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# Reconfiguring technologies by funding transitions: priorities, policies, and the renewable energy sources in the European Community funding schemes

## Abstract

The article examines the changes in the European Community (EC) research funding priorities and how they determined the character of the photovoltaic and wind technologies developed between 1975 and 2013. We address two research questions: What role has the EC's energy policy played in directing research policy? How did the EC's research funding priorities define the character of wind and photovoltaic technologies? We argue that EC energy policy directed research policy, even in unintentional ways. Furthermore, we argue that the politics of scale, for wind technologies, and material politics, for photovoltaics, had a prominent role in defining the priorities and shaping their technical characteristics.

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## INTRODUCTION

### Aim and Approach

1 The paper focuses on the European Community (EC) research funding priorities in the field of non-nuclear energies (NNE), particularly for solar photovoltaic (PV) and wind energy (WE) technologies.[1],[2],[3] The analysis covers the period from 1975 to 2013. It focuses on the EC research funded and promoted through the Research and Development programmes (R&D) and the corresponding NNE sub-programmes.[4] We argue that changes in EC funding priorities shaped the technical characteristics of both PV and wind turbines (WTs). We analyse the aims and objectives of EC R&D programmes and of the NNE sub-programmes between 1975 and 2013, tracking shifts in energy technology-related research priorities, the meanings attributed to the developing technologies, and the characteristics of various renewable energy sources (RES).[5] We claim that studying the political economy of research as well as the strategies and dynamics of shaping research policy in the RES industry is important in exploring how the EC energy policy directed research policy. We consider research policy as something that is shaped and structured through pressures by the EC energy priorities, national priorities, transnational competitions and the research networks.

The two case studies were chosen because of the determinant role of these two technologies in shaping EC research policy for the promotion of energy technologies that are considered 'environmentally friendly' and key contestants of the hydrocarbon energy policies developed at European level. The importance of both PV and WE technologies in EC research policy is also reflected by the level of funding they received from EC R&D programmes. PV ranked first in funding among all RES from 1975 until 2002, when biomass took the lead. WE ranked second and third in funding during the same period, but gradually lost its privileged status between 2003 and 2013. 2

Thus far, scholars in the history of science and technology and environmental history have examined the role of experts, legislation, non-governmental organisations, and citizen activism in energy transitions. They have showed that different political, ideological and cultural conditions can affect technological styles both at the level of innovation and at that of technological networks.[6],[7] They have compared various energy programmes within national contexts and examined the impact of international treaties and agreements as well as the specific conditions that foster varieties of styles. Scholars have argued that various cultural particularities and needs can deeply influence the adopted style and energy system. In particular, Sovacool deploys the concept of research styles to denote the cultural differences that shape and direct research and result in different technologies.[8] He has 3

**1** RES fell under the NNE field.
**2** For simplicity reasons we employ the term EC to denote the European Economic Community (EEC)/EC. The EEC was renamed to EC when the Maastricht Treaty entered into force in 1993 and became one of the European Union pillars. All R&D programme Decisions made direct references to European Community R&D, including the FP7 Decision that was issued in 2006. Since 2009, when the Lisbon Treaty entered into force, the EC pillar was abolished.
**3** Throughout the article when referring to Europe or European we refer to EC funding, unless stated otherwise.
**4** First Energy R&D Programme (1975-1978); Second Energy R&D Programme (1979-1983); FP1 (1985-1988); FP2 (1988-1991); FP3 (1990-1994); FP4 (1994-1998); FP5 (1998-2002); FP6 (2002-2006); FP7 (2007-2013).
**5** By 'meanings of technologies' we refer to how the epistemic communities assessed or attributed value on the developing technologies with the potential of efficiency increases (for PV) and scale up (for WTs).
**6** Matthias Heymann, "Signs of hubris: The shaping of wind technology styles in Germany, Denmark, and the United States, 1940-1990", *Technology and Culture,* vol. 39/4, 1998; Ulrick Jørgensen, Peter Karnøe, "The Danish Wind-Turbine Story: Technical Solutions to Political Visions?" *in* Arie Rip, Thomas Misa, and Johan Schot (eds.), *Managing Technology in Society. The Approach of Constructive Technology Assessment* (London: Pinter, 1995).
**7** The term 'technological styles' used draws from Heymann's work (cf. note 6). It is employed to describe technological developments or changes directed by cultural, socio-economic and political conditions, which influence the technical characteristics and result in different technologies.
**8** Benjamin Sovacool, "The importance of open and closed styles of energy research", *Social Studies of Science*, vol. 40/6, 2010.

approached research conducted in emerging innovations in energy regimes as a dynamic system of relations among companies, users, governments, engineers and other stakeholders. His unit of analysis are state-bounded energy regimes. While all the above approaches are very important and contribute to the understanding of energy transitions, this paper aims to shift attention towards research conducted on energy technologies and its importance in defining the technical characteristics of energy innovations. Furthermore, by focusing on the political economy of R&D at an EC level, we unravel this entity's role in shaping, directing and controlling technological change in energy technologies.

4 Thus, our story goes beyond the existing national historiographies by studying the socio-political dynamics that have shaped EC research policy in the field of RES technologies. Our approach has been influenced by the work of Mazzucato and Semieniuk who have stressed the importance of studying the ways in which choices concerning funding affect the direction of innovation in the field of RES; in our analysis, the focus is on the EC R&D funding schemes for RES technologies.[9] Our research, resonates with their approach by identifying a) research strategies that linked research, experimentation and production in the making of energy innovations, b) mission-oriented energy innovations, and c) research policies, research programmes and funding schemes that invested in risky technologies that had not been tested and were still far from deployment.

5 By conducting an in-depth historical analysis of the role played by R&D funding in the introduction of RES technologies and in shaping the EC energy markets, we contribute to the existing scholarship, which has studied energy transitions by focusing on the socio-political and financial dynamics of the energy regimes at national and transnational level.[10] We argue that we need to look at the funding flows and their direction in the making of the technologies and thus we seek to link funding schemes with the technical characteristics of 'green' technologies. Towards this end, the article addresses the following research questions: What role has the EC's energy policy played in directing research policy? How did the EC's research funding priorities define the character of wind and photovoltaic technologies? Throughout the examined period –1975-2013– there have been several changes in the EC energy policy strategy and the research priorities, both in general and specifically for RES. In sections 2.1 and 2.2, we discuss some of these major changes and landmarks in regards to the EC energy policy strategy and energy research priorities, which have had significant bearing on the EC research priorities in the domain of RES technologies.[11] Studying the impact of research funding and research policies in the technological change of RES technologies, we have identified two major periods. During the first period –1975-1998– the research agenda was characterised by technological pluralism and continuous experimentation. Research policy advocated the pursuit of varied energy technologies but

**9** Mariana Mazzucato, Gregor Semieniuk, "Financing renewable energy: Who is financing what and why it matters", *Technological Forecasting and Social Change*, vol. 127, 2018; Mariana Mazzucato, Gregor Semieniuk, "Public financing of innovation: new questions", *Oxford Review of Economic Policy*, vol. 33/1, 2017.

