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Intellectual Property Rights and Renewable Energy Technologies: Patent Data as Proxies of Photovoltaic Industry Development

Prof. Massimiliano Granieri
SUPERVISOR

Prof. Ian Paul McCarthy
CO-SUPERVISOR

Niccolò Bagnara ID no. 747661
CANDIDATE

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List of Abbreviations

CBAM	Carbon Border Adjustment Mechanism
COP	Conference of the Parties
CO2	Carbon dioxide
CSP	Concentrated Solar Power
EIA	US Energy Information Administration
EPO	European Patent Office
ETS	Emission Trading System
EPC	European Patent Convention
FAO	Food and Agriculture Organization
FDI	Foreign Direct Investment
GDP	Gross Domestic Product
GHG	Greenhouse gas
GW	Gigawatt
GWEC	Global Wind Energy Council
IC	Installed capacity
IEA	International Energy Agency
IMF	International Monetary Fund
IPC	International Patent Classification
IPCC	Intergovernmental Panel on Climate Change
IP	Intellectual property
IPR	Intellectual property rights
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
LOOCV	Leave One Out Cross Validation
NASA	National Aeronautics and Space Administration
NDC	Nationally Determined Contributions
OECD	Organization for Economic Cooperation and Development
OWID	Our World in Data
PCT	Patent Cooperation Treaty
PLT	Patent Law Treaty
PV	Photovoltaic

RE	Renewable energy
RET	Renewable energy technology
RES	Renewable energy sources
TW	Terawatt
TRIPS	Trade Related Aspects of Intellectual Property Rights
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
WTO	World Trade Organization
WIPO	World Intellectual Property Organization
WMO	World Meteorological Organization
WRI	World Research Institute

Introduction

In today's fast-paced economic landscape, intellectual property (IP) is both a strategic asset for companies and a key driver of economic growth. This instrument both contributes to the incentivization of innovative activities and to the diffusion of them, while at the same time being a powerful tool for economic evaluations through IP analytics. The pressing challenge of climate change, on the other hand, has made the expansion of renewable energy industry pivotal in our economy, with the photovoltaic (PV) sector being one of the most developed. In this context, the research focuses on the creation of a model capable of approximating the future development of the photovoltaic installed capacity through an IP metric such as the patent count and verify their correlation. Italian scenario is analyzed along with the global one, and the existence of a lag effect between the variables is investigated.

Global warming, the rise of the oceans, drought and loss of biodiversity are just a few of the issues caused by climate change, as the first chapter illustrates. States and international organizations on the opposite side are working to slow down the negative effects with policy programs and treaties boosting the diffusion of cleaner energy like the REPower EU plan, the IRA, the Green Deal, and the Paris and Tokyo agreements. Technological progress in the photovoltaic industry is object of a quick overview in the same chapter, from the discovery of the photovoltaic effect to the cutting-edge current generation panels. The fundamentals of intellectual property rights are covered in the second chapter. Their pivotal role in our economy is reflected by the intense activity of institutions to regulate and enforce them. Despite this, the debate is still open among scholars regarding IP presence being positive or damaging knowledge diffusion.

Chapter 3 illustrates how the literature contributed to the shaping of the research question: the use of patent count as proxy for innovation and the influence that IP related variables have on the underlying development technologies are crucial as a solid theoretical base.

Chapters 4 and 5 are technical chapters addressing the data collection process and the statistical analysis and model creation, including the results. Regarding the main hypotheses, the correlation between cumulated photovoltaic tech patent count and cumulated photovoltaic installed capacity was proved to be strong, both in the global and in the Italian cases. But while the global proxy function can be considered an effective tool, the Italian one does not reflect the most likely development. The existence of a lag effect was not proven to be relevant. Despite this, the accuracy of the global forecast function could find appliance for both companies and policymakers.

1. Renewable Energy in 2023: Diffusion and Future Perspectives

1.1Global Unsustainability Issue

In order to approach the issue of sustainability in a complete way, this paper proposes a quick look at the causes and effects of climate change and points out why the current energy production and consumption system is not sustainable anymore under many aspects.
The paragraph will explore the main causes, and then the effects of the global warming, thus laying a base for the following chapters with an approach focused on trends by numbers. The last one of the consequences, which is the impact on the economy, will be the main point of attention. This part will guide the discourse towards sustainability and policies, found in the following paragraphs, by showing proof of the incumbent need to switch as fast as possible to renewable energy sources and underlining their importance.

According to the latest data published in the United Nations Climate report (2023), the biggest cause of global warming is attributed to the use of fossil fuels, which together contribute more than 75 percent of global greenhouse gas (GHG) emissions and about 90 percent of global carbon dioxide emissions (CO2).
There is no doubt that the concentration of CO2 in the air has been caused by the human activity; according to NASA's last measurement, this value is now (February 2023) 419ppm. If we compare it with the concentrations of the past thousands of years before 1950, we can state that the current number is 50% higher than its natural maximum level, which goes from 180ppm to 300ppm. It is well known that CO2 is naturally part of the air we breathe, and its presence inside the atmosphere is not bad per se: the problem is that this concentration is getting too high. This greenhouse gas traps the sun's heat, too much of it and we get climate change, with a series of cascading effects on our ecosystem and our everyday life.

1. Among the main causes of the climate change, the UN mention the generation of power. The reason is that we are heavy users of coal, oil, and gas as sources of electricity. These sources, as mentioned before, have a negative impact on the environment. By giving a look at the reports regarding energy consumption across the years, we can notice an upwards trend:

According to Statista's Global Primary Energy Consumption Report (2021), the aforementioned consumption measured in exajoules has increased from 395 to 595 in the last twenty-one years alone. Following the same report, the distribution of consumption is also an interesting aspect to take into account: with China leading the ranking with 26% of the global total in 2021, followed by the United States contributing with 15%, in turn succeeded by India (6%) and Russia (5%), with Japan not even reaching 3% of the total and finally all the other countries with less consistent numbers (BP, 2021).

Wanting now to create a dialogue between the data on emissions and those on global energy consumption, we can easily see that the same industrialized countries, which therefore consume more energy, are also those that over the years have contributed most to emissions on our planet due to their heavy use of energy and, inevitably, of large quantities of fossil fuels that unfortunately still represent a large part of energy sources.

In the Global Report on Emissions (Statista, 2021), cumulative CO2 emissions from 1750 to 2020 measured in billions of tons were taken into account. The results show an exponential increase of them: if before 1900 Europe contributed to three quarters of global emissions, with 30 billion cubic meters of CO2, by 1950 the United States had produced 95, almost as much as Europe at the time; a surprising fact if we consider that the United States began their industrialization process late compared to the old continent. In the same year, China did not even emit 2 GtCO2, and then reached 14.62% of cumulative global emissions by 2020, compared to 24% in the United States, when the total in the world reached about 1700 GtCO2 (World Bank; Global Carbon Project; Expert(s) (Andrew et al. (2021))).

2. However, the exponential trend in energy consumption (and therefore production) is not the only reason why the current consumption model is not considered sustainable: deforestation is the second cause highlighted in the United Nations climate report. Although it is not the goal of this discussion to focus on emissions from deforestation and as much as we want to keep the focus on direct energy use, we cannot help but mention it briefly together with the impact that food production has on our planet. This phenomenon attributable to human action contributes strongly to global greenhouse gas emissions along with other activities related to land exploitation,

totaling about a quarter of global emissions. This is because plants absorb CO_2, which is then released into the air once it is destroyed. Over the past 30 years, FAO has recorded a decrease in the total global area covered by forests from 4.24 billion hectares to 4.06: in the period from 1990 to 2000 alone, the total area decreased by 7.4%, by a further 5.17% in the following decade and finally by another 4.74% in the following ten years (FAO, UNEP, 2021). In previous data we can see a trend towards a reduction in the use of this practice, but environmental conditions are rapidly worsening and the abandonment of deforestation in its entirety would be the most desirable way at the moment.

3. Food production also contributes to global warming for reasons that are linked to deforestation itself, the creation of monocultures, the transport of food products through very high emission boats and planes, the use of fertilizers, direct emissions related to livestock and finally the packaging of finished products. Livestock farming itself is a major source of pollution as meat production requires the use of feed, which in turn is often derived from inefficient processes in terms of land use and resources. In addition, animals contribute in part to the emission of methane into the atmosphere. To feed a population that is growing faster and faster, the food industry has had to organize itself in such a way as to be increasingly efficient. The Statista Report on World Food Production highlights how since the 60s the system has evolved rapidly also due to the change in people's food needs, with more and more disposable income (even if not equally distributed) and needs that become more specific and difficult to follow.

Food waste is also part of the concerns of recent times: it is estimated that 931 million tons of food were wasted in the world in 2019 alone, for a total of 121 kilograms per capita (UNEP 2020).

4. Continuing with the causes of climate change, we have transport: whether sea, land, or air, private or public, most of it is still powered by non-renewable energy (UN, 2023). Their impact on global greenhouse gas emissions has been growing over the years: from 1990 to 2019 it grew from 4.73 billion tons per year to 8.43; with a continuous and rapid increase slightly decelerated by the Covid-19 pandemic. In this context, Asia leads the ranking of the highest emissions with 33% per year in 2021,

followed by North America (30%) and Europe (16%) (EDGAR/JRC; European Commission; Expert(s) (Crippa et al.), 2022).

5. The manufacturing industry, associated with the discourse on industrialization, is also involved in the discourse of pollution. To produce materials used in products intended for companies and consumers, as well as for the transport sector, the sources used to meet energy demand are most often made up of non-renewable and polluting sources. Similar to the food industry, moreover, the lifestyle of the increasingly informed and demanding consumer (and in ever greater numbers) requires companies to produce substantial volumes, which must be supported by adequate flows of raw materials and energy. According to a study by the World Economic Forum (2022), the impact of the manufacturing industry accounts for 54% of total energy consumption globally and a fifth of CO_2 emissions.

6. The last but not least culprit of global pollution is consumption related to the power supply of homes. Linked to the increase in the population and its needs in terms of comfort such as temperature control systems, connected devices and smart technologies for the home (UN 2023). According to the IEA's 2022 report, 30% of global energy consumption is attributable to the operation of buildings, which in any case also impact from the point of view of their construction and possible disposal. Also, in this case the energy consumed is mostly generated from non-renewable sources.

Turning now to the consequences of climate change, one cannot help but briefly mention rising temperatures, storms, droughts, rising oceans, biodiversity loss, food shortages and related health risks. All these phenomena in turn contribute to substantially changing our economy and will continue to do so. The effects of pollution on the environment will then be treated in the rest of the paragraph in brief and accompanied by data that give an idea of the current situation and its evolution, with a focus at the end on the economic effects.

1. Now consider the first of the impacts: global warming. This phenomenon, as stated by numerous studies and confirmed by the UN report, has been accentuating more and more since the 80s. This in turn has fallout that consists of heat waves, more frequent and aggressive forest fires, and melting glaciers.
   A study containing data ranging from 1971 to 2018 also shows that warming does not occur uniformly in our globe, but is concentrated above all in the ocean, which in the period of time considered has contributed 91% of the total temperature rise, with an increase of only 5% of the earth, a 3% related to the loss of glaciers and only 1% associated with atmospheric temperature. The heavy effect of this phenomenon on the oceans causes shocks in the life of the marine ecosystem (IPCC, UNEP, World Meteorological Organization).

2. More powerful and intense storms are one of the effects of climate change, linked in particular to rising temperatures. This is because with a warmer climate the humidity evaporates more going to exacerbate the effect of normal thunderstorms, which often turn into hurricanes, typhoons and cyclones which consequently lead to flooding and destruction of homes, damage to objects and danger to the safety of people (UN, 2023). In fact, it is estimated that climate disturbances in a direct way have caused, in the worst years and in a period of time ranging from the 90s to 2020, damage up to 0.49% of global GDP, with the lowest value recorded of 0.03% (Visual Capitalist; OWID; EM-DAT). This has had knock-on effects on the lives of 32 million people, as highlighted by the same sources, which in another report show that the deaths caused by these phenomena always exceed thousands per year, with peaks linked to tragedies of substantial dimensions in 1991 (storm wave in Bangladesh) and 2008 (cyclone in Myanmar), when the deaths exceeded 140,000 in both years.

3. The rise in temperature is also causing an increased risk of drought, which is becoming a problem especially in countries that are naturally poorer in water. This phenomenon in turn causes problems for the agricultural sector, with the enlargement of the areas covered by deserts, the displacement of large masses of sand even from one continent to another and the alteration of ecosystems (UN, 2023).
   Drought will have its negative effects on more and more people over time if the trend does not change; in fact, with increasing temperature the phenomenon is exacerbated

and tends to worsen more rapidly and more strongly the living conditions of a greater number of people.

If with 1.5 degrees Celsius of global warming in 2022 the population impacted by drought was 0.95 billion, it is estimated that with increasing temperature the number can increase substantially, to reach 1.29 billion in the event of an overall increase of 3 degrees Celsius (WRI, IPCC).

4. The discourse of the rise of the oceans is also dependent on the increase in temperature: the waters rise not only because of the melting of the glaciers, but also because their volume increases with the increase in water temperature, which, as seen above, is the element of the terrestrial ecosystem that has suffered the most shock from this point of view.

   In this way, the inhabitants of the coastal areas and islands of the world are at risk of losing their homes or their businesses in the coming years (UN, 2023).

   Also in this case, as in others, the trend of the average annual sea level rise is unfortunately exponential: if from 1901 to 1971 in fact the average was 1.3 mm per year, in the period from 1971 to 2006 it becomes 1.9 mm, to pass to an average of 3.7 mm between 2006 and 2018 (IPCC; UNEP; World Meteorological Organization).

   The population will have to adapt its lifestyle to cope with a phenomenon that will force many to emigrate from their place of origin or to face substantial expenses to be able to adapt, building special infrastructures or replacing existing ones that will be damaged by water, such as many underground wirings used for internet connection or simply roads.

5. The loss of biodiversity is the fifth of the consequences that we are going to consider: at the moment the loss of both terrestrial and aquatic animal and plant species is taking place at the highest rate ever, which is about a thousand times higher than any other value ever recorded. Habitats are disrupted by temperatures, which make life impossible for some species, while others are forced to adapt or, if possible, emigrate. In addition, intensive fishing, soil and water pollution, fires and deforestation carried out to accommodate monocultures have serious repercussions on the survival of a wide range of living beings (UN, 2023).

   In the coming decades, the UN estimates that one million species will be further lost.

The last UN biodiversity conference was held in Montreal in December 2022. The main points of the same will be highlighted in the next paragraph concerning the policies and measures that countries are putting in place to counteract the negative effects of climate change.

6. A theme that is linked to global warming, the agricultural situation and drought, the melting of glaciers and activities such as intensive farming and unsustainable fishing is precisely that of food.
   The lack of food presents an important issue and a challenge for the coming years as much as the production of energy: the sea absorbs pollutants thus becoming more acidic and inhospitable for many species, desert areas advance with consequences on crops and livestock that are supplied from those crops. The yield of crops decreases as nutrients in the soil decrease, of available water and increasing thermal stress; while in cold areas of the world subsistence activities such as hunting and fishing risk disappearing with the disappearance of prey, leaving local inhabitants at food risk (UN, 2023).
   The World Food Programme reported that 345 million people currently (2023) are facing a situation of serious food risk across 82 countries in the world: a situation not only attributable to climate change but also to shocks such as the Covid-19 pandemic, which still leaves negative consequences on the conditions of many, and the war in Ukraine, which has caused the prices of many fuels, interrupted some supply lines of raw materials including food with cascading effects on the cost of goods for the consumer.
   In particular, as highlighted by a study on food prices carried out by the FAO, the real food price index has been increasing during 2022 with the outbreak of the conflict, and then re-established at levels higher than those taken as a reference, ie those ranging from 2014 to 2021. Some food commodities such as cereals, for example, peaked 70% above baseline values, subsequently declining by an average of 19% in the following months (IMF 2023).

7. Health risks and poverty are linked to the climate change through the previously mentioned phenomenon of pollution, poor nutrition, droughts, and catastrophic natural events. People who live in countries made unhospitable by climate change are

forced to spread across the globe, away from their home and often in very precarious situations. The consequences are both physical and psychological (UN, 2023).

In the final part of this paragraph, poverty and the economic shocks linked to climate change will be the protagonists: various academic studies and databases will be consulted in order to give the reader a quick look at the current state.

An interesting report from Schroders (2016) points out that the worst-case impact of climate change on global economy is expected to produce a 1% yearly global GDP decrease, distributed in an uneven way across the various countries of the globe, where the poorest will be also the most hindered. This study also takes into consideration the evolution of technology in function of the global warming: our economy is in fact adapting to the changing conditions: new industries emerged in the last decades, such as the renewable energy technologies (RETs), while others are changing and are being reshaped by the compelling necessities of sustainability, such as the automotive industry and its gradual shift to electric cars.

Damages to infrastructure, loss of productivity and migration are the main issues for the authors, who also point out how investment opportunities will also have to adapt in order to take into account now more than ever the risk of natural calamities. Governments and companies that will manage to adapt to the situation will probably emerge as winners in the end, but those who will not be able to reconfigure the resource distribution towards maintenance and risk coverage, also because of budget constraints, have the risk to succumb.

The same fact is linked to another paper from Kahn et al. (2021), which also remarks that most of the countries whose economic system is heavily dependent on agriculture will be heavily penalized along with the ones which, for budget reasons, will not be able to afford increasingly high expenses caused by natural events and necessity of infrastructures.

The previously mentioned report also talks about inflation and energy costs: it is in fact proved that uncomfortable temperatures increase the need and consumption of energy used to cool or heat buildings. Higher seasonal energy demand along with decreased efficiency of power plants, hit by higher temperatures, will likely cause the increase of the overall energy prices. The same energy is moreover produced mainly by consumption of non-renewable sources, which creates a vicious loop.

World Economic Forum also shows interesting but alarming data: it is estimated that by 2050 the global economy is going to lose 10% of its total value (*This Is How Climate Change Could Impact the Global Economy*, 2022). The scenario analysis also takes into account various context in which different levels of intensity of actions are taken to avoid further consequences: in the best-case scenario, in which the Paris Agreement targets are met, the loss will be 'only' 4% by 2050, with a worst-case scenario of 18% loss if no actions are taken. This analysis is in line with the previously mentioned studies on the topic of inequality of the severity of the effects on different world regions. In this case Asia is the region with the highest risks in the negative scenarios, with severe losses concentrated in the poorest countries, and 24% just in the case of China.

An original and well supported point of view is also given by the famous economist W. Nordhaus.
William Nordhaus won the Nobel prize in Economics in 2018 thanks to its article "Integrated Economic and Climate Modeling". The article comes after years of studies of the phenomenon by the expert, who represented the climate change as an example of public good. This public good is intended in a worldwide sense: single countries have to bear the costs of research and infrastructures supporting sustainability, while the benefits of the avoided damages are gathered by everyone indistinctly. This said, it is then supported the thesis of international cooperation and the use of a system of carbon pricing like taxes or cap-and-trade mechanisms as the main opportunities for our world to stand against the effects of the climate change.

The use of this last article remarks the importance of global cooperation in the energy transition and should serve as a premise for the following paragraph treating the different environmental policies around the world, along with the main international organizations and conventions created by heterogeneous and often culturally distant countries to unite against the climate change to find a win-win compromise.

1.2Political Outlook

In this paragraph the main political and regulatory initiative to face climate change will be taken into consideration at a global level, with an eye to the most important international climate conventions too. As said in the previous paragraph, climate change is a global issue and cooperation is key as we will see. The following pages will be complementary to the previous ones in laying a base to the situation underlying the more specific topics of IP and renewable technologies, which will be analyzed later.

The first international convention specifically created to address the negative effects of climate change is the United Nations Convention on Climate Change (UNFCCC), which entered into force in 1994. The UNFCCC has currently 197 Parties who agreed on its conditions, with the whole European Union counting as one. Among the most relevant members of the convention, we can find China and the United States, which are two of the original signatories and the countries with the highest emissions of greenhouse gases in the world, so their collaboration is crucial. The convention is specifically constituted to reduce greenhouse gas emissions and it has paved the way for two of the most important treaties against climate change: Kyoto (1997) and Paris (2015).
Thanks to the UNFCCC and its legally binding agreements, countries are incentivized to respect the terms found in the treaties and collaborate in funding sustainable projects and transfer technology to the less developed areas of the world. Developed countries, in particular those belonging to the so called 'Annex I' are the ones who have in past contributed the most to pollution, they belong to the Organization of Economic Cooperation and Development (OECD) and are the ones who have the greatest responsibilities in terms of cutting emissions and reporting progress made yearly in a much more detailed way than the others. Parties of the convention gather annually in different locations around the world to discuss the main concerns of the moment, state the progress made and organize future actions.

