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Identifying technological sub-trajectories in photovoltaic patents

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Abstract

This paper proposes a search strategy for photovoltaic patents which allows to distinguish the photovoltaic system into sub-trajectories. Identifying and analyzing sub-trajectories is of particular importance for understanding micro patterns of technological change. The proposed search strategy is modular and replicable. It performs similar to leading benchmark search strategies but allows to distinguish three cell sub-trajectories and two system components. Descriptive analysis reveals that inventive activity differs between sub-trajectories. The market dominating silicon wafer cell sub-trajectory shows hardly any patented inventive activity. Country comparison reveals that Asian countries focus on the emerging cell sub-trajectory. The USA focus on the established thin-film sub-trajectory and inventive activity in Germany focuses on module components. While the proposed search strategy allows for a fine-grained analysis of inventive activity in photovoltaics, the empirical assessment of sub-trajectories in general can increase understanding of technological change and can be used to implement policy interventions at a micro-technological level.

Keywords: Innovation; Sub-trajectory; Patent search; Photovoltaics

JEL Classification: O31, O34, Q42

1 Introduction

Technological progress unfolds along technological trajectories by accumulation of knowledge and competences (Dosi, 1982). While technological trajectories summarize the means to solve specific problems, inside a trajectory sub-trajectories can be present. Such sub-trajectories provide the same solution, but via different means or with different performance characteristics (Durand, 1992). Sub-trajectories emerge in the continuum of incremental and radical innovations and provide opportunities for substantial improvements along the trajectory. At this micro level of the trajectory, dynamics can take place, such as the emergence of new sub-trajectories or shifts in the dominating sub-trajectory, which constitute and shape the development of the overall trajectory (Durand, 1992). Sub-trajectories can open up new potentials for improvements or widen the application space of a trajectory (Kash and Rycoft, 2000; Funk, 2003). Competition between different sub-trajectories can take place and technological lock-in into inferior outcomes may emerge, hampering overall technological progress of a trajectory (Arthur, 1989; Cowan and Hulten, 1996). Revealing and understanding such dynamics on the sub-trajectory level can provide valuable insights about the innovation process, help to understand drivers of technological change and can be used to forecast future potentials and developments of trajectories.

However, analyses on the sub-trajectory level are scarce and disaggregation of inventive and innovative activity at this fine-grained level is not common in economic analysis. Patent data, for example, can be used to empirically assess technological progress along sub-trajectories and provide a better understanding of knowledge creation and accumulation inside a trajectory. Photovoltaics (PV) is a particular good example to study technological change at the sub-trajectory level, since it is highly dynamic and several sub-trajectories emerge over time. Furthermore, PV is a means to mitigate climate change and understanding the dynamics of technological progress of PV can help to accelerate performance improvements. For this end, I propose a replicable and modular patent search strategy for PV patents, which allows to separate the PV trajectory into its sub-trajectories. Based on keywords and patent classifications derived using established procedures (Porter et al., 2008; Costantini et al., 2015), the proposed search strategy distinguishes the overall PV system into three different cell sub-trajectories and two generic components.¹

The proposed search strategy is evaluated against two benchmark search strategies. It is comparable in its scope and coverage, but separates PV patents better from adjacent technologies, which do not belong to the core of the PV trajectory. On the sub-trajectory level, descriptive results show that there are differences in the inventive activity between sub-trajectories. The market-dominating silicon wafer cell sub-trajectory shows the least patented inventive activity. Changes in the relative shares between sub-trajectories unfolds over time and nowadays the emerging cell sub-trajectory shows the highest patent share. Geographical differences between countries can be observed as well. Asian countries, for example, focus their inventive activity on the emerging cell sub-trajectory, while the USA focuses on the established thin-film sub-trajectory and inventive activity in Germany focuses on the module component.

¹ While there are many search strategies for PV patents (see Bruns and Kalthaus, 2017, for an overview and comparison), none of these distinguishes sufficiently between the different sub-trajectories and components.

A better understanding of technological development on the sub-trajectory level has several implications for economic research and policy. Using sub-trajectories helps to open-up the dichotomy of radical and incremental innovation, since there are substantial changes inside a trajectory which need to be considered if technological progress is analyzed. Patent data can be used to uncover such changes over time and search strategies as well as economic analysis should consider sub-trajectories more frequently. Analysis on the sub-trajectory level is especially relevant if sub-trajectories reach their physical boundaries and active search for alternatives is required. In such a case, governmental intervention is helpful to support search processes to foster technological progress. However, technology neutral policies can hinder progress if sub-trajectories with high potential but initially higher cost/performance ratio are locked-out from the market, a lock-in into an inferior solution might occur and deter overall progress of the trajectory. While this situation is observed between trajectories, it is so far not considered on the sub-trajectory level, but might be more frequent. This has implications for technological progress and respective policy interventions, which should be designed to support emerging sub-trajectories with high potential. Also, the emergence of new sub-trajectories needs to be monitored to forge ahead in international competition by supporting upcoming solutions early on.

While the descriptive results show substantial differences in the sub-trajectory dynamics, the proposed search strategy can be further used to analyze how these differences translate into other economic relationships. For example, the sub-trajectories can influence industrial dynamics, as shown by [Kapoor and Furr \(2015\)](#) for entry in the PV industry. These findings could be extended by accounting for inventive activities in these sub-trajectories or how it influences firm survival. With respect to the technological development, [Momeni and Rost \(2016\)](#) and [Park et al. \(2015\)](#) show that different sub-trajectories emerge over time, but they do not provide an overall assessment of the technological development, which is possible with the proposed search strategy. Furthermore, the knowledge dynamics along each sub-trajectory can be analyzed in more detail, as proposed for example by [Jamali et al. \(2016\)](#) or [Lacerda and van den Bergh \(2016\)](#) to uncover how knowledge is integrated or shared between the sub-trajectories.

The paper proceeds with a theoretical discussion of sub-trajectories in Section 2. In Section 3 the technological and economic dimension of the PV sub-trajectories and components are discussed. The patent search strategy is derived in Section 4 and analyzed in detail in Section 5. Section 6 concludes.

2 Technological progress along sub-trajectories

A technology can be characterized by the dynamic accumulation of knowledge and competences to solve a specific problem ([Dosi and Nelson, 2010, 2013](#)). Thereby variation among possible solutions can exist which constitute a technological paradigm, or as [Dosi \(1982, p. 152\)](#) defines it: “... we shall define a “technological paradigm” as “model” and a “pattern” of solution of selected technological problems, based on selected principles derived from natural sciences and on selected material technologies”. Such a technological paradigm sets boundaries and provides orientation for research and inventive activity to solve a particular problem. These activities foster technological process which unfolds along a technological trajectory, which provide the

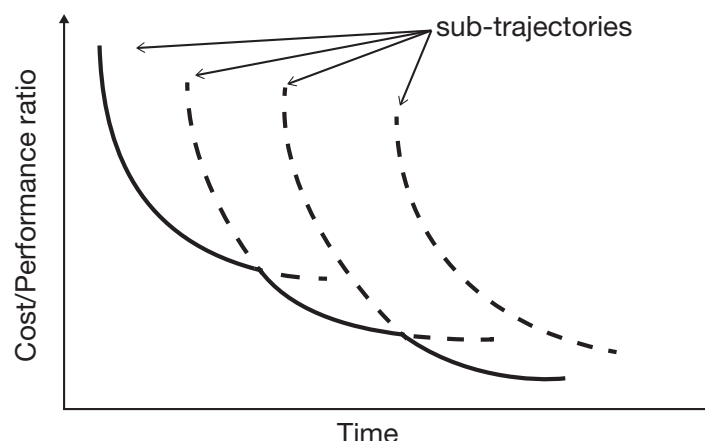


Figure 1: Sub-trajectories in a trajectory.

Source: Adapted from Durand (1992).

solution for the problem. This progress is incremental and improves techno-economic characteristics of the artifact or process over time via accumulation of knowledge (Dosi, 1982; Dosi and Nelson, 2013). Since multiple technological trajectories can be present in a paradigm, competition between these can take place (Arthur, 1989). Such a selective competition can result in a dominant design which defines the paradigm (Abernathy and Utterback, 1978; Murmann and Frenken, 2006).

While there can be multiple trajectories present in a paradigm, also the technological trajectory can consist of multiple sub-trajectories, which provide the same solution for a problem, but have different techno-economic characteristics. Such sub-trajectories are introduced along the trajectory by “*micro-radical innovations*” (Durand, 1992, p. 363), in “*transition patterns*” (Kash and Rycoft, 2000, p. 822) or by “*proactive development of technical alternatives*” (van de Poel, 2003, p. 59), which do not alter the trajectory itself, but opens up variation inside through new solutions to the same problem, usually with potential to improve the technology further. Thereby the technological trajectory envelopes the sub-trajectories and represents the frontier of technological performance (Durand, 1992). As depicted in Figure 1, the trajectory is the envelope curve (solid line) consistent of four sub-trajectories which each improve over time and possibly outperform one another by decreasing costs and/or increasing performance. However, usually emerging sub-trajectories have higher costs and/or lower performance than existing ones, but higher learning rates might be possible, especially if the technological potential of existing sub-trajectories is exhausted. It is not likely that each sub-trajectory provides the best characteristics and selection between them takes place, therefore certain sub-trajectories fail or do not improve as fast as other sub-trajectories (Cowan, 1990; Durand, 1992). Furthermore, the emergence of sub-trajectories is necessary if the established one reaches its full potential, for example if physical boundaries restrict further improvement (Sahal, 1985; Kash and Rycoft, 2000). Besides changes in the cost/performance ratio, these sub-trajectories can increase the application space or change trade-offs in the product design or can help to establish a dominant design (Funk, 2003).

