving averages)



In the context of the present study, we differentiate between three types of firms: Firms that specialize completely in REN innovation (REN firms), firms that specialize completely in FF innovation (FF firms), and firms that engage in both types of innovation (mixed firms) over the observed period. Table 1 presents a number of descriptive statistics regarding the relative importance of these three firm types in our sample, as well as the share of innovation for which they are responsible.

TABLE 1: Innovation by firm type

	Firms (N)	Firms (%)	REN pats (N)	REN pats (%)	FF pats (N)	FF pats (%)
REN firms	1,776	33	3,524	76	-	-
FF firms	3,392	62	-	-	10,031	60
Mixed firms	265	5	1,108	24	6,823	40
Total	5,433	100	4,633	100	16,854	100

The majority of firms in our sample are FF firms (62%), whereas mixed firms are the clear minority (5%). However, mixed firms' patent counts in the sample are highly disproportional. Overall, they are responsible for 37% of all patents. Splitting this out further between REN and FF innovation, mixed firms capture 24% of the former and 40% of the latter. This implies that mixed firms are much larger – in terms of innovation, but as we will see below, also in other respects – than specialized firms.

Figure 2 illustrates the innovation dynamics of specialized and mixed firms, and essentially constitutes a breakdown (by firm type) of Figure 1. From the figure it is clear that the sharp increase in REN patents after 1995 was for the most part due to increased patenting by specialized REN firms. In contrast, we only observe somewhat of an uptick in REN patenting by mixed firms after 2005. The trends in FF patenting in specialized and mixed firms on the other hand track each other quite closely.

FIGURE 2: The development in patents per firm type (3-year moving averages)

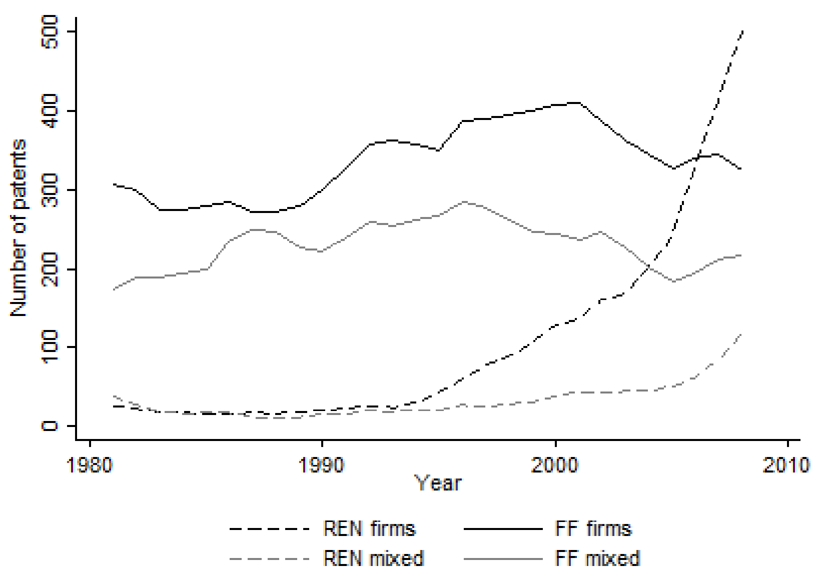
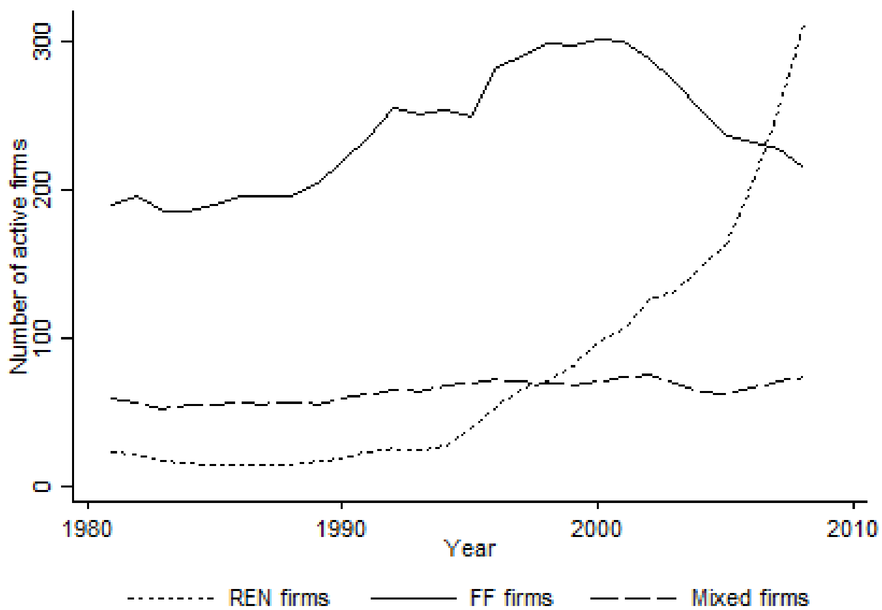


Figure 3 tracks the firm-dynamics in our sample over the period 1980-2009. In particular, it depicts the number of *active* firms in each year, which is defined as the number of firms that were granted a patent in that year. Three aspects are notable. First, the increase in the active number of REN firms closely tracks the development in their REN patents (in Figure 2), not just in terms of the general pattern, but also in terms of the absolute numbers. This suggests that the increase in specialized firm REN patenting after 1995 was strongly driven by the extensive margin (i.e. *new* firms patenting) rather than the intensive margin (i.e. *existing* firms patenting more). A comparison of patent and firms count (Figure 1 and 3) suggests indeed that specialized firms are relatively small in terms of their total patent counts. Although REN specialized firm are small and innovate only occasionally, the fact that many new specialized firms have become active REN innovation (`innovation entry') in the last fifteen years is the main cause of the surge in REN patents since the mid-1990s. As emphasized in Noailly and Smeets (2015), innovation entry dynamics of small specialized REN firms is key in driving technological change towards clean technologies in the European electricity generation sector.