The Kyoto Protocol was adopted in 1997 and has been ratified during one of the annual Conventions of Parties (COP). It is a legally binding treaty stating that the Parties involved (currently 192) have "common but differentiated responsibilities and respective capabilities" meaning, as mentioned before, that every country should contribute to reduce emission based on its previous emission history and available resources. Emission reduction targets were set, and the original commitment period had to be from 2008 to 2012. This was then renewed until 2020, with new objectives thanks to the Doha Amendment (2012). Emission permits were also used to reach the objectives, along with three market mechanisms: International Emission Trading, Clean Development Mechanism and Joint Implementation. These systems encouraged green investments in renewable technologies in developing countries with economic incentives. Transparency was also a preeminent part of the treaty: parties had to report emissions annually and adopt a registry system to track transactions. Finally, a fund to incentivize the adoption of sustainable projects was instituted and financed by using Clean Development Mechanism proceeds.

The Paris Agreement is the successor of the Kyoto Protocol and was adopted in 2015 during the COP 21. This is the first universal agreement and sets the clear objective of limiting global warming to maximum 2 Celsius degrees in total, with a more ambitious option to keep it around 1,5 degrees. The treaty is legally binding and allows countries to set Nationally Determined Contributions (NDCs), which means that they get to calibrate their objectives based on resources and circumstances, and they are to be reviewed every five years and eventually adapted to the mutating scenario. For instance, the last enhanced NDC submitted by the EU in 2020 set an emission target of 55% less than 1990 before 2030.
It is interesting to note that the US decided to withdraw from the Paris Agreement in 2017 under the Trump administration, and then return in 2021 under the Biden administration.
It is recognized by the UNFCCC itself that developing countries will take some more time to adapt, but goals have to be set and every country will try to contribute based on its possibility, without putting its economic and social stability at risk. Financial support is also expected to be given to developing economies by developed countries: by 2020, $100 billion were mobilized to countries in need, and this number is set to rise by 2025.
Similarly, to the transparency promoted in the Kyoto Protocol, this treaty forces its participants to submit accountability reports periodically.

These were the most important agreements at a global level about climate change, however, sustainability in general is a much vaster topic, this is why countries met and agreed on many other issues caused by the excessive and irresponsible exploitation of our planet. As mentioned in the previous paragraph, the consequences of climate change forced administrations to sign treaties and join conventions created to avoid these negative effects,

such as the Basel Convention against hazardous waste (1989), the convention on International Trade in Endangered Species of Wild Flora and Fauna (1973), the Convention on Biological Diversity and the Ozone Treaties of Montreal and Vienna among the others.
Since they are not strictly related to energy production, we will not enter the topic more in deep, hence we will get closer to the main topic of the thesis in the next paragraph, which will synthetically outline the most important internal policy measures related to renewable energy technologies issued by the EU and the US.

1.3 REPowerEU, Green Deal, US IRA

In order to better understand the reasons behind the Green Deal and REPowerEU plan, we must underline the reasons underlying them. Then we will see in detail both the regulatory framework (Green Deal) and the action plan (REPowerEU), in a chronological order.

The European Union has decided to promote the project with the objective to face the worldwide energy market disruptions caused by the Russian invasion of Ukraine and is intentioned to do so by diversifying its energy providers and investing heavily in renewable energy sources inside its boundaries.
In 2021, the EU was satisfying only 17,5% of its primary energy demand with power produced using renewable energy technologies, hydroelectricity included (BP Statistical Review of World Energy, 2022). In Europe the most consumed resources to produce energy are oil and natural gas. The Union also was, and still is, even if at a lower level, heavily dependent on natural gas imports, at 84% of its total supply as of 2020 (Energy Monitor, 2022); and a great part of that import used to come from Russia: around one third of the total in 2021 (Statista, 2021). The strong dependency on foreign natural gas has also been boosted by the decision of many European countries to divest from nuclear energy, whose production had to be somehow replaced starting from 2011, when the nuclear disaster in the nuclear power plant in Fukushima happened (Statista, 2023).
In 2020, also oil imports have been very high: 57% of oil came from extra EU countries, with some European states almost completely dependent on imports both for gas and oil. The overall dependency on energy imports reached 60% of the total in recent years (Statista, 2022).

Billions of Euros every year are spent on energy, and one of the concerns of the EU is that such large amounts of money are certainly an important source of financing for a war in the case of Russia, which is a country with an economic system strongly dependent on the export of fossil fuels.

The European Green Deal, presented in the end of 2019 for the first time, is a comprehensive policy framework involving the members of the Union, to reduce emissions of 55% compared to 1990 levels by 2030 and make the EU carbon neutral by 2050. The plan points out the necessity of both preserving the environment, but also jobs and competitiveness of European companies.

From the clean energy market point of view, this plan contained an objective of 40% of the overall energy production from renewables in 2030. The energy supply has to be affordable for investors and consumers, efficiency is promoted from every point of view as we will see later, and digitalization is one of the most important instruments to create a European integrated energy market.

One of the main measures taken by the EU are the expansion of the Emissions Trading System (ETS), which is a trading system which poses a limit to the emission of GHG that companies can emit, to more sectors. The Carbon Border Adjustment Mechanism (CBAM) establishes a carbon pricing system of imported goods, so they are treated just like goods produced inside the EU from the environmental restrictions point of view, in order to avoid the avoidance of said restrictions by companies who relocate production processes abroad. Renewable energy investments will also receive a boost of 32% by 2030, which is a very important consideration given the topic of this thesis. Solar photovoltaic will be crucial in this case, with plans to deploy 100GW of new production capacity by 2030.

Among the other themes contained in the EU Green Deal we can find mobility: targets for this sector are a reduction of 55% of emissions of cars by 2030, and 50% from vans, while new cars will be zero-emission starting from 2035. Road, sea and air transport will also receive limitations regarding emissions with emissions trading for land vehicles, carbon pricing and sustainable fuel for planes and ships.

The overall framework has also the objective of permanently reducing the energy consumption by eliminating waste and decarbonize the industrial sector as much as possible. For the first goal, citizen awareness will be key, and targeted information campaigns have

been used to reach the objective. While for the second issue electricity and hydrogen are set to be the main replacements for gas, and oil fueled production plants.
Innovation in the construction industry will be encouraged by increasing the energy efficiency of existing building and setting goals beneficial for the environment, such as 49% of renewables in buildings by 2030, and a minimum of 3% of renovation of public structures. Environment restoration is another objective of the Commission, which will help reducing the CO2 emissions and slow down climate change.
Cleaning the energy sector and preserving the environment also means more jobs: buildings, green mobility and natural restoration will grant European citizens more work opportunities, 160.000 in the building industry only (*Delivering the European Green Deal*, 2021).

In 2022, after many small actions taken by the EU Commission to incentivize production of clean energy and be increasingly independent from Russian fuels, the REPowerEU plan was approved, thus allowing member states to implement it into their individual recovery and resilience plans.
In the short run the states must take fast measures to cut their supplies from Russia in particular, this is done by looking for alternative and more reliable energy suppliers. Diversification is key in this case: the risk of giving too much contractual power to te counterpart must be avoided. An accessory option in the short term is also creating awareness among the population and reduce energy consumption as much as possible.
Another way to act is of course by investing more in renewable energy sources: investments in this field have been made by the EU to promote it as the best way to stabilize the situation in the long run too. This topic is the protagonist of middle term plans, to be completed before 2027. Huge amounts of resources have been made available by the EU: €300 billion were added under the modified Recovery and Resilience Fund to support investments, and another €3 billion of frontloaded projects under the Innovation Fund. The target for renewables in Europe has been also increased to 45% by 2030. To make this possible, regulations that make the development of new renewable energy projects easier and faster have also been promoted, with less restrictions on permits, especially in low environmental risk areas.
During the Ukrainian conflict, energy prices have seen a huge increase: among the plans of the REPowerEU we have the reduction of them by internal production, and solar will be crucial. The EU Solar Energy Strategy is expected to create 320 new GW of solar photovoltaic by 2025, and 600 GW by 2030 (*REPowerEU: Affordable, Secure and*

Sustainable Energy for Europe, 2022). This is particularly important in our study because it shows the utility of having the most effective means possible to work on renewable sources, read data about them and get insights. In fact, moving away from Russian dependency on gas has its own economic advantages: EU taxpayers currently spend around €100 billion on Russian fossil fuel, while additional investments of €210 billion will be necessary to finally cut current costs and stabilize the energy prices in our continent.

The US currently satisfies around 12% of its total energy demand with renewable sources (EIA, 2021), and, differently from the European Union, it is not heavily dependent on Russian fuel.

United States have also recently decided to address the issue of sustainability in a very serious way: the Inflation Reduction Act signed in 2022 by President Joe Biden has in fact the objective to fight inflation and climate change by investing in clean energy production and emission reduction. This is an ambitious plan with the ultimate goal of reducing carbon emissions of 40% by 2030, among other socially useful achievements to be made in the medical care field. $359 billion will be invested in Energy Security and Climate Change programs only, along with other $300 billion for Deficit Reduction to fight inflation.

The act laying the foundations of the IRA is actually the Bipartisan Infrastructure Law, approved in 2021, which poses the ambitious objectives of modernizing infrastructures such as electric car charging stations, improving the supply chain of batteries, making public transport more effective, thus promoting its use, investing in clean energy, and reducing pollution. Just like the European Green Deal, innovation and modernization will create new job opportunities for many citizens (The White House, 2023).

The IRA will help American citizens and companies realize the desired objectives by granting them tax benefits, loans, grants, and rebates linked to the economic plan. Taxation will also be affected in the highest earning families and companies, and tax elusion loopholes will be addressed to grant a more equal redistribution of the resources.

Now that the most notable incentive regulations have been treated, the next paragraph will provide the reader with a panoramic of the current renewable energy technologies scenario, their technical features in brief and their diffusion around the world.

1.4 RE Technologies Overview

With the major world economies like the US, Europe and China strongly committed in improving the diffusion of RE, this paragraph will be key in briefly explaining the current scenario and future developments divided by technology. Solar photovoltaic (PV), which is the focus of this thesis, will be analyzed more in depth in the next paragraph, while this one will provide a quick overview of the other RETs too.

We will now start by showing some data and future perspectives about RE in general. According to the "Renewables 2022" report from the International Energy Agency (IEA), and as stated previously, countries are moving towards sustainability not just to become more independent from one another or to preserve the planet, but also because it is becoming more convenient thanks to the increasing costs of fossil fuels and to the refinement of the production processes of green power plants components. According to a study (IEA, 2022), the share of renewable electricity generation reached 28% worldwide in 2021, and following the information from the previously mentioned report, it is expected to reach 38% of the total in 2027. The simultaneous development of enabling technologies such as energy storage, technology and infrastructure must be reached in order to allow the development of RETs. In fact, it is estimated that many developing countries could have difficulties in implementing green energy for this precise reason.

The expansion of these technologies will be faster than ever: 85% from the previous five years, which will make renewables the source of more than 90% of globally generated electricity in 2027. This rapid expansion is also boosted by favorable policies, regulations, and market reforms from the leading economies.

In the meantime, fossil fuels are still far from being replaced totally for heating purposes: high power consumption makes renewables' diffusion slow in this field, with an usage rate moving from 11% to 14% by 2027 (IEA, 2022).

Renewable energy sources are solar, wind, bioenergy, biofuels, geothermal, hydropower and ocean. They can be replenished naturally and, differently from the nonrenewable ones, can be used continuously without being depleted.

Renewable energy technologies are on the other hand the physical systems used to convert renewable energy sources into energy. Each type of RES has its own corresponding RETs.

Moving on to specific technologies, we will start with the ones related to solar energy, which are solar photovoltaic and concentrated solar power (CSP).

Solar PV systems use solar cells made from semiconductors to convert sunlight into electricity. These solar cells are arranged in modules connected with each other into a solar panel. Solar light hitting the panel is then converted into electricity, and it also works in cloudy environments. It has recently been introduced a new set of policies by many countries volved to produce hydrogen by using energy from solar PV, which will in turn boost the growth of the aforementioned technology (IEA, 2022).

At the end of 2020 the capacity installed reached 710 GW, 125 GW more than the previous year, making it the fastest expanding renewable energy source (Irena, n.d.). This capacity is set to triple over the next few years: by 1500 GW by 2027, thus exceeding both coal and gas, which are on the contrary slowing their expansion (Table 1) (IEA, 2022). One of the strengths of this technology is also the ease of installation and accessibility for private use, in fact it can be applied on rooftops and through mobile home kits. Prices are also making it even more affordable, since they fell by 93% in the period between 2010 and 2020 (Irena, n.d.). This detail is easily attributable to the large investments of many countries (China above all) in the technology, with technological improvements and a supply which is even expected to surpass the total demand in 2027, given the growth rate. $25 billion are expected to be invested by US and India in the following years just on production, while China dominates the market thanks to its huge production capacity, capable of supplying around 80-95% of total market demand and it’s expected to invest $90 billion over the next years, by 2027 (IEA, 2022). This cost reduction trend has recently stopped though because of the surge in energy prices due to the Ukrainian conflict. Producers, especially Europeans, have to afford higher electricity costs, thus being forced to charge more for their parts: compared to 2021, PV and wind technologies have seen an increase of respectively 44% and 21% in the EU. All while the prices for the same goods remained almost unaffected in Asia Pacific region (IEA, 2022).

Concentrated solar power plants are based on mirrors that concentrate sunlight to heat up fluids or gases, thus generating steam which on turn drives an electricity generating turbine. These power plants can also be equipped with molten salts, which allow heat storage which enables electricity generation even at night. This kind of technology is less diffused than PV, with a global installed capacity of 7 GW in 2020, although it is expected to hugely increase in the next years (Irena, n.d.).

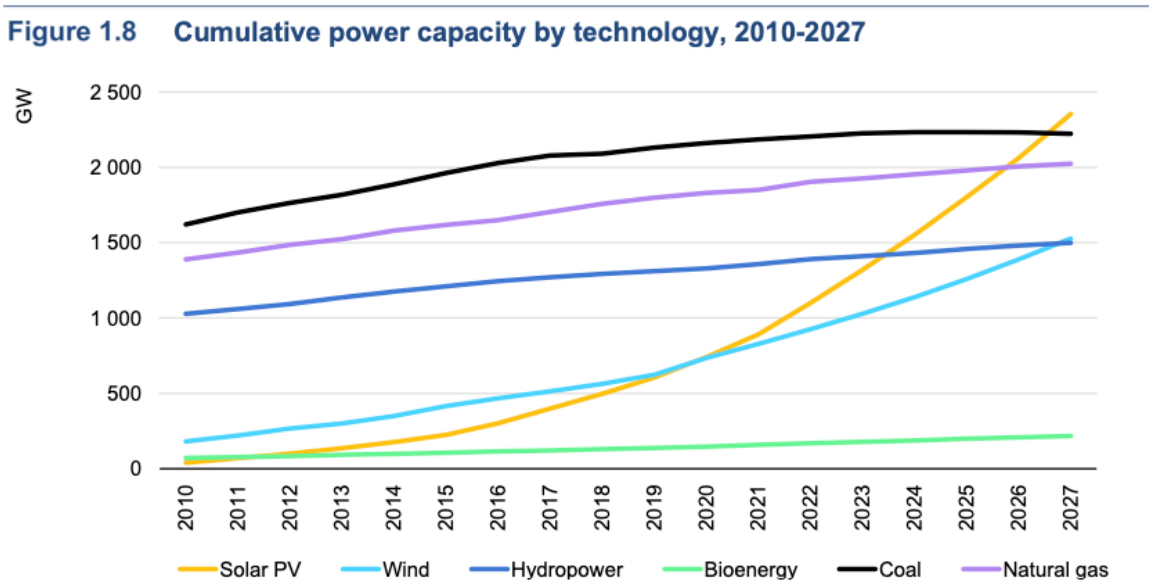

Table 1: Cumulative power capacity by technology (IEA, 2022)

Hydropower technology allow the harnessing of falling or running water to generate electricity. Moving water is capable of moving a turbine thanks to kinetic energy, the actioned turbine converts it in electricity. Run-of-the-river use kinetic energy of water flowing through a river and diverted using pipelines or channels into the power plant, while pumped storage systems store water in a high placed reservoir for the purpose of releasing it during periods of high electricity demand. One of the points of strength of hydropower is that it is not affected by weather, unlike solar energy technologies. However, droughts might be a problem in this case, and the construction of dams has sometimes negative impacts on the environment, damaging local flora and fauna equilibrium.
In 2021, hydropower contributed to the total installed renewable energy capacity by around 1,2 TW over a total of around 3,1 TW (Statista, 2023, REN21, 2022). China is the leader in the sector, being the largest producer of hydropower related energy. The technology is set to expand in the next year, but it is expected to fall behind solar PV by 2027 thanks to the huge expansion of the latter (IEA, 2022).

Wind energy converts the kinetic power of wind in electricity by using onshore and offshore turbine. This technology is very versatile, since it can be used in many locations, from small to large scale. In the last twenty years the technology has seen an increase of more than 100%, reaching around 750 GW of installed capacity in 2021 (Statista, 2023, GWEC, 2022).

Technology has improved during the years and just like other components, wind turbines' costs have fallen: onshore wind plants have seen a reduction of 56% between 2010 and 2020, while offshore costs have decreased by 48% in the same time span (Irena, n.d.).

Ocean energy uses the power of the ocean to generate electricity. There are many ways of doing this: ocean related RETs can capture energy from the movement of the waves through water columns that trap air to move a turbine, or can use converters that oscillate thanks to moving water, and alternatively employ overtopping converters which play on heights differences to generate electricity, or semipermeable membranes that separate water based on salinity and using the flow of ions between the two sides of it to gather power. These technologies are very promising since oceans cover around 70% of the Earth surface, however they are still in development stage and not available commercially because costs are too high (Irena, n. d.).

Traditional bioenergy technologies are energy production systems that imply the use of biomass (organic matter deriving from plants, animal waste) to produce energy through a variety of different methods, such as gasification, pyrolysis, combustion, and anaerobic digestion.

Biofuel technologies on the other hand employ biomasses in order to produce biofuel, which is in turn used to fill compatible transportation vehicles. Biofuels are produced in a different way from traditional bioenergy. Since the final product is different, in fact, these processes require enzymes and microorganisms that break down biomass into biofuel. Biofuels have the advantage over fossil fuels in terms of carbon emissions, which are very low in the first case. However, we must consider that intensive production of biomass to be converted in biofuels can have negative effects of our environment caused by potential deforestation, land use change, excessive exploitation and a difficult tradeoff between crops and biomass to be cultivated.

Other forms of biomass technologies are still in development stage, but they share the same set of advantages and disadvantages with the other two mentioned above, plus the issue of costs which are still too high in many cases.

The sector leader in this case is China, with special programs dedicated to the recovery and use of waste for bioenergy, and it is expected to contribute to the overall worldwide growth by 60% by 2027 (IEA, 2022).

Bioenergy currently covers around 10% of the total primary energy supply worldwide, and it is expected to remain constant over the next years; we must consider though that the total primary energy supply will grow, so a stable rate of supply over the total still means growth for this technology (Statista, 2022, Bohlsen, 2020).

Geothermal energy is generated by the heath located beneath the Earth surface. Many different types of technologies are employed to harness this type of energy, at variable stages of development. The main advantages are that the energy input is constant, emissions are low, does not use much land and it is cost efficient. However, not every country has the same opportunities in this case, since in order to generate electricity, underground reservoirs must be discovered and accessed, the steam or hot water (depending on the case) needs to be brought in surface where it will drive turbines. Areas with volcanic activity, geysers and hot springs are advantaged in this case. Moreover, initial costs are high since plants are expensive and so is drilling. Another potential issue with this technology is that sometimes water is needed to cool power plants, and the removal of fluids from beneath the surface can cause stability issues in the affected area.
The leading countries in this sector worldwide are US, Philippines, and Indonesia by total installed capacity (Statista, 2023, Irena, 2022), however some other territories are capable of satisfying around 90% of their heating demand with this type of source, such as the case of Iceland (Irena, n.d.).
Because of the lack of adequate policies and high resource exploration risks, this RET is expected to only increase by 6 GW of total installed capacity by 2027 (IEA, 2022).