**10** Ronan Bolton, Timothy J. Foxon, "A socio-technical perspective on low carbon investment challenges - Insights for UK energy policy", *Environmental Innovation and Societal Transitions*", vol. 14, 2015; Ronan Bolton, Timothy J. Foxon, "Infrastructure transformation as a socio-technical process: Implications for the governance of energy distribution networks in the UK", *Technological Forecasting and Social Change*, vol. 90, 2015; Adrian Smith, Andy Stirling, Frans Berkhout, "The Governance of Sustainable Socio-Technical Transitions", *Research Policy*, vol. 34/10, 2005; Frank W. Geels, "From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory", *Research Policy*, vol. 33/6-7, 2004; Frank W. Geels, Johan Schot, "Typology of sociotechnical transition pathways", *Research Policy*, vol. 36/3, 2007; Timothy J. Foxon, Peter J. G. Pearson, Stathis Arapostathis, Anna Carlsson-Hyslop, Judith Thornton, "Branching points for transition pathways: assessing responses of actors to challenges on pathways to a low carbon future", *Energy policy*, vol. 52, 2013.

**11** The sections provide a brief analysis of some of the main changes in EC energy policy and research priorities; they are not exhaustive.

with clear funding frontrunners (i.e. research on several solar cells but dominance of c-Si in the first period and thin films in the second period). During the second period –1998-2013– research shifted towards industrial exploitation of near-market products and large-scale production, with research on the integration of RES technologies to the electricity grids, accompanied by a thrust towards boosting the EC's global industry competitiveness, and research on the design of the technologies.

### Methodology and Data Analysis

6 The material for the present study consists of various published yet hitherto unstudied sources. We analysed the first two energy R&D programmes, the seven Framework Programmes (FPs), their respective NNE sub-programmes, the funded projects for PV and WE technologies for electricity production, as well as various assessments, reports, legislative material and secondary sources. The FPs, sub-programmes, and projects were retrieved through advanced searches at the "Europa" website.[12] From Europa, booklets that contain the funded projects were retrieved. These booklets contain information regarding the exact funding each project received, the contractors' names, as well as a presentation of each project (aims, objectives, description etc.).[13] Additional information for the funded projects was obtained through the Cordis database.[14] Cordis does not always offer all necessary information (e.g. funding may be missing for some projects) and it is up-to-date only for projects funded since FP5. Thus, we used Cordis only as a supplementary source of information, especially for projects from FP5 onwards.

7 All the funded projects that correspond to the sub-programmes, for both PV and WE, were examined and analysed. Projects using PV and WTs for non-electricity production purposes were excluded from our analysis. Moreover, our analysis does not include the analysis of the demonstration programmes. Our calculations for the funding of the projects were based on the information provided in the above-mentioned material. The evaluations, assessments and reports were also retrieved from Europa, as well as FP-specific sites. These sources were used to enrich the analysis with further information and to help us contextualise our story and research material. To further assist the analysis, we used the legislative material accessible via the EUR-lex website.

## ENERGY POLICY AND ENERGY RESEARCH PRIORITIES: FROM 1975 TO 2013

### From Energy Strategy to Common EC Energy Policy

Until 1993, the EC had no concrete common energy policy and it lacked the institutional power to establish the requisite institutional, legislative and policy tools for implementing a common EC-wide energy policy across the member states. Moreover, the member states had conflicting interests, which led them to having opposing stances as regards energy policy issues and the means of dealing with them.[15] Thus, what existed were national energy policies –either fragmented or coherent– and an EC energy policy strategy.[16],[17] The lack of a common energy policy was acknowledged by the EC. Only a few domains like the Energy R&D programmes consisted of a 8

**12** https://europa.eu/european-union/index_en

**13** By contractors' name we mean all the information about the project leader (name, institution name etc.); the same information is provided for all partners involved in the project(s).

**14** https://cordis.europa.eu/

**15** Alberto Tonini, "The EEC Commission and European Energy Policy: A Historical Appraisal", *in* Rosella Bardazzi, Maria Grazia Pazienza, Alberto Tonini (eds.), *European Energy and Climate Security: Public Policies, Energy Sources, and Eastern Partners* (New York, London: Springer, 2016).

**16** *Id.*

**17** Both strategy and policy set targets to be achieved through objectives. The two terms are used to indicate the changes in the acquired institutional powers of the EC. Thus, we employ the term strategy to denote the lack of 'tools' required and/or presupposed to reinforce the necessary actions taken towards achieving the targets at an EC level (i.e. the EC did not have the institutional tools to implement the objectives in the member-states). In contrast, policy indicates that the required 'tools' for implementing the actions necessary exist (the EC acquires more powers that enable the implementation of the objectives in the member states).

common action (i.e. consensus amongst member states to undertake joint research at the EC level).[18,19]

9 The first EC energy policy strategy objectives were set to address the challenges deriving from the 1973 oil crisis. In particular, the objectives consisted of measures to reduce oil dependency and to ensure energy security and energy supply.[20] These objectives, which arose in response to the oil crisis of 1973 and were further boosted during the oil crisis of 1979, aimed to quell the uncertainty, unease, and urgency to secure an energy supply for Europe. It was within this context of uncertainty that the first Energy R&D Programme launched in 1975 to explore potentially viable energy options such as RES. However, the EC's energy policy strategy objective to decrease imports of oil products in order to ensure the security of the energy supply, was to be met primarily via nuclear energy and natural gas, not RES.[21,22] The pathways towards oil substitution varied, depending on cultural, geographical and political specificities, as well as on the availability of energy resources. For example, Germany opted for coal, and later for nuclear energy.[23] France launched a massive nuclear energy programme in 1974, whereas Denmark prioritised coal in combination with natural gas.[24,25] Accordingly, the national R&D programmes on RES also had varying priorities. Germany, France and Italy dedicated funds both for PV and WE, whereas Denmark and the Netherlands prioritised WE.[26] From 1986 and throughout the 1990s, apart from the Chernobyl disaster that briefly boosted RES R&D efforts, public funding for RES declined worldwide.[27]

A common energy policy slowly took form with 10
the 1992 establishment of the European Single Market (SEM). Additionally, SEM gave more power to the EC and helped harmonise energy policies across the member states.[28,29] The energy policy-relevant actions concerned setting up of 'common rules for the internal market in electricity'. A major trigger behind a common energy policy was climate change.[30,31] The objective of $CO_2$ emissions reduction played a significant role in (re)defining the European energy policy and its objectives. For example, the 1997 Kyoto Protocol and Energy White Paper called for reductions in greenhouse gas (GHG) emissions, setting specific reduction targets expressed in percentages in relation to the baseline year 1990 (for the EC, 8% reduction of the six GHGs within the first commitment period of 2008-2012).[32] This overall target was divided into country-specific targets via a European Union (EU) burden-sharing agreement. Country-specific targets varied widely from one country to another, depending on each country's wealth as well as its earlier energy efficiency and emission reduction