FIGURE 3: Active firm dynamics (3-year moving averages)



Second, the trend in firm dynamics of firms specialized in FF innovation (FF firms) also mirrors the trend in their patenting behavior, although the absolute numbers are slightly more different, suggesting that the intensive margin is a relatively more important driver of patenting. Finally, the story is very different for mixed firms. A comparison of Figures 2 and 3 clearly shows that they are much bigger and more persistent innovators than any of the two types of specialized firms. In this case, the intensive margin clearly outweighs the extensive margin as a driver of innovation.

3.2. Balance sheets' data

Using the financial database of Orbis, we have access to data on firms' (consolidated) balance sheets and income statements. We match our set of firms with patents in REN and FF technologies with the financial database of Orbis. Unfortunately, our sample of firms is reduced after the matching as: 1) not all firms can be found back in the financial database 2) data availability is severely limited before 1995. We conduct a series of consistency checks as in Kalemli-Ozcan et al., (2015) recommended when working with financial variables in Orbis (see Appendix) and we trim the 1% tails of all regression variables. We are left with a sample of 1,300 firms (about 400 REN firms, 800 FF firms and 90 mixed firms) over the 1995-2009 period for which we can exploit balance sheets data.

We consider the following indicators of financing sources:

- *Cash flow*: This is computed as total cash flow (including depreciation), divided by the end-of-last-period stock of total assets.
- *Long-term debt*: This is computed as the annual change in total long-term debt, divided by the end-of-last-period stock of total assets.
- *Stock issues*: This is computed as the annual change in outstanding issued share capital, divided by the end-of-last-period stock of total assets.

All variables are measured in 100,000 USD, using the exchange rate data from the International Energy Agency to convert the financial variables into US dollars. We further include a number of firm-level control variables also borrowed from the financial database of Orbis and include (net) sales[6], the number of employees and the age of the firm.

In addition, we also include a control for the change in firm-level stocks of cash (and cash equivalents). This variable aims to capture so-called "R&D smoothing" (Brown and Petersen 2011). As firms face high R&D adjustment costs, whenever they need to reduce R&D due to financing constraints, they would need to fire R&D workers with a lot of intrinsic knowledge, which has high (opportunity) costs. As a result, firms have a tendency to smooth R&D investment over time, which they typically do using cash holdings. In particular, during downturns such stocks are depleted to maintain a basis level of R&D, whereas in upswings they are replenished from excess cash flow. As a result, failing to control for the change in cash stocks may lead us to underestimate the relationship between innovation and financial constraints.

Table 2 presents summary statistics of financial variables for the different types of firms. The bottom part of the table confirms what we already observed in the previous subsection: Both specialized REN and FF firms are significantly smaller in terms of their patents counts than mixed firms. In addition, REN firms tend to be younger on average than FF firms, and both types of specialized firms are significantly younger than mixed firms. On average, REN firms have a smaller number of employees than FF firms but

[6] Sales are computed as the ratio of net sales to end-of-last period total assets.

the difference is not significant, while both types of firms are significantly smaller in terms of employees than mixed firms.

The top part of the table considers a number of financial variables. We can observe that mean stock-issues-to-assets-ratios (Stk) and mean-debt-to-assets-ratios (Dbt) are always smaller than the mean cash flow ratios (CF), showing the importance of cash as a source of funding. Median values of debt and stock issues are close to zero. The fact that stock issues do not appear as a very large source of funding could be due to the fact that we look at European firms, as the literature which is mostly focused on American firms generally finds higher levels of equity finance. Average cash holdings ratios (Cash) are also large showing that firms have some important stocks of liquidity to be able to smooth R&D during transitory shocks.

Looking at differences across firms, we find no significant difference in terms of cash flows or cash holdings between specialized and mixed firms. Instead, average stock issues ratios for REN firms are significantly larger than for mixed firms, while there is no significant difference in terms of stock issues between REN and FF firms. Stock issues are used primarily in the early stage of the firm's life cycle, so the relative importance of stock issues for REN firms could be explained by the fact that these firms are less mature. Finally, mixed firms show the highest average levels of debt-to-assets-ratio, which is significantly larger than for REN firms. Overall, there are mostly no significant differences in terms of funding sources between FF and mixed firms.

TABLE 2: Summary Statistics, balance sheets data per type of firms.