Analyzing technological progress on the sub-trajectory level helps to understand mechanisms and drivers in more detail, since patterns at the sub-trajectory level might be indistinguishable

on the trajectory level or unfold only for key components, but exert substantial improvements. The development of sub-trajectories and their influence on the overall trajectory have been studied for many technologies, but not always explicitly considered as such. [Durand \(1992\)](#) uses several examples, such as insulin production, public switching in telecommunication, dynamic random access memory, and semiconductors to illustrate that sub-trajectories emerge frequently and influence the development of the respective trajectory. Their emergence can furthermore rejuvenate a technology if it reaches its technical or physical limits ([Sahal, 1985](#)). An example are aircrafts, where moving from propeller to jet engines overcomes aerodynamic limits ([Constant, 1980](#)). [Rennings et al. \(2013\)](#) illustrates the case in which artificial limits are imposed on a trajectory by tightening emission regulations in coal-fired power plants. In this case, sub-trajectories opened up possibilities to further improve performance but at the same time complying with environmental regulations. In a similar vein, [Oltra and Jean \(2009\)](#) integrate environmental performance into the assessment of sub-trajectories and show for car engines that this additional performance measure influences the prospects of a sub-trajectory. Competition between different sub-trajectories can have detrimental effects on technological progress, if a lock-in in an inferior sub-trajectory emerges, as shown by [Cowan \(1990\)](#) for nuclear reactor and [Cowan and Hulten \(1996\)](#) for car engines. The opposite is shown by [Funk \(2003\)](#) for mobile internet, where the emergence of sub-trajectories increases competition which leads to product innovations and overall expands the application space and broadens the trajectory.

The emergence of sub-trajectories also influences industry dynamics as shown for the flat panel display trajectory by [Mathews \(2005\)](#). In the flat panel display trajectory several new ‘generations’ with respect to the production process were introduced over time and changes in the industry composition are attributed to it, especially entry. Similar effects were found for the aircraft industry. [Bonaccorsi and Giuri \(2003\)](#) emphasize that different sub-trajectories exist for different types of customers and firms specialize and learn from the heterogeneity of sub-trajectories and thereby influence industry composition. Also [Durand \(1992\)](#) stresses this point and concludes that the emergence of sub-trajectories and the increases in technological performance increases competition and that firms can ‘surf the waves of change’.

Sub-trajectories are also present in the photovoltaics trajectory. In PV, different cell generations emerged over time and are in competition with each other. [Menanteau \(2000\)](#) shows that path-dependency and learning from related knowledge increases efficiency. Due to exhausting technological potential, a lock-in occurs and new sub-trajectories need to overcome this situation. [Sartorius \(2005\)](#) points out that this lock-in into an inferior PV sub-trajectory can be overcome if policy support would not be technology neutral but favor the emerging sub-trajectories that show favorable characteristics and support their technological progress. Otherwise accumulation of knowledge would increase the lock-in situation while competition between the sub-trajectories would foster overall progress. The competition between the different sub-trajectories affects also entry decisions in the PV industry, as for example shown by [Kapoor and Furr \(2015\)](#).

Since sub-trajectories are important for technological change in general and particularly in PV, in the following the PV system and its sub-trajectories are discussed from a technical and economic point of view to derive a patent search strategy to analyze inventive activity on the sub-trajectory level.

3 Sub-trajectories in the photovoltaic system

3.1 Technological components of the photovoltaic system

The PV system consists of three components: The PV cell, the PV module and the balance of system components (comp. Figure 2). The core component is the PV cell, which converts the sunlight into electricity. The PV cells are encapsulated in a module which connects several cells and protects them from the environment. The modules need to be connected to and managed by grid infrastructure, which are so-called balance of system components. While the two latter components are generic for every PV system, whereas for the PV cell multiple technological solutions exist. These different cell types are the sub-trajectories of the overall PV trajectory. In the technical literature, they are referred to as generations and have distinct technological and economic characteristics (e.g. [Green, 2001](#); [Conibeer, 2007](#); [Jayawardena et al., 2013](#))². Currently, three PV cell generations can be distinguished. The first generation uses crystalline silicon wafer, the second generation uses semiconductor thin-films and the third generation uses novel materials (some authors distinguish this generation further and propose a fourth generation, see [Jayawardena et al., 2013](#)). These different generations or sub-trajectories co-exist and research and development is performed in all of them. The different cell generations emerge at different points in time and their improvement is heterogeneous (see also [Green et al., 2017](#)). In the following, I briefly discuss the different components of the PV system and the different PV cell sub-trajectories.

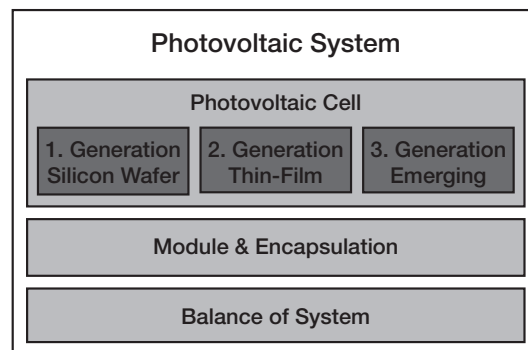


Figure 2: Components of the photovoltaic system.

The photovoltaic cell The PV cell is the core component of the PV system. The cell absorbs the sunlight and converts it to electric energy via the photoelectric effect.³ The capacity to absorb sunlight depends on the material used for the PV cell. Semiconductors, such as silicon, germanium, or gallium-arsenide, have a so-called band gap, which is the distance between the valence band and the conducting band, which have free electrons to conduct a current ([Sze and Ng, 2007](#)).⁴ The photoelectric effect results from the energy content of the photon and the

² To be in line with the technical literature, in the following the term generation is used to refer to the different sub-trajectories.

³ For a more detailed discussion of the following physical principles and components of a PV system see [Green \(1982\)](#), [Fonash \(2010\)](#), [Fraas and Partain \(2010\)](#) and others.

⁴ Technically speaking, all materials have a band gap, however, conductors (usually metals) have no or a very small band gap, so electrons can easily move between the band, and insulators have a very large band gap,

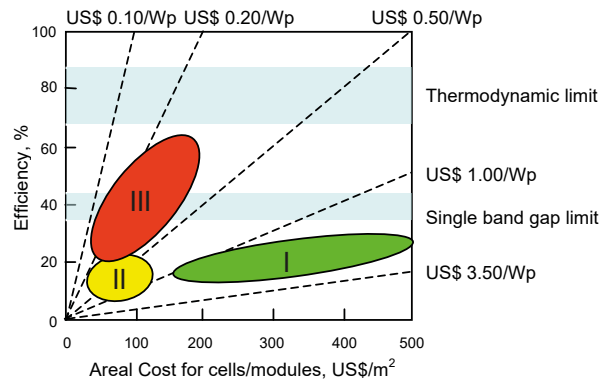


Figure 3: Photovoltaic sub-trajectories and their efficiency and physical limits.

Figure note: Source: [Conibeer \(2007\)](#). The ellipses for the cost/efficiency range are indicative, only for the first generation, silicon wafer cells, (green ellipsis) the area is quite accurate, while for the second generation, thin-film cells, (yellow area) and third generation, emerging cells, (red area) they are based on predictions.

material's band gap. If the energy content of a photon is high enough to allow an electron to move from the valence band to the conducting band, a current emerges. To convert this current to electricity, the charge needs to be separated and directed to prevent the electron to go back to its initial state. This separation is usually achieved by a so-called n-p-junction if the same material is used or a hetero-junction, if the cell consists of different materials ([Sze and Ng, 2007](#)). This junction is usually an electric field created by doping (inserting) different materials in the absorber layer so that a positive and a negative current are present ([Fonash, 2010](#); [Fraas and Partain, 2010](#)).

Since the material's band gap is a decisive factor for the conversion of sunlight into electricity, different materials can be considered based on their band gap. However, the so-called Shockley-Queisser-limit restricts the conversion for a single band gap cell. This limit sets the theoretical conversion maximum of sunlight in a material (the limit can be increased if the light is concentrated) and is based on the material's band gap ([Shockley and Queisser, 1961](#)). This limit can only be overcome if multiple layers of different materials are combined to absorb different energy contents of photons. This combination of different materials is however restricted eventually by a thermodynamic limit, which restricts the overall energy conversion ([Vos and Pauwels, 1981](#)).

Three different cell generations can be distinguished so far. They can be described based on their conversion efficiency, related to the material used, and their costs. Figure 3 depicts the three different cell generations with respect to these two dimensions. The first generation, silicon wafer cells, are expensive, but also efficient and have reached their physical conversion limit. The second generation, thin-film cells, are much cheaper in general, but not as efficient as the first generation. Only the third cell generation can, especially by combining different materials in multi-junction cells, overcome the Shockley-Queisser limit and at the same time be

making it very difficult for electrons to move between the bands. For further details on the physical principles, see, for example, [Sze and Ng \(2007\)](#).

cost competitive (see also [Green, 2001](#); [Conibeer, 2007](#), for further discussions). In the following, the different cell generations are discussed in detail.