The next paragraph will now explore more in deep the case of PV technologies, their history in brief, the types, some aspects of the supply chain, the major players in the industry and the key challenges for their further development and technology transfer.

1.5Focus on Photovoltaic Technologies

As seen in the previous chapter, solar PV is set to be the most important technology worldwide in the energy transition and it will be the growth leader in sustainable energy along with wind energy in the next years (IEA, 2022). Its expansion will be driven particularly thanks to the REPowerEU and the Inflation Reduction Act, along with the 14th Five Year

Plan from China. But how has this type of renewable evolved across the years, before receiving such great attention, and why is it so important?

The first time the photovoltaic effect was observed was 1839, when the French physicist Alexandre Becquerel was conducting an experiment on silver and platinum electrodes exposed to light. It was only many years later however, that the first solar cell was developed. In 1877 in fact, a professor called Adams and his student Richard Day created the first device of this kind using selenium, for an overall efficiency of just 0,5%. One year later Charles Fritts managed to double the efficiency by disposing selenium in a wafer between two layers of metal. The real breakthrough though happened in 1939, when Russel Ohl replaced selenium with silicon. This innovation opened the path for many others, among which we can find the silicon solar cell, developed in collaboration with Bell Labs. These cells were capable of generating current in an amount that was directly proportionate to the wavelength of the radiation and their intensity. The first commercial use they found however was not as electricity generators, but as sensors. When the efficiency actually increased thanks to the use of lithium to 6%, solar cells found application as energy collectors in the US on a telecommunication center. In 1958, NASA launched a program where they were used as a power source, and a few months later, Sputnik-3 was equipped a photovoltaic panel and launched by the Russian space agency. The space conquest run was a great booster for this technology, which was still unfortunately too expensive to increase its reach to consumers.
In the 70s, a Comsat employee successfully increased efficiency of panels by 50% and left the company to found one of his own called Solarex. Despite the patent of the invention being of property of Comsat, Solarex became a huge player, with 50% of market share by 1980 thanks to the great capabilities of its engineers. The oil crisis furtherly increased the interest for photovoltaic technology, giving it more attention from the scientific community. Polycrhistalline silicon and amorphous silicon replaced the monocrystalline silicon because of cheaper production costs. Continuous incremental innovation brought the widespread diffusion of silicon-based cells with a wafer-based structure (also called 1st generation cells, while the other two generations are much less used) accounting for around 95% of the total installed capacity, with energy efficiency peaking around 26% (Lameirinhas et al., 2022).

Focused policies are now supporting the investments in renewables in general and in PV in particular. As mentioned before, the major economies have all organized plans to expand green energy. China published its 14th 5 Year plan in 2022, with a specific target of an 18% increase in investments for solar PV and wind energy only. In the same year, the US approved the IRA, encouraging investments in renewables through tax credits, faster procedures, and other means. In 2021 the EU also approved the REPowerEU plan, boosting solar PV installations by 600 GW. Solar PV is also the main focus of India, that during COP26 has announced support for renewable energy technologies in the next years, with plans to be net zero emissions in 2070 and installing renewable energy capacity for 500 GW by 2030 (IEA, 2023).

The issue of technology transfer on the other hand still has not be treated in this chapter, That's because it needs a brief introduction that the reader will find in the next one, along with the specific situation of solar PV regarding the matter, the dispositions of authorities to encourage it in the specific case of RETs, and an interesting debate among scholars about the positive and negative effects of IP on RE technology diffusion.

2. *IP Rights and Renewable Energy Technology: Literature review*

2.1. IP Rights Overview and Legal Framework

Intellectual property (IP) is a form of protection of newly generated knowledge volved at encouraging innovation by the means of exclusion. Innovators are pushed by institutions towards continuous development of new ideas that could potentially improve our lifestyle and bring benefits for the organization or individual that generates them. Assumed that innovation is good for the society, the exclusion of the use of the invention derived from it must be balanced to avoid the opposite effects.

Intangible assets are the object of IP protection, covering aesthetic creations, inventions, domain names, plant varieties and commercial trade names (Granieri, 2022).

Exclusion of subjects other than the owner of the IP right is not an advantage per se, in fact the process of generating value through IP is risky since the very beginning, with huge costs in many cases for R&D registration procedures and renewal fees, risks of legal battles with

competitors, infringement and the absence of anything that grants the success of the creation itself on the market.
This kind of property enables the owner to exploit it in two different ways, which can in many cases be complementary: direct use and indirect use.
Direct use implies the utilization of the creation in connection with an industrial or commercial activity based on the sale of goods or the provision of services based on the underlying IP rights (Granieri, 2022).
The second use is based on licensing of the IP to third parties in exchange for money or other resources, thus enabling the aforementioned third parties to produce, sell and distribute goods (Granieri, 2022).
Diverse forms of protection have been instituted to preserve knowledge creation: the most important ones are patents, trademarks, copyrights and in a particular way trade secrets. Since this work aims at refining prediction methods related to the industry development on photovoltaic technologies and patents, we will dive more in deeply on patents themselves, giving the reader just a quick overview on the other means of protection, which are, in many cases, still very important and affect the industry.
The basic idea that explains patent protection is that there is an exchange between the inventor disclosing his invention and the legal system awarding him a time limited exclusivity (Granieri, 2022, Dam, 1994: 264).

Patents are form of protection awarded at a national level, however, the coordination among countries is strong in this matter and many international treaties ensure inventors the safeguard of their work.
The Paris Convention for Protection of Industrial Property is the first example of an international attempt to coordinate the discipline. Signed in 1883, this treaty not only regulated patents, but also trademarks, industrial design, and other types of intellectual property. The rationale of the agreement was providing applicants the same IP protection in each participating country, thus harmonizing the framework.
The Patent Cooperation Treaty (PCT) is another relevant agreement signed in 1970. This time the objective was not the level of protection, but the procedure. The PCT allowed inventors to file and prosecute patents in multiple countries through in international patent application recognized by everyone. The benefits for the inventors were this time linked to a reduction both in application costs and complexity of the procedure.

An important institution treating patents is the European Patent Office (EPO). Despite the name, it is not considered a European organization, it was in fact created in 1973 with the Munich Convention, and some of the signees are states not-belonging to the European Union (Granieri, 2022). This said, the Office issued the European Patent Convention (EPC), a framework which harmonizes procedures and administrative activities like filing, examination, and prosecution. Patents filed under the EPC will benefit from recognition at an international level from EPO states.
The next important convention in temporal order is the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS), signed in 1994. The treaty was part of a set of agreements by the World Trade Organization (WTO). Again, diverse kinds of IP protection were covered in the convention, including patents. Patents in particular have now to be granted by parties, given that the underlying invention is useful, non-obvious and new.
Another relevant treaty is the Patent Law Treaty (PLT), which came into force in 2005. After many years of negotiations about patent regulation and protection worldwide, the World Intellectual Property Organization (WIPO) adopted it. The intent was to standardize and streamline patent procedures, but also clearly stating substantive patent law rules. Minimum requirements were provided regarding applications, and as of March 2023, 40 countries are members of the PLT, including US and many EU states.
Moreover, the exclusivity right had to be granted to the inventors by signatory countries.
Other treaties do actually exist on IP and patents but are mostly referred to specific industries or do not provide such game changing effects on the discipline like the aforementioned ones, at least not regarding this thesis' subject. One example is the Budapest Treaty, which regulates patent protection in industries related to microorganisms.
To conclude the discourse on harmonization, we must specify that despite the international agreements, there is not a globally unified patent system, especially for enforcement strategies. This is a major source of uncertainty and risk since patents are still granted at a national level and patent cases are still decided by judges before national courts (Granieri, 2022, EC Commission, 2007).

Let's now focus on patents, considering laws deriving from EPC and the other international treaties mentioned before.

Exclusivity means that third parties, if not authorized, must not make, use, sell the protected good or service. Sometimes the utilization of the knowledge contained is a patent requires the access given by the inventor of another patent, upon which the first one is based.
The subject matter of the patent is the invention; however, international European regulation does not define this word, but clarifies the technical and concrete character as a requisite, whatever the technology field is. In order to qualify for protection, the patentable object must have three attributes: novelty, inventive step, and industrial application, as established by the EPC.
Formally, patent documents look similar to technical scientific papers, with some characteristics that distinguish them. They have a title, a number, a filing date, and an application date, an abstract, a technical description and even drawings of the invention in many cases.
Patent protected goods are characterized by the exhaustion principle, implying that once they are sold for the first time, the buyer is free to put them on the market again without incurring in further expenses.
Moreover, it may happen that in order to preserve the social good, compulsory licensing is enforced, even though it is limited to some critical sectors such as pharma and well defined in the TRIPS agreements at an international level.
Patent procedure starts with the examination of the patent document by the national authority, who verifies the requisites. Once the application is filed, it receives the priority date, that determines the ‘winner’ of the patent race, discriminates the prior art for novelty assessment and makes the twenty-year duration count start, along with the one determining the possibility of filing the same patent in other countries under the PCT which lasts twelve months. The owner can now enjoy the first form of protection, to be extended when the patent is granted. After 18 months from filing, the patent becomes prior art, moreover, once it is granted, the owner will have to pay renewal fees.

Trade secrets are another important form of knowledge subject to protection, even if in a different way from patents.
Anything can be considered a secret, and it is estimated that trade secrets comprise two thirds of value of firms’ information portfolio (Granieri, 2022, Forrester Consulting, 2010).
Given the nature of the secret itself, it is not possible to obtain protection by filing, however, TRIPS agreements discourage dishonest commercial practices through sanctions. We must

note here that this form of protection only comes in play once the damage has been made, thus making protection of secrets very expensive for the organizations who must take security measures to avoid the spread of classified information.
The advantage of unlimited duration of a secret is counterbalanced by other disadvantages: the information could be lost, the situation must be monitored by the organization, some secrets are discoverable by reverse engineering and the transfer of a secret is complex because of the nature of the knowledge itself.
Even if trade secrets will not be the subject of this work, their presence in the RE industry, among the others, is still very important.

In brief, copyright protection is a form of safeguarding for the expression of ideas in an original way. Contrarily to patents, copyright cannot be extended to independent development of protected work. Generally, registration is not even needed to obtain protection.
Another difference with patents is the duration: copyright last up to fifty years after the author's death in Europe, and one hundred and twenty in the US (Granieri, 2022).

Trademarks, on the other hand, provide protection for signs distinctive of goods and services. They can be renewed unlimited times, once every ten years. Their protection is related to classes of goods: the same sign can coexist for two different classes as long as confusion is avoided.

The next paragraph will get more specific in the thesis' main topic: RE industry and IP will be linked one another, and some interesting insights will spill out from the analysis of the existing literature.

2.2 The Debate on IP Rights as Growth Drivers in RE Technologies

Intellectual property rights have been at the center of a debate regarding their role in the diffusion of renewable energy technologies. The debate focuses on whether they are beneficial in order to boost the innovation on diffusion of knowledge in the sector, or if they actually slow down the run for sustainability energy transition.

Different perspectives will be examined in this paragraph, and as we will notice, we will find both scholars in favor and against strong IP rights in the renewables sector. Some papers analyzing our matter of interest, which is the photovoltaic industry, will be also taken into consideration.

Along with the debate about the effect of IP on RETs, we will notice from many examined papers that their approach uses patent data to measure the development of a certain type of technology, which is the same approach proposed in this thesis, serving as a proof that a similar research lays on solid bases. However, more focused studies on the precise relation among the variables we will use will be explored in the next chapter, to support the hypotheses and generate the research question.

The key arguments in favor of strong IP protection in the industry is that is incentivizes innovation by rewarding inventors with commercial benefits to put their new project on the market and recoup R&D expenditures, which are in most cases very high. Moreover, the temporary market limitation for competitors could ensure the innovator a good slice of profits, provided the idea is well developed and managed. Investments in renewables become in this way more attractive to potential investors, thus contributing to the diffusion of a way of producing energy which is not dangerous for the planet.

On the other hand, the fact that patents prevent others from using the same technology may be seen as a barrier for the development of innovative products based on the patented ones. Another critic is related to the concentration of patents in the hands of a small number of companies who detain a very high market share and apply higher prices. The cost of obtaining patents is also often very high, and maintaining a large patent pool across the years is in some cases prohibitive, especially for small companies. Developing countries are also monitored in the literature, along with the impact that IP protection has on them in terms of innovation, which is, for many researchers, negative. According to them, IP is seen as a cost barrier for some countries who cannot afford to neither invest in R&D nor in-license existing inventions, thus paralyzing the RE sector.

Let’s now dive deeper into the existing literature, starting with the one that sustains that strong IP rights are beneficial.

Strong IP protection, as mentioned before, has the advantage of encouraging innovation. In fact, research found that stronger IP protection was positively correlated with markets with higher innovation levels, and the contrary was also true.

From the point of view of investments, Hall et al. (2010) discovered that strong IP is associated with higher spending in RE technology, particularly those related to the wind energy sector, which was the object of the study.

A similar study conducted on energy storage technology also confirmed that the stronger the IP protection is, the higher the innovation. This happened because companies felt like they were rewarded by the legal system for their investments, and this same system encouraged them in investing even more.

Moreover, regarding the PV industry, companies which obtained strong protection were more likely to invest more and even patent more inventions, thus boosting innovation, in the same line with the previously mentioned paper. Another interesting conclusion is that the more companies practice R&D and patent creations, the more their R&D department becomes efficient and the more their inventions are high quality.

Higher number of patents, as demonstrated in 2000 by Crosby, is positively linked both with innovation, as a consequence, and with strength of protection from the legal system, as a cause. This same study also covered the matter of investments, and as expected by the researcher, it was proved that the more IPRs protect inventions, the more people feel safe to invest in, and the more funds they manage to attract.

Another aspect in favor of strong IP protection is that it boosts diffusion by licensing and technology agreements, as Ockwell et al. (2010) observed. They also state that this diffusion could be useful for developing countries, where investors can often not afford direct investments on R&D ad need to access RE technology fast, at a more affordable cost and with less uncertainty of the result of the expenses. The same authors however recognize the limitations of the current IP system but consider the negative aspects as a “passing symptom”.

Because of the nature of patent protection itself, cumulative innovation is major issue, especially in the RE industry, according to many researchers who argue that strong IP protection hinders innovation. Excessively strong IP protection is damaging the RE industry since new potential patentable inventions cannot lay their bases on patented ones unless licenses are acquired before putting them on the market.

Existing patents are also seen by some scholars as an implicit barrier to research because they discourage further improvements of existing patented creations, thus slowing development. In their study, Bessen & Meurer (2009) argue in fact that some players in the market avoid working on patented content since they fear to incur in infringements. Patent Thickets is the name of the phenomenon that most of all petrifies every push towards developments in some sectors, according to the same source. This means that large amounts of patents regarding the same invention, all retained by the same actor in the same area are the culprits to causing the preventive drop of every research on the field.

Knowledge sharing and interorganizational collaboration is also hindered by the very existence of a patent system.

Prices are another critical point, according to Lerner & Tirole (2003) since the owners of dominant patents tend to apply high prices on their inventions and/or on the corresponding licenses. In this way, the final price for the consumer is inevitably too high.

Moving to the small firms' point of view, we can find another interesting study stating that patent protection is a deterrent to innovate for companies of reduced dimension, given the sometimes-prohibitive costs required to both obtain and enforce them.

Market concentration is taken into consideration too. Murray & stern (2007) say in their paper that IP tend sometimes to halt innovation both form the outside of the company, and from the inside of the company itself. This means that one a player secures a patent, it might find convenient to exploit it on the market as much as it can, without focalizing on innovating more and making the patented invention any better.

A similar result is reached by David & Greenstein (1990), arguing that IP rights slow down the pace of innovation in the RE industry by favoring a technological lock in. This happens, according to the researchers, because once a company has found a new technology and has successfully patented it, it may find economically convenient to exploit it on the market, without furtherly expanding the IP portfolio with more inventions and/or improvements.

Beise & Rennings (2005) see IP rights as a real impediment for the fight against climate change: they argue that by restricting the free circulation of knowledge they slow down the spread of RE technologies, with higher emissions over time as a direct consequence.

Mistrust in developing countries' authorities and the enforcement of IP rights is also the cause of the inexistent development of the corresponding technologies in some states. In fact, some patent owners might avoid licensing their IP to those countries with poor control over intellectual property infringements because of the risk of the infringement itself going unpunished or even undetected.

Some other papers instead analyzed the link between IP rights and RETs without focusing particularly on negative or positive effects of the first one on the development of the latter. Instead, they had with the intent of giving the reader an overview of both aspects along with some ideas for the policy makers volved to strike a balance in terms of intensity of the IP protection.

For example, the study from Raiser et al. (2017) investigates this relation with a corporate oriented approach. They conclude that on one hand IP incentivizes companies to invest in RE thanks to legal protection and commercial benefits. On the other hand, barriers to entry were effectively posed against potential new entrants, thus slowing down innovation itself. Hence the authors state that there is a disproportionate number of benefits in favor of large corporations and institutions at the disadvantage of developing countries. They also propose some solutions to the IP regime, with the objective of redirecting investments to developing countries and redistribute the technology diffusion equally across the globe. This would, according to the researchers, favor the battle against climate change too. Open innovation is also taken into consideration as a possible solution to the excessive concentration of IP. A collaborative approach that involves universities, governments, no profit organizations, could help dissemination of knowledge and overcome the barriers posed by IP.

The same system of incentives for innovating firms against creation of entry barriers has also been observed by Tee et al. (2021). The authors this time also add to the debate the fact that countries with stronger levels of IP actually manage to produce more energy from renewable sources thanks to the encouragement to companies to invest more. While a strong set of IP protection laws might be beneficial, an excessively restrictive legal framework is responsible for causing issues with the competition, thus stifling innovation, instead of preserving it. These authors, like the ones of the pervious paper, also conclude that a balanced approach between protection and freedom to innovate is necessary, without pointing to any extreme measure.

Various studies also observed a correlation between IP protection and the quality of the underlying patents. The conclusion is that, since IP protection looks convenient in some countries, companies are encouraged to patent all kinds of inventions, even the less relevant ones, instead on focusing on patenting groundbreaking findings and leaving the rest to public domain. This behavior has the consequence to largely increase the number of patents along with the risk of infringements. They also agree to the fact that a balanced approach to IP intensity is needed to boost innovation.

Diverse studies about IP and PV technologies demonstrate that this specific RET has characteristics in line with the rest of the industry when it comes to IP influence. The next papers will serve as proof of this statement, thus implying that such characteristics, which are related to patent data in some studies could be used as a basis to start from when trying to generalize the application of the correlations at the center of this thesis.

The link between IP protection and higher profits for inventors is in fact observed in the PV sector too. These higher profits serve, again, as an additional incentive to innovate even more and expand the diffusion of the technology itself.

By consulting the literature, it can be noticed that PV technologies which are protected by IP can serve as collateral for loans to be reinvested in the practical realization of the projects themselves.

Licensing to developing countries is a real thing in PV too. Some countries in fact lack adequate resources to afford R&D, whose results are uncertain. Licensing is sometimes the best choice since the result is safer, it just needs funds and the correct management of the physical development of the power plant and the related organization.

The patent thicket phenomenon is not unknown to the PV industry too: stagnation in the requests of IP protection applications for RE technologies, including PV, related to certain aggregates of patents has been observed in this case too.

The industry, as seen before, is not a stranger to the negative effects of IP too. Arora (1995) argues that some companies in the PV sector tend to produce IP for the sake of patenting and protecting it instead of developing new technologies and collaborating with other organizations to improve them. Patent data has been used in this research to show this phenomenon, and open innovation has been proposed as a means to overcome the issue. The same conclusion is also expanded, and it was concluded that since IP protection becomes the top priority for some companies, they are less likely to improve it and collaborate. This behavior slows down the rate of diffusion of green energy, including PV.

With regards to foreign direct investments (FDI), we also have at our disposal a recent study from Dussaux et al. (2022), stating that while in the observed OECD and non-OECD countries stronger IP rights seem to boost the technology transfer, the results are not the same in the case of the impact of IP on trade in low carbon capital goods.