**18** Neil Nugent, "Policies", *in* Neil Nugent, William E. Paterson (eds.), *The Government and Policies of the European Union* (Basingstoke: Palgrave Macmillan, 2006).
**19** Commission of the European Communities, *Energy in Europe: Energy policies and trends in the European Community* (Luxembourg: Office for Official Publications of the European Communities, 1989), 6.
**20** Council Resolution, of 17 December 1974 concerning Community energy policy objectives for 1985 (*Official Journal of the European Communities*, 1975).
**21** *Id.*
**22** Council Resolution of 16 September 1986 concerning new energy policy objectives for 1995 and convergence of the policies of the Member States (No C 241, 25.09.198) (*Official Journal of the European Communities*, 1986.
**23** Frank Laird, Christoph Stefes, "The diverging paths of German and United States policies for renewable energy: Sources of difference", *Energy Policy*, vol. 37/7, 2009.
**24** Miriam J. Boyle, M. E. Robinson, "French Nuclear Energy Policy", *Geography*, vol. 66/4, 1981.
**25** Mogens Rüdiger, "From import dependence to self-sufficiency in Denmark, 1945–2000", *Energy Policy*, vol. 125, 2019.
**26** Maarten Wolsink, "Dutch wind power policy: Stagnating implementation of renewables", *Energy Policy*, vol. 24/12, 1996.
**27** Ch. Breyer *et al.*, "Research and Development Investments in PV: a limiting factor for a fast PV diffusion?", *25th European PV Conference*, 2010.
**28** Tonini, "The EEC Commission and European Energy Policy", *op. cit.* 13-35 (cf. note 15).
**29** SEM was to create a unified European market by deregulating. It provided the EC with more powers and, along with the Single European Act, 'allowed' regulating energy policy.
**30** Directive 96/92/EC (*Official Journal of the European Communities*, 1996).
**31** Jegen Maya, "Energy policy in the European Union: The power and limits of discourse", *Les cahiers européens de Sciences Po*, n°2, 2014.
**32** European Commission, Energy for the Future: Renewable Sources of Energy White Paper for a Community Strategy and Action Plan, COM (97)599 final, 1997.

measures. These GHG emission reductions were accompanied by EC policies and measures that were to be undertaken to reach the targets.

11 Similar goals regarding RES share in energy consumption were integrated into EC legislation. The 2001 Directive set the goal for an indicative share of 22.1% electricity from RES by 2010.[33] The 2009 Directive established an overall binding target of 20% contribution of RES energy to final energy consumption by 2020, which was followed by national binding targets for each member state.[34] These aims and objectives in the EC legislation and policy were influenced, especially during the 2000s, by environmental concerns (relating to, for example, fossil fuels and nuclear power). Moreover, it was the Lisbon Treaty (2007) that defined energy policy "[...] as an area of priority action by primary (i.e. treaty) law [...]", hence a common EC energy policy, centrally regulated.[35] These legislative changes, which facilitated further integration of RES in the national electricity grids, drew attention towards RES. During this period, financial incentives were adopted to facilitate the integration of RES into the electricity grids. For example, feed-in-tariffs were introduced in several countries like Germany, France, Greece, Italy, and the UK.[36] These incentives were accompanied by programmes such as the 1998 German 100.000 roofs programme and the 2001 Italian 10.000 rooftops programme.[37]

12 Therefore, in 1993 a common and centrally driven EC energy policy began to shape and direct national energy policies. Member states agreed to relinquish a (small) part of their sovereignty as they adopted the more-or-less binding joint measures concerning energy policy that were indicated in EC regulations and directives. Within this framework, a common vision was created, and energy policy was shaped by specific environmental challenges and problems. From 2001 onwards, the EC has encouraged further energy production by RES, moving from indicative to binding targets concerning the share of RES in electricity generation. These binding targets helped to steer development towards the goals of the energy policy, notably those relating to RES and emission reductions. At the same time, as will be illustrated in section 2.2, the character of EC research policy became less experimental and explorative, and more focused on the integration of RES technologies into the electricity grids. At the EC level, this shift was accompanied by environmental concerns (e. g. climate change, GHS emission reductions) that provided political legitimization to public policies that supported the investments in RES technologies.[38] Hence, energy and environmental policy were moving in the same direction, both calling for further integration of RES technologies into the electricity grids. It was believed that this could be achieved by following supportive research policies.[39] Three sets of EC policies—energy, environmental, and research—were aligned in that they pursued similar energy policy goals by reinforcing the further development and integration of the RES technologies to the electricity grids. This synergism of energy, environmental, and research goals helped the EC to achieve its

**33** Directive 2001/77/EC (*Official Journal of the European Communities*, 2001).

**34** Directive 2009/28/EC (*Official Journal of the European Communities*, 2009).

**35** Jale Tosun, Sophie Biesenbender, Kai Schulze (eds.), *Energy Policy Making in the EU: Building the Agenda* (London: Springer, 2015), 22.

**36** Luigi Dusonchet, Enrico Telaretti, "Comparative economic analysis of support policies for solar PV in the most representative EU countries", *Renewable and Sustainable Energy Reviews*, vol. 42, 2015.

**37** Ahmad Zahedi, "Solar photovoltaic (PV) energy; latest developments in the building integrated and hybrid PV systems", *Renewable Energy*, vol. 13/5, 2006.

**38** Climate change became a policy priority soon after the Kyoto Protocol (see: Tim Rusche, "The European climate change program: An evaluation of stakeholder involvement and policy achievements, *Energy Policy*, vol. 38/10, 2010), and the same applies for GHG emission reductions (see: European Commission, Report from the Commission to the European Parliament and the Council Progress Towards Achieving the Kyoto and EU 2020 Objectives, COM(2014) 689 final).

**39** Research, both for PV and WTs, was supporting the integration of RES into the electricity grids (e.g. through funding problems that addressed the resolution of connectivity issues). Such research themes can be traced already from the first pilot projects but it was-especially-in the late-1990s that such topics gained prominence in the R&D programmes.

targets for GHS emissions and RES integration to the electricity grids and to enhance the sustainability of its energy policy.