1. Generation: Silicon wafer cells The first PV cell generation emerged in the 1950s and uses a silicon wafer to absorb light ([Chapin et al., 1954](#)). These cells are simple to produce and knowledge and competences are related to the microelectronic sector ([Sze, 1981](#); [Green, 2000](#)). Since silicon has a favorable band gap, its conversion efficiency is high. However, silicon is an indirect semiconductor, which requires that the material needs a certain thickness to absorb and convert the sunlight. Since silicon is a rather expensive material, the costs for silicon wafer cells are high and cost reductions due to thinner wafers have reached its technical boundaries ([Fraunhofer ISE, 2017](#)). There exist several approaches to fabricate the cell material, which divides the cells in two groups, mono- or single-crystalline and poly- or multi-crystalline cells. The mono-crystalline silicon cells are cut out of a single silicon crystal, which is most frequently produced by the Czochralski process. Poly-crystalline silicon cells consist of silicon which is cast in ingots from smaller silicon pieces and then cut into cells. A specific technique to produce polycrystalline silicon is the so-called ribbon silicon, which, however, did not reach the competitive efficiency levels ([Nakayashiki et al., 2006](#)). In general, the poly-crystalline cells can be produced cheaper, but they have lower conversion efficiency than mono-crystalline cells ([Miles et al., 2005](#)).⁵

Overall, silicon wafer cells are characterized by high conversion efficiency and high costs.

2. Generation: Thin-film cells The high cost of the first generation cells lead already in the 1960s to the development of cells, which can be produced cheaper ([Fraas and Partain, 2010](#)). For these kinds of cells, direct semiconductor materials are deposited on a (flexible) substrate to absorb sunlight. These thin-film cells widens the application space, since they are lightweight and flexible, which allows integration, e.g. in clothing or other objects. The cell materials can be divided in two kinds, one relying on the use of amorphous silicon films and another uses materials from the so called II-VI-, III-V-, and I-III-VI-groups of the periodic table ([Miles et al., 2005](#); [Fraas and Partain, 2010](#)). Amorphous silicon is an alloy of silicon and hydrogen and can be deposited in very thin layers on a substrate ([Miles et al., 2005](#)). However, the cells suffer from severe degradation in sunlight, the so called Staebler–Wronski effect. To overcome this effect and to increase the cell efficiency, layers of different absorptive materials are combined to double- or multi-junction cells. Further variations of silicon thin-films use micro- or nano-crystalline silicon which assemble closer to the physical characteristics of mono-/poly-crystalline cells but have the favorable characteristics of a thin-film material.

From the II-VI-group, especially cells which use cadmium-telluride (CdTe) are favorable, since CdTe has a nearly optimal band gap ([Miles et al., 2005](#)). CdTe cells are characterized by very low production costs and nowadays high efficiency rate ([Fraas and Partain, 2010](#)). Materials from the I-III-VI-group, so-called chalcopyrites, are among others copper-indium-diselenide (CuInSe₂) and copper-indium-gallium-diselenide (CuInGeSe₂), also called CIS and

⁵ The cells receive also further treatment to increase the absorptive capacity. For example, the single crystal cells are etched to create a surface structure consisting of small pyramids which reflect the light downwards. Also the cells receive anti-reflection coating to reduce losses (see for further treatments [Green, 2000](#)).

CIGS cells. These cells also have already high efficiency and low costs, but contain still expensive and toxic materials and cells based on copper-zinc-tin-sulfide (CZTS) are a possible replacement.

A particular case are the materials from the III-V-group, which are also semiconducting thin-films, but very expensive.⁶ In this group, especially gallium arsenide (GaAs) but also indium-phosphide (InP) and gallium-antimonide (GaSb) are considered for PV cells. These materials are expensive, but have favorable characteristics, especially for space applications. These materials are in most cases combined in multi-junction cells and/or used with a concentrator to focus light on the cell (Miles et al., 2005). Their terrestrial application is only marginal due to their high costs (Fraunhofer ISE, 2017).

Overall, thin-film cells for the mass-market are generally characterized by low costs and low efficiency.

3. Generation: Emerging cells While the first and second generation of PV cells reach a state of maturity, several other approaches emerged. These emerging cells usually do not use semiconductors but other materials, which are frequently combined in tandem structures to increase efficiency (Miles et al., 2005; Conibeer, 2007; Brown and Wu, 2009; Jayawardena et al., 2013). Most prominent are dye-sensitized solar cells (DSSC) or organic cells. The DSSC were invented by O'Regan and Grätzel (1991) and utilizes the highly porous structure of titanium-dioxide (TiO₂) which increases the absorptive surface in the cell. Organic or polymer PV cells use a polymer as an absorber and use the physical principles of organic electronics (Nelson, 2011). Recent approaches use perovskite as an inorganic component in an organic cell and provide very promising efficiency rates (Kojima et al., 2009). Furthermore, quantum dot cells which use semiconducting particles of different size to create different band gaps are recently explored (Baskoutas and Terzis, 2006). Also recently, the introduction of different inorganic nanomaterials in polymer cells are considered as having the potential to lead to a fourth cell generation (Jayawardena et al., 2013). Additionally, several materials allow for the production of semi or fully transparent cells, which extends the range of application to e.g. windows or screens (Zhao et al., 2014).

Overall, third generation cells are characterized by (potentially) high efficiency and low costs.

Module and encapsulation The PV cells need to be connected to each other to form a PV module, which needs encapsulation and further components. Several parts of the module were improved over time to increase efficiency and to reduce costs. Especially the electric contacts on the front and back of the cell, as well as the components for encapsulation were improved substantially. Furthermore, there is great flexibility in where to use a PV module, such as installment on the ground, integration into a building and mounting on a vehicle or spacecraft (Fraas and Partain, 2010).⁷ In principle, these parts of the PV system are generic and independent from the cell generation used.

⁶ There is no consensus in the technical literature to which generation these cells should be attributed. Here, they are attributed to the second generation, since they use traditional semiconducting materials.

⁷ Some researchers treat this mounting component as an independent part and separate it from the module encapsulation (e.g. Huenteler et al., 2016).

Balance of system components The last part of the PV system connects the PV module to the electricity consumer. Several distinct ways are possible, but usually separated into off- and on-grid applications. The off-grid applications usually use the direct current produced by the PV module to either power specific applications or to store the electricity in a battery. However, the battery itself is not considered, but only the charging component. The on-grid application usually needs an inverter to convert the direct current into an alternating one (Fraas and Partain, 2010). Furthermore, there are several ways to optimize the energy production, for example via tracking systems to follow the sun's movement (Mousazadeh et al., 2009). The balance of system components are also generic for the PV system.

Overall, the PV system consists of three components, while among the PV cell, three or even more sub-trajectories exist which are in competition among each other. The other two components, the module and encapsulation as well as the balance of system components are generic components and are required in every PV system.

3.2 Economic assessment of the photovoltaic system and its sub-trajectories

The PV system and the different sub-trajectories can be evaluated from an economic point of view. Technological progress in the overall trajectory but also in the different sub-trajectories is remarkable and allowed PV to be cost competitive with other electricity generating technologies. Substantial learning effects and steep learning curves are present in PV (Fraunhofer ISE, 2017) and development follows a generalized Moore's law (Farmer and Lafond, 2016). For example, Fraunhofer ISE (2017) calculates a 24% learning rate for the last 36 years for PV modules. Even though there are several approaches how to estimate learning curves, such as two- or multi-factor learning curves (Yu et al., 2011), all reveal a strong reduction in module costs.⁸ Since 1990 the energy payback time, the time the PV system needs to produce energy to cover the energy needed for its own production, more than halved and ranges nowadays from one till less than three years, depending on geographical location and technology (Fraunhofer ISE, 2017). Similar development holds also for greenhouse gas emissions during production of the PV system (Louwen et al., 2016).

The decrease in module prices can be observed for the different sub-trajectories as well. Figure 4 depicts the learning curves for the silicon wafer and thin-film sub-trajectories. Silicon wafer cells have a learning rate of about 29% for the last ten years while thin-film cells have a learning rate of about 25%. However, thin-film cells reach about the same price level with only a tenth of the cumulative production of silicon wafer cells. Other components of the PV system increase in efficiency and decrease in price as well. Fraunhofer ISE (2015) calculates a learning rate of about 19% per year for small scale PV inverters from 1990 until 2013. Cost reductions of different components lead to overall cost reductions for PV systems in general but nowadays the balance of system components have a larger share of the PV system costs than the PV modules (Fraunhofer ISE, 2017).

The efficiency increases and reduction in costs can be partly attributed to strong political support. Demand as well as supply side policies such as feed-in tariffs, quota systems and R&D subsidies were in place supporting R&D as well as diffusion (Watanabe et al., 2000; Johnstone

⁸ For further influences on the cost reductions in PV, see Nemet (2006), Candelise et al. (2013), or Pillai (2015).

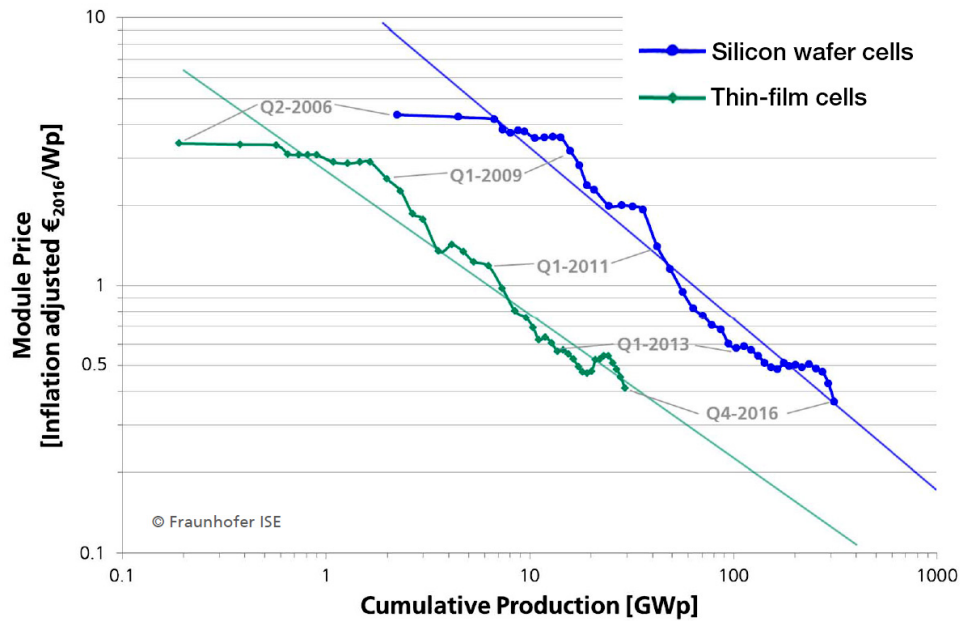


Figure 4: Global learning curves for silicon wafer and thin-film cells.