Lastly, but not less important, we have a very interesting book analyzing the current situation of IP and its interaction with RETs development across the globe by Zhuang (2017). The author proposes extensive research of the literature and the legal framework, along with many suggestions for policymakers which can still be useful despite the study not being among the most recent ones. The distinction between developing and developed countries is not to be considered relevant anymore in the field, according to the author, because while the majority of countries leading the low carbon race are high income, some others (China, Brazil, India) are not. The researcher also observes that IPRs are somehow inhibiting the information flow because of the choice of some companies not to license to some countries or doing it under abusive conditions. An original solution is proposed by the writer: extending some clauses of the Doha agreement (2001), originally created to allow pharmaceutical goods to be spread across the globe with less restrictions, to RETs. This would have to be done through a separate convention covering the RETs subject matter. Compulsory licensing is, according to the book, one of many solutions proposed to fight climate change. Hard critics are also pointed to organizations who exploit IP to gain a monopolistic position on the market and ask for licensing prices which are considered anti-competitive. Fair, reasonable, and non-discriminating (FRAND) licensing models are hence put onto the table as a possible solution to the issue. To conclude, as also mentioned by the author and as a general remark, IPRs are not the only variable into play when it comes to RETs diffusion. This limitation will be of crucial importance when talking about patent data as proxies to measure the advance of certain technologies.

The next chapter will finally reach the core of the thesis, and it will do that by proving the relations between some variables found in patent data and the development of the underlying technology: PV in our case. This last paragraph has shown the reader the crucial impact of the existence of IP on the diffusion of inventions in general, and more precisely in the RE sector, along with the corresponding implications from an environmental point of view.
This said, a more technical part of the literature will lay the bases for the generation of the research question.

3. *Conceptual Framework*

3.1. Research Question

This short paragraph will serve as the source of explanation and clarification of the precise research questions of this paper. It will also present in words the content of the next chapter, in which data will be shown along with calculations and analyses.

As we know, patent procedure generally precedes the realization of the technology itself, in order to protect it. It must also be said that as we will see in the next literature, installed capacity depends on many other factors than patent counts, and inside the IP world itself phenomena like trade secrets play a crucial role, with the huge drawback for analysts of not being exactly quantifiable.

The first question that will be analyzed is, knowing that similar studies have already been conducted, a more updated and focused version of them. In fact, it just covers the PV industry, not renewable in general. We will hence investigate and explain changes in installed capacity of PV power plants around the world in a timespan of twenty years as a function of patent counts.

H1. Cumulated global patent count in the PV industry is correlated with global cumulated PV capacity installed.

H2. Cumulated Italian patent count in the PV industry is correlated with Italian cumulated PV capacity installed.

H3. A lag effect affects the previous relationships.

Once the calculations are performed in the next chapters, this study will use patent landscape statistics to gain insights from the results, underline the limitations, and suggest possible ways of investigating the industry to future research. Not just the existence of a correlation between variables will be analyzed, but the entity and capability of the resulting model at making predictions for the future will be assessed too.

3.2. Previous Studies and Hypotheses

According to the previously conducted studies that we will explore in the next lines, it has been proved that patent count is one of the most effective proxies to measure innovation in a specific sector. Hence, in order to support the hypotheses mentioned briefly in the introduction, scientific literature will be analyzed and presented as a proof of validity of this study. This specific research, as already mentioned, will focus on the PV sector both on a worldwide scale, and from the point of view of Italy.

Now, it has to be said that the choice of patent count and installed capacity for our study has a precise meaning. As we will see, literature about patent data and its relationship with tech development is very vast, and patent data are generally taken into consideration as dependent variables in many studies. This is because they are in fact influenced by many factors, mostly related to macroeconomic policy measures adopted to promote certain projects. The result of policy decisions, the sentiment of the investors, safety regulations and the intrinsic characteristics of each economic system or country have an effect on the patent landscape, which, in turn, influences the development of technologies.
The last step in this complex system of cause-effect relations, from the point of view of IP and RETs, is the measurement of the effective installed capacity or, alternatively, energy consumption or production. Installed capacity has therefore been chosen by the author over energy consumption, since it better reflects the potential of energy production in the future, and it is less affected by events like for instance, a pandemic in the case of consumption, and climate conditions in the case of production.

This thesis will explore a theme that has been only partially covered currently for the following reasons: the last part of the cause effect chain has not been completely explored, and a specific study focused on PV utilizing the same two variables is not present; there are actually similar studies extended to the whole RE sector, or different sub sectors of the RE industry, or even focused of some specific regions/countries; a comparison between Italy and the world data regarding this relation is missing too; patent count as innovation proxy instead is not a new topic at all, as we will see, and a solid base was needed to obtain robust results.

A simplified version of a patent landscape analysis will be also presented in the next chapter in order to discuss findings under the light of market data regarding patents and PV power plants diffusion.

Let’s now discuss the choice of patent counts as an independent variable.
The first study taken into consideration took place in Germany: “The Impact of Feed-in Tariffs on Innovation: Empirical Evidence from Germany”. In this research patent count has been used to measure innovation as a dependent variable, linked to the effect of feed in tariffs as an independent variable. Despite recognizing some limitations to this metric to measure innovation, such as the lack of capability to capture all forms of innovation, being affected by the patenting strategies of companies and not considering the value of each single invention, the authors appreciated the fact that the metric is not affected by perception biases, and it is quantifiable. Moreover, regarding the patent value issue, it must be said that the quantification of the metric itself is a debated topic, since patent valuation methods may differ, so the output value is not always the same.
This same paper also cited other interesting studies about the validity of patent count as an innovation measure, and the relation between patent counts and innovation itself.

The paper “Citations, family size, opposition and the value of patent rights” by Harnoff et al. in fact underlines the role of patents in innovation. The discussion in this case is similar to the one in the previous chapter: the authors consider patents as boosters for R&D and hence a good element to encourage new inventions. Thus, proving their role in contributing to new creations generation.
Another scientific publication, called “Patent quality and research productivity: Measuring innovation with multiple indicators” by Lanjow and Schankerman (2004) is also important to remark the solidity of this study. The authors recognize that, despite the aforementioned limitations, patent count as measure for innovation is an effective metric, since they capture the range of innovations, and are easy to use in empirical studies because they are accessible data and are not complex to use.

Moving to a more sector specific research, we can consult the paper “Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts” by Popp et al. (2008) to see how the authors applied patent count measurement of innovation to the RE

sector. The researchers explicitly state that *"Despite their shortcomings, patent counts are still the best available source of data on innovation which is readily available and comparable across countries".* In this case, they use patent count as a proxy for innovation in the RE industry, which in their study is a dependent variable influenced by environmental policy measures.
The choice of the independent variable in this last case lays its bases on a study by Griliches (1990), who observed how patent count is positively correlated with R&D spending, thus making it a perfect proxy for innovative activity, independently from the industry.

Since this study will start from the worldwide data, evidence of previous use of global patent information to measure innovation should be presented to the reader. This is the case of a paper analyzing this phenomenon through the worldwide count of priority patent filings. Thanks to this approach, all patent filings are taken into consideration, thus eliminating the geographic bias. The authors also use family count instead of the straight count, this allows them to measure innovation without the jurisdiction bias, since some countries' applicants tend to file many more patents because of the different regulations (De Rassenfosse et al., 2013). This analysis, despite being based on patent application counts, and not cumulated patent counts, still manages to give an overview of the patent filing situation worldwide and the differences between each country in terms of innovation. Scholars and policy analysts could find the aforementioned document useful when it comes to observation of patenting trends and patent office attractivity, and the same subjects will likely be able to get insights from this same analysis, given the similarity between the two.

"Effects of policies on patenting in wind-power technologies" (Schleich et al., 2017) is one of the most important documents used to demonstrate the validity of this research. The authors in fact use patent counts as indicators for innovation in the wind power industry, in a panel of twelve OECD countries. Their analysis used an econometric model to estimate the impact of policy and other factors on patenting activity. The results of the study show that patenting activity was positively correlated with R&D expenses and the installed capacity in the analyzed countries. In particular, policies related to the achievement of certain total capacity thresholds tend to encourage patenting activity, which in turn contributes to the effective development of the wind energy power plants. The importance of this study also goes beyond the policy point of view: it shows that energy prices have a lagging but positive

influence on the patenting activity, as well as the general patenting activity in the RE sector does.
“Exploring the determinants of renewable energy innovation considering the institutional factors: A negative binomial analysis” (Li & Shao, 2021) considers installed capacity as a metric to measure the market potential and takes patent count as a measure of innovation. The authors, among other conclusions, find that installed capacity positively contributes to the increase of innovation in the renewable energy industry. Moreover, they also discover that a high proportion of renewable energy generated over the total energy mix negatively influences innovation. This conclusion is supported by another study (Cheon & Urpelainen, 2012), and justified by the fact that countries with less installed capacity, and hence less RE power generation, have more room for innovation in the sector.
Another very important discovery for this study consists in the findings by Zheng et al. (2021), who analyzed a panel of data from different Chinese provinces from 2005 to 2017 and proved that renewable power generation is positively correlated with innovation. The researchers used patent count to measure innovation level and have conducted a study about how this metric has an impact on RPG on a certain territory and the provinces surrounding it. This paper is crucial for my study since it’s the one that poses a direct link between patent count and renewable power generated, with the latter being the object of the discussion in the following lines.

Since this study is focused on a world basis, and only on a second level on the local aspect, the renewable power generated is not chosen as a variable object of the analysis, because it very much varies depending on the type of climate of a certain country or on the technology involved in its production, along with its novelty and decay level. However, the logic link between capacity installed and power generated is used to assume the object of this research. The relation between the two metrics is also empirically proven by the data provided by IRENA (2022) in its yearly reports on RE: it is shown in fact that RPG increases along with installed capacity, even if it is not one hundred percent dependent on it, as mentioned earlier. The total installed capacity is chosen as the dependent variable and it is used to represent the development level reached by the PV technology, as the aforementioned papers show and as already experimented by many researchers.

4. Research Methodology and Model Creation

4.1. Data Collection and Elaboration

This chapter will finally deal with the metrics of the research.
The sources of the data gathered will be explained in this paragraph, while in the next one a simplified version of a patent landscape analysis will be used to gain insight from the current situation in the PV industry and form a dialogue with the results of the research question in the sections related to implications and conclusions.

The data regarding the patents have been retrieved thanks to the International Renewable Energy Agency's (IRENA) portal, in a section dedicated to International Standards and Patents in Renewable Energy (INSPIRE).
The database contains data starting from 2000, when the number of patents in the renewable energy industry started becoming more relevant and reaches until 2021. It is important to notice that the database does only reach 2021 as data availability because of the time lag between the filing date and the publication in the regular process of patent procedures. Data regarding the last two years would be incomplete, thus altering the results of the study.
Data retrieved on IRENA's portal is based on the IP software EPO PATSTAT 2022 Spring edition and on the Climate Change Mitigation Technologies (Y02) classification.
PATSTAT, on its hand, gathers data from more than forty patent authorities around the globe, for a total of more than one hundred million patent documents.
The new Y02 classification is not just an instrument of this research but also a proof of the growing importance of renewable energy related technologies in the patenting world. This classification has been appositely developed by the European Patent Office to classify and make renewable energy patent data easily retrievable. Since the code has been introduced recently, we cannot expect to find every existing patent in the RE world automatically included under its reach, but we can find the most recent ones by using it.
The information retrieved on the IRENA portal have then been transferred on Excel by the author and furtherly elaborated, in order to extract information relevant to the PV industry, analyze the country of origin of the IP, create infographics and arrange the information in a way that is more suitable to the objective of this research paper.

The understanding of this dataset is crucial for the development of this study. Data is split into categories, divided by country of registration of the patent, year of filing, the sector where the invention should be used and sub technology type. Each column of the table has one of these labels as headers, and each unique combination has its own number, corresponding to the number of patents for the aforementioned invention, in that precise year, in a precise country, to be applied in a certain sector using the same sub technology.

Moving on to the sub technology: some information must be furtherly explained. The dataset contains patents from pure PV inventions, PV-Thermal Hybrid inventions and Solar Thermal. The difference between the three categories is a discriminant for their exclusion or inclusion into the analysis. Pure PV technologies are based on the use of the photovoltaic effect, consisting in a photon coming from the sunlight impacting a surface made by a semiconductor, thus generating the release of electrons. Semiconductors are fundamental materials for the construction of photovoltaic panels, some examples are monocrystalline, polycrystalline, and amorphous silicon and cadmium telluride. The resulting solar cell is integrated in a larger solar panel, which reaches the desired levels of voltage and can be connected to the grid through an inverter, as it is done in the majority of cases.

In the case of pure solar thermal, the working principle is different, but the production of consumable energy is still the objective. In solar thermal systems water or other dedicated fluids are used to gather heat from the sunlight. Semiconductors are not needed, and the heated fluid is used to run a steam engine, turbine, or similar device in order to produce electricity or heat up water (mostly used in domestic devices).

PV thermal-Hybrid collectors, on the other hand, employ both types of technology, thus cogenerating both thermal and electric energy. Since they employ two different methods to heat a single component, the efficiency of utilization of the solar spectrum is higher than the one of regular PV panels. Since the PV technology is used in this case, it has been decided to include these systems into the research, while pure solar thermal technology has been excluded, given its technical differences with PV.

Moving on the next source of data: Statista has been chosen as information provider for the installed capacity metrics across the last twenty years.

A research report published by Solar Power Europe outlines the cumulative solar PV installed capacity worldwide from 2000 to 2021. This is the precise metric that we will need later to perform the regression analysis with the number of patents filed. The same report will also be used to get data and insights about the sector and some information about the current situation in Italy and in the rest of the world, which will be interesting to compare once the analysis regarding patent data will be complete.

Renewable Energy Capacity Statistics 2023 is another key component of the data collection process. We are talking about a very recent (March 2023) comprehensive report from an authoritative source in the matter, which includes up to date information about the industry and it is focused on the installed capacity of each renewable technology in the last ten years. While the timespan is not sufficient to perform a twenty year-long regression analysis, we already have the data source for it, so this dataset will be used to get more information about the current installed capacity and help with the reasoning, along with granting us other valuable metrics, useful to assess the current state of things.

Furthermore, focused data about patents have also been retrieved through the software Orbis Intellectual Property. This software contains data about patenting activity from more than 2.4 million organizations around the globe and allows the visualization of the current patent owners. Patent documents can also be individually searched for and analyzed with the help of international patent classification indexes and other filters. Both filters by keyword and filters by Intellectual Property Classification Code have been used in this case. In particular, the words “PV” and “Photovoltaic” with the operator “OR” have been useful in retrieving data regarding patents which contained the keywords in their title or abstract. On the other hand, technical scientific literature has been consulted to figure out the correct IPC classification codes of PV technologies, and search by IPC code has been used occasionally to clarify specific topics of interest during the research.

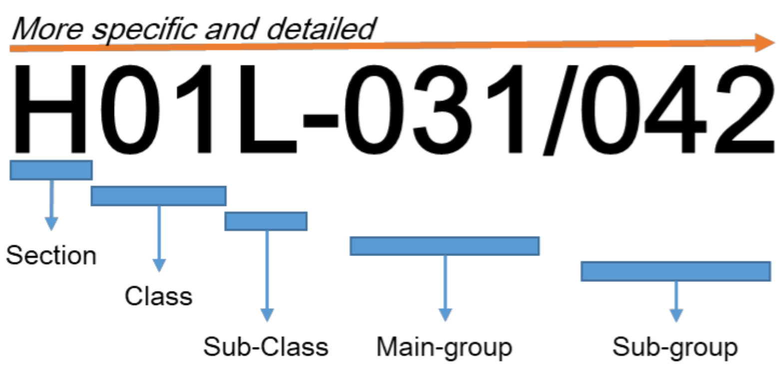

Image 1, IPC patent code structure, source: Son and Cho, 2020

After the signature of the Strasbourg Agreement in 1971, the World Intellectual Property Organization (WIPO) started publishing information about the International Patent Classification (IPC). This kind of classification consists in a series of levels which are section, class, subclass, group, and subgroup. Each of them corresponds to a classification criterium, and the more two patents are similar from the IPC code point of view, the more their underlying inventions have things in common. Patent classification systems have the advantage of being language independent and the underlying documents being directly available, however, classifications remain subjective to the evaluation of the examiner, who has the role of continuously updating them. The aforementioned elements of the IPC code move in hierarchical order, from the most comprehensive to the most specific one.
This structure is clearly shown in image 1.
The main source of information regarding this aspect is a journal article from Shubbak (2019), focused on technology review and patent trends of the solar PV industry (see table 2).

IPC codes of the PV technological system components.

GROUPS	SUBGROUPS	IPC CODES	
Cells	**1. Crystalline Silicon Cells**	H01L 31/028	H01L 31/068
		H01L 31/0352[b]	H01L 31/18[b]
	1.1 Monocrystalline (Single Crystal)	C01B 33/02[a]	H01L 31/061
		C30B 29/06[a]	H01L 31/077
		C30B 15/00–36[a]	
	1.2 Polycrystalline	C30B 28/00–14[a]	H01L 31/0368
	1.3 Silicon Hetero-structures (HIT)	H01L 31/0747	
	1.4 Thin-film Silicon Microcrystalline	H01L 31/06[b]	H01L 31/072[b]
	2. Thin-film Technologies	H01L 27/142	H01L 31/0475
		H01L 31/0445	H01L 31/065
		H01L 31/046	H01L 31/0248[b]
		H01L 31/0256[b]	
	2.1 CIGS, CZTSSe	H01L 31/032	H01L 31/0749
	2.2 CdTe	H01L 31/0296	H01L 31/073
		H01L 31/0264[b]	
	Both 4.1 and 4.2	H01L 31/0272	H01L 31/0336
	2.3 Amorphous Si:H	C23C 14/14[a]	H01L 31/0392
		C23C 16/24[a]	H01L 31/075
		H01L 31/0376	H01L 31/20
		H01L 31/04[b]	H01L 31/07[b]
	3. GaAs Cells	H01L 31/0304	H01L 31/0735
		H01L 31/0693	
	4. Multi-junction Cells	H01L 31/0312	H01L 31/0725
		H01L 31/0328	H01L 31/074-0745
		H01L 31/043	H01L 31/076
		H01L 31/047	H01L 31/078
		H01L 31/0687	
	5. Emerging Photovoltaics		
	5.1 Dye-sensitized Cells	H01G 9/20	
	5.2 Organic Cells	H01L 27/30	H01L 31/0468[b]
		H01L 31/0384	
	5.3 Perovskite Cells	H01L 51/42-48	
	6. Common Elements	H01L 31/036	
	6.1 Electrodes	H01L 31/0224	
	6.2 Surface Textures	H01L 31/0236	
	6.3 Cells Connection	H01L31/0463-0465	H01L 31/05
	6.4 Doping Materials	H01L 31/0288	
Panels	**1. Coating/Protection**	H01L 31/0216	H01L 31/041
	2. Containers/Encapsulation	H01L 25/00	H01L 31/0203
		H01L 25/16–18[a]	H01L 31/048-049
		H01L 31/02	
	3. Roof Covering and Supporting Structures	E04D 1/30	H02S 20/00-32
		E04D 13/18	H02S 30/00-20
		H01L 31/042	
	4. Optical Elements/Arrangements	H01L 31/0232	H02S 40/20-22
		H01L 31/054-56	
	5. Thermal Elements/Arrangements	H01L 31/024	H01L 31/052-0525
	6. Cleaning	H02S 40/10-12	
	7. Power Plants	H02S 10/00-40	
Electronics	**1. Junction Box (Bypass Diodes)**	H01L 31/044-0443	H02S 40/34-36
	2. MPPT	G05F 1/67	
	3. Inverters, Feeding Circuit	H02J 3/38	H02S 40/32
	4. General Electronic Elements	H02S 40/30	
Energy Storage	**1. In-cell Storage (Capacitors)**	H01L 31/053	
	2. Battery Charging Arrangements	H02J 7/35	
	3. Batteries	H02S 40/38	
Monitoring/Testing	**1.Testing during manufacturing**	H01L 21/66	
	2.Testing after manufacturing	H02S 50/00-15	
Devices	**1. Lighting Devices**	F21L 4/00	F21S 9/03
	2. Thermal Devices (heating, cooling)	H02S 40/40-44	
Combined	Combinations of the groups above	H01L 31/00	H02N 6/00
		H02S 40/00	H02S 99/00

[a] Global subgroups (not only for PV).
[b] Mainly for the designated subgroup but might contain other cell technologies.

Table 2, IPC codes of PV system components, source: Shubbak, 2019

As we can notice from this table, in some cases the research by IPC code can lead to a slightly vaster number of patents included in the results. In fact, certain subgroups cannot be furtherly divided and comprehend both PV related inventions and unrelated ones. This is one of the reasons why an authoritative source such as IRENA has been chosen as data source for the regression analysis. Targeted research of patents and patent owners by IPC code or company name is still very reliable though, and Orbis Intellectual Property by Bureau Van Dijk is a very comprehensive database. By replicating the research performed by the author of the table with the same filters, PV technology inventions are in fact successfully isolated in said software.