	REN firms (N=403)			FF firms (N=813)			Mixed firms (N=90)		
	Mean	Std. Dev	Median	Mean	Std. Dev	Median	Mean	Std. Dev	Median
CF_{t-1}	0.135	0.448	0.096	0.129	1.056	0.085	0.146	0.448	0.096
Dbt_{t-1}	0.045 [b]	0.268	0.002	0.020	0.180	0.000	0.098	0.268	0.002
Stk_{t-1}	0.024 [a]	0.079	0.004	0.021	0.100	0.004	0.015	0.079	0.004
$Cash_{t-1}$	0.160	0.280	0.076	0.148	0.532	0.064	0.132	0.336	0.056
$\Delta Cash_{t-1}$	0.048	0.213	0.008	0.033	0.512	0.003	0.052	0.213	0.008
$Sales_{t-1}$	2.091 [b]	2.610	1.592	1.669	2.936	1.369	2.006	7.172	1.110
Age	14 [a,b]	26	6	23 [a]	32	13	39	39	31
Employees	1607 [a]	15779	60	2071 [a]	10060	116	20022	55604	1301
REN patents	0.2 [a]	0.6	0.1	-	-	-	0.3	0.6	0.1
FF patents	-	-	-	0.2 [a]	0.4	0.1	1.2	0	0
All patents	1.8 [a,b]	8.4	0.2	2.8 [a]	17.9	0.3	51.8	8.4	0.2

a indicates significant difference with Mixed firms, b indicates significant difference (below 10%) with FF firms. All balance sheets data (except age and number of employees) are scaled by beginning of the year ratios to total assets. N refers to minimum number of observations in each sample.

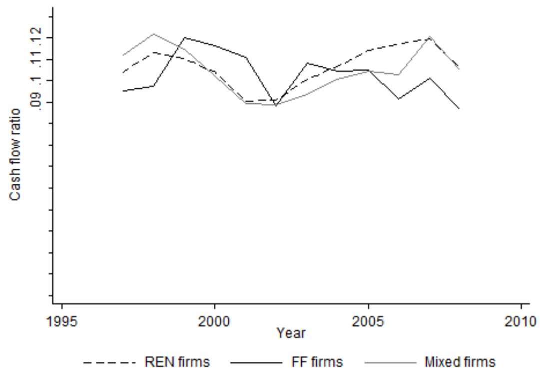
Figure 4 considers the evolution of the three financing factors for each of the three firm types during the period 1995-2009. Panel *a* depicts the evolution of the average cash flow ratios per type of firms. There is a clear cyclicality in this metric for all firm types. Cash flows drop in the run-up to the burst of the dotcom bubble in the early 2000s, then swing back up, until the onset of the great recession in 2007, when they drop down again. It is notable that the increase in cash flow for REN firms largely coincides with the period of strongly increased REN patenting (cf. Figure 2).

As demonstrated in panel *b* of Figure 4, the dynamics in long-term debt ratios are less cyclical and remain relatively stable at low levels across the period. We only observe an increase in long-term debt ratios for mixed firms after 2005.

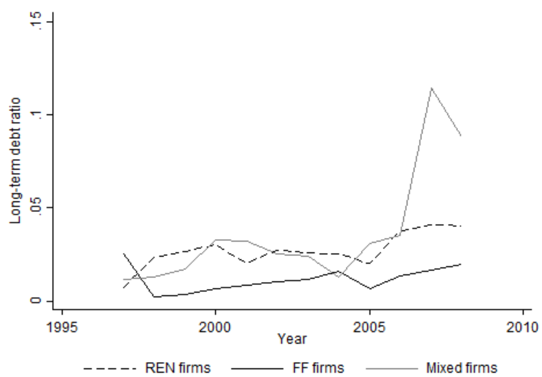
Finally, panel *c* presents the evolution of average stock issues ratios per firm type. The stock issues ratios for REN and mixed firms increase to a peak around 2000 and decrease afterwards before slowly increasing again after 2005. The patterns for FF firms look different with some up and down swings until 2003 before a steady decrease from 2004 on.

FIGURE 4: Dynamics in financing constraints (3-year moving averages)

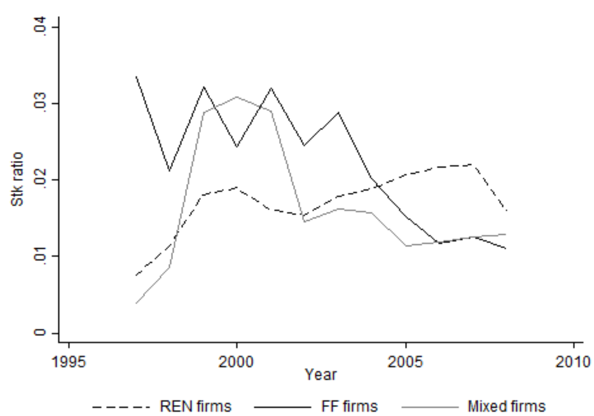
a) Cash flow ratios



b) Long-term debt ratio



c) Stock issues ratio



3.3. Macro-economic variables

Finally, we also consider variables that aim to capture changes in the macro-economic environment of the firm in particular with respect to the market and policy environment affecting REN and FF technologies in Europe over the last decades. The following variables are included based on the analysis in Noailly and Smeets (2015):[7]

Energy prices: we extract data from the Energy Prices and Taxes database of the International Energy Agency on country-level prices (indexed as *p* in Table A.1) of the different fossil-fuel energy sources, namely: oil, gas and coal (indexed as *f* in Table A.1).[8] To make FF prices firm-specific, we weight FF prices according to the firm's distribution of patent filings across countries (indexed as *c* in Table A.1) using information on patent families as in Noailly and Smeets (2015) and Aghion et al. (2016).[9] Since energy prices include taxes, this variable can proxy for carbon pricing policies.

Market size: we extract data from the Energy Statistics database from the IEA on electricity output from REN and FF sources per country in total number of gigawatt hours generated by power plants. For FF energy, we use data on electricity output in oil, gas and coal, while for REN energy we have access to disaggregated data on electricity output from solar, wind, hydro, marine, geothermal, biomass and waste energy. Market size variables (denoted as *M* in table A.1) also capture demand-pull policies, such as feed-in tariffs, put in place in specific countries. We compute firm-specific market size by using designation country weights (indexed as *c* in Table A.1) as well as technology weights (indexed as *s* in Table A.1) in each firm's patent portfolio (see Noailly and Smeets, 2015). Market size variables are likely to capture demand-pull policies (e.g. guaranteed tariffs, investment and production tax credits) that aim to increase the market for renewables.