Source: Fraunhofer ISE (2017).

et al., 2010; Peters et al., 2012; Polzin et al., 2015). However, most of these policies were technology neutral or data about a finer grained support is not available. For Germany, a distinction of R&D funding for the different PV sub-trajectories is available. Figure 5 shows the governmental R&D subsidies for different research areas. Silicon wafer cells receive most funding and over time the funding for thin-film cells is reduced in absolute and relative terms.

Due to efficiency increases and declining prices, the diffusion of PV increased exponentially in the last decades and nowadays PV contributes substantially to electricity production globally (REN21, 2015). With respect to the different cell sub-trajectories used, Figure 6 displays the production shares of silicon wafer and thin-film cells over time. The silicon wafer cells clearly dominates the market. But among the silicon wafer cells, a shift from mono-crystalline to poly-crystalline takes place. Thin-film cells play a minor role and account in 2016 for about 6% of

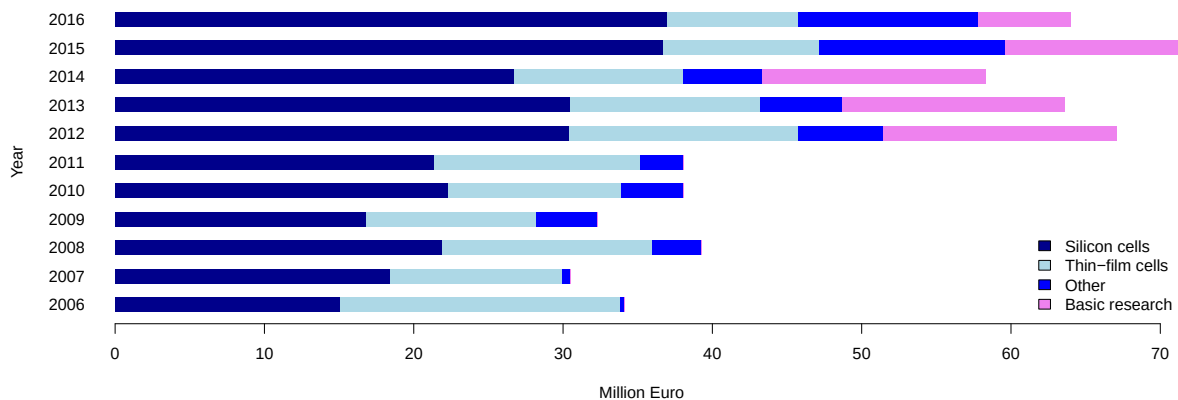


Figure 5: German R&D subsidies for photovoltaic sub-trajectories 2006–2016.

Data source: BMWi (2013, 2017).

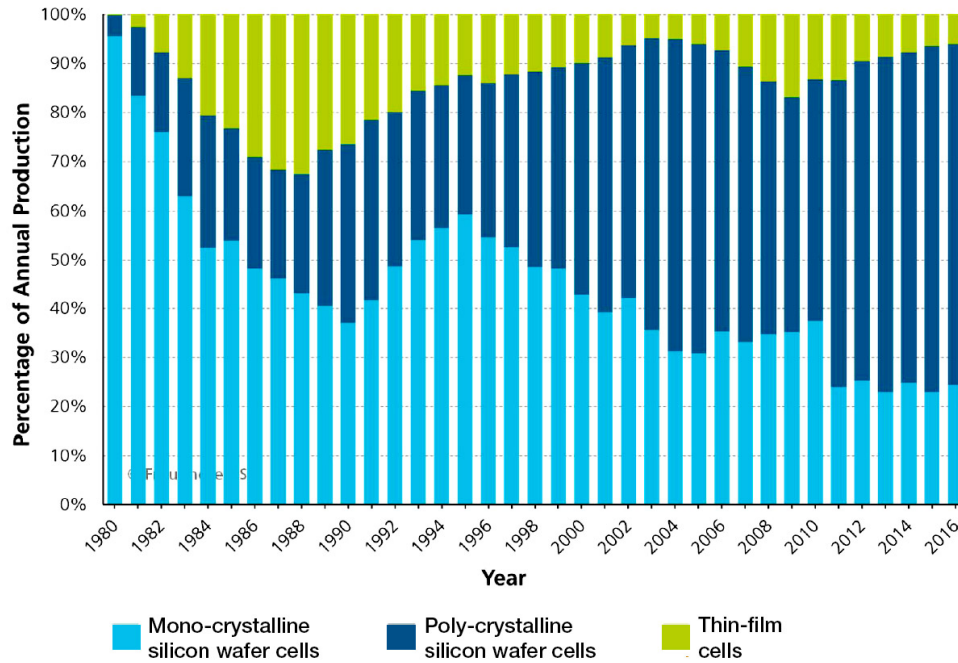


Figure 6: Share of annual worldwide photovoltaic cell production.

Source: Fraunhofer ISE (2017).

overall cell production (Fraunhofer ISE, 2017). Among the different thin-film cell technologies, dynamics are present as well. In the early 2000s, amorphous silicon dominated among the thin-film technologies but is replaced by CdTe over time (Fraunhofer ISE, 2017). Emerging cells as well as cells with concentrators are produced only in very small amounts and their market share is yet negligible (Fraunhofer ISE, 2017).

4 A patent search strategy for photovoltaic sub-trajectories

The previous section discussed the technological and economic differences between the PV sub-trajectories and components. In the following, a patent search strategy for the PV system and its cell sub-trajectories and generic components is developed to be able to analyze inventive activity in the different sub-trajectories. The development of the search strategy follows established procedures, especially Porter et al. (2008) and Costantini et al. (2015). First, different patent search methods and their advantages and disadvantages are discussed. Second, the development of the search strategy is elaborated in detail and third, an evaluation and comparison of the proposed search strategy and two benchmark search strategies are presented to validate the proposed one.

4.1 Patent search strategies

Patent data is stored in databases, usually managed by the respective patent offices. The selection of patents for economic analysis requires a search strategy to identify relevant patents in databases. A multitude of approaches exist to search for technology specific patents (see Abbas et al., 2014, for an overview). The most common and easy to replicate search strategies

use either a classification scheme or technology specific keywords as well as the combination of both (Eisenschitz and Crane, 1986; Dirnberger, 2011; Xie and Miyazaki, 2013).⁹

Classification schemes are used by patent offices to support the examination process and to ease their search for prior art (Jaffe and Trajtenberg, 2002). These schemes are structured according to technological principles and are not designed for economic analysis on a product or process level (Vijvers, 1990; Costantini et al., 2015). One frequently used classification scheme is the International Patent Classification (IPC) managed by the World Intellectual Property Organisation (WIPO).¹⁰ Additionally, recently the Cooperative Patent Classification (CPC) was introduced, which has a specific classification for emerging cross-sectoral technologies such as PV (Veefkind et al., 2012). Using a classification scheme is relatively easy and can derive sufficient results if the desired product or process is exclusively covered by one or multiple classes. However, the use of classification scheme to select patents has potential problems. One major problem emerges if a technological principle is used in several products or processes and using such a class to select patents might include patents which are not related to the product or process under consideration. Furthermore, it is also possible that a product or process combines different technological principles and if a class is not considered, relevant patents are missing.¹¹

A keyword search can deliver sufficient results, if a technology can be described by a set of specific keywords. However, several problems exist, since keywords can be used for multiple products or processes not related to the one under consideration. Therefore, keywords need to be selective to avoid including patents which are not related to the relevant product or process. Furthermore, patent documents can be intentionally written to avoid specific keywords to keep the invention hidden from competitors or not to reveal all details about the invention. Also, language differences or differences in the terminology can affect the number of selected patents (Montecchi et al., 2013).¹² A combination of both, a classification scheme and a set of keywords can mitigate some the above mentioned problems, but can be more restrictive than each one individually.

4.2 Patent search strategy for the photovoltaic system and its sub-trajectories

In the following, I explain how the proposed search strategy is developed using a combination of IPCs and keywords to provide an overall patent search strategy for the PV system and its different components and sub-trajectories. Similar approaches were proposed earlier, but they do not sufficiently cover the different cell sub-trajectories and PV components.¹³ In order to

⁹ Other possible approaches use, for example, co-occurrences of classifications or keywords on patents, use a pre-defined set of patents to train a search algorithm, or use citations from a specific set to retrieve previous patents (Abbas et al., 2014). However, these approaches are not easily replicable and are sensitive towards the database used.

¹⁰ Further classification schemes are the ones by the United States Patent and Trademark Office (USPTO) or the Japan Patent Office (JPO). See Held et al. (2011) or Wolter (2012) for comparisons.

¹¹ Other problems relate to the classification system itself, such as changes over time or that patent examiners misclassify a patent or assign too many or too few classes to a patent.