Statista has also been very useful when it came to the gathering of data regarding energy markets and energy consumption reports. Its utility becomes even clearer during the analysis of the most active players in the patenting environment, both as states and as single organizations.

Our World in Data's research has provided a good amount of information to be evaluated, as well as many graphical representations of the global current consumption and use of renewable and non-renewable energy sources. Since the mission of the organization underlying the database is fully dedicated to informing people through the use of open access data provided by reliable sources, regarding issues affecting the whole global community, the author considers this tool very valuable for the research.

The next paragraph will deep dive on a brief version of a patent landscape analysis for the PV industry, thus introducing the following part, containing the heart of the paper: the regression analysis of the relation between PV installed capacity and patent activity.

4.2. Patent Landscape and market Data

Technological information contained in patent documents is fundamental for companies and other institutions when it comes to financing new research projects and expanding in new markets. Thanks to this kind of documentation, the creative process is easier and less risky for the organizations because the state of the art is assessed, along with an eventual grey area in the market.

In fact, 70% of the technological information found in patent documents cannot be found elsewhere (Sampaio et al., 2018).

Moreover, other than simply providing information about the current technology, patents are useful to avoid infringements by consulting them, and avoiding the duplication of R&D activities. The reach of the protection, the presence of loopholes and the identification of sector specialists are other of the possible tasks possible thanks to these documents.

Specialized literature is also a preeminent source of technical information. This is the reason why a quick overview of the market and the patent landscape in the photovoltaic industry is necessary as an introduction for the next paragraph: it will work as a framework from which useful insights will be extracted.

As mentioned in the first chapter, the renewable energy industry is rapidly growing. In order to have an idea of the market dimensions, the following data about renewable energy consumption will be used, and then furtherly divided into more specific categories associated to the current dimensions of the Photovoltaic industry.

First of all, we can start from the total amount of primary energy covered by renewable sources around the globe. As shown in image 2, the situation is drastically different depending on the country.

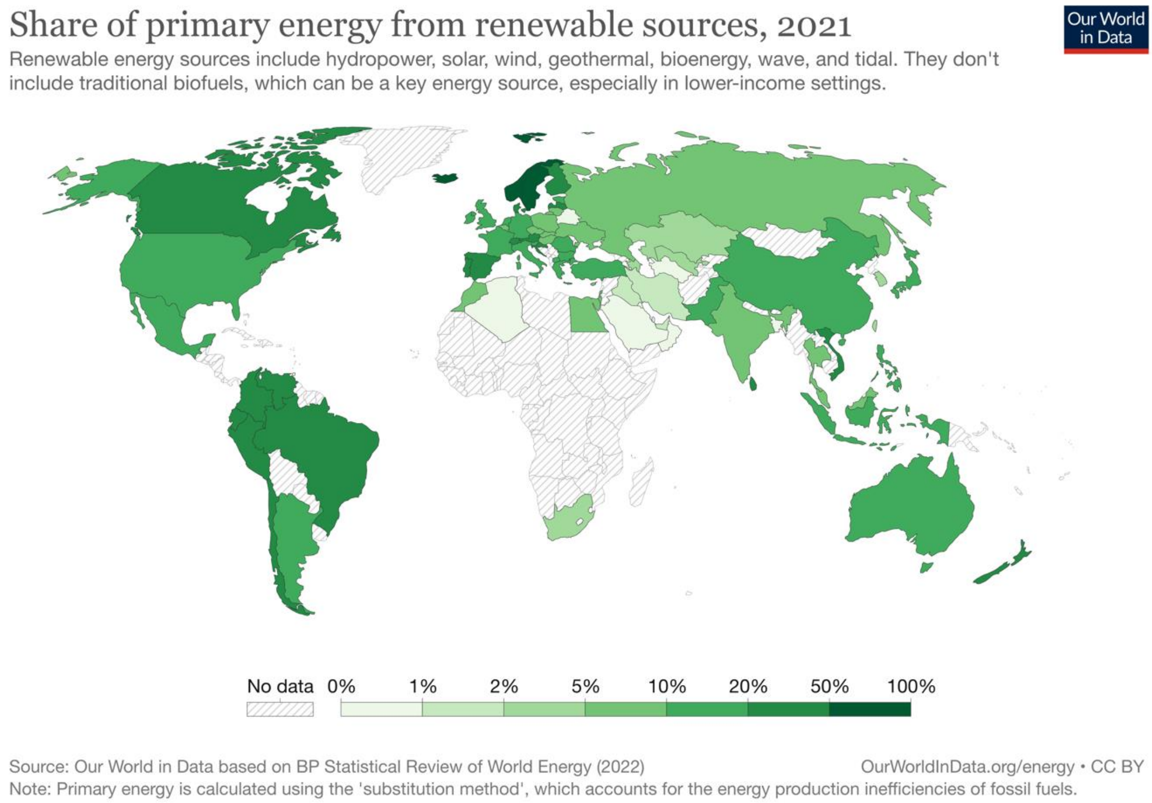

Image 2, primary energy share from renewable sources, 2021 source: Our World in Data

Primary energy in this case is the amount of energy in its raw form before it is converted into other states by human work. When we refer to primary energy, hence we mean how much energy is consumed, independently from the sources of it, which can be traditional fuels, renewables, coal and more. The data shown in the following tables is based on the values of primary energy calculated with a method called ‘substitution method’. This calculation tries to take into consideration the loss of energy that happens during the conversion of each source to usable energy. The ‘direct’ primary energy, on the other hand, does not take into account this energy loss, so the result is lacking part of the information, but has the advantage of not relying on too many approximations, since energy loss is an estimation. Now, this consideration is important because renewable sources and nuclear do not generate waste energy, while traditional fuels such as oil can reach a share of wasted energy of around 60% in some cases, depending also on the efficiency of the power plant or machinery used to convert it.

In this case, data calculated with the substitution method is shown, since it is generally considered more representative of the actual energy production, moreover, it is the same method preferred by the Intergovernmental Panel on Climate Change (IPCC).

As we can state from image 2, most countries don't even reach the 50% level of total energy production from renewable sources. The most virtuous country, according to the data, is Iceland, with around 86% of primary energy share covered by renewables as of the end of 2021. This country is a world leader in sustainability, thanks to the geological conformation of the state, which grants precious sources of geothermal energy, a small population of 370.000 people and a very well-organized central government which aims to reach the total carbon neutrality by 2040. The most difficult challenges will probably be the transport and fishing industry to reach this objective.

Similar situations can be found in Norway and Sweden, with respectively 71% and 51% of primary energy share satisfied with renewables.

The most populated countries on the other hand, are having a harder time at reaching higher values of energy demand satisfaction with renewables. China for example, despite being actively working to increase the use of sustainable resources to produce energy, still has a renewable primary share of 15%, with a population of 1.43B. India is in a similar situation: 1.41 people registered at the end of 2021and still covers just 9% of its primary energy with clean sources.

Other preeminent countries in the world economy, such as the US and Germany, respectively reach 10% and 19% of sustainable energy share, although they are both taking important steps towards greater sustainability such as the IRA and the RePowerEU plans.

Moving on to the situation in Italy, since this country will be compared in the following patent focused analysis, we can see from the graphic that by 2021, 18% of primary share was satisfied by renewables, with a population of 60M. A rapid growth in the first value has been seen after 2007, when the metric moved from 6% to 18% in just fourteen years, after remaining constant or even declining for more than thirty years (Table 3).

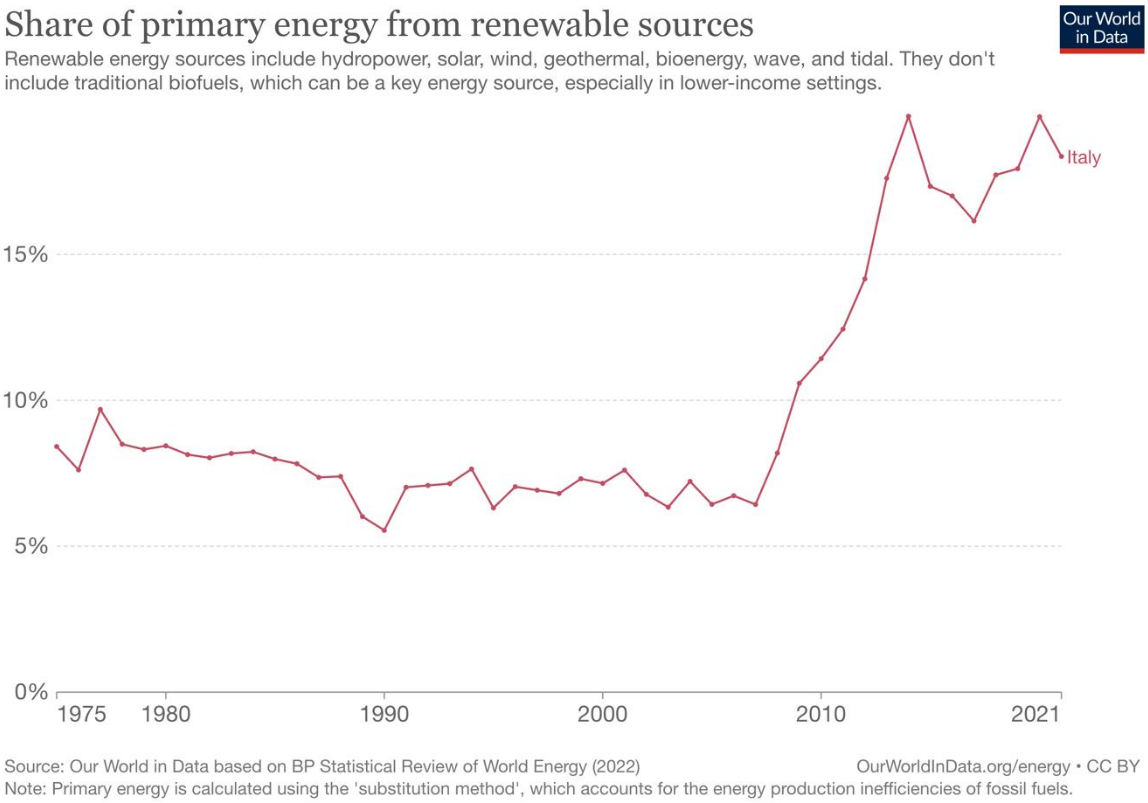

Table 3, share of primary energy from RES, source: Our World in Data

Table 4 shows the current energy mix and how it evolved during the last twenty years. We can state that globally the energy market is still largely dominated by fossil fuels, with more than 80% of the energy consumption coming from them. Oil is still the most important among them, followed by coal and gas. Hydroelectric energy is on the other hand the greatest contributor among the renewable energy sources to the energy mix.

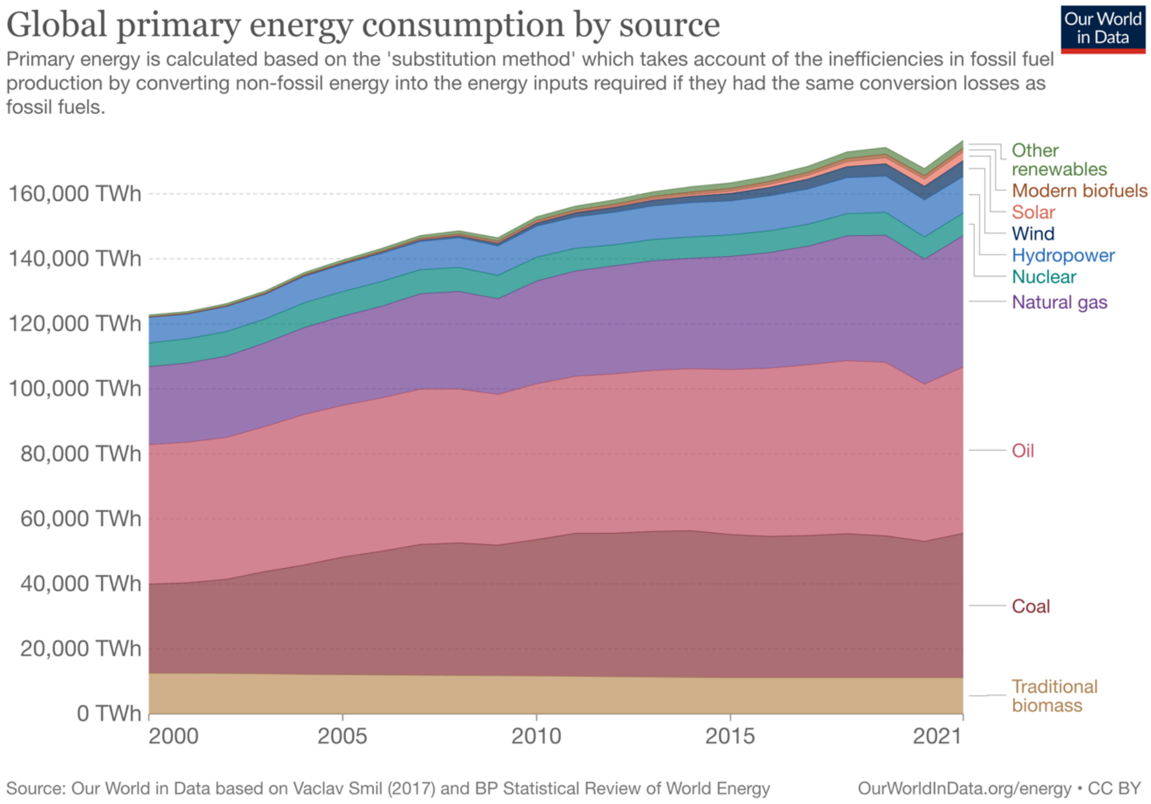

Table 4, Global primary energy consumption by source, source: Our World in Data

In 2021 in fact 163.000 Terawatt-hours were produced globally, of which 51 coming from oil alone, 41 and 38 from coal and gas respectively and just 11 from hydropower. Compared to the values from 2000, it can be noticed that while nonrenewable sources have seen consistent absolute growth values, mainly due to the increase of population and hence of the energy demand, renewables became more and more relevant. While oil use increased by 19% in the last 20 years, coal use grew by an incredibly high 62%, and natural gas by 68%. The same metrics, applied to renewable energy sources might look very promising after seeing their evolution, but a little bit less after noticing that the absolute value is still too low to provide sustainable means of production of energy for everyone, since they just satisfy less than 20% of the global energy demand.

In the meantime, however, thanks to the coordinated incentives and international agreements signed with the EU and international conventions, Italy managed to reduce its percentage of non-green energy sources from the energy mix. In fact, a -56% was achieved in the use of coal, -42% in the use of oil and just a slight 7% increase in the use of gas. With the latter likely going down in the next yearly reports because of the Russian-Ukrainian conflict and the related sanctions. While a metric representing the relative percentage increase in renewable energy production in Italy would lead to difficult interpretation due to the rapid growth from zero which happened in the last twenty years, table 5 is useful to allow a quick look at the evolution of renewable installed capacity in our country in the last period.

Moreover, Italy is the third largest producer of renewable energy in Europe. The geographical conformation of the country is in fact a valuable resource in this case: the northern area is excellent for the construction of hydroelectric power plants thanks to its steep surfaces, southern Italy's latitude encourages the development of photovoltaic, geothermal energy is mainly sourced in Tuscany and wind energy is exploited through wind farms in the islands and in the center south. While our country is a leader in hydroelectric, the other renewables are still very important. Photovoltaic, for instance, has seen a rapid growth in the last few years thanks to the steep decrease of the levelized cost of energy by more than 80% in a decade. Sustainable sources satisfy more than a third of the 320-Terawatt hours of electricity needed yearly in this country. If 42% of the total comes from hydro, a good 20% of it is produced with photovoltaic, and 16% with wind power.

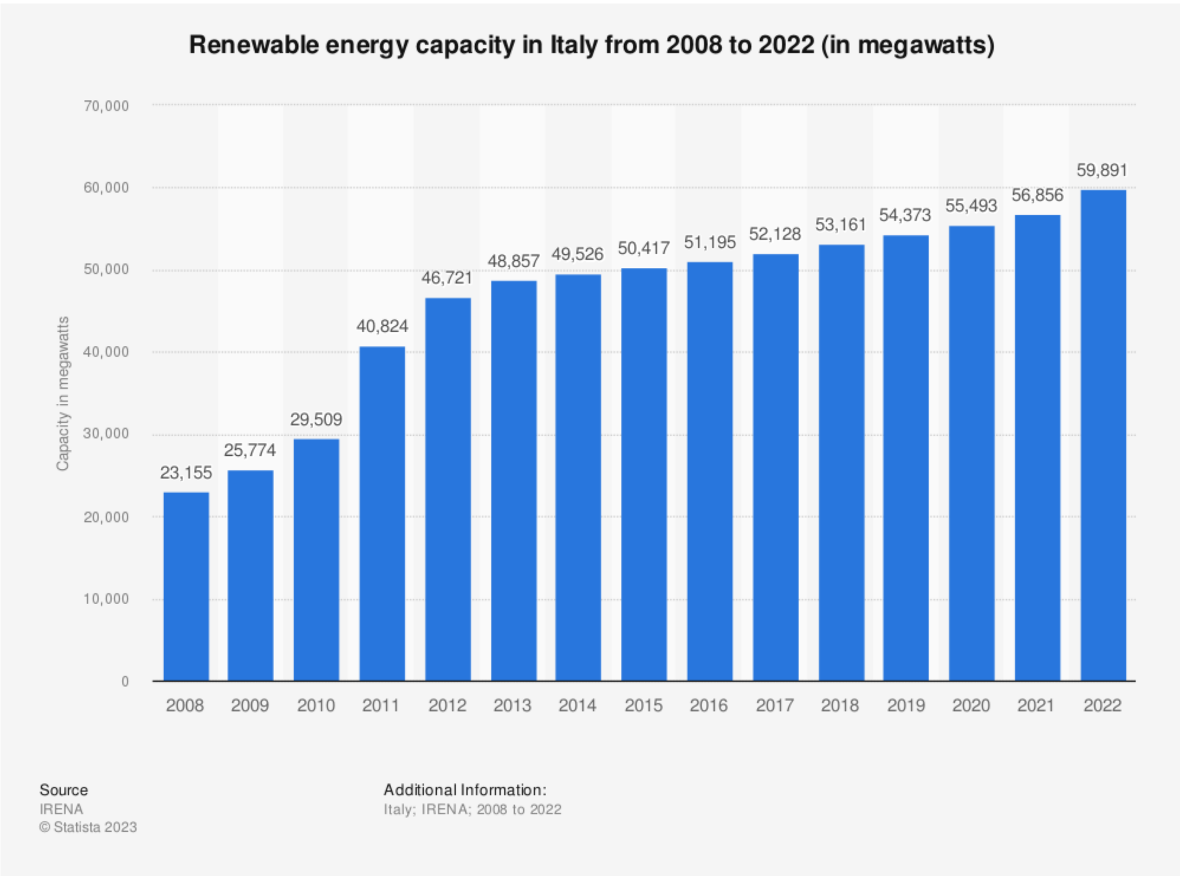

Table 5, RE capacity in Italy from 2008 to 2022, source: Statista

Another reason why photovoltaic is so relevant in Italy is the value of investments dedicated to it in the last years. In fact, by looking at image 4.6, it can be noticed that PV technologies have received the greatest amount of invested money among renewables in 2021.