**Energy and Research Policy Alignment**

13 Throughout the examined period, there were several important changes in the EC research priorities; we will briefly touch upon three changes that are of major importance. The first change was introduced by the Single European Act in 1987, which provided a new legal basis for R&D and redefined the aim of the research activities.[40],[41] Within this framework, R&D was instrumental for strengthening European industry and its international competitiveness. The second change was introduced by the establishment of the European Research Area in 2000, responsible for aligning EC and member state research activities, programmes and policies. The ERA was envisioned to become the equivalent of the SEM but for research; create an integrated space for science and technology. With the ERA, alignment was pursued through joint research ventures under the EC R&D umbrella, accompanied by funding increases (3% of GDP goal), to overcome fragmentation across Europe, between different countries.[42] The third important change was introduced by the implementation of the Strategic Energy Technology Plan (SET-Plan) in 2007, which emphasised low carbon technologies and coordinated the criteria for research and innovation. SET-Plan essentially called for better coordination and alignment between energy policy and research policy for RES technologies, towards achieving the 2020 goals. This was to be achieved through the creation of the European Technology Platforms (ETPs), introduced in 2004. ETPs are industry-led fora that publish Strategic Research Agendas, which connect visions to challenges and suggest responses to the latter by outlining research priorities to infiltrate the EC R&D priorities.[43]

In 1998 the R&D and Demonstration (RD&D) sub-programmes were merged. The R&D sub-programmes were managed by the Directorate General for Research and Development, responsible for research policy, and the Demonstration sub-programmes were managed by the Directorate General for Transport and Energy, responsible for energy policy. The importance of this merger lies in its impact on research. Research that could narrow down the gap between research and market was prioritised, as well as projects that could resolve connectivity issues for the integration of RES to the electricity grids. 14

An important question needs to be addressed before examining the changes in energy and research policy: in which ways, if any, did the consecutive EU enlargements influence energy R&D funding? As illustrated in Figure 1, during FP1, NNE received significant funds, showing the influence of the 1970s oil crises. In FP2 and FP3, NNE received a smaller portion of funds as compared to those dedicated to nuclear energy, clearly indicating the high priority of nuclear energy. This significant funding increase allocated for nuclear energy can be attributed to the Chernobyl nuclear disaster, which was the major trigger behind increased nuclear funding – especially on nuclear safety. During FP4 and FP5, NNE funds were almost equal to the funds for nuclear energy. Therefore, when compared to the funds NNE received during the previous two FPs, during this period, NNE gained prominence. The variability in funding between NNE and nuclear energy between FP1 and FP5 seems to have been influenced by broader energy issues and pressures. Critical events such as the oil crises and the Chernobyl disaster were the driving force behind changes in energy funding, rather than the enlargements. 15

**40** Single European Act (*Official Journal of the European Communities*, 1987).

**41** Dan Andree, Priority-setting in the European Research Framework Programmes (Stockholm: VINNOVA, Swedish Governmental Agency for Innovation Systems, 2009), 17.

**42** Thomas Banchoff, "Politic Dynamics of the ERA", *in* Jacob Edler, Stefan Kuhlmann, Maria Behrens (eds.), *Changing Governance on Research and Technology Policy: The European Research Area* (Cheltenham, U.K. and Northampton, Mass: Edward Elgar, 2003).

**43** For more information on ETPs see **https://etip-pv.eu/** and **https://etipwind.eu/**.

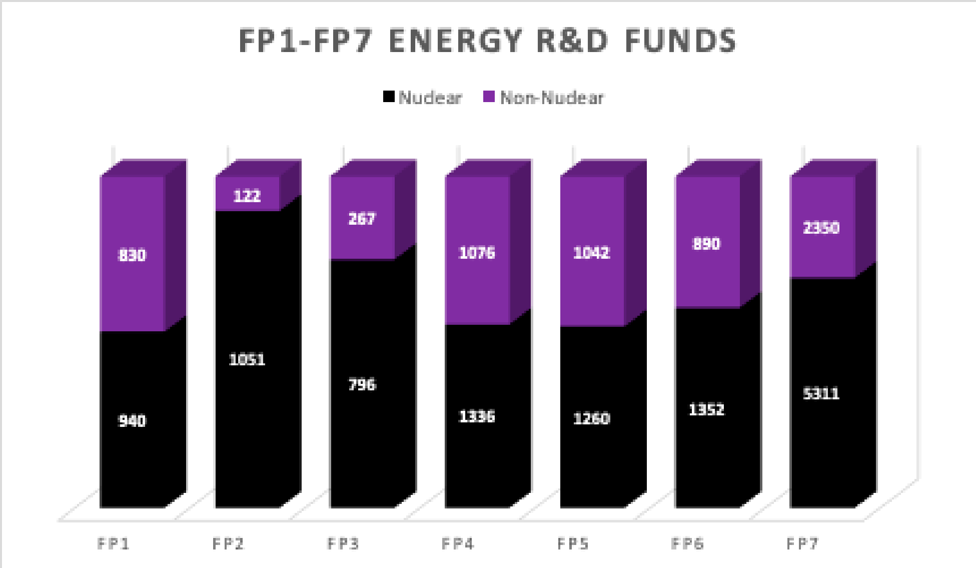


**Figure 1:** FP1-FP7 Energy R&D Funds (in EUR million). Adapted from: Vilma Radvilaite, "EU budget 2014–2020 deal: opportunities for wind energy", *European Wind Energy Association*, 2013, 3.

In FP6, funding for NNE declined, whereas the NNE funds during FP7 almost tripled and funding for nuclear energy nearly quadrupled. The 2004 and 2013 enlargements included the accession of several countries with nuclear power stations (Lithuania, Hungary and Bulgaria). The Kyoto protocol required GHG emission reductions, sustainable energy production figured amongst the EC's energy priorities, and the nuclear industry sought to rebrand nuclear energy as a safe and clean energy source.[44] The EC invested both in NNE and nuclear energy in its attempt to balance between energy security, energy efficiency and sustainable energy production. Global trends, competition with the USA and China, as well as the energy crises like the January 2006 gas conflict between Russia and Ukraine, also spurred funding for NNE and nuclear energy in the last period of our study.[45]

**44** Andrei Stsiapanau, Lithuania-Short Country Report, HoNESt Project, 2018; Mathew Adamson, Gábor Palló, Hungary-Short Country Report, HoNESt Project, 2017; Ivan Tchalakov, Ivaylo Hristov, Bulgaria-SCR, HoNESt, 2019.

**45** Frank Umbach, "Global Energy Security and the Implications for the EU", *Energy Policy*, vol. 38/3, 2010.

## BLOWING THE WIND WHILE SEEKING THE SILICON: EC RESEARCH POLICY ON WIND TURBINES AND PHOTOVOLTAICS

We distinguish two periods for both case studies; the first from 1975 to 1998 and the second from 1998 to 2013. The reasoning behind this periodisation lies in the overall rationale underpinning research policy, its aims and objectives and, by extension, the specific choices for both PV and WTs. 16

During the first period, research aimed to support the European industry's international competitiveness. Towards this aim, research was designed to strengthen the industry's scientific and technological basis. The R&D programmes aimed to provide a basis for cooperation among member states and their various actors (e.g. universities and research centres). Research was to support the overall EC energy policy strategy goal of securing energy supply and decreasing energy imports. The research agenda of the EC was characterised by technological pluralism and continuous experimentation. EC research policy advocated the pursuit of varied energy technologies but with clear funding frontrunners (e.g. research on several cells but with a clear dominance of crystalline Si cells). 17

18 During the second period, research was (re) directed at solving new problems and this resulted in both its role and use being re-casted. R&D sought to foster economic development, sustainable development, and solving environmental and societal problems whilst aiding the European industry's global competitiveness. The systematic emphasis given to economic development was directly in line with the "Lisbon agenda" (2000), which sought to turn the EU into "the world's most competitive and dynamic knowledge economy."[46] Environmental objectives, especially $CO_2$ emissions were highlighted, especially for the RES-related activities. Moreover, research was envisioned as the focal point of innovation and knowledge-production, and R&D programmes portrayed research as a means of achieving these economic objectives. Within this context, there was a constant effort to narrow the gap between research and market, aiding the commercialisation of products which emerged from the research. This shift became evident as R&D programmes came to increasingly value and foster innovation and economic applications. Furthermore, energy policy was strongly geared towards addressing environmental challenges. As such, energy policy clearly affected research policy. During this period, research shifted towards industrial exploitation of near-market products and large-scale production, the resolution of connectivity problems that would aid the integration of RES technologies to the energy grids, and research on the design of the RES technologies.