¹² Additionally, patent databases are not always complete and titles, abstracts, or other content can be missing which leaves out potentially relevant patents.

¹³ For example, Liu et al. (2011) and Breyer et al. (2013) distinguish different PV-cell materials but do not take into account other components of the PV system. Jang et al. (2013) select patent for different parts of the PV value chain. Jamali et al. (2016) use the recently introduced Cooperative Patent Classification (CPC) to distinguish between different PV generations, but here other components of the PV system are neglected.

collect the specific keywords and patent classifications for PV, the technical as well as economic literature was reviewed to define the boundaries of the technology. During this process, the three different components and the three different cell sub-trajectories are identified (compare Figure 2). Such an in-depth analysis is a crucial part since several other technologies are very close in the technological space. For example, other means exist to convert sunlight into electricity, such as concentrated solar power, which collects heat to run a steam engine and also solar heat collectors are quite similar (see, for a comparison Peters et al., 2011). But these technologies follow different technological principles and are not related to a PV system. Furthermore, the core technological principle of PV is the same as for light emitting diodes, but in the case of PV the light is not emitted, but absorbed.¹⁴ Other technologies and products are also close to PV, such as optical sensors or digital cameras. With respect to the materials used, semiconductors are essential in the microchip industry as well. Even though there are spillovers from adjacent technologies (Sze, 1981; Nemet, 2012), the aim of the search strategy is to understand the development in the different PV sub-trajectories and therefore requires a sharp distinction from adjacent technologies.

Based on the overall understanding of the technology, IPCs and keywords for the different components of the PV system and the different cell sub-trajectories are collected. The keywords and classes are grouped according to the different PV system components and sub-trajectories. Special attention is given to the different materials and processes used in PV cell production to avoid inclusion of non-relevant patents if the material or process is used elsewhere. Patent classifications are selected based on an in-depth review of the IPC system. The scope of the IPCs is intentionally wider (the 8-digit main group level) than in comparable IPC search approaches. Since patents assigned to these classes are searched also by keywords, this allows to capture patents which are misclassified or which are affected by changes in the classification scheme and would be missed out otherwise.

Overall, six different sets of classes and keywords are identified: the three different cell sub-trajectories as well as the module and encapsulation and the balance of system components. For the sub-trajectories, differentiation between the materials is possible, such as mono- and poly-crystalline cells, but since the sub-trajectory is the level of analysis, such more product like separation is not considered in more detail, but possible.¹⁵ However, there are cases where the patent document does not have enough information to attribute it to any of the sub-trajectories or components. A residual category is introduced for all patents which are related to the PV system in general, but cannot be attributed to a sub-trajectory. There are at least three reasons for a patent not being able to be assigned to the different components. The first could be that the list of keywords miss certain aspects and the respected keywords are not included. Second, the patent is intentionally written to avoid certain keywords to disguise them from competitors. The third reason is incomplete data, since patents can be stored with missing information and have, for example, only a title which could be very simple, such as “photovoltaic cell” and no

¹⁴ A light emitting diode uses a semiconductor and via a n-p-junction light is emitted (see Schubert, 2006, for a technical discussion).

¹⁵ The list of IPCs and keywords in Table 3 contains for each cell sub-trajectory two sets. The silicon wafer cells can be separated in mono- and poly-crystalline cells, the thin-film cells in silicon thin-film and cells using materials from the II-VI-, III-V-, and I-III-VI-groups, and the emerging cells can be separated in organic cells and cells with inorganic materials.

abstract is present to infer about the actual content of the patent. Since these patents are also relevant for the PV system, they are included in this residual category.

The sets of IPCs and keywords for each component and cell sub-trajectory was validated in an iterative process by leading experts in the field covering different parts of the PV system and having a background in academia and practice.¹⁶ The final list of IPCs and keywords is presented in Appendix 7.1.

4.3 Evaluation and comparison with benchmark search strategies

To evaluate the quality of the proposed search strategy in terms of scope and coverage, the patents which can be selected by the proposed search strategy are compared with two other leading patent selection approaches, the WIPO Green Inventory for PV (GI) and the Cooperative Patent Classification for PV (CPC).¹⁷ For this purpose, patent data is extracted from the Worldwide Patent Statistical Database (PATSTAT) (EPO, 2014).¹⁸ Patents from 1970 until 2011 are selected. Two different patent quality dimensions are considered: priority patent applications, which includes first filings of patent applications and triadic patents, which are applications jointly filed at the USPTO, JPO and the EPO, which are considered to be very valuable patents (Grupp, 1996; Dernis et al., 2001).

There are in total 49,171 priority patents in the proposed search strategy, while there are 129,253 priority patents based on the GI and 57,508 priority patents based on the CPC (comp. Table 1). While there is a difference in the magnitude, structural differences in the development over time are not present (comp. Figure 7). The proposed selection and the selection based on the CPC have nearly the same development over time. The development of the Green Inventory follows the same pattern, but with a greater magnitude. The results for the higher valued triadic patents is similar in its development. The overall triadic patent count is smaller, with 2,952 from the proposed search strategy, 9,865 for the Green Inventory and 3,577 in the CPC. The development over time is different between priority and triadic patents. Especially the surge of priority patents the last years is not present for triadic patents¹⁹ but there is again no structural difference between the search strategies.

A closer evaluation of the selected patents reveals that the overlap between different search strategies is considerable.²⁰ About 84% of the patents from the proposed search strategy are included the GI search strategy, while, on the other hand, only 32% of the patents in the GI are also in the proposed selection. However, the GI selects a very large number of patents overall. With respect to the CPC, the proposed selection contains 75% of the patents which

¹⁶ Personal interviews to validate the different keywords and IPCs for the components and sub-trajectories took place in November 2014 in Jena, or via phone or email. Documentation is available on request.

¹⁷ Both search strategies are widely used in the literature, the WIPO Green Inventory for example in Lei et al. (2013), Martinez et al. (2013), Choi and Anadn (2014), Gallagher (2014), Groba and Cao (2015), and the CPCs for example in Bointner (2014), Stek and van Geenhuizen (2015), Leydesdorff et al. (2015), Diederich and Althammer (2016), Glachant and Dechezleprêtre (2016), Jamali et al. (2016).

¹⁸ Patents are selected by first searching for the respected classes and keywords in all patents in the database and then selected based on the patent's DOCDB patent family the priority patent. This approach allows capturing patents where title or abstract are only available for family members.

¹⁹ The decline in the last year stems from the delay in the patent offices procedures.

²⁰ The overlap between the different search strategies is calculated by $\frac{PatentsA \cap PatentsB}{PatentsA}$. For example, the share of patents from the proposed search strategy that are also in the Green Inventory is: $\frac{49,171 \cap 129,253}{49,171} = \frac{41,268}{49,171} = 0.839$.

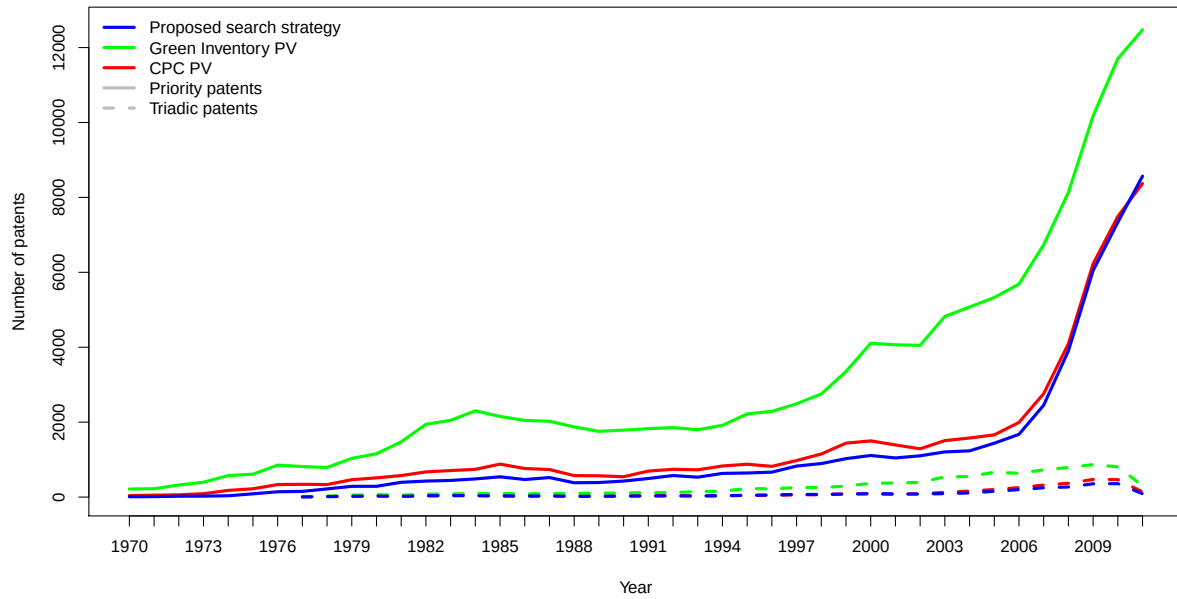


Figure 7: Comparison of different patent search strategies for photovoltaics over time.

Table 1: Priority patent overlap between different search strategies.

	Absolute overlap				Relative overlap		
	Proposed	GI	CPC		Proposed	GI	CPC
Proposed	49,171			Proposed	—	0.839	0.744
GI	41,268	129,253		GI	0.319	—	0.410
CPC	36,564	52,963	57,508	CPC	0.636	0.921	—

Note: In the right table, the bold diagonal represents the number of patents per search strategy while the lower triangle represent the absolute overlap between two search strategies.

can be selected by the CPC, while the CPC contains about 64% of the patents that are selected by the proposed search strategy. A comparison between the GI and the CPC reveals that the CPC is nearly (92%) a complete subset of the GI, but far more restrictive. Overall, there are 35,197 patents which are selected by all three approaches. If the overlap is considered for triadic patents, the share of patents from the proposed search strategy in the GI and CPC search strategies increases marginally (comp. Table 4 in the Appendix).