4. Empirical strategy and results

4.1. Empirical strategy

In order to investigate the impact of the various financial constraints on the patenting activity of the firms in our sample, we largely follow the literature on the corporate financing of R&D (Brown et al., 2009; Brown and Peterson, 2011; Brown et al., 2012). We estimate the relationships between patents and internal and external financing flows:

$$P_{ict} = \beta_0 + \beta_1 CF_{it-1} + \beta_2 DB_{it-1} + \beta_3 STK_{it-1} + \beta_4\, \Delta CashHold_{it-1} \qquad (1)$$
$$+X_{ict} + \eta_i + \mu_c + \nu_t + \epsilon_{ict}$$

[7] Table A.1 in the Appendix provides specific definitions of all these variables and their data sources.

[8] These are prices paid at the power plant for electricity generation, i.e. prices paid by electricity facilities for a certain type of fuel (including taxes).

9 For each firm, we compute a specific weight, which captures the share of each country in the firm's overall designation country portfolio. In addition, we weight the different countries' prices with their FF market size to ensure that small countries do not have a disproportionate impact on computed prices.

where subscripts *i*, *c*, and *t* denote firm, country, and year; *P* captures (REN or FF) patent counts; *CF* are cash flows; *DB* is long-term debt; ΔCashHold is the growth in cash holdings; *X* is a vector of control variables (including firms' ratio of sales to total assets, firm's age and number of employees); η, μ, and ν capture unobserved firm, country, and time heterogeneity, respectively; and ϵ is an IID error term. The theoretical prediction is that financially constrained firms should a positive coefficient on cash flow and a negative coefficient on cash holdings growth, since a reduction in cash holdings release cash for innovation activities.

As discussed earlier, all financial variables are normalized by end-of-previous-period total asset stocks. Lagged realizations of the financial variables are included to allow for dynamic adjustments of innovation to cash constraints. Patenting at time t corresponds to the application year of the patent, which is the year most closely related to the date of invention (rather than the granting date).

Unobserved country and time heterogeneity are captured by the inclusion of country and year dummies. The presence of firm-level heterogeneity presents a problem, for two reasons. First, given the unbalanced nature of the panel, the available time-series of many (mostly specialized) firms in our sample are too short to warrant consistent estimation while including firm fixed effects. Second, fixed effects estimation is further hindered when estimation equation (1) using count data models (see below). Therefore, we do not incorporate firm fixed effects in our models, instead relying on the host of firm-level variables to capture the majority of cross-firm heterogeneity.

Using the absolute patent count as the dependent variable, we employ Negative Binomial regression. In the latter case, the regression model becomes:

$$E(P_{ict}|X_{ict}, \eta_i, \mu_c, \nu_t) = \lambda_{ict} \quad (2)$$

$$s.t.\ \lambda_{ict} = \exp(\Omega_{ict})$$

where Ω_{ict} denotes the model in (1). As is well known, compared to the Poisson model, the Negative Binomial model does not impose equidispersion (i.e. the equivalence of the conditional mean and variance). In robustness analysis, we will also consider the Poisson model.

Along our analysis, we also aim to estimate the impact of financial factors on the extensive margin of innovation, i.e. innovation entry, as Figure 3 showed that the rise in REN patenting in recent years was mainly caused by the entry of specialized REN firms. Hence, in our empirical strategy, we will conduct additional estimations in which we make a distinction between the extensive margin of innovation (i.e. a firm's decision to enter a specific type of innovation) and the intensive margin of innovation (conditional on positive entry decision, firms make a decision regarding how much to innovate). In the data, these two different processes (intensive vs. extensive margins) can be reflected into a firm's zero patent counts. First, there are structural (excess) zeros which stems from the fact that the firm has not found it profitable to undertake R&D (i.e. to enter the innovation market). Second, the standard zeros are the realization of a Poisson process and reflect the fact that after entry, innovation has not been successful that year (as innovation is an uncertain process). To capture these two margins, we will consider additional specifications, namely zero-inflated Poisson models, in which in a first step a logit distribution first determines the extensive margin decision, i.e. the likelihood of having a zero outcome (i.e. no innovation entry) for the count variable, estimated as:

$$\Pr(P_{ict=0)} = \Delta(\mu_{ict}) = \frac{e^{\mu_{ict}}}{1+e^{\mu_{ict}}} \quad (3)$$

Where Δ denotes the logistic distribution function and $\mu_{ict} = \log(\lambda_{ict})$ as in (2). Note that the interpretation of the coefficients is based on the likelihood of (excess) zero patents (i.e. no entry). Then, a second stage Poisson distribution governs the actual realization of the outcome. Hence, the intensive margin decision is given by a log-linear Poisson model as in (2).

4.2. Baseline estimations

In Table 4, we present the baseline results of estimating equation (1) by negative binomial models. All models include full sets of country and year dummies (not reported). Columns (1) and (2) present an estimation of the model for specialized REN and FF firms, respectively, while columns (3) and (4) provide the results for mixed firms. The dependent variable in every column is the number of patents (either REN or FF) per firm i and year t.