19 In other words, during the two periods, research had to respond to different problems, had distinct roles and was used differently. The targeted problems and solutions from each period corresponded to different ideologies concerning the political economy of research. In turn, this resulted in different visions for the role of research and the character of the specific energy technologies. In the first period, the aims and objectives of research were informed by EC energy policy, which was oriented to resolve the corresponding energy challenges. During the second period, research policy was harnessed to reflect the emergent needs of the EC's energy policy, which had reoriented to address environmental and economic challenges. The alignment and reorientation of energy and research policy influenced the kinds of technologies and the character of those technologies that were developed through these programmes.

As was illustrated in section 2.1, several important changes occurred in energy policy from the first to the second period. All these changes were configured within different ideological frameworks and therefore the visions that were embedded in the research priorities for each period differ. In the second period, the Lisbon agenda gained prominence and its vision to turn the EU into a leading knowledge-based economy in the world prevailed.[47] The resulting socio-political and economic changes were also reflected in the aims and objectives of the EC research policy, which was now designed to increase production capacity, which would assist the large-scale deployment of energy technologies, create products that are near market implementation, etc. While occurring within the same policy landscape, each case study has its own particularities owing to the differences between the technologies. The WE case study is characterised by constant upscaling of WTs (in MW terms), whereas the PV case study is characterised by transnational competition for determining the 'dominant' raw materials used for the solar cells. 20

### Funding the wind: from replacing fossil fuel power plants to the creation of wind power plants

The WE case study begins in 1979, with the second Energy R&D programme and concludes with FP4.[48] This period can best be described as one of experimentation, exploration, research primarily on onshore WTs, and several pilot projects. The second period includes FP5 to FP7. This period includes further design improvements, 21

**46** Decision No 1513/2002/EC (*Official Journal of the European Communities*, 2002), 1.

**47** *Id*.

**48** It was proposed in the first energy R&D programmes' assessment to include WE research in the second energy R&D programme.

and implementation and integration of both offshore and onshore WTs. R&D gradually shifted to offshore WTs, accurate short-term forecasting, and optimal installation locations. Both periods exhibit the constant upscaling of WTs (in MW terms). However, the rationale for their upscaling differs, with each period's rationale reflecting its own distinct ideologies and visions. In the first period, R&D on WTs was justified as an investment that would bolster energy supply security and ensure the competitiveness of wind power with fossil fuel power plants. During this period, WE development aimed to upscale WTs, reaching the policy goal of large WTs with a capacity of 1-2 MW. In the second period, further WT upscaling was justified as a response to growing demand for more energy and concern for sustainable development. Research focused on large onshore WTs – up to 12 MW – and large offshore WTs – reaching 20 MW - primarily in wind farms known as 'wind power plants'. The further upscaling of WTs in this period was accompanied by the additional aim of integrating them into existing electricity grids. In order to address connectivity problems, research was redirected to enable more accurate short-term weather predictions and optimal installation locations for WTs, and to assess their integration and contribution to the electricity grids.

*Experimentation: wind turbines as competitors to fossil fuel plants*

22 The main drivers for research at the beginning of this period were the oil crises, the consequent need for security of energy supply accompanied by the need to decrease oil imports, and the desire to enhance the European industry's competitiveness. The second Energy R&D programme had a highly exploratory character.[49] It focused on the creation of wind atlases, collection of the corresponding data and figuring out possible installation locations.[50] During this programme, large 'wind machines', in the 1,5-2MW range were deemed competitors of conventional fossil fuel plants.[51] Hence, WE was to become competitive with fossil fuel plants and the integration of WE into the electricity grids was to be achieved through R&D of large wind machines. Towards this end, research projects focused on the development of 630kW wind turbine prototypes, small-scale WTs in the 10-55kW range, and wind farms of medium-sized WTs in the 300-500kW range.[52]

Research efforts during FP1 focused on completing the wind atlases and wind resource assessment(s), determining the optimal installation locations and experimenting and developing several prototypes. The rationale for funding the development and use of large WTs was based on economies of scale that contend 'when producing in series the costs will decrease'.[53] Throughout this programme, research focused on large WTs (around 1MW), small and medium WTs (up to 750kW), whereas research on offshore WTs was also pursued. 23

Research during FP2 focused on measurements, modelling, and experimentation in design. During this period, research on large-scale WE exploitation focused primarily on the potential of wind farms; following visions from the EC energy policy. Moreover, the research projects focused on cost reduction, wind predictability, modelling and operational problems. Research on large scale WTs was a way of sharing the risk with industry, particularly the risk concerning the commercialisation of a given technology.[54] 24

**49** C. Boffa, *et al.*, *Evaluation of the Community cost-shared research programme on solar, wind and biomass energy and of the Joint Research Centre's programme on non-nuclear energies (1979-1985)* (Luxembourg: Office for Official Publications of the European Communities, 1987), XV.

**50** *Ibid.*, 84.

**51** We employ the term of competitors to denote the economic viability of the technologies.

**52** For more detailed information on the projects see **https://cordis.europa.eu** and **https://publications.europa.eu/en/home**.

**53** Hermann Bondi H., *et al.*, *Evaluation of the R & D programme in the field of Non-Nuclear Energy (1985-1988)*, (Luxembourg: Office for Official Publications of the European Communities, 1988).

**54** Throughout the article we use the terms 'risk' and 'risky' to denote the character of the EC R&D. These terms were deployed by the EC itself to express the uncertainty in the outcome of the research undertaken, as well as the timeframe (10-15 years) needed for the research to materialise in something concrete. What this means is when

25 During FP3 and FP4, research efforts focused primarily on design and manufacturing improvements. The rationale for R&D of RES, and especially WE, was to advance the future large-scale applications of wind installations in electricity grids. Towards this end, R&D of such technologies was coupled with terms like 'Renewable Energy Power Plants' and the aims focused on their introduction into the EC's electricity grids. RES was intended to contribute to the long-term EC energy security, and therefore, research focused on the industrial deployment of 1-2 MW range WTs, whereas several projects for offshore WTs in wind farms were also included.