Further differences between the search strategies can be found in their technological coverage. Each patent has one or several classes assigned to it. On average, the patents selected by the proposed search strategy have 2.6 classes per patent, while patents selected by the GI have 3.5 classes and the CPC patents have 3.0 classes per patent. Since all search strategies use a pre-defined set of classes, calculating the share of classes that should be covered and classes that are not covered, gives an idea how widespread the patents are in the technological space. If we assume that the more concentrated the search is on the technological landscape, the better it is to distinct the technology from other technologies. To get an idea how well a search strategy selects the patents, I calculate the share of classes which are not in the pre-defined set over all classes obtained by the respective search strategy. The higher this share, the broader are the patents distributed on the technological landscape. The share of non pre-defined classes is for the proposed search strategy 29%, while it is 67% for the GI and 65% for the CPC. This conveys that the proposed search strategy discriminates better between relevant and irrelevant

patents. However, we need to keep in mind that the initial set of relevant classes is larger for the proposed search.

Figure 9 in the Appendix depicts a graphical representation of the technological landscape by the classification co-occurrences of the priority patents. The figure displays in blue the classes (at the group level) which were used to query the patent data and in red are classes which are also assigned to these patents. The classes are connected to each other if they co-occur on the same patent. The size of the nodes represents the number of this co-occurrences per class (in log transformation). The proposed selection has a large fraction of blue nodes in the landscape representing the relevant IPCs. Red nodes are only peripheral and not that large. The landscape derived from the Green Inventory has many more red nodes of considerable size. The CPC landscape however has only one central blue node, which is the Y02E 10 group which covers all PV patents. However, there are also many other classes which co-occur on these patents.

With respect to the country coverage by the different search strategies, Figures 10 and 11 in Appendix 7.2 depict country shares of priority and triadic patents over time.²¹ No structural differences between the three search strategies are immanent, indicating that the use of keywords in the proposed search strategy does not bias the selection of patents. Japan has the highest share of priority patents, which is related to their patent regulations in the past, which allowed only one claim per patent, while other patent offices allowed broader patents. This inflation of patents declined after regulation changed in 1988 (Sakakibara and Branstetter, 2001). The second and third countries are the USA and Germany. In recent years, Asian countries, especially South Korea and China, gain remarkable shares as well. With respect to the triadic patents, the USA has the highest share, but it declines over time. Japan is second, followed by Germany. Asian countries have hardly any triadic patents. Especially for China, hardly any triadic patents are filed. de la Tour et al. (2011) attribute this lack of filing patents internationally to the low quality of Chinese patents, since Chinese firm use patents to signal the government that they are inventive rather than to protect their inventions.

Overall, the proposed search strategy does not structurally differ from the two benchmark search strategies in terms of development over time and country coverage. However, the absolute number is much lower compared to the GI, which seems to be broader in its technological coverage. The proposed search strategy as well as the CPC are more focused on the core PV patents. Therefore the proposed search strategy is comparable to the benchmark search strategies, but has the advantage to distinguish the sub-trajectories, which are analyzed in the following.

5 Sub-trajectories in photovoltaic patents

Based on the proposed search strategy, it is possible to analyze the development of the different sub-trajectories over time. The disaggregated patent data for the different components and sub-trajectory is given in absolute and relative terms for the priority patents in Figure 8 and for

²¹ A patent is assigned to a country based on the patent office of the priority filing.

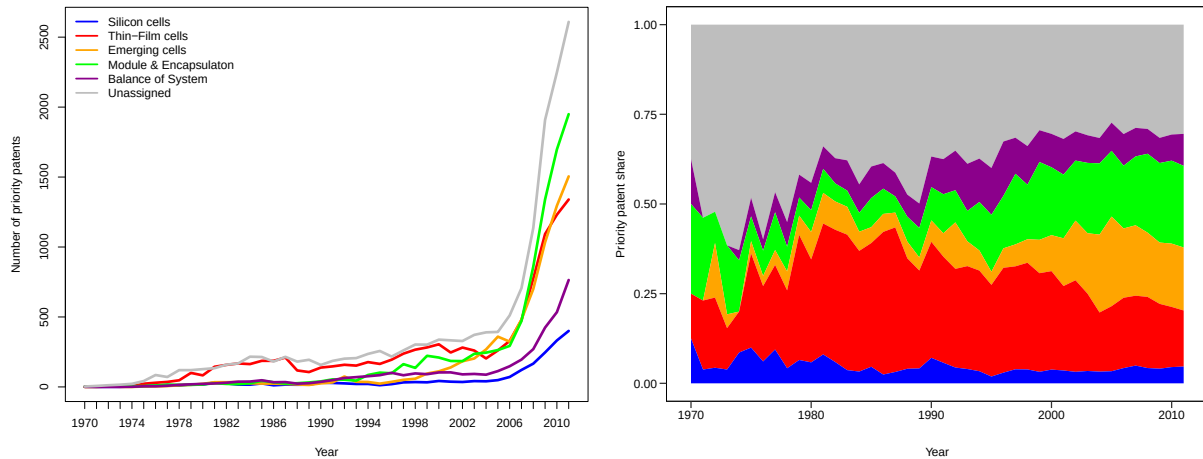


Figure 8: Absolute and relative number of priority patents per sub-trajectory.

triadic patents in Figure 12 in Appendix 7.3.²² However, there are hardly any differences between the two patent quality definitions. We observe a steady increase in absolute inventive activity in all sub-trajectories, especially in the last years. With respect to the relative development, it is surprising to see that the share of the silicon wafer cell sub-trajectory is very low and invariant over time. Even though it increases in absolute numbers, its relative share is very small. This is also remarkable since these cells clearly dominate the market and have high learning rates. With respect to the thin-film sub-trajectory, there is an increase in inventive activity in the 1970s and 1980s when the majority of patents were filed for this sub-trajectory. However, from the 1990s onwards, the relative share of thin-film patents declines, but is still about three times as high as for the silicon wafer cell sub-trajectory. The emerging cell sub-trajectory starts to get relevant shares from the 1990s onwards, especially with the introduction of the Grätzel-Cell and follow-up inventions. Nowadays they have even a higher share than the thin-film cells, indicating in which direction further inventive activity will unfold.

With respect to the module and encapsulation component, there is also an increase in inventive activity. This increase can be related to the fact that especially the silicon wafer cells have reached their physical boundaries and cost reductions and increases in efficiency can only be achieved if the whole module is improved, for example, by reducing the size of the electronic contacts which reduces the absorptive area of the cells. The share of the balance of system component does not change over time, even though a steep learning curve is present (Fraunhofer ISE, 2015). Unfortunately, there is a considerable share of patents which cannot be attributed to the different components and sub-trajectories. However, this share declines over time and shifts between the different components and sub-trajectories. The overall development trend of sub-trajectories should not be affected by unassigned patents.

There are several country differences between the sub-trajectories (Table 2). As indicated earlier, countries differ in their patenting intensity, but there is also a focus of some countries on specific sub-trajectories. For example, while priority patents for silicon wafer cells account

²² There is a small fraction of patents which is assigned to two or multiple sub-trajectories. In case a patent is assigned to two or more cell sub-trajectories, it is counted fractionally, if a patent is assigned to a cell sub-trajectory and a component, it is assigned only to the cell sub-trajectory.

Table 2: Priority patents per country and sub-trajectory from 1970-2011.

	Absolute per sub-trajectory						Relative per sub-trajectory					
	US	DE	JP	KR	CN	RoW	US	DE	JP	KR	CN	RoW
Silicon wafer cells	165	102	660	262	727	183	3%	3%	3%	4%	9%	3%
Thin-film cells	1,434	501	4,833	1,438	1,294	991	27%	14%	24%	21%	16%	19%
Emerging cells	482	271	3,167	1,324	1,495	628	9%	8%	16%	19%	19%	12%
Module & encaps.	1,019	1,135	3,417	1,355	1,096	1,259	19%	32%	17%	20%	14%	24%
Balance of system	465	260	1,546	408	886	483	9%	7%	8%	6%	11%	9%
Unassigned	1,831	1,288	6,482	2,150	2,424	1,712	34%	36%	32%	31%	31%	33%
Total	5,396	3,557	20,105	6,936	7,922	5,255	100%	100%	100%	100%	100%	100%

for about 3% in most countries, in China these cells account for nearly 10% of their patenting activity. Another example is the thin-film cell sub-trajectory for which the US has a quite high share of 27%, while, for example, Germany has only half of that share. However, Germany has a high share of patents for module and encapsulation. Emerging cells have about twice the share among priority patents in Asian countries compared to the US and Germany, indicating their direction of research. Furthermore, it is noteworthy that there is hardly any differences between the share of unassigned patents across countries, indicating that there seems to be no bias between countries but also not between sub-trajectories.

Triadic patents are greatly reduced in absolute numbers (Table 5 in the Appendix), especially for China, where less than 1% of all priority patents are filed as triadic patents. The overall distribution of triadic patents inside countries is similar as for priority patents. However, remarkable is the high share of triadic patents for the module component for Japan, which exceeds the high share of Germany. There are also some changes for China. Even though the total number of triadic patents is very low, half of them are for emerging cells, indicating that China tries to secure their inventive activity in this promising sub-trajectory internationally.