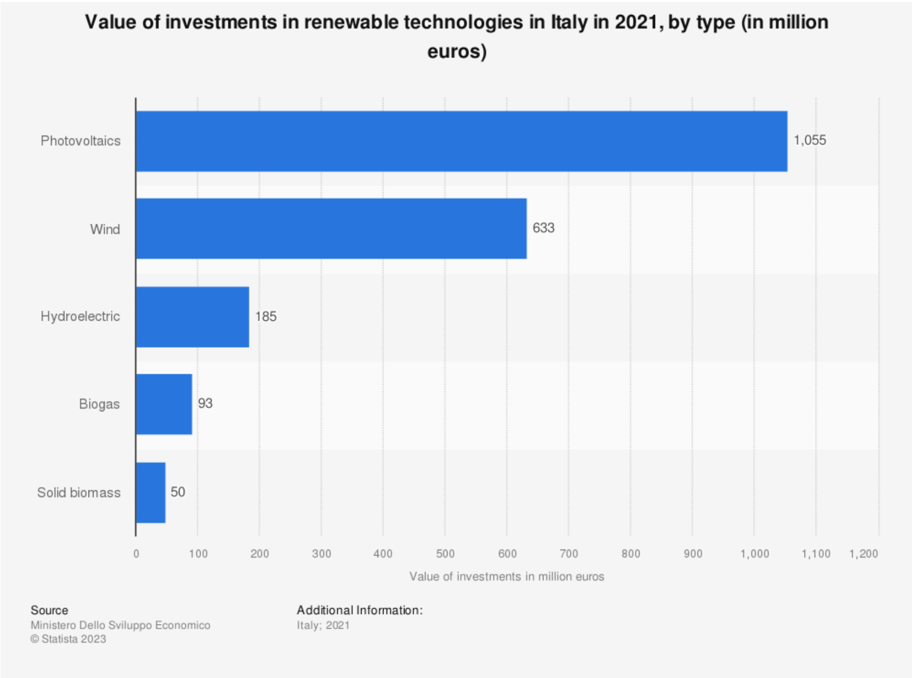

Table 6, Value of investments in RETs in Italy in 2021, by type, source: Statista.

With more than € 1B, PV received the largest amount of invested capitals in that year, which is greater than the sum of all other resources dedicated to different types of green technologies during the same period.

The overall value of green investments kept increasing in during the last decades on a worldwide level, as shown in table 7. New investments in renewable energy jumped from just $ 32B in 2004, to $ 495B in 2022. The most interesting metric to notice is the pace of this continuous growth which is exponential. Public support to the sustainability cause, major improvements in existing technologies, the emerging of new inventions related to energy and enabling tech, more and more private organization focused on the theme all contributed to the flourishing of the industry. Among all the green sources, solar and wind energy are the two which have seen the greatest funds contributing to their improvement. From the geopolitical point of view, China leads the way as the major investor, followed by the US. In fact, in 2021 newly installed PV capacity was almost 55GW, more than 30% of the newly installed PV capacity globally. Further 99GW are planned to be added by 2025.

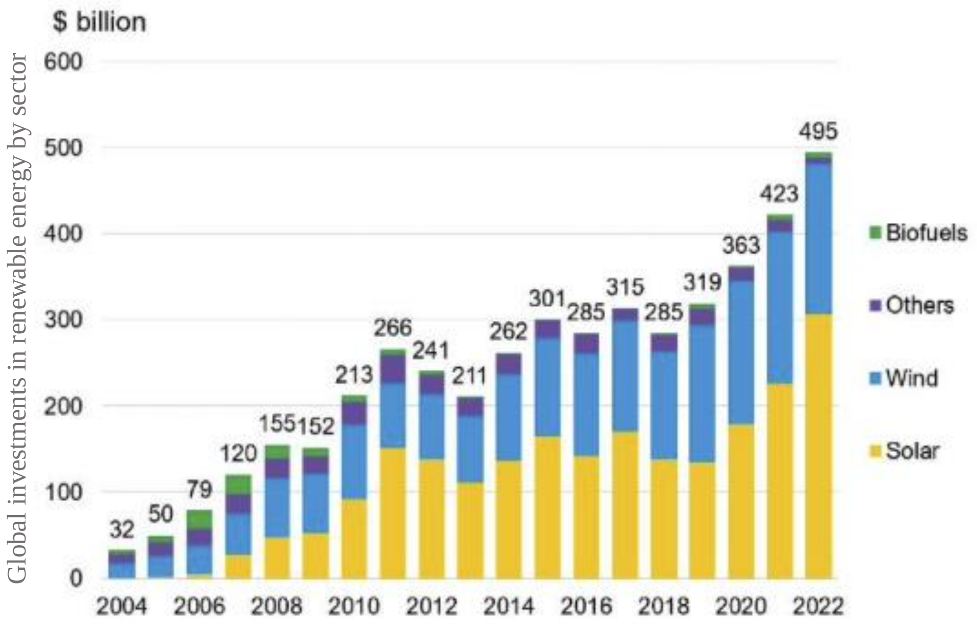

Table 7, Global investments in RE by sector, source: Bloomberg

As previously mentioned, the last but not less important market indicator influencing the development of green energy is the private investment sector. This part can be useful to give the reader a quick overview of the most important companies active in the industry by market capitalization, worldwide.

The first companies from this list have renewable energy power generation and installation as main business activity.

As for April 2023, the pure renewable energy company with the highest market capitalization is NextEra Energy Inc, with $ 159B. This is a US based company which generate a capacity of 30.000 watts mainly from wind and solar sources. This company is considered the largest utility worldwide by market cap.

Iberdrola takes the second place. This time we are talking about a Spanish multinational utility company which markets its services to more than forty countries. Iberdrola produces, transports, and sells energy from both renewable and nonrenewable sources, although the green component is very relevant to the business. Its market cap is currently around $ 80B.

At the third place we can find a Danish company called Orsted A/S. The market cap this time is around $ 37B and its activities include mainly the construction, development, and use of

wind farms. They have more than 7.5 GW of installed capacity of offshore wind power plants, the highest globally. The company is actually part of a way larger group.
Another important player is Vestas Wind Systems A/S, based in Denmark and specialized in wind turbines, with a market cap of around $ 27B. They operate worldwide and the main activities consist in developing, building, and managing wind turbines, of which they have already installed a total of 145 GW around the globe.
Other notable companies are Siemens Gamesa RE SA from Spain, Plug Power Inc. based in the US, Algonquin Power and Utilities Corp and Canadian Solar Inc., based in Canada, and Daqo new energy Corp from China. Sinohydro Corporation, China Yangtze Power Co. Ltd and Tina Solar Ltd are other main players in the Chinese market, which is currently the one showing the greatest growth.
However, many other larger companies have huge interests in play into the RE field. We could just mention companies like Tesla, with a market cap of around $520 B at the time of writing to give an idea. However, in this case the organization's core business is the automotive sector, and accessory products which are Solar Panels, Roofs, Powerwall and Megapacks are developed and sold to both private and business customers. The total renewable installed capacity by Tesla is 'just' 10GW currently.
Shell Plc is another industry giant, with a market cap of around $ 210B and a reach of more than 80 countries. The company's core business is on traditional energy provision, although around 7GWh of renewable capacity is being installed by the organization.
Total Energies SE, which is based in France has currently installed 16 GW of renewables and has a capitalization of $ 141B. The company has ambitious plans in the renewable field, aiming to reach an installed capacity of 100GW by 2030.
Similarly to Total, British Petroleum, a company based on the commercialization of traditional fuels, is trying to accomplish a shift to renewables. With a market cap of $ 116B, this British market leader aims to reach net zero emissions. They have already installed more than 31 GW of wind and solar power plants and the plan is to keep up at this pace.

Moving closer to Italy, Eni S.p.A., based in Rome, with a market cap around $ 50B and operations in 69 countries is the proof that even in our country, some companies are making important steps towards sustainability. The plans of the company consist in over 15GW of green capacity installed by 2030, with a current value of just 2GW. In order to reach this objective, the company is also trying to perform strategic acquisitions in the sector.

The next step consists in analyzing descriptive statistics about the diffusion of PV technologies through patent data. The following analyses will be useful as ideas for the discussion of results in the next chapter.

The first part of this phase examines the spread of new inventions across countries during the last 22 years, which is the reference period of this research. In order to perform this process, the IRENA database about patent data has been imported in Excel, the data cleaned to suit the objective of the research and the dataset deprived of unnecessary information. The pivot table function has then been used to display the number of cumulated patents filed for each country in the last 22 years related to photovoltaic technologies. The results have then been sorted in decreasing order as shown in table 8.

Country	Cumulative Patent Count
China	201.977
USA	67.911
Japan	57.279
Republic of Korea	46.049
Chinese Taipei	14.588
Germany	13.245
Australia	6.542
Canada	4.425
Spain	3.366
France	2.952
United Kingdom	2.299
Brazil	2.147
Mexico	1.598
Russian Federation	1.592
Austria	1.280
Italy	1.264
Singapore	1.151
Israel	1.014
Poland	958
South Africa	831
Hong Kong	667
Denmark	664
Netherlands	662
Portugal	576
Chile	403
Morocco	379
India	328
Malaysia	325
Philippines	285
Switzerland	279
New Zealand	269
Hungary	239
Ukraine	232
Croatia	209
Slovenia	192
Argentina	187
Czechia	174
Sweden	174
Turkiye	174
Greece	165
Norway	164
Finland	135
Tunisia	128
Colombia	116
Saudi Arabia	107
Belgium	103
Peru	94
Cyprus	92
Lithuania	89
Slovakia	78
Romania	67
Serbia	65
Egypt	59
Bulgaria	45
Luxembourg	35
Costa Rica	33
Ecuador	33
Ireland	31
Republic of Moldova	30
Cuba	26
Jordan	20
Uruguay	18
San Marino	17
Estonia	15
Latvia	15
Dominican Republic	14
Guatemala	13
Montenegro	11
Nicaragua	10
El Salvador	5
Algeria	4
Georgia	4
Honduras	2
Indonesia	2
Kazakhstan	2
Monaco	1
Panama	1

Table 8, Cumulative PV patent count by country, 2000-2021, own elaboration

This table lets us visualize the most active countries in patenting during le last years.

Another graphical elaboration of this table is shown in image 3. This image uses the data from table 8 to convert them into a tree map and give the reader a visual representation of the descriptive statistics.

Italy has been marked with a different color in table 8, to make its metric easier to retrieve.

The results will be discussed in the next chapter; however, we can notice that China is the most active issuer of patents, followed by USA, Japan, Korea, Germany, Canada, and Australia. It's also worth noting the discrepancy between the Chinese and American metric, the latter not even reaching half of the first one and being very similar to the Japanese value.

Italy only places sixteenth in the ranking, with 1.264 patents.

Moreover, while reading these data, we must consider that number of patents is not directly proportional to the effective magnitude of innovation happening in a country, since other factors such as policy may encourage filing of many different patent documents even for small inventions. However, this metric as discussed in the previous chapters has been chosen by many scholars as the best proxy available, and it will be object of further study in this paper.

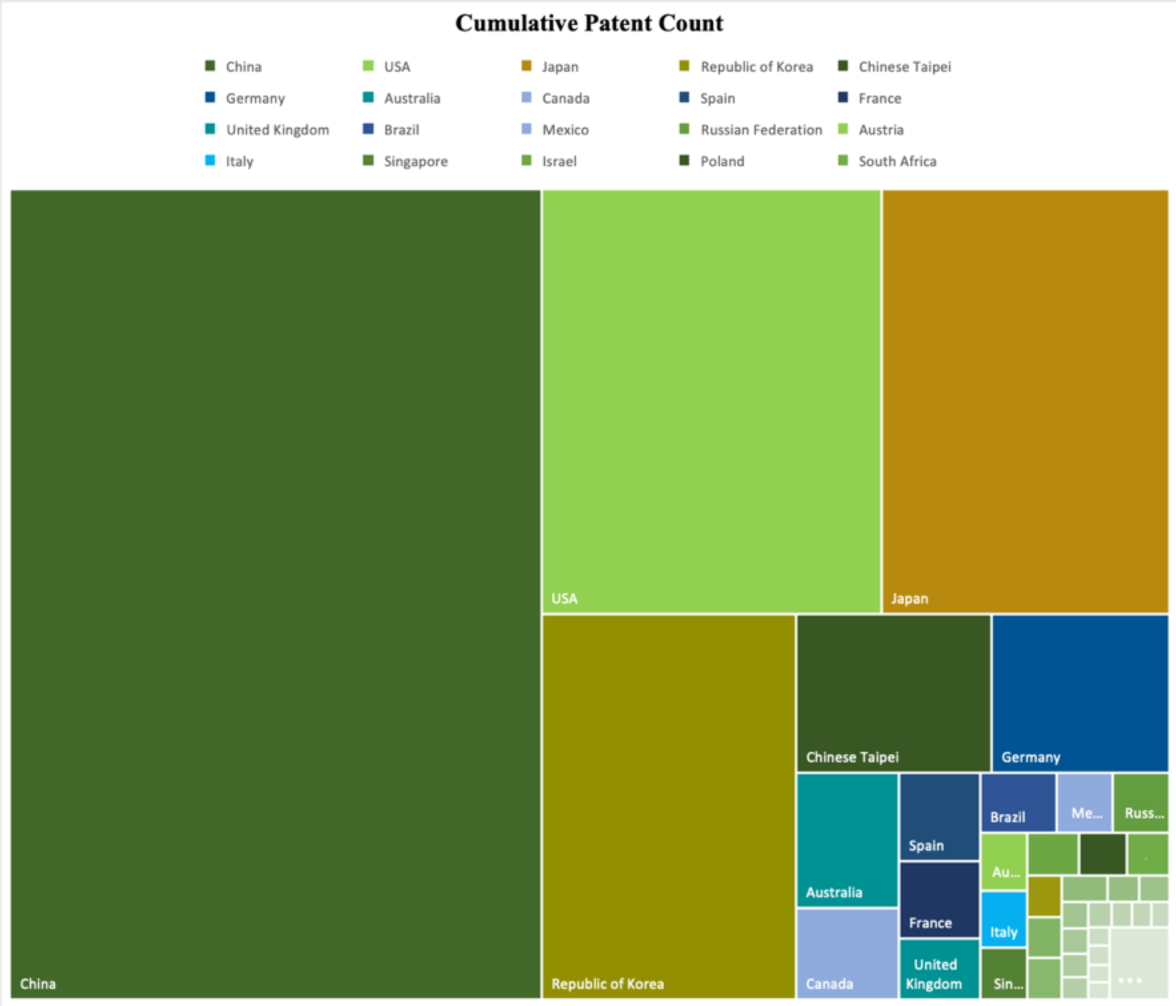

Image 3, cumulative PV patent count by country, 2000-2021, own elaboration

Another way to visualize the evolution of the industry from the point of view of innovation is by temporal order. Since the patent count is the protagonist of this study, it has been chosen as the main metric used in the patent landscape section. This time we will look at the number of new patents filed each year, just to analyze the cumulated yearly value later in the chapter. One more elaboration has hence been performed using the same dataset from IRENA, but this time focusing on new patents filed each year globally.

The pivot function was used once again to sort data and sum the global filings for each year, and the output rearranged in a table and represented graphically using a column graph, as seen in table 9.

The image shows a rapid growth of patented inventions in PV technologies all over the world, reaching exceptional values in 2019. Since data have been collected in May 2022 by IRENA, and the 2021 value is extremely low compared to the previous ones, this can be attributed to the fact that the patent applications, once filed, are not accessible before eighteen months, period in which the invention is not published by the patent authority, so it is not registered on the publicly accessible databases. One the same line, the value from 2020 will be considered reliable, since patent procedures started by the end of 2020 are assumed to have been made accessible by May 2022, except few exceptions (for example the patent applications started in December 2020). To clarify: this observation regards additional patents by year, this is not the same metric that will be used in the research question, in that case we will be analyzing a cumulative value, made already available from the same source for consistency.

Year	Additional Patents
2000	3.813
2001	3.969
2002	3.828
2003	4.371
2004	5.016
2005	5.995
2006	7.436
2007	10.320
2008	14.718
2009	21.633
2010	27.571
2011	30.210
2012	29.742
2013	26.703
2014	27.809
2015	29.708
2016	34.572
2017	37.652
2018	38.959
2019	33.666
2020	33.234
2021	9.810

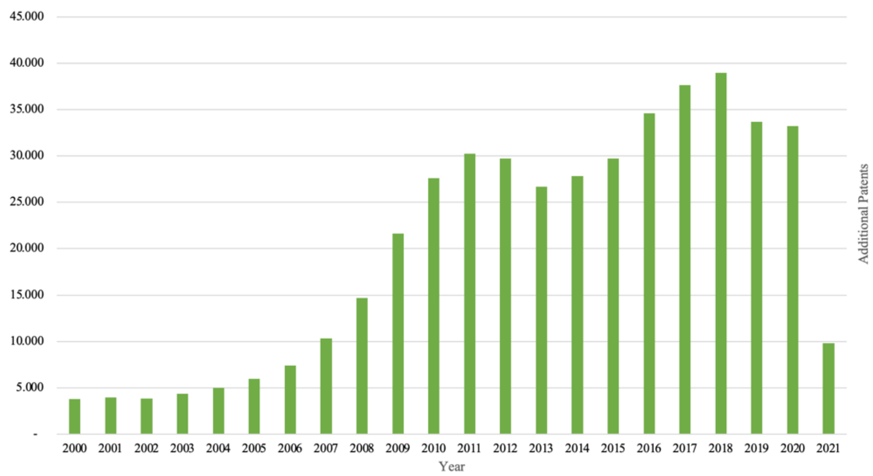

Table 9, additional PV patents filed by year worldwide, 2000-2021, own elaboration.

This said, the last piece of reasoning about descriptive statistics will focus on the sector for which the invention was conceived.

The same dataset was taken as reference and an operational process which is similar to the last two has been used.

This time we want to visualize which are the sectors that are mostly affected by innovations in the PV industry around the world. Cumulative patent counts and macro sector are hence the two variables in play. As shown in table 10, the most popular application of PV technologies is in the power generation sector. The building sector takes a smaller percentage of the pie: 12%. Some examples of applications in this case are power plants mounted on buildings and their supporting structures, which can in some cases rotate to catch the most amount of sunlight, or other kinds of roof coverings and integration systems used to connect the power generation unit to the building and its electrical system. Waste sector patents on the other hand are related to waste management and recycling of miscellaneous materials or the panels themselves. The powering of waste recycling systems is also an option in this case.

Sector	Cumulative Filed Patents
Power	369.143
Building	52.714
Waste	18.878

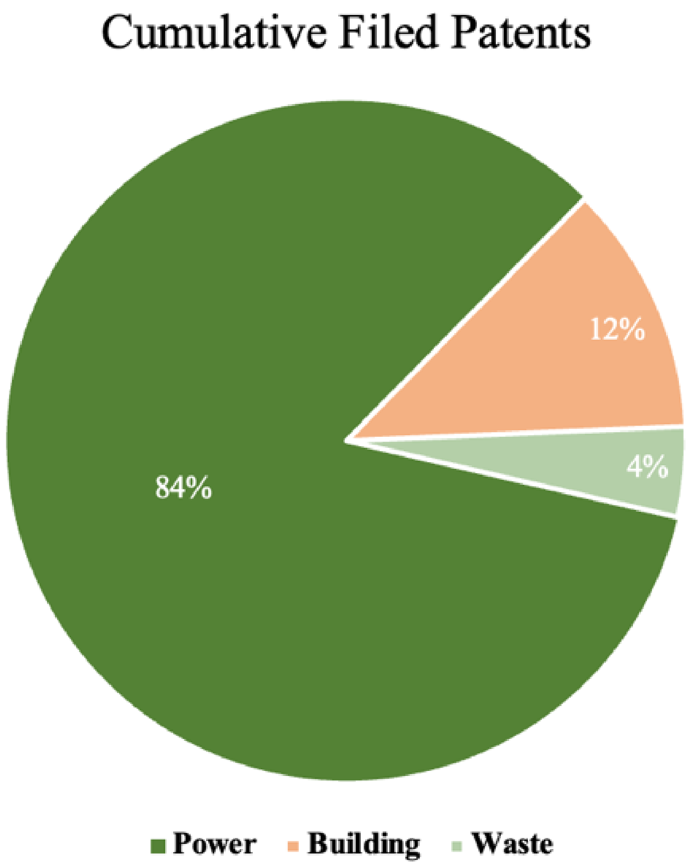

Table 10, cumulative PV patents filed worldwide by sector, 2000-2021, own elaboration.

The next paragraph will analyze the data related to the research questions, a create the model to be discussed in the next chapter.

4.3. Model Shaping and Research Methods

The first part of the paragraph takes into consideration the two variables mentioned in the first hypotheses, which are:

1. cumulated global PV patent count as a yearly value from 2000 to 2020, which is the independent variable.
2. cumulated global PV installed capacity as a yearly value from 2000 to 2020, which is the dependent variable.

The first hypothesis (H1) is: cumulated global PV patent count is correlated with cumulated global PV installed capacity.

Hence, the null hypothesis (H0) in this case is: cumulated global PV patent count is not correlated with cumulated global PV installed capacity.

As already mentioned in the previous chapter, according to literature the relation between patent count and installed capacity has been already proved, moreover, the temporal precedence logic suggests that patent count comes first in the cause affect relation, since patents are usually filed before the technology is put on the market. The correlation between the variables will also be shown in this chapter as additional proof supporting the solidity of the research.