### *Implementation and integration: the wind power plants*

26 The second period's (1998-2013) research rationale was to increase WE capacity, reduce the cost of WE production, and integrate WE into the electricity grids on a large-scale. R&D pursued these goals through the implementation of large onshore and offshore WTs, primarily as wind farms.

27 FP5 aimed to strengthen the European industry's global competitiveness and provide technically and economically efficient energy to a competitive EC. This goal was to be achieved through the large-scale use of RES and large-scale generation of electricity, hence the focus on large-scale WTs. Main research themes of this programme were short-term forecasting, more accurate mapping to reduce operational and investment risks, resolution of problems regarding transportation and erection of WTs (especially in complex terrains), aerodynamics and aeroelasticity, and decreasing the noise caused by WTs (primarily caused by the rotors). During this programme, R&D concentrated on the development of 1,3-5 MW range onshore WTs, as well as offshore WTs for areas of greater sea depth.

and whether a technology or the processes, methods etc. employed for its development will lead to an end-product that can/will become commercial. Moreover, these terms were used by the EC to justify why publicly funded R&D was/is needed, since the private sector was/is not willing in partaking in long-term research on its own.

During FP6 and FP7 (2002-2013), sustainable development was framed as a contribution to economic development and the global competitiveness of the European industry. Moreover, terms like 'sustainable energy economy' gained prominence in the EC research policy. These terms were coined with the aims and objectives of helping the European industry to compete globally, the large-scale deployment of WE, and creating the conditions for the successful grid connection of WTs. Projects during this period sough to clear roadblocks to the integration of WE into the electricity grids, such as the intermittency of WE production, short-term wind forecasting predictions, foundation and support structure (offshore WTs), design limitations of large on and offshore WTs, and issues regarding aerodynamics and aeroelasticity. Throughout this period, very large offshore WTs of up to 20 MW were being researched. The majority of the projects focused on wind farms that could help WE reach higher levels of market penetration. Additionally, research for offshore WTs and the resolution of the problems with their integration into the electricity grids were steadily gaining attention. 28

## Powered by the sun: a tale of competing materials

In the PV case, two themes recur throughout both periods: a) increasing the cell efficiency b) decreasing the cell costs.[55] Both periods are also characterised by transnational competition between Europe, USA, Japan, and during the 2000s, China. Throughout the entire period examined (1975-2013), both c-Si and thin film cells received funds. The main shift in these two periods is in the R&D funding prioritisation of the materials used for the cells. The first period is characterised by intense experimentation and exploration of the PV potential, research on different techniques and methods for increasing the cell efficiencies and several pilot projects. The cell material that prevailed during this period was crystalline Silicon (c-Si). The second 29

55 Cell efficiencies are expressed in percentages that correspond to the amount of sunlight the cell can convert into electricity.

period was characterised by industrial exploitation and large-scale production of PV, research had a strong industry-led character and thin film cells took the lead in R&D funding.[56]

***The crystalline-silicon solar cell 'era'***

30 Throughout the first period, PV received the largest share of the funding, among all other RES.[57] PVs were understood as a long-term solution that could reach their potential towards the electricity needs of Europe in the $21^{st}$ C.[58],[59]Although both c-Si and thin-film PV were researched, the former prevailed, and especially single-crystalline silicon (sc-Si) cells. Sc-Si solar cells were described by the EC as 'conventional' because of the materials' extensive use for space applications since the 1950s.[60] On the other hand, multi-crystalline silicon cells (ms-Si) were known but not considered conventional. Thin film cells like amorphous silicon (a-Si), Cadmium Sulphide ($CdS\text{-}Cu_2S$), and Cadmium Selenide (CdSe) were all categorised as 'alternative cells.'[61]

31 From 1975 to 1983, the projects funded focused on the exploration of various techniques intended to increase cell efficiencies and reduce related costs. Funding decisions prioritised the 'most promising cells and their development' in order to enhance European international competitiveness in the c-Si field, especially with the USA.[62],[63],[64] During the first period, the motivations for competing with the USA and Japan were entirely different from those prevailing during the second period. During the first period, the main driver for PV R&D was energy security. R&D endeavoured to strengthen the scientific and technological basis of the European PV industry, as well as to aid the European industrial actors in establishing a place in the newly formed PV market. During the second period, the main motivation was to help the European industry to maintain its existing market share, whilst assisting its further expansion.

Throughout the first period, the USA and Japan interchangeably led global PV cell/module production, swapping the leading position. The USA led PV cell/module production until the late 1980s and then again during 1993-1998. The USA's leading role in PV during the 1980s has largely been attributed to Jimmy Carter who dedicated funds towards PV R&D during his presidency (1977-1981).[65] Between those periods when the USA led PV cell/module production, from 1988 to 1992, Japan assumed the leading role.[66] This shift can be attributed to Japan's strong national R&D programme promoting PV, the 'Sunshine' programme.[67] Japan dedicated research funds primarily to a-Si but also for c-Si, with the rationale that the former was "[...] better suited for mass production."[68] Therefore, Japan developed c-Si but strong emphasis was put on a-Si development. In 1993, Japan began the 'New Sunshine' programme, providing initiatives for PV and specific targets for installation, which, along with 32

**56** Industry-led refers to the efforts in narrowing the gap between R&D and the market.

**57** Based on the authors' own calculations of the funded projects.

**58** Ugo Farinelli, *et al.*, *The evaluation of the Communities' energy conservation and solar energy R&D sub-programmes* (Luxembourg: Office for Official Publications of the European Communities, 1980).

**59** Based on forecasts about the member states' energy requirements and PV corresponding contribution to the said requirements (i.e. electricity production), PV were expected to contribute 'significantly' from the year 2000.

**60** Boffa, *et al.*, *Evaluation of the Community cost-shared research programme*, *op. cit.*, 55 (cf. note 49).

**61** *Id.*

**62** Paul Maycock, "The world photovoltaic market 1975-1998", *PV Energy Systems*, 2002.

**63** Ronald H. Brown, Jeffrey E. Garten, *U. S. Industrial Outlook* (DIANE Publishing: 1994).

**64** c-Si is divided into sc-Si and mc-Si. sc-Si and mc-Si differ in certain, crucial, aspects: a. efficiencies achieved; sc-Si cells have the largest efficiencies (e.g. 22% for sc-Si modules vs 18% for ms-Si for 2018), b. cost of cells; sc-Si are more expensive ($0.165 per watt for sc-Si vs $0.133 per watt for ms-Si for 2018). The above examples are based on the same basis (maximum efficiencies and cell prices for 2018). However, given the differences per manufacturer and each country's legal basis the numbers may vary.

**65** Wolfgang Palz, *Power for the World: The Emergence of Electricity from the Sun* (Pan Stanford Publishing Pte. Ltd., 2011).