Overall, the proposed search strategy for the different PV sub-trajectories reveals that there are surprising differences in the inventive activity. First, the currently prevailing sub-trajectory, silicon wafer cells, shows the smallest share of patents among the whole PV system, despite its market domination and political support. However, this might not be that surprising, since this sub-trajectory reached its physical limits and improvements in efficiency are nearly exhausted or incremental. However, inventive efforts might have switched to the module production, which could reduce costs further for modules using this cells. The development of thin-film cells is more dynamic and increased in relative inventive activity until the 1990 and decreases since then, when the emerging cell technologies achieved a break through with the Grätzel-Cell. Nowadays inventive activity is focused on this emerging cell sub-trajectory, since it allows to overcome the physical limits of the other sub-trajectories. There are also geographical differences in inventive activity in the different sub-trajectories. For example the US focuses inventive activity on the thin-film sub-trajectory, while Germany focuses on inventive activity in modules. Asian countries seem to focus on the emerging cell sub-trajectory.

6 Conclusion

The aim of this paper is to propose a modular and replicable patent search strategy for the photovoltaic system and its sub-trajectories. Previous patent search strategies are not able to sufficiently distinguish PV patents at the sub-trajectory level and therefore detailed techno-economic analysis of the PV system and its components was not possible until now. To distinguish sub-trajectories in the PV system, the proposed patent search strategy is developed following established procedures (Porter et al., 2008; Costantini et al., 2015). The proposed search strategy is evaluated against two benchmark search strategies, the WIPO Green Inventory for PV and the newly introduced CPC Classification for PV. The proposed search strategy provides overall similar results in terms of patent numbers over time and country coverage, but it is more restrictive and separates PV better from adjacent technologies.

The analysis of the development of sub-trajectories provides a better and finer-grained understanding of technological progress in PV. Surprising results are revealed, especially that the prevailing sub-trajectory, silicon wafer cells, has the lowest share of patenting activity, even though it dominates the market. This indicates that inventive activity in this cell sub-trajectory is either kept secret or not patentable. Further dynamics, such as the emergence of new cell technologies, which shifted the focus of inventive activity away from thin-film cells, are revealed. Also differences between countries and their focus on sub-trajectories are uncovered. Here, Asian countries seem to focus on emerging technologies, which have high potential in the future, while for example Germany and the US stick to established sub-trajectories.

The results provide implication for research and policy makers. Using sub-trajectories helps to open-up the dichotomy of radical and incremental innovation, since there are substantial changes inside a trajectory which need to be considered to understand technological progress in more detail. This is also relevant for evaluations of policy intervention. In the case of PV, the effect of demand inducing policies might be overstated, since inventive activity in the dominant cell technology, silicon wafer cells, is the lowest, questioning the effect of these policies on inventive output. Furthermore, the design of policy instruments supporting R&D in PV should account for sub-trajectories to avoid a lock-in into an inferior sub-trajectory. The currently market dominating silicon wafer cells do not have the potential for substantial improvements and their patented inventive output is the lowest, but for example in Germany, most research funding is directed to this sub-trajectory. While these lock-in situations are well understood at the trajectory level, the presence of lock-ins at the sub-trajectory level has been neglected so far. In such a situation, policy intervention should support the search process for new solutions or support promising emerging sub-trajectories to avoid lock-in into inferior or technologically exhausted sub-trajectories. With respect to industrial policy, the illustration how different sub-trajectories emerge and develop is key to receive or sustain a competitive advantage. Asian countries seem to direct their research efforts into the promising emerging cell sub-trajectory, while for example Germany invests most of its R&D funding in silicon wafer cells, which allow only for incremental improvements.

While the results presented here are only descriptive, the proposed search strategy opens up further avenues for more detailed analysis of the development of the PV system and its sub-trajectories. For example, it is possible to analyze in more detail the source of efficiency

improvements and factors affecting learning curves of PV. With respect to the market dominating silicon wafer cells, the descriptive results show low inventive activity in the cell sub-trajectory but high inventive activity in the module component, indicating that learning effects may have their origin not in the cell sub-trajectory anymore. Understanding such a possible shift in more detail can be used to improve technological forecasting. In a similar vein, the emerging cell sub-trajectory increases its share substantially. This increase and the inventive activity in this sub-trajectory can be analyzed in more detail to model further technological progress in PV. With respect to the innovation process, in [Kalthaus \(2016\)](#) I can show that knowledge recombination by German inventors differs between sub-trajectories, indicating that different competences and knowledge are required for the different sub-trajectories. Such an analysis can be extended to understand for example differences in citation pattern between sub-trajectories. Furthermore, the possibility to analyze the technological development in more detail can also be useful for studies on the firm and industry level, since technological choice of firms has an effect on its entry ([Kapoor and Furr, 2015](#)) and possibly on its survival.

Besides the direct implications on understanding technological progress for the PV system, analyzing sub-trajectories in general can reveal interesting patterns and should be considered in other technologies as well. The concept of sub-trajectories and their emergence, for example via micro-radical innovations ([Durand, 1992](#)), helps to understand determinants of progress in more detail. Even though there are several examples of detailed analysis, studies using patent data have neglected this dimension so far. Promising cases are for example sub-trajectories in battery technologies, which emerged over time and provide different characteristics to store electricity and are a vital part to transform the energy system.

However, there are also several shortcomings with the proposed search strategy. First, the keywords and classes do not cover sub-trajectories which will emerge in the future and updating the search strategy is necessary over time. Also there is a considerable share of patents which is not assigned to the different sub-trajectories, which only gives indication of the distribution of patents per sub-trajectory. Increasing data quality or using different databases could mitigate this shortcoming. Lastly, even though the scope of the search strategy is broad, there are certainly patents which are not considered. With respect of using patent data to understand the development of sub-trajectories the problematic nature of patent data has to be considered ([Griliches, 1990](#)) and that only a fraction of inventions is patented ([Cohen et al., 2000](#)). Therefore using patent data to understand sub-trajectories is necessary, but not sufficient.

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7 Appendix

7.1 The search strategy for photovoltaic sub-trajectories

The combination of IPCs and keywords for the search strategy is presented in Table 3. Title and abstract of the patent documents are searched for the keywords while restricted to the specific IPCs. The keywords and IPCs are grouped by their sub-trajectory to reduce the overlap with other adjacent sub-technologies and should be searched accordingly. The “_” and the “%” symbol are used as wildcards for single and multiple characters. “|” and “+” are logic operators for “or” and “and” combinations of keywords. The SQL code for the search strategy is available on request.

Table 3: List of IPCs and keywords for the proposed photovoltaics search strategy.

Sub-trajectory	IPCs	Keyword combination
Silicon wafer cells	C30B 15% H01L 21% H01L 31%	((%monocrystalline_silicon% %monocrystal_silicon% %crystal_silicon% %silicon_crystal% %silicon_wafer%) + (%photovoltaic% %solar%)) %back_surface_passivation% (%pyramid% + %etching% + %silicon%)
	C01B 33% C30B 15% C30B 29% H01L 21% H01L 31%	((%polycrystalline_silicon% %multicrystalline_silicon% %poly_Si% %polysilicon%) + (%photovoltaic% %solar%)) (%ribbon% + (%photovoltaic% %solar% %silicon%)) (%edge_defined_film_fed_growth% + %silicon%) %Metal_wrap_through% %emitter_wrap_through% %ribbon_growth%
Thin-film cells	C23C 14% C23C 16% H01L 21% H01L 27% H01L 29% H01L 31%	((%chemical_vapour_deposition% %PECVD% %physical_vapour_deposition% %PVD% %solid_phase_crystallization% %laser_crystallization% %nanocrystalline% %microcrystalline%) + (%photovoltaic% %solar% %silicon%)) ((%tandem% %amorphous_silicon% %silicon_substrate% %silicon_film%) + (%photovoltaic% %solar%)) %staebler_wronski%
	C23C 14% C23C 16% H01L 21% H01L 25% H01L 27% H01L 29% H01L 31%	((%cadmium_telluride% %CdTe% %copper_indium_diselenide% % CIS % %CuInSe% %indium_tin_oxide% %gallium_arsenide% %GaAs% %roll_to_roll% %surface_textur% %thin_film% %thinfilm%) + (%photovoltaic% %solar%)) %copper_indium_gallium_diselenide% %CuInGeSe% %CIGS% %copper_zinc_tin_sulfide% %CZTS% %kesterite%
Emerging cells	C08G 61% C08K 3% H01B 1% H01G 9% H01L 21% H01L 31% H01L 51% H01M 14%	((%dye_sensiti% %titanium_oxide% %titanium_dioxide% %TiO2% %organic% %polymer%) + (%photovoltaic% %solar%)) %gr_tzel% %graetzel% %hybrid_solar_cell%
	H01G 9% H01L 31% H01L 51% H01M 14%	((%quantum_dot% %perovskite% %organic_inorganic% %plasmon% %nanowire% %nanoparticle% %nanotube%)) + (%photovoltaic% %solar%))
Module and encapsulation	B64G 1% E04D 13% H01L 25% H01L 21% H01L 27% H01L 31% H01R 13% H02N 6% H02S 20% H02S 30%	((%anti_reflection% %encapsulat% %back_contact% %buried_contact% %bypass_diode% %rear_surface_protection% %back_sheet% %building_integrat% %mounting_system%) + (%photovoltaic% %solar%)) %solar_panel% %photovoltaic_panel% %solar_modul% %solar_cell_modul% %photovoltaic_modul% %solar_cable% %photovoltaic_wire% %solar_array% %photovoltaic_array% %BIPV% %solar_park% (%spacecraft% + (%photovoltaic% %solar_cell%))
Balance of system	F21S 9% G05F 1% H01L 31% H02J 3% H02J 7% H02M 3% H02M 7% H02S 10% H02S 40% H02S 50%	((%off_grid% %inverter% %DC_to_AC% %DC_AC% %MPP% %grid_connected%) + (%photovoltaic% %solar%)) ((%tracking% %tracker% %energy_management%) + (%photovoltaic% %solar_cell%)) (%maximum_power_point% + %track%) %anti_islanding_protection% %solar_charge% %solar_powered%
Unassigned	B64G 1% C01B 33% C08K 3% C08G 61% C23C 14% C23C 16% C30B 29% C30B 15% E04D 13% F21S 9% G05F 1% H01B 1% H01G 9% H01L 21% H01L 25% H01L 27% H01L 29% H01L 31% H01L 51% H01M 10% H01M 14% H01R 13% H02J 3% H02J 7% H02M 3% H02M 7% H02N 6% H02S 10% H02S 20% H02S 30% H02S 40% H02S 50% H02S 99%	(%photovoltaic% %solar_cell%)

7.2 Search strategy evaluation

Table 4: Triadic patent overlap between different search strategies.