Regarding the impact of financial factors, we expect to find a stronger link between the financial variables and R&D in the groups of firms most likely to be financially constrained. For the sample of firms that specialize in REN innovation only (column (1)), we find that the coefficient for lagged cash flows is positive and significant (at 5% levels). Instead, cash flow coefficients are positive but insignificant for other firms (in columns (2) to (4)). This result confirms our hypothesis that REN firms in particular are financially constrained. FF firms, although younger and smaller than mixed firms, do not appear to be financially constrained and, similarly, patenting activities by mixed firms do not seem to be sensitive to cash flows ratios.

We do not find any positive significant impact of stock issues and long-term debt financing in the various samples of firms. The only, somewhat puzzling, significant coefficient is a negative impact of long-term debt on patenting by FF firms. A possible interpretation for this result is that FF firms might rely on long-term debt financing for other activities, such as investment in physical capital, which might crowd out R&D.

Overall and as expected, for mixed firms the fact that none of the financial factors are statistically significant is consistent with our hypothesis of no financial constraints for these large mature firms predominantly innovating in FF technologies.

The lagged coefficient on Cash holdings growth are negative as expected in most specifications. Cash holdings growth was expected to be negatively associated with R&D as reductions in cash holdings at the firm level free liquidity for R&D smoothing. Cash Holdings growth is, however, only significant in column (3) which considers specifically REN patenting activities by mixed firms. This indicates that mixed firms rely on cash holdings to smooth R&D, and in particular REN innovation. This suggests that mixed firms, may use their stock of liquidity as a buffer to finance their REN activities.

Regarding firm-levels controls, we find no impact of the sales ratio on patenting activities. Firm's age tend to have a negative impact on firms' innovation, except for REN activities of mixed firms (but the coefficient is not significant). In columns (1) and (2) for the sample of specialized firms, the results show that larger firms tend to patent more, while firm's size has no significant impact on mixed firms's patenting activities.

Finally, the impact of firm's knowledge stocks and other macroeconomic variables is in line with previous results found in Noailly and Smeets (2015): 1) there is evidence for within-firm path-dependency as firm's specific past knowledge stock in REN (FF) technologies affect current patenting REN (FF) activities[10] 2) REN (FF) market size has a positive (negative) impact on REN innovation, 3) higher FF prices can either encourage or discourage both types of innovation.[11].

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[10] Just as in Noailly and Smeets (2015), there is also evidence for complementarities in knowledge within mixed firms as the stock of FF patents has a positive impact on REN innovation by mixed firms.

[11] Higher FF prices might encourage firms to innovate more in FF technologies (to develop more efficient and cheaper technologies) but could also encourage firms to develop alternative technologies such as REN technologies. Note that the negative impact of FF prices on FF innovation in column (2) is not robust to other specifications, such as Poisson model (see Table 6).

TABLE 4: Baseline, Negative Binomial Results

VARIABLES	(1) REN firms REN patents	(2) FF firms FF patents	(3) Mixed firms REN patents	(4) Mixed firms FF patents
CF_{t-1}	1.079**	0.059	0.785	0.324
	(0.546)	(0.164)	(0.877)	(0.784)
Dbt_{t-1}	-0.198	-0.762**	-0.247	0.014
	(0.177)	(0.296)	(0.700)	(0.360)
Stk_{t-1}	-1.538	0.173	-7.228	-0.441
	(1.051)	(0.552)	(5.888)	(2.616)
Δ $Cashholdings_{t-1}$	-0.318	0.008	-2.878*	-0.012
	(0.222)	(0.258)	(1.498)	(0.373)
$Sales_{t-1}$	0.029	-0.058	0.100	-0.181
	(0.043)	(0.054)	(0.141)	(0.182)
$Log(Age)_t$	-0.312***	-0.155***	0.234	-0.235**
	(0.089)	(0.056)	(0.154)	(0.118)
Log $(Employees)_t$	0.084**	0.094***	-0.045	-0.061
	(0.035)	(0.025)	(0.052)	(0.046)
Log(REN knowledge $stock)_{t-1}$	0.606***		0.555***	-0.268*
	(0.153)		(0.171)	(0.152)
Log(FF knowledge $stock)_{t-1}$		0.871***	0.652***	1.180***
		(0.075)	(0.149)	(0.103)
Log (FF $prices)_{t-1}$	-0.285	-0.299*	-2.364**	0.466
	(0.277)	(0.176)	(1.055)	(0.640)
Log (REN market $size)_{t-1}$	0.050**	0.013	0.130**	0.045
	(0.025)	(0.048)	(0.056)	(0.036)
Log (FF market $size)_{t-1}$	-0.023	0.060	-0.438***	0.017
	(0.043)	(0.052)	(0.073)	(0.067)
Constant				
Year FE[a]	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Observations	2,093	4,811	536	536
Number of firms	403	813	90	90
Log Likelihood	-1027	-2436	-291	-481

[a] Due to convergence issues based on a small number of observations, in column (4) we use 2-years dummies rather than individual year dummies.

[b] * p<0.1, ** p<0.05, *** p<0.01. Robust standard errors are clustered at the firm level. Fossil fuel price and market size variables are constructed by using firm-specific weights reflecting the firms' patent portfolio and designation countries as in Noailly and Smeets (2015). The dependent variable in every column is the number of patents per firm i and year t.