The expected result of the model is a trendline and its corresponding equation which estimates the installed capacity starting from patent count at an acceptable precision, which means an R square of at least 0,70. Additionally, we must consider that both patent count and installed capacity are non-negative variables, so any predicted models, linear or nonlinear, approximating results to negative values shall be considered not reliable in our case. Regression analysis will be used to assess the entity of the relation between the variables, along with the measurement of the lag effect and the accuracy of the function that will be given by the Excel software. By definition, regression analysis is a mathematical tool characterized by extreme flexibility, and which has seen extensive use in previous quantitative studies as means of investigation of the relationships between an independent and one or more dependent variables.

The table below (Table 11) shows the results of data gathering, cleaning and elaboration. Data has been gathered from IRENA INSPIRE portal in the case of patents, and STATISTA in the case of installed capacity.

Year	Cumulated PV Installed Capacity Worldwide (GW)	PV cumulated Patent Count Worldwide
2000	1.288	3.813
2001	1.615	7.782
2002	2.069	11.610
2003	2.635	15.981
2004	3.723	20.997
2005	5.112	26.992
2006	6.660	34.428
2007	9.183	44.748
2008	15.844	59.466
2009	23.185	81.099
2010	40.336	108.670
2011	70.469	138.880
2012	100.504	168.622
2013	138.856	195.325
2014	178.391	223.134
2015	229.300	252.842
2016	306.500	287.414
2017	404.500	325.066
2018	509.300	364.025
2019	633.700	397.691
2020	772.200	430.925

Table 11, cumulated PV IC and cumulated PV patent count worldwide, 2000-2021, own elaboration

Graphical representation of these data is offered below (Table 12 and table 13) to show the temporal evolution of the two variables and accompany the reader to the correlation analysis as previously announced.

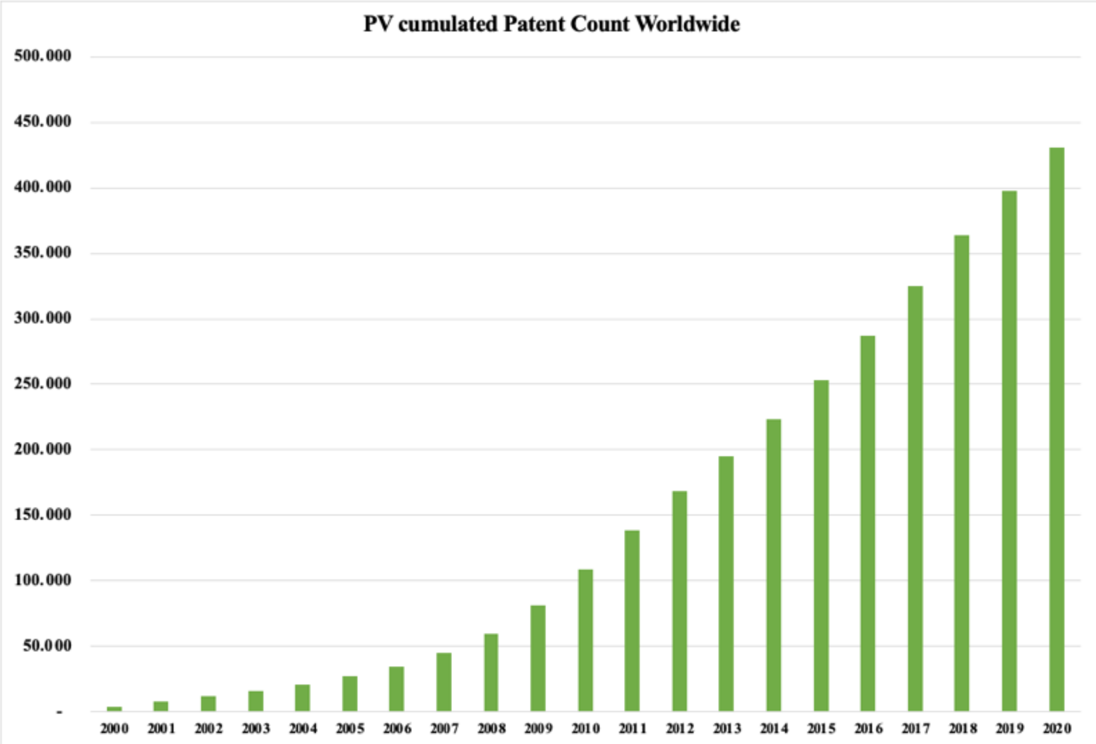

Table 12, PV cumulated patent count worldwide, by year, 2000-2021, own elaboration

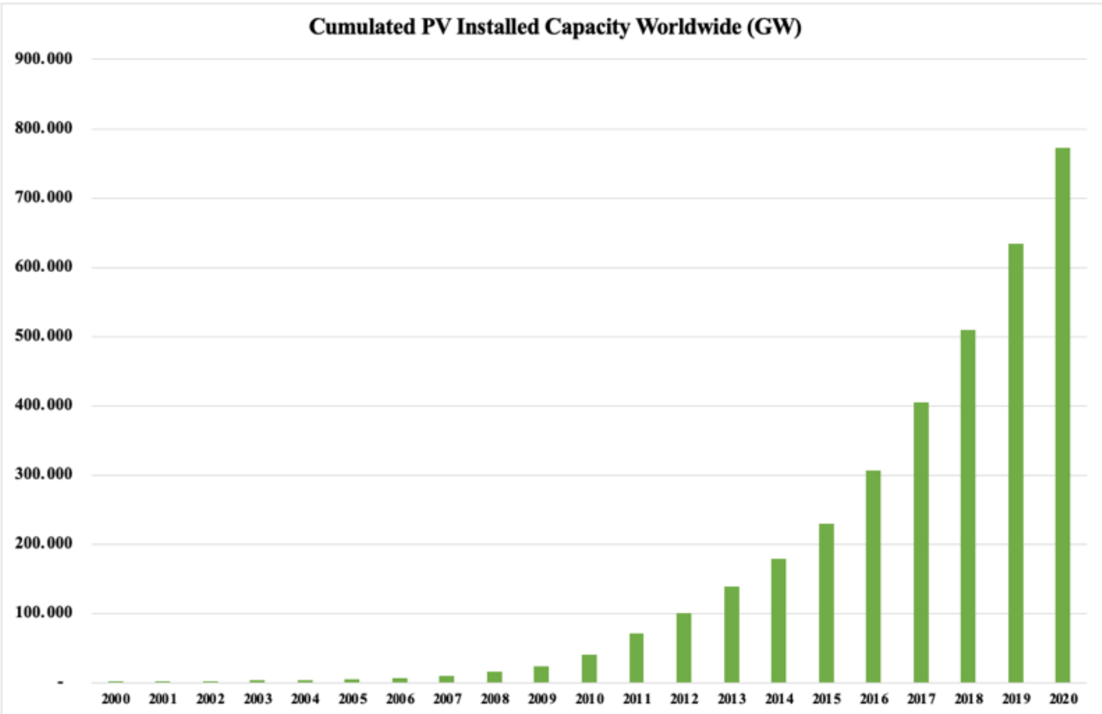

Table 13, PV cumulated installed capacity worldwide, by year, 2000-2021, own elaboration.

As tables 12 and 13 show, both variables rapidly increased during the last twenty-one years. This upwards trend can be attributed to many causes: policies which are favorable to green technologies, financial aid to the sector, also the fact that the technology, while not being completely new, is still in a growth phase since it is continuously improving and expanding. Finally, the same direction trend may suggest, even if it is not sufficient on its own, correlation between the variables.

The following chapter will dive deeper into this dataset and use the regression analysis to estimate which equation better represents the relationship between the variables, with the objective of obtaining the most accurate result possible without compromising the efficiency of the calculation.

The Italian counterpart of this dataset, on the other hand, will be object of comparison with the obtained results when it comes to the conclusions of the research. In order to give the reader a glimpse of the metrics, the table below will briefly show the Italian dataset, with information gathered from IRENA INSPIRE in the case of patent data and Our World in Data in the case of installed capacity. Unfortunately, local patent data were not available beyond 2019 from said database, so the elements of the analysis will be slightly fewer, but for sake of consistency the data provider will be the same.

The second hypothesis (H2) is: cumulated Italian PV patent count is correlated with cumulated Italian PV installed capacity.
Hence, the null hypothesis (H02) in this case is: cumulated Italian PV patent count is not correlated with cumulated Italian PV installed capacity.
The table below (Table 14) shows the precise values for Italy, while tables 15 and 16 are the corresponding graphical representations of them.

Year	Cumulated PV Installed Capacity Italy (GW)	PV cumulated Patent Count Italy
2000	0,02	8
2001	0,02	15
2002	0,02	25
2003	0,03	37
2004	0,03	51
2005	0,04	68
2006	0,04	93
2007	0,11	155
2008	0,48	241
2009	1,26	409
2010	3,59	588
2011	13,13	790
2012	16,79	940
2013	18,18	1.024
2014	18,59	1.027
2015	18,90	1.063
2016	19,28	1.124
2017	19,68	1.182
2018	20,11	1.233
2019	20,87	1.264

Table 14, PV cumulated patent count and installed capacity Italy, by year, 2000-2019, own elaboration

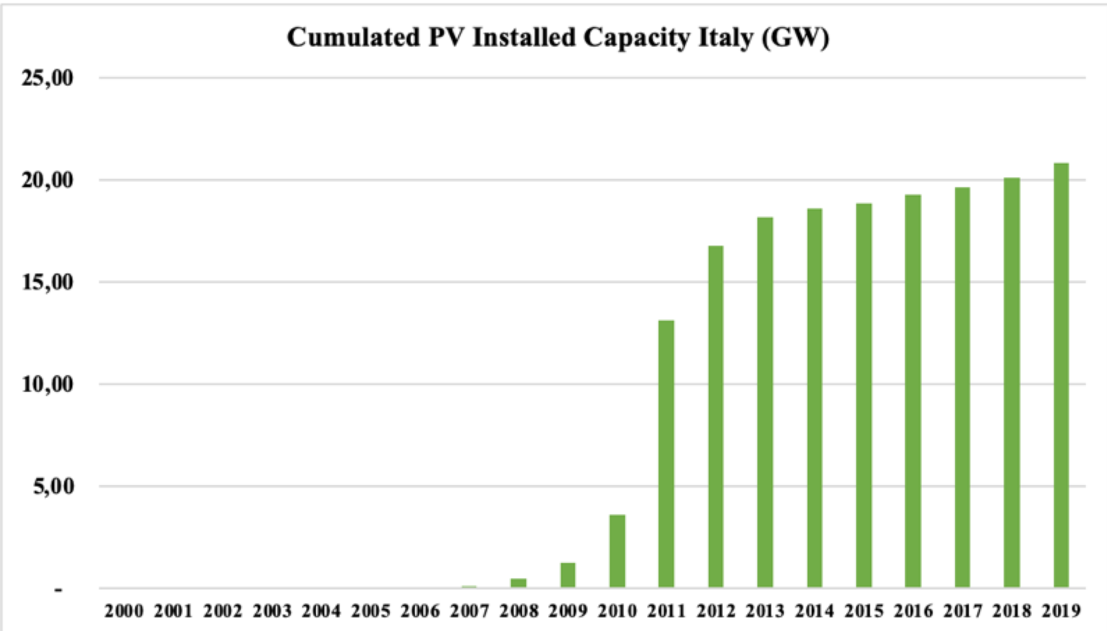

Table 15, PV cumulated installed capacity Italy, by year, 2000-2019, own elaboration.

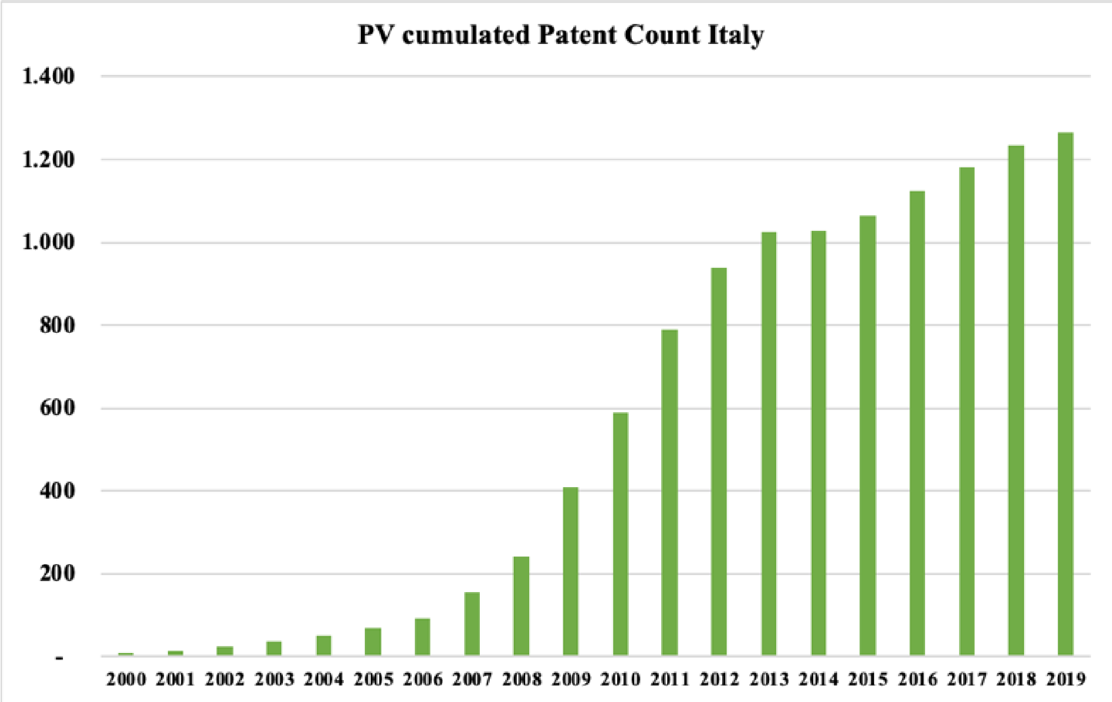

Table 16, PV cumulated patent count Italy, by year, 2000-2019, own elaboration

H3, stating that there is a lag effect between the variables, will be analyzed and its validity checked both in the global and Italian scenarios. In this case, the null hypothesis is H03: there is no evidence of any lag effect between global/Italian patent count and global/Italian photovoltaic installed capacity. The regression tool will be used in this case too, and resulting approximation functions will be compared to the original non-lagged function to see which one better approximates the real-world numbers. Lag effect will be measured on a yearly basis, and with a maximum value of $\Delta t = 4$, where Δt is the number of years of lag.

5. Results

5.1 Key findings and Effectiveness

In this chapter we examine the results of the analysis, based on the data shown previously, and highlight the main findings along with the effectiveness of the model.

As a premise: a practical oriented approach will be used to evaluate the results and get insights in both this chapter and the next one, always considering real world data and the possible evolution of the analyzed sector. Hence, statistical results will not be treated as isolated source of knowledge but will be supported by economic data.

- *Testing H1 - Global Scenario*

The first hypothesis to be taken into consideration is H1, linking global cumulative patent count to global cumulative installed capacity. The first being represented by '*X'* in the examined equations, and the latter by '*Y'*. The hypothesis wants to prove that PV patent count is correlated with PV installed capacity. On the other hand, H01, the null hypothesis, states that said relationship is not statistically significant.

The research will not just investigate the statistical relevance of the link but assess its entity. The regression analysis tool available on Excel has been applied to the dataset in order to show what is the relationship between the two variables and, subsequently, calculate the predictive potential of the resulting function and its error margin.

Image 4 represents the output graphically.

The first procedure was running the regression analysis utilizing the software. After that, the predicted trendline along with its equation has been implemented. The first thing to be noticed though regarding the latter, is that the predicted values corresponding to the earlier years of patent count return negative values of installed capacity as result. Precisely, by looking at the graph, we can see how the first eight predicted points (in red) through which the straight dotted line passes are negative. Hence, we can state that a linear predictive model cannot be applied to the relationship for a pure logical reason: the variables in play cannot physically be negative. The result shows that the relation cannot be approximated to a linear function. To conclude, the resulting linear relation, $y = 1{,}5442x – 70{,}725 + e$, is not to be considered representative.

The immediate consequence is that a different kind of equation has been looked for by using the same software to better show the connection.

Exponential, power, logarithmic and polynomial types of equation were tested, but the latter turned out to be the best one, thanks to its higher fit with the dataset compared to the others (highest R^2), and the absence of negative parts in the line. The outcome is a parabola graph resumed by the following equation: $y = 5E\text{-}6x^2 – 0{,}2678x + 8876{,}1 + e$. A very high value of R^2 is the proof of the previous choice, with precisely $R^2 = 0{,}999$.

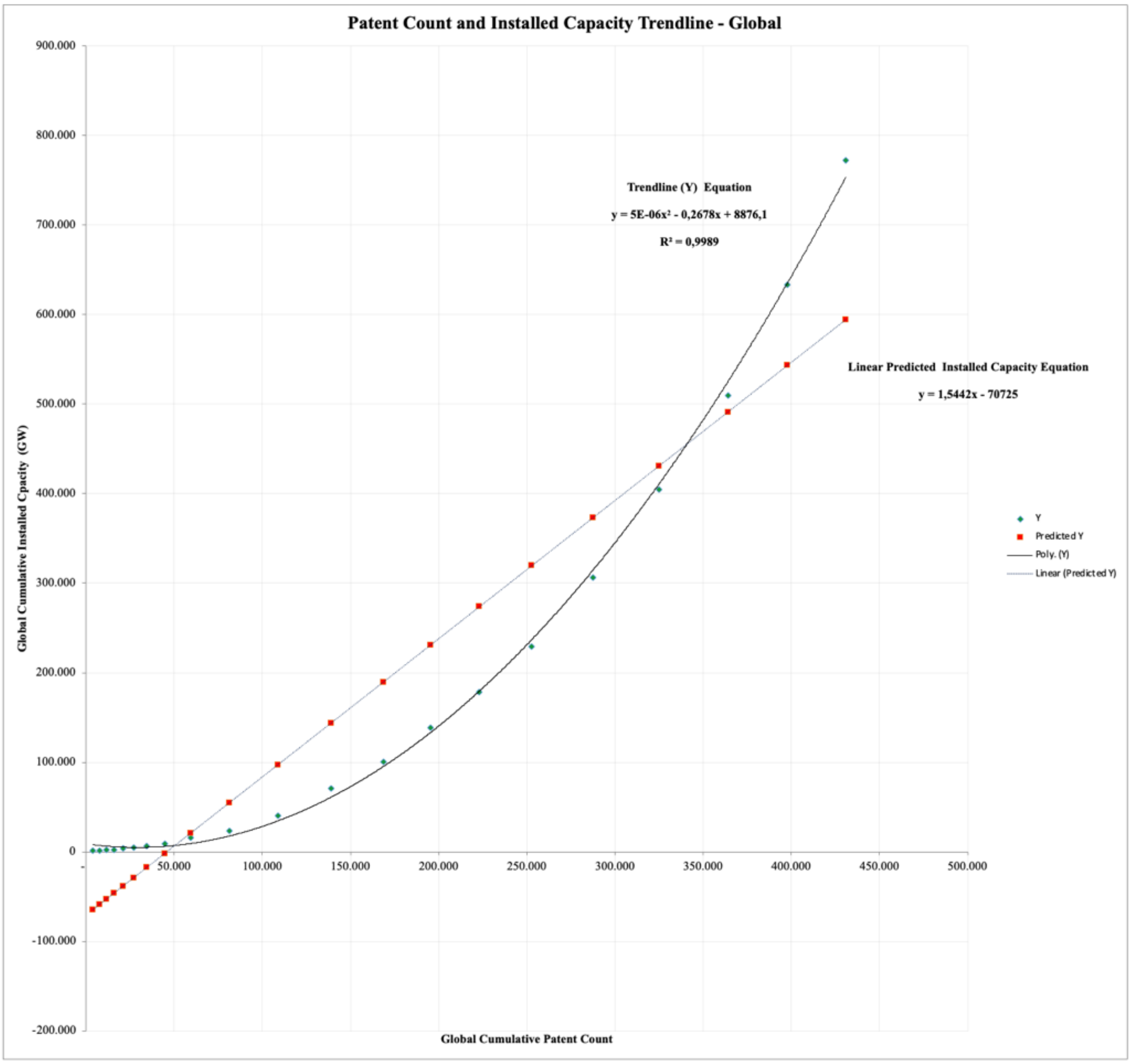

Image 4, regression analysis, PV cumulated patent count and IC worldwide, 2000-2020, own elaboration

The order or the function could have been increased to further improve its accuracy, but it was found not to improve the fit enough, since even by increasing it by four, the R^2 would have remained the same to the fourth decimal place. Hence, the order of equation representing the relation has been chosen to be two, which is for the author, the best compromise between simplicity and accuracy in this specific case.