**66** Arnulf Jäger-Waldau, *PV Status Report 2008* (Luxembourg: Publications Office of the European Union, 2008).

**67** *Id.*

**68** Palz, *Power for the World op. cit.* (cf. note 65).

low interest rates, helped Japan regain its leading role in 1999.[69]

33 During FP1, the largest share of R&D funding was dedicated to a-Si research, although c-Si cells continued to receive funding. Funding for a-Si cells was prioritised in order to become competitive with Japan, then the leader in the a-Si research and production.[70],[71] Within this programme, two companies coordinated/led the a-Si research.[72] These companies were Messerschmitt-Bölkow-Blohm, of the Federal Republic of Germany, and Solems, of France.

34 For the remainder of the first period, R&D was reoriented towards c-Si, which seemed to offer efficiency improvements. The a-Si field was deemed 'somewhat disappointing', because it had not delivered the expected efficiency improvements, while c-Si cells seemed more promising in this regard and became the primary object of R&D.[73] Towards the end of this period, there were some new cell entrants (e.g. dye-sensitised nanocrystalline, molecular plastic and organic), which received R&D funding during the subsequent period but were not the main recipients of PV funding.

### *'Silicon Crisis' in PV: thin-film cells take the funding lead*

35 During the second period, thin-film cells gradually took the lead in R&D funding: in FP5 thin film R&D received approximately 18% of the total PV R&D funding, whereas c-Si received around 28%. Correspondingly, for FP6, thin films received approximately 35%, while 29% was dedicated to c-Si. In FP7, the corresponding numbers were approximately 44% for thin films and 12% for c-Si. We argue that an important event—the silicon crisis in PV—played a crucial role in the changing of research priorities. The silicon crisis in PV lasted from 2004 to 2008. Shortages in purified silicon feedstock made it difficult for the PV industry to meet its needs for feedstock. Concomitantly, silicon prices skyrocketed from approximately 24 USD per kilo in 2003 to 500 USD per kilo in 2008.[74] Soon after silicon prices steeply rose, they started to decline: in 2009 the price dropped to 50-55 USD per kilo, and in 2014 reached 14-16 USD per kilo.[75] At the same time, the world PV cell/module production significantly increased from 744,1 MW in 2003 to 1195 MW in 2004, and further to 7350 MW in 2008 and 23500 MW in 2010, with a continuous increase thereafter.[76]

The silicon crisis resulted from the increasing demand for silicon feedstock from the PV industry, a demand that silicon manufacturers could not fulfil. This increase in demand was caused by the constant growth of the PV industry, both in terms of its production capacity and the number of PV companies. This can be partly attributed to the entrance of Taiwan and China into the PV market: their PV cell/module production was 124 MW in 2004, 1070 MW in 2007, and approximately 5.6 GW in 2009.[77] Between 1999 and 2006, Japan led global PV cell/module production, until China assumed the lead.[78] China has steadily led PV cell/module production at such an unprecedented pace that there is a large divide between their productive outputs and those of all other PV-producing nations. Global PV cell/module production measured approximately 11,5 GW in 2009, 50% of which was produced in China and Taiwan.[79] By 2016, China had further consoli- 36

69 Arnulf Jäger-Waldau, *PV Status Report 2010* (Luxembourg: Publications Office of the European Union, 2010).

70 Data drawn from: Arnulf Jäger-Waldau, *PV Status Reports 2003-2017* (Luxembourg: Publications Office of the European Union).

71 Boffa, *et al.*, *Evaluation of the Community cost-shared research programme, op. cit.*, 57-58 (cf. note 49).

72 Only these two companies participated in the EC-funded a-Si research; the other contracts signed were coordinated by Universities and Research Centres/Organisations.

73 Roger Booth, *et al.*, *Evaluation of the JOULE Programme (1989-1992)* (Luxembourg: Office for Official Publications of the European Communities, 1994).

74 The 2008 USD price corresponds to 260 EUR and the 2014 USD price corresponds to 12-14 EUR.

75 Arnulf Jäger-Waldau, *PV Status Report 2016* (Luxembourg: Publications Office of the European Union, 2016).

76 Data drawn from: Arnulf Jäger-Waldau (cf. note 70).

77 Data drawn from: Arnulf Jäger-Waldau, *PV Status Reports*, issued by the JRC (2008 and 2010).

78 Jäger-Waldau (cf. note 66).

79 Jäger-Waldau (cf. note 70).

dated its leadership; global production measured approximately 81,9 GW, of which approximately 60 GW were produced in China and 11 GW in Taiwan.[80]

37 Glimmers of the impeding silicon crisis were foreshadowed in the early 2000s. The European Solar PV Conference is a conference of central importance for the European and global PV communities which draws attendance from politicians and policy makers. During the 2001 European Solar PV Conference, industry stakeholders raised issues surrounding silicon feedstock supply.[81] For example, two Bayer executives made direct reference to an impeding silicon crisis whilst highlighting the need for new Si-feedstock.[82] Furthermore, a 2002 article in Solar Energy Materials & Solar Cells, a journal of central importance in the field of solar PV, notes: "[...] the feedstock used to date [...] is already limiting the PV market expansion even if a true shortage is not expected before 2004-2005 according to a 'low growing PV market scenario'. This conclusion implies that a new silicon feedstock not depending on electronic grade silicon production chain must be available on the market from the years 2004 to 2005".[83] Silicon feedstock shortages were also stressed in research proposals submitted during FP5. These project proposals made direct references to the forthcoming silicon feedstock shortages and proposed various ways to overcome them, such as new production methods and processes, and the embrace of techniques that consume less silicon feedstock.[84] Worries concerning shortages of silicon feedstock were reflected in the character and themes of the projects funded. Concerns arising from the silicon crisis shifted research priorities for both thin-film and c-Si cells. Ultimately, this crisis shifted research priorities in favour of thin-film cells.

38 While the funding of research utilising thin-film cells became prioritised, research utilising c-Si still garnered significant amounts of funding. Yet, the silicon crisis had a major impact on c-Si research. During this period, the divide between RD&D begun to blur, largely attributed to the convergence of energy and research policy. Furthermore, the potential of large-scale production became a central 'evaluation' criterion guiding the selection of projects.

39 During FP5, mc-Si was first in funding, but thin-film cells also had a strong funding presence. Under FP5, micromorph Si (a-Si/μc-Si) made its debut, mainly explained by the desire to narrow down the gap with Japan that was leading in this materials' research and production front. During FP6, thin-film cells prevailed in R&D funding, and research efforts focused on thinner and larger area thin film cells. Thin film cells also enjoyed increased efforts from private industry. From 2005 to 2009, the number of thin film companies significantly increased from 130 in 2007 to over 200 in 2009.[85] At the same time, their respective market share increased from 6% in 2005 to 10% in 2007 to 16-20% in 2009.[86] It is worth noting that beginning in this period and extending through the present day, c-Si has maintained the largest market share (approximately 90%) and a significant share of R&D. C-Si research shifted to alternative techniques for processing the feedstock and reductions in the Si consumption for the production of the cells. Additionally, c-Si research included the use of different substrate materials, decreases in the wafers' thickness and the development of larger area cells.