4.3. Robustness tests

In this section, we conduct a series of robustness tests. First, as there are intrinsic differences among REN and FF firms (cf Table 2) we may be concerned by the fact that the positive impact of cash flows found in Column (1) of Table 4 may be due to the fact that REN firms are less mature (i.e. significantly younger) than FF firms, rather than to the fact that they specialize in a different type of innovation. To investigate this issue, Table 5 reports the results of a pooled estimation for specialized firms, in which we add interactions variables between cash flow ratios and the age and number of employees' variables, as well as with a dummy for REN firms. The results in Table 5 show that the cash flow variables interacted with age is negative but not significant, suggesting that there is no evidence that especially younger firms among the sample of specialized firms are financially constrained. The coefficient on the interaction variable $Log(Employees)_t \times CF_{t-1}$ is also not significant. Instead, the interaction variable between CF and the dummy for specialized REN firms is positive and significant at the 5% level, suggesting that REN firms are more financially constrained than FF firms, not because they are younger or smaller, but more likely because of the specificities of REN technologies, which are perceived as more risky by investors.

Finally, as a last robustness test, Table 6 shows that our results remain robust to a Poisson estimation.

TABLE 5: Estimations for specialized firms, with interaction terms

Negative binomial estimation	(1) Specialized Firms (pooled) Patents
CF_{t-1}	-0.100
	(0.896)
CF_{t-1} x REN firms	0.927**
	(0.437)
REN firms	0.574***
	(0.162)
Dbt_{t-1}	-0.382*
	(0.208)
Stk_{t-1}	-0.291
	(0.533)
$Log(Age)_{t}$	-0.192***
	(0.053)
$Log(Age)_{t}$ x CF_{t-1}	-0.011
	(0.281)
Log $(Employees)_{t}$	0.093***
	(0.023)
Log $(Employees)_{t}$ x CF_{t-1}	0.015
	(0.119)
$Sales_{t-1}$	0.036
	(0.035)
Δ $Cashholdings_{t-1}$	-0.286*
	(0.163)
Log(knowledge $stock)_{t-1}$	0.854***
	(0.063)
Log (FF $prices)_{t-1}$	-0.340*
	(0.191)
Log (REN market $size)_{t-1}$	0.079***
	(0.025)
Log (FF market $size)_{t-1}$	0.030
	(0.037)
Constant	-1.629
	(1.149)
Year FE	Yes
Country FE	Yes
Observations	6,904
Number of firms	1,216
Log Likelihood	-3516

[b] * p<0.1, ** p<0.05, *** p<0.01. Robust standard errors are clustered at the firm level. Fossil fuel price and market size variables are constructed by using firm-specific weights reflecting the firms' patent portfolio and designation countries as in Noailly and Smeets (2015). The dependent variable in every column is the number of patents per firm i and year t.

Table 6: Robustness, Poisson models

Poisson Estimation	(1)	(2)	(3)	(4)
	REN firms	FF firms	Mixed firms	Mixed firms
VARIABLES	REN patents	FF patents	REN patents	FF patents
CF (t-1)	0.283**	0.078	0.617	0.632
	(0.124)	(0.132)	(0.877)	(1.006)
Dbt (t-1)	-0.129	-0.747***	-0.236	-0.282
	(0.145)	(0.285)	(0.699)	(0.302)
Stk (t-1)	-1.215	0.382	-8.420	-7.910
	(1.153)	(0.538)	(6.429)	(6.038)
Δ Cashholdings (t-1)	-0.204	0.017	-3.142*	0.654
	(0.173)	(0.213)	(1.623)	(0.429)
Sales (t-1)	0.074*	-0.076	0.086	-0.158
	(0.041)	(0.056)	(0.148)	(0.169)
Log(Age) (t)	-0.366***	-0.174**	0.216	-0.293***
	(0.124)	(0.073)	(0.157)	(0.080)
Log (Employees) (t)	0.104***	0.093***	-0.062	-0.045
	(0.035)	(0.027)	(0.052)	(0.038)
Log(REN knowledge stock) (t-1)	0.884***		0.563***	1.263***
	(0.068)		(0.187)	(0.084)
Log(FF knowledge stock) (t-1)		0.907***	0.666***	0.566
		(0.075)	(0.155)	(0.647)
Log (FF prices) (t-1)	-0.220	-0.222	-2.297**	0.046
	(0.255)	(0.186)	(1.009)	(0.036)
Log (REN market size) (t-1)	0.074*	0.028	0.131**	-0.027
	(0.038)	(0.046)	(0.059)	(0.064)
Log (FF market size) (t-1)	-0.022	0.082	-0.425***	-0.280
	(0.048)	(0.061)	(0.078)	(0.160)
Constant	-1.297	-2.529**	12.606***	-3.038
	(1.866)	(1.260)	(4.587)	(3.554)
Year FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Observations	2,093	4,811	536	536
Number of firms	403	813	90	90
Log Likelihood	-1138	-2596	-294	-511

[a] Due to convergence issues based on a small number of observations, in column (4) we use 2-years dummies rather than individual year dummies.

[b] * p<0.1, ** p<0.05, *** p<0.01. Robust standard errors are clustered at the firm level. Fossil fuel price and market size variables are constructed by using firm-specific weights reflecting the firms' patent portfolio and designation countries as in Noailly and Smeets (2015). The dependent variable in every column is the number of patents per firm i and year t.