	Absolute overlap				Relative overlap		
	Proposed	GI	CPC		Proposed	GI	CPC
Proposed	2,952			Proposed	—	0.867	0.763
GI	2,560	9,865		GI	0.260	—	0.316
CPC	2,251	3,121	3,577	CPC	0.629	0.873	—

Note: In the right table, the bold diagonal represents the number of patents per search strategy while the lower triangle represent the absolute overlap between two search strategies.

Table 5: Triadic patents per country and sub-trajectory from 1977-2011.

	Absolute per sub-trajectory						Relative per sub-trajectory					
	US	DE	JP	KR	CN	RoW	US	DE	JP	KR	CN	RoW
Silicon wafer cells	28	21	30	8	1	25	3%	5%	4%	4%	2%	4%
Thin-film cells	291	100	211	56	10	141	34%	22%	25%	29%	20%	24%
Emerging cells	119	69	118	58	24	98	14%	16%	14%	29%	49%	17%
Module & encaps.	125	107	222	18	2	102	15%	24%	27%	9%	4%	18%
Balance of system	43	24	49	7	3	29	5%	5%	6%	4%	6%	5%
Unassigned	248	127	198	50	9	184	29%	28%	24%	25%	18%	32%
Total	853	447	828	197	49	578	100%	100%	100%	100%	100%	100%

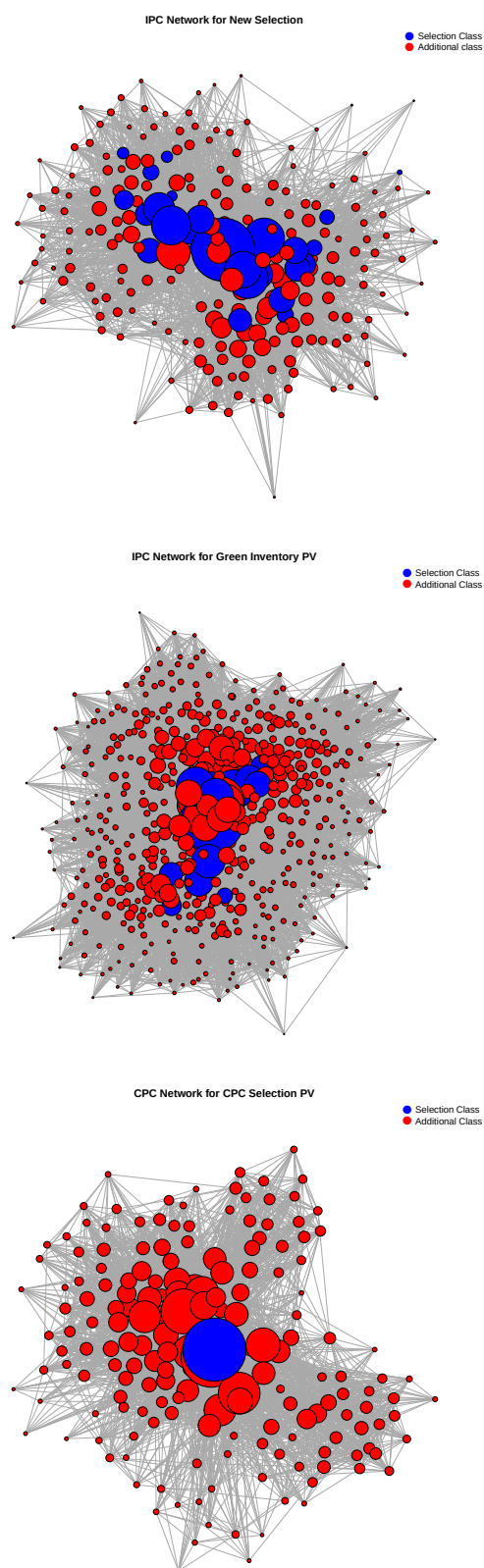


Figure 9: Classification co-occurrence for different search strategies.

Figure note: The nodes represent IPC or CPC classes at the group level, while edges represent co-occurrences of classes on patents. The size of the nodes as well as the edges is log-transformed.

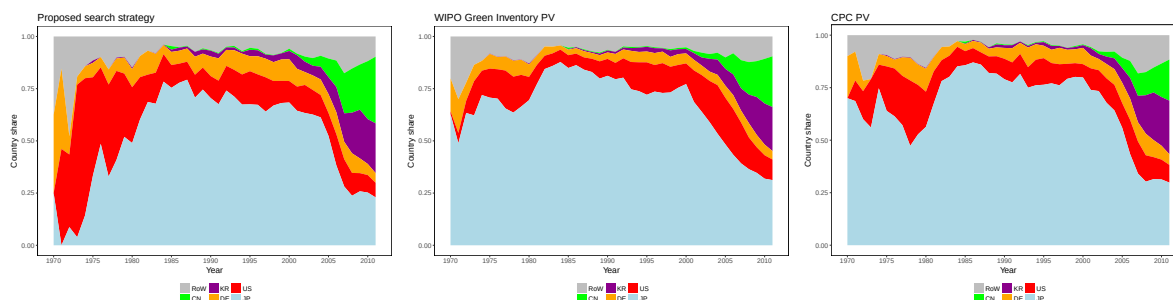


Figure 10: Country share of priority patents for different search strategies over time.

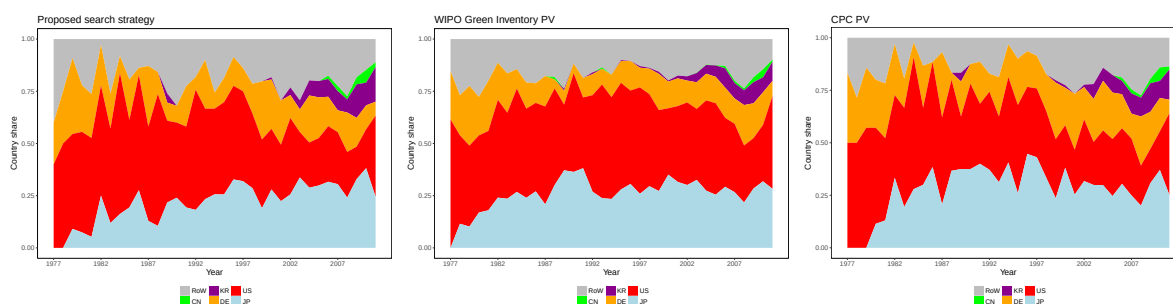


Figure 11: Country share of triadic patents for different search strategies over time.

7.3 Sub-trajectories in triadic patents

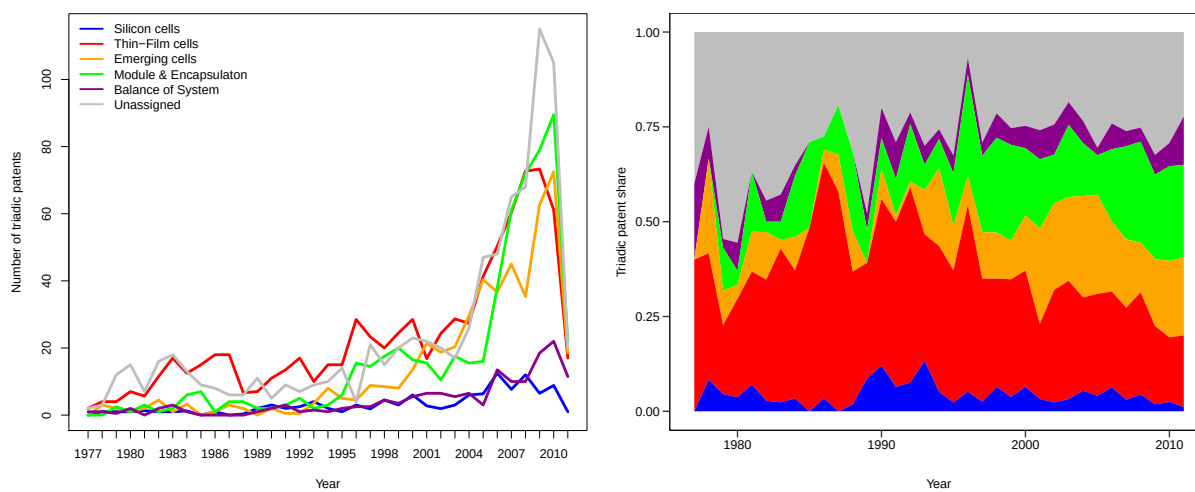


Figure 12: Absolute and relative number of triadic patents per sub-trajectory.

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