40 During FP7, thin-film cells still had prominence as a recipient of R&D funding. However,

**80** Jäger-Waldau, *PV Status Report 2017* (Luxembourg: Publications Office of the European Union, 2017).
**81** Hubert Aulich, Friedrich-Wilhelm Schulze, "Silicon feedstock for the photovoltaic industry", *17th European Photovoltaic Solar Energy Conference and Exhibition,* 2001, Munich.
**82** Wolfgang Koch, Peter Woditsch, "Solar grade silicon feedstock supply for PV industry", *17th European Photovoltaic Solar Energy Conference and Exhibition*, 2001, Munich.
**83** Peter Woditsch, Wolfgang Koch, "Solar grade silicon feedstock supply for PV industry", *Solar Energy Materials & Solar Cells*, vol. 72/1-4, 2002, 11.
**84** For example, see FP5 PV projects: SOLSILC, SPURT and NESSI.
**85** Data drawn from: Arnulf Jäger-Waldau, *PV Status Reports*, issued by the JRC (2008-2012).
**86** *Id*.

concentrator photovoltaics (CPV) gained the second highest share of PV R&D funding, 31% of the total. Under FP7, several collaborative projects with Japan, India, and Mediterranean countries on CPV were funded. CPV had been known for several decades, as demonstrated by the existence of research projects beginning with the first R&D programme. CPV had also earned the attention of private industry, with several companies worldwide working on CPV. Isophoton, a Spanish company, had specialised in CPV for several decades, whereas CPV was also developed in California and by Sharp in Japan. Therefore, further research that will determine why CPV gained prominence during FP7 is required.

## CONCLUSIONS

41 Our research has shown that the EC energy policy directed research policy and the research priorities, partly unintentionally. Research priorities and strategies were configured and reconfigured in response to either energy policy targets or to energy crises and the challenges that they imposed on national and transnational energy systems. Our approach has stressed the importance of researching the funding scheme and the political economy dynamics in the making of the technologies. Research capabilities and choices significantly shaped the market of RES technologies by setting the technological characteristics of the innovations, and by legitimising certain technical options while excluding others (e.g. prioritising the cell materials for PV and the scale for WT). We argue that market interests and transnational competition, especially during the second period, drove the innovation of RES technologies. The funding schemes developed by the EC configured knowledge networks that create knowledge, social and cultural capital, and that directed technological change in the RES technologies along specific technological styles.[87]

42 The first R&D programme was created shortly after the first oil crisis to explore other potentially viable energy options. However, it was not until FP5 that energy policy was truly shaped in tandem with research policy. Since FP5, the EC's energy policy objectives have slowly come to influence the research objectives and define the research priorities of funded projects. During the second period, the EC funded research that assisted the RES transition in response to various problems and concerns (e.g. environmental, societal). This choice was deeply influenced by energy policy, which cast the vision for the RES transition. The close relationship between energy and research policies can also be traced to the merger of the RD&D sub-programmes.[88] This merger, in turn, strengthened the integration of energy and research policies, as well as the changing research priorities for RES. Moreover, with the merging of the two sub-programmes, research that could shorten the value chain was prioritised (i.e. develop near-market products directly from research projects). This was primarily expressed through the continual emphasis placed on innovation and the interconnection of research with the market and industrial production. This also becomes evident in the RES research policy by the recurrent efforts to facilitate the integration of RES technologies to the electricity grids and the implementation of both PV and WTs (i.e. wind power plants and increase in cell efficiencies).

Throughout this paper we have argued that changes in the funding priorities affected the selection and the character of the specific technologies both for WTs and PV. We have argued that these changes were directly associated with the changing political economy of research and the corresponding visions that favoured specific technological choices in each period. During the first period, research was aiding the industry's competitiveness by strengthening its scientific and technological basis. During 43

**87** See the introduction.

**88** RD&D refers to the merge of the R&D and Demonstration programmes in the second period; the importance of the merger lies in how it impacted research and the corresponding themes, as well as the technologies (e.g. prioritising research that could narrow down the gap between research and market). For further information see pages 7 and 15.

the second period, the priorities of EC-funded research changed as it responded to a plethora of environmental and economic challenges. This resulted in various changes in the research priorities both for PV and WTs. For PV, research priorities shifted towards large-scale production and had a strongly industry-led character (i.e. decreasing the time from research to market). Additionally, emphasis was given to projects that promised to deliver applicable end-products and not merely research results (i.e. applied research rather than «open skies» research), which could be directed towards assisting the industry's global competitiveness and increasing its manufacturing capacity. WT research shifted its focus to large wind farms and their integration into energy supply systems, in order to facilitate the transition towards RES.

44 In both cases, we illustrated that a crisis can significantly impact the selection of research pathways and, thus, of the relevant technologies. For WE, the oil crises influenced the selection of large-scale WTs which could compete with fossil fuel power plants. The silicon crisis in PV (2004-2008) significantly impacted both the selection and prioritisation of thin-film cells and the research priorities of the formerly dominant c-Si cells. Even though thin-film PVs still hold a modest market share, during the years of the silicon crisis their market share and pace of diffusion increased, although c-Si remained dominant. Our work has shown that there was an emphasis on funding research projects that would reduce the time needed to turn research and experimentation into innovations. That means that the emphasis was on provisions that would facilitate the market deployment of research results.

45 Furthermore, our research corroborates Mazzucato and Semieniuk's argument that stresses the importance of mission-oriented innovations. We have shown that funding schemes promoted mission-oriented RES innovations since they were steered by the oil crises, energy supply security and, later, were influenced by energy policy and the fast implementation of the RES transition. Public financing, in the form of EC R&D funding schemes, has been highly risky.[89],[90],[91] In the case of WE, this was illustrated by the consistent funding of constantly upscaled, and larger, WTs. The larger scales funded were not yet commercial nor was their 'successful' commercialisation certain. In the case of PV, even when the R&D programmes favoured c-Si, they nevertheless continued to fund other materials as well. During the second period, the EC took a huge risk by devoting the bulk of its funds to thin-film cells, which were a high-risk investment because they did not yet have a significant market presence. Yet, our research goes beyond the types of innovation activities promoted through public funding schemes identified by Mazzucato and Semieniuk, by stressing the importance of transnational competition in shaping funding priorities and thus innovation pathways.

**89** Booth, *Evaluation of the JOULE Programme*, *op. cit.*, 130 (cf. note 73).
**90** Directorate General for Research and Innovation, *Non-nuclear energy programme (1990-94) JOULE II – Vol 1* (Luxembourg: Office for Official Publications of the European Communities, 1997), 75.
**91** Nicholas Chrysochoides, *et al.*, *Clean, Safe and Efficient Energy for Europe: Impact assessment of non-nuclear energy projects implemented under the Fourth Framework Programme* (Luxembourg: Office for Official Publications of the European Communities, 2003), 8.

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