4.4. Extensive margin estimates

Finally, we estimate equations (2) and (3) using a zero-inflated Poisson model. The results are presented in Table 7. The top panel of the table presents the coefficient estimates of the Poisson model for the number of patents (level equation, intensive margin), while the bottom panel presents the coefficient estimates of the logit model in the inflation equation for the likelihood of observing (excess) zero patent counts. To save on space, we only report the results for the balance sheet and income statement variables.[12] We interpret the results of the inflation equation as the impact on the extensive margin of innovation, i.e. the likelihood of participating in the innovation market (innovation 'entry'). A negative impact on the likelihood of (excess) zero patents is thus interpreted as a positive impact on the likelihood to enter into REN or FF innovation. Columns (1) and (2) of Table 6 presents the results for specialized firms. The Vuong test statistic reported at the bottom of Table 6 suggests that the zero-inflated Poisson model performs better than the standard Poisson model for specialized firms. Due to a limited number of observations for mixed firms (N=90), we do not report the results for mixed firms as the zero-inflated models face convergence issues in this specific sample.

We investigate the positive impact of cash flow on REN innovation and in particular on entry of firms into REN innovation. The inflation equation at the bottom panel of Column (1) shows a positive and significant impact of cash flows ratios on the likelihood of REN innovation (recall that the inflation equation estimates the probability of zero innovation, so that a negative coefficient implies an increased likelihood of innovation). Hence, this suggests that REN firms are particularly constrained in their decisions to enter the REN innovation market. Instead, we do not find any impact of cash flows the innovation entry decisions of FF firms. Looking at the intensive margin in the top panel of Table 6, we do not find any more a positive impact of cash flows on the rate of innovation of REN specialized firms, which suggests that once they have entered and conducted their initial patents, REN firms do not appear to be financially constrained. The inflation equation in Column (2) also shows that a higher long-term debt is negatively associated with innovation entry of FF firms, although the coefficient is only marginally coefficient. This is in line with the results in Table 3: FF firms use long-term debt to finance other activities than innovation.

Results on the extensive margin of innovation confirm thus what we had previously established, namely that there is evidence that REN firms are financially constrained, while this is not the case for FF firms. The results rather highlight that since specialized firms tend to innovate only occasionally and then exit the innovation scene rather quickly the entry stage is particularly problematic.

[12] See Noailly and Smeets (2015) for a more detailed investigation on the role of FF prices and market size on innovation entry.

Table 7: Zero-inflated Poisson estimations.

Zero-inflated Poisson VARIABLES	(1) REN firms REN patents	(2) FF firms FF patents
Intensive margin Level equation		
CF (t-1)	0.150	0.157
	(0.129)	(0.588)
Dbt (t-1)	0.209	0.351
	(0.527)	(0.571)
Stk (t-1)	-5.764	-0.436
	(3.519)	(0.689)
Δ Cashholdings (t-1)	-0.140	-0.598
	(0.588)	(0.548)
Sales (t-1)	0.016	-0.341***
	(0.075)	(0.106)
Log(Age) (t)	-0.452***	-0.027
	(0.122)	(0.086)
Log (Employees) (t)	0.156***	0.082**
	(0.053)	(0.039)
Extensive margin Inflation equation		
CF (t-1)	-1.322**	0.012
	(0.672)	(0.403)
Dbt (t-1)	0.614	2.031*
	(0.568)	(1.095)
Stk (t-1)	-5.509	-2.115
	(6.381)	(2.117)
Δ Cashholdings (t-1)	-0.113	-1.424
	(0.752)	(1.413)
Sales (t-1)	-0.085	-0.481***
	(0.136)	(0.185)
Log(Age) (t)	-0.248	0.229**
	(0.183)	(0.116)
Log (Employees) (t)	0.064	-0.024
	(0.072)	(0.053)
Additional controls	Yes	Yes
Year FE	Yes	Yes
Country FE	Yes	Yes
Observations	2,093	4,811
Number of firms	403	813
Log Likelihood	-1048	-2465
Vuong test	3.60***	5.60***

[b] * p<0.1, ** p<0.05, *** p<0.01. Robust standard errors are clustered at the firm level. Fossil fuel price and market size variables are constructed by using firm-specific weights reflecting the firms' patent portfolio and designation countries as in Noailly and Smeets (2015). The dependent variable in every column is the number of patents per firm i and year t. Both level and inflation equations include additional controls for Log(patent stocks), FF prices, REN and FF market sizes as in Table 3.

5. Conclusions

The objective of this paper has been to look at evidence for financing constraints of firms innovating into energy technologies, making a distinction between renewable and fossil-fuel energy. We combined data on patents in REN and FF technologies held by firms with data on balance sheet and income statement borrowed from the Orbis database for a set of 1,300 European firms over the 1995-2009 period. Our descriptive analysis showed some important distinctive features between firms that specialized in REN innovation, firms that specialize in FF innovation and firms that mix both types of innovation in their patent portfolio. First, firms specializing in REN innovation tend to be small and young occasional innovators. Yet, the new entry of these firms since the mid-1990s explains the recent surge in patenting activities in renewable technologies in Europe. These firms appear thus as key actors in driving the electricity generation sector towards renewable technologies. Second, firms specializing in FF technologies are relatively older and larger than REN firms but they also only innovate occasionally. Finally, other important actors are large incumbent firms which tend to conduct innovation in both REN and FF technologies (`mixed firms'), although their patent portfolio appears to be predominantly dominated by FF technologies. These firms are much older and larger than other firms and are more persistent innovators.

This paper aimed to test the central hypothesis that firms specializing in REN innovation are more financially constrained than either FF or mixed firms. Compared to FF innovation, REN innovation is more uncertain and risky for investors, due to the lower maturity of the technologies and the larger reliance on (uncertain) policy support. Our descriptive analysis of firms' balance sheet data also confirms that the bulk of REN innovation tend to be undertaken by smaller and younger firms than firms conducting FF innovation. Using negative binomial and Poisson estimation techniques, we estimate the sensitivity of firms' patenting activities to three financing factors, namely cash flows, long-term debt and stock issues, controlling for R&D smoothing as well as other firms' and market characteristics. We find evidence that financing constraints matter for firms specialized in REN innovation but not for small FF firms or large mixed firms. Results from a two-stage zero-inflated Poisson models confirm that financing constraints are particularly relevant for the firm's decision to start innovating ('innovation entry').

Our results have important implications for policymaking. First, the results emphasize that small innovative newcomers in the field of renewable energy are particularly vulnerable to financing constraints, not solely because they are younger and less mature than other established firms, but mainly because they focus on new clean technologies that are still perceived as more risky by investors than the incumbent technologies based on fossil-fuels electricity generation. Government and policymakers should thus pay particular attention to ease financing constraints of start-up companies into renewable energy. Some options for policymaking include for instance providing venture capital for REN start-up firms or providing specific R&D subsidies for small innovating firms in renewable energy. Our results highlight thus the need for sector specific subsidies (rather than generic policies for all firms) and for the need to configure investment policies to steer investments towards clean technologies, for instance in the form of specific capital grants, venture and equity funds or low-interest loans for starters in clean energy. Public regulators can also more actively use the option to lend directly to the renewable energy sector via public investment banks on terms more favourable than those of the market.

Finally, while this work has presented a first empirical analysis of the role of financing constraints on the direction of innovation in the electricity generation sector, future work could take advantage of larger datasets to produce a more refined analysis, for instance by looking at variation across countries or across time. The impact of the financial crisis of 2008 on firms' financing constraints for REN vs. FF innovation, which could not be examined here due to the long-time lags of patent granting processes, is left for future research.

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Appendix

Appendix 1 – Variable definitions and data sources

Table A.1: Variable definitions and data sources

Variable	Construction	Data source
Renewable (REN) patents	Count of patents in wind, solar, hydro, marine, biomass, geothermal, and waste energy technologies.	Orbis-EPO (PATSTAT)
Fossil fuel (FF) patents	Count of patents in fuel gases by carbureting air, steam engine plants, gas turbine plants, hot-gas or combustion-product positive displacement engine, steam generation, combustion apparatus, furnaces, and improved compressed-ignition engines technologies.	Orbis-EPO (PATSTAT)
Stock issues	$\frac{Capital_t[\mathbf{CAPI}] - Capital_{t-1}}{Total\ Assets_{t-1}[\mathbf{TOAS}]}$	Orbis
Long-term debt	$\frac{Long\ term\ debt_t[\mathbf{LTDB}] - Long\ term\ debt_{t-1}}{Total\ Assets_{t-1}[\mathbf{TOAS}]}$	Orbis
Cash flow	$\frac{Cash\ Flow_t[\mathbf{CF}]}{Total\ Assets_{t-1}[\mathbf{TOAS}]}$	Orbis
Sales	$\frac{Sales_t[\mathbf{TURN}]}{Total\ Assets_{t-1}[\mathbf{TOAS}]}$	Orbis
∆Cash holdings	$\frac{Cash\ \&\ equivalents_t[\mathbf{CASH}] - Cash\ \&\ equivalents_{t-1}}{Total\ Assets_{t-1}[\mathbf{TOAS}]}$	Orbis
Log employees	Log(Employees [**EMPL**] +1)	Orbis
Log age	Log((Year-Date of incorporation [**DATE**]) + 1)	Orbis
Publicly listed	Publicly listed company [**LIST**]	Orbis
Fossil fuel (FF) price	$\sum_c \left(\frac{P_{ic} \times M_{FFc}}{\sum_c P_{ic} \times M_{FFc}}\right) \times \sum_f \left(\frac{M_{fc}}{M_{FFc}} \times p_{fct}\right)$	IEA, PATSTAT, INPADOC
Renewable (REN) and fossil fuel (FF) market size	$\sum_c \sum_s \frac{P_{isc}}{\sum_s \sum_c P_{isc}} \times M_{sct}$	IEA, PATSTAT, INPADOC
Renewable (REN) and fossil fuel (FF) knowledge stock	$(1-\delta)K_{it-1} + P_{it}$	Orbis, PATSTAT

Notes: Orbis variable identifiers within square brackets in bold.

Appendix 2 – Methodology and data cleaning of the Orbis dataset

To construct the firm-level financial variables, we follow the following steps for data cleaning as in Kalemli-Ozcan et al., (2015).

1. We check the consistency of accounting identities (ratio should not be larger than 10%)
    - fixedassets-tangiblefixedassets-intangiblefixedassets-otherfixedassets)/fixedassets
    - totalassets - fixedassets-currentassets)/totalassets
    - noncurrentliabilities - longtermdebt - othernoncurrentliabilities)/noncurrentliabilities
    - currentliabilities - loans - creditors - othercurrentliabilities)/currentliabilities
    - totalsharehfundsliab-loans)/totalsharehfundsliab
    - totalsharehfundsliab-longtermdebt)/totalsharehfundsliab

2. We drop the entire company (all years) if total assets is negative in any year.

3. We drop the entire company (all years) if sales is negative in any year.

4. We drop the entire company (all years) if tangible fixed assets (such as buildings, machinery, etc) is negative in any year

5. For some firms, there are some inconsistencies in the units of financial variables (as noted by Kalemli-Ozcan on p.29). The moment of switch in units coincides with an “unreasonable" move of total assets, often clustered around the year 2000. To solve for this, we focus on firms with total assets above 1 million USD.

6. We also winsorize all financial variables by trimming the data at 1%.

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