Once obtained the parabola equation, two further analyses can be performed to get more insights on the model: first, we can eliminate part of the data, for example the last five points of the dataset, to make a prediction and verifying how good is our function; or we could slide the dependent variable in the dataset table by a number of years called Δt and then measure the lag effect.

The first process consists in deleting the last part of the dataset, running the linear regression, and observing the resulting equation associated with the trendline passing through the remaining points. Then we can use the original patent count values to feed them back to the newly obtained equation and see the margin of error that is returned. For instance, considering that we will delete the data relative to 2016 and on, we could run the model, obtain the equation, then substituting the patent count value for each year from 2016 and see how much the estimated installed capacity value is close to the original one. A negligible average percentage error is expected, since the R^2 is high, but empirical evidence will be used to confirm or reject this expectation.

In order to do this, the last five observations were cut off the dataset and a new regression was run on Excel to determine the new test function. The graphical representation of the latter can be found in image 5.

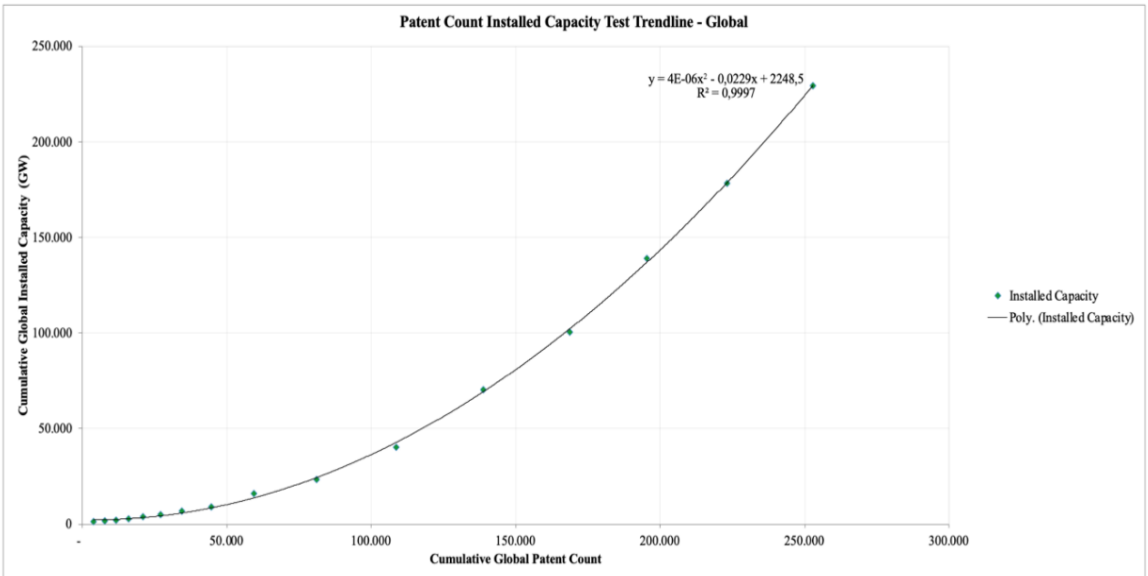

Image 5, regression analysis, PV cumulated patent count and IC worldwide test trendline, 2000-2015, own elaboration

The reiteration of the procedure previously used in the research of the most representative function for the relationship has been applied, and a polynomial function of order two was

chosen once again. The high R^2 value of 0,999 shows extremely good fit to the truncated dataset. Precisely, the written form of the equation is: $y = 4E\text{-}06x^2 - 0{,}0229x + 2248{,}5 + e$.
The next step is feeding the original patent count value to the software, by substituting it to the *x* variable in both the test function and the original function. Once the results are returned by excel, they must be compared to the original values of installed capacity to find the error. In the table below (table 17), we can see results of this test, considering that the test function is the one obtained by running the regression on the partial dataset, and the original function is the one coming from the complete dataset. Only the last five values (marked in yellow in table 17) of the dataset will be considered as representative, since the other sixteen have been used to train the test function.

GLOBAL SCENARIO

Year	Test Function Estimated IC (GW)	Original Function Estimated IC (GW)	Real IC Value (GW)	% Error Test Function
2000	2.219	7.928	1.288	
2001	2.313	7.095	1.615	
2002	2.522	6.441	2.069	
2003	2.904	5.873	2.635	
2004	3.531	5.457	3.723	
2005	4.545	5.290	5.112	
2006	6.201	5.583	6.660	
2007	9.233	6.905	9.183	
2008	15.032	10.632	15.844	
2009	26.700	20.043	23.185	
2010	46.997	38.820	40.336	
2011	76.219	68.122	70.469	
2012	112.121	105.886	100.504	
2013	150.383	147.327	138.856	
2014	196.294	198.065	178.391	
2015	252.175	260.810	229.300	
2016	326.094	344.941	306.500	6,393%
2017	417.476	450.163	404.500	3,208%
2018	523.969	573.961	509.300	2,880%
2019	625.774	693.165	633.700	-1,251%
2020	735.166	821.956	772.200	-4,796%

Table 17, global test function error measurement, own elaboration

The percentage error has been calculated for the test function, and the average value is equal to 1,287% for the test function. The value is very low, thus showing the accuracy of the function at predicting the future.
Calculating the error of the model, along with the previously mentioned R^2, is the chosen way to verify H1 in this research. Low average percentage error (at least lower than 10%) on a test function along with a high R^2 (at least higher than 70%) result is enough to prove it.
Since the R^2 value exceeds the expectations needed to confirm H1, and the chosen model performs well at predicting the future, we can state that the null hypothesis H01 is rejected: there is a solid correlation between global cumulative patent count and global cumulative

installed capacity (IC). Hence, H1 is accepted. In particular, the entity of the relationship is positive: increases of patent count cause increases of IC in a nonlinear way.

- Testing H3 - Global Scenario

Going on with the research questions, since we have tested H1 for the global scenario, the available data will allow us to investigate the existence of a lag effect between patent count and IC relationship, namely H3. In order to do this, the dataset has been manipulated by shifting the IC value by one, two, three and then four periods, thus obtaining the inputs for the regression analyses with Δt ranging from one to four years. To calculate the existence of a lag effect, the lagged datasets' regression trendlines should return R^2 values that are higher than the one of the original non-lagged datasets. We will not use Pearson's coefficient, since the relationship is not linear.

The results are the following:

- The dataset with Δt = 1 returned R^2 = 0,998
- The dataset with Δt = 2 returned R^2 = 0,996
- The dataset with Δt = 3 returned R^2 = 0,994
- The dataset with Δt = 4 returned R^2 = 0,995

Which, compared to the R^2 of the original dataset, equal to 0,999, show that it is not possible to confirm the presence of a lag effect, neither to confute it. This is because all four R^2 values are very high, despite being lower than the original one. The conclusion is that in this case, with the data and tools available, it is not possible to prove the existence of the lag effect, thus H3 is not confirmed for the global scenario. At the same time, for said scenario, it is not possible to reject the null hypothesis H03, since all of the results are strong numbers, showing that there might be a lagged relationship between the variables, but further analyses could deepen this topic by using larger dataset or different quantitative methods.

- Testing H2 – Italian Scenario

Moving on to the Italian dataset analysis, we can start by applying the same procedure that has been used before to find the best fitting function approximating the relationship between the variables. This time though, the presence of a static period in Italy, during which installed capacity did not achieve relevant progress, has forced the author to treat this database in a different way compared to the previous one. In order to keep consistency, the very low initial installed capacity values could have been converted from GW to MW, thus making the resulting function easier to work on. Alternatively, in order to keep consistency with the previous analyses already performed using the GW as a measure for installed capacity, a part of the dataset has been cut off. Precisely, data from 2010 to 2019 have been used to obtain the regression and its trendline. This way the analysis can focus on the effective development stage, without the slow technology testing phase influencing the results. Ten observations instead of twenty-one like in the previous analyses have the disadvantage of risking to be uncapable of making the research get useful insights on the relationship.

Once again, the best fit trendline was found to be the polynomial, with an R^2 of 0,994 and an equation written as follows: $y = -4E\text{-}5x^2 + 0{,}0949x - 38{,}687 + e$. The parabola was chosen also to keep consistency with the previously obtained trendline for the global dataset, and compared to the linear approximation, it also showed a better fit, measured by it high R^2 versus the same metric of the linear, equal to 0,8838 (red line in image 6).

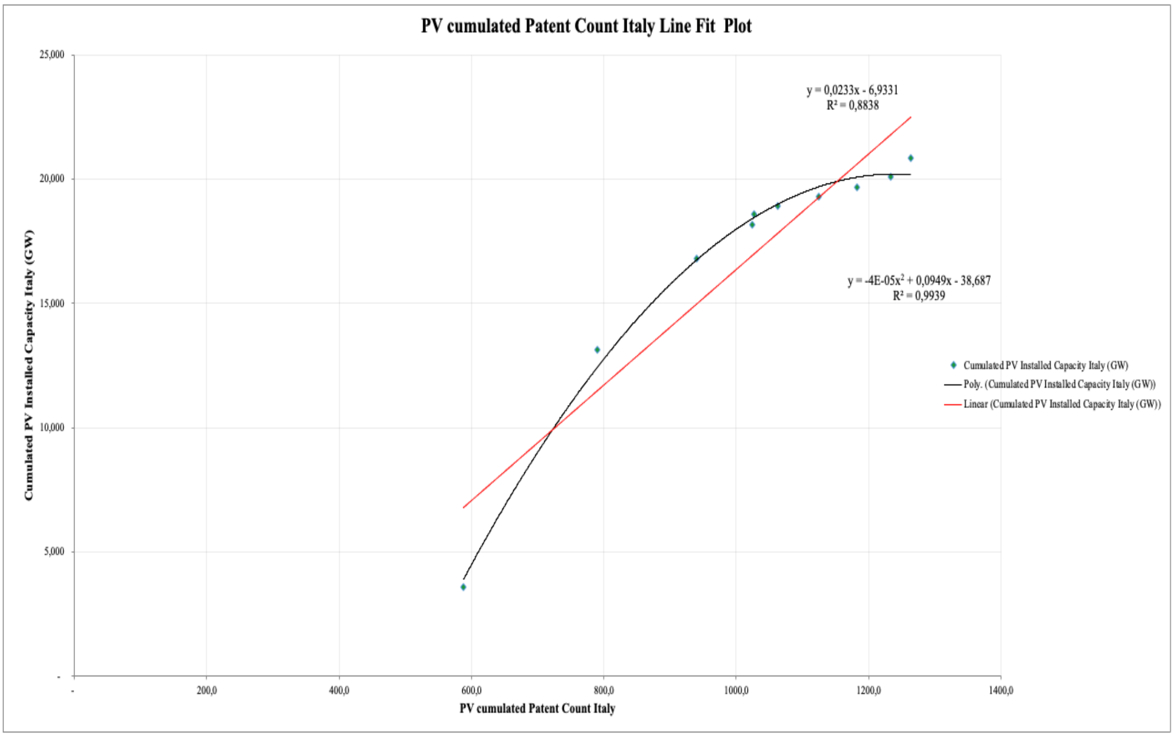

Image 6, regression analysis, PV cumulated patent count and IC Italy, 2000-2019, own elaboration

Just like in the case of the global dataset, the trendline fits very well the current dataset.

Furthermore, we must also recall that the dataset considered was way smaller than the global one, with negative repercussions on the reliability of the results when it comes to use them in actual forecasts and insights extraction. However, having at least ten observations like in our case keeps the reliability of the results still at an acceptable level for a regression.
It can be noticed that the graph in this case is a downwards facing parabola, and the vertex can be found in the same location of the last observation. Meaning that, according to this function, a descending trend is expected, like a sort of market saturation/decline. While the diminishing of installed capacity is in reality very unlikely, considering the existing policies and the whole plans to increase the use of renewable energy, from a statistical point of view this is justified by the very slow growth/stagnation of the last few years. This same stagnation brought the dataset to depict the relationship this way, and the model to predict future decline. The causes of the phenomenon will be analyzed more in depth in the next chapter and supported by economic data.

The next step at this point is measuring how well the model approximates the results and predicts the future, by calculating the average percentage error of both the original trendline and a test trendline, generated with a partial dataset. This time though, generating a test trendline with a total number of points which is very low: 10 in fact, would not produce reliable outputs, considering that we would have to split the dataset in half to train the model. Hence, another method can be used: a cross validation method called 'leave one out cross validation' (LOOCV). This method consists in training different models, as many as the number of observations (10 in this case), on the same dataset while excluding each time a single different observation. Then the error that each single function returns on its prediction of the corresponding excluded observation is used to get the average percentage error of the whole system. In this way, the lack of variety in the database is compensated and the results are reliable once again. Ten regression analyses have been run on excel, each one trained with nine values out of ten, each one excluding a different observation. Table 5.2 shows the results of the test, along with the various equations returned by the software. In said equations, 'y' is the dependent variable (installed capacity), and 'x' is the independent variable (patent count). The fourth and fifth columns show a comparison between the actual values of the dataset and the estimated IC for the corresponding year, calculated with the LOOCV method.

ITALIAN SCENARIO

Year	Year Out in LOOCV	LOOCV Function	LOOCV Function Cumul. IC estimate (GW)	Cumul. IC Real Value (GW)	Percentage Error
2010	2010	$y = -3E-05x^2 + 0,0678x - 24,377$	5,117	3,590	42,535%
2011	2011	$y = -4E-05x^2 + 0,093x - 38,262$	10,244	13,130	-21,980%
2012	2012	$y = -4E-05x^2 + 0,0946x - 38,579$	15,001	16,790	-10,655%
2013	2013	$y = -4E-05x^2 + 0,096x - 39,164$	17,197	18,180	-5,407%
2014	2014	$y = -4E-05x^2 + 0,0943x - 38,42$	16,237	18,590	-12,658%
2015	2015	$y = -4E-05x^2 + 0,0953x - 38,854$	17,251	18,900	-8,724%
2016	2016	$y = -4E-05x^2 + 0,0956x - 39,012$	17,907	19,280	-7,119%
2017	2017	$y = -4E-05x^2 + 0,0956x - 39,012$	18,102	19,680	-8,017%
2018	2018	$y = -4E-05x^2 + 0,0943x - 38,472$	16,988	20,110	-15,523%
2019	2019	$y = -4E-05x^2 + 0,1019x - 41,476$	23,418	20,870	12,208%

Table 18, model prediction error measurement with LOOCV, Italy, own elaboration

In said equations, ‘y’ is the dependent variable (installed capacity), and ‘x’ is the independent variable (patent count). The fourth and fifth columns show a comparison between the actual values of the dataset and the estimated IC for the corresponding year, calculated with the LOOCV method. The result is an average percentage error of -3,534%. Once again, the result is satisfying, since conventionally, a value under 10% is considered good. This means that the dataset used in the analysis is effective at making predictions.

As for H1, H2 can be confirmed too: the high fit of the trendline at representing the dataset along with the efficacy of the latter at predicting unknown values are enough to prove that patent counts affect IC in the Italian scenario.

- Testing H3 – Italian Scenario

Lastly, the lag effect has been analyzed in the Italian case too. The same range of Δt values have been applied: from 1 to 4.

The whole Italian dataset has been taken into consideration this time, since furtherly cutting it would have made the results completely unreliable. Moreover, there is no issue in measuring the lag effect of a relationship possessing a certain number of periods of stasis.

- The dataset with Δt = 1 returned R^2 = 0,952
- The dataset with Δt = 2 returned R^2 = 0,918
- The dataset with Δt = 3 returned R^2 = 0,869
- The dataset with Δt = 4 returned R^2 = 0,838

The original R^2 of 0,994 related to the original equation is still the highest, however, just like in the previous case, all of the four results coming from lagged datasets show high values for said metric. A change in the second decimal unit is not enough to confute the presence of a lag effect. On the other hand, high *r* values associated to the lagged ones are not sufficient to demonstrate the existence of it, considered the database and tools used. Hence, H3 cannot be confirmed, and the null hypothesis H03 for the Italian case cannot be rejected. Further research will likely be able to afford this topic more in deep: a larger dataset will be certainly of help, along with the future reports about new installed capacity in Italy in the following years.

6 Conclusions

6.1 Summary of Findings

The main objective of this research was finding the existence and entity of the relationship between a variable linked to the IP world such as patent count and another metric: the installed capacity of PV power plants, in order to create an instrument to be used to forecast the phenomenon in the near future on a global basis. Moreover, the author wanted to further investigate the relationship between the variables in the Italian context, and verify if, both on a global and local level, the presence of a lag effect would have been able to represent the relation more accurately or not. While this paragraph will focus on the statistical results, the next one will evaluate them in light of economic factors and policies affecting the industry.
To recap, the research questions tested in this thesis are:

H1. Cumulated global patent count in the PV industry is correlated with global cumulated PV capacity installed.

H2. Cumulated Italian patent count in the PV industry is correlated with Italian cumulated PV capacity installed.

H3. A lag effect affects the previous relationships.

The empirical analysis section is preceded by a part dedicated to illustrating how the global and Italian PV industry was moving, from a purely industrial point of view and from a patenting point of view. We noticed that, while some giants of the industry like China and

US are very active in this field, others have started their process of technology development later compared to the average. Italy perfectly fits in the middle when it comes to timing, and although not being a world leader, the country's technology has still much development to face and the resources and scenario (especially linked to the geographical conformation) could push the state in a preeminent position with the right execution. The true 'boom' of expansion of PV patenting activity and installation took place around 2008-2009, paving the way for an exponential growth for the future.

This said, starting from the global dataset findings, we tried to verify H1: global cumulative patent count is correlated with global cumulative installed capacity. After the analyses of the previous chapter, it can be stated that this first hypothesis is confirmed. As a proof for this, the results of this research show how well the function in image 5.1 represents the relationship, along with its impressive R^2 value of 0,999. The linear approximation model has been abandoned during the research because it returned negative predicted values, physically not acceptable, moreover, a linear approximation of the relationship is a brave assumption and its fit to the model was inferior to the one of the polynomial function.
Said parabola written as $y = 5E\text{-}6x^2 – 0{,}2678x + 8876{,}1$ (x is the patent count, y is the installed capacity) fits the dataset almost perfectly. Such high R^2 value suggests that the relationship is not just coincidental, but predictive, although it is not enough on its own to confirm causality. If fact, another test has been conducted.
As an additional proof, the model was tested to measure its efficacy at predicting how future changes in patent count could serve at forecasting installed capacity. The results showed once again that the dataset used is a good fit, since the average percentage error is 1,287% for the test function. This test function is a parabola just like the originally calculated one to keep consistency with the whole analysis, and its equation is $y = 4E\text{-}06x^2 - 0{,}0229x + 2248{,}5$. While its fit with the training dataset is reflected by an R^2 equal to 0,999.
This said, and as will be better specified in the limitation section, there are also many other factors influencing the progress of our variables. By considering both the model and real-world economic data such as policy programs, incentives and third sources forecasts, the predictive capability of the system can be furtherly judged too, as it will be shown in the managerial implications section.

Remaining on the global scenario, H3 was tested: the presence of a lag effect in the previous relationship. The installed capacity variable has been shifted in the dataset column by one to four years in the future, to simulate the relative number of years of lag.

- The dataset with $\Delta t = 1$ returned $R^2 = 0{,}940$
- The dataset with $\Delta t = 2$ returned $R^2 = 0{,}930$
- The dataset with $\Delta t = 3$ returned $R^2 = 0{,}921$
- The dataset with $\Delta t = 4$ returned $R^2 = 0{,}915$

Which, compared to the R^2 of the original dataset, equal to 0,949, show that it is not possible to confirm the presence of a lag effect, neither to confute it, since all values are similar. The consequence is that H3 cannot be accepted, nor strictly rejected.

Moving on to the Italian dataset, the testing of H2 started similarly to H1, but some complications were met along the way. The first decade of slow technology development contributed to leaving installed capacity metric at a low level. The real expansion started around the end of the first decade of 2000'. In order to obtain reliable results based on effective growth, and excluding the embryonal stage, the dataset was cut in half, with negative consequences on the reliability of the results, which still remains at an acceptable level (10 observations, considering the lack of data after 2019, while the global dataset went up to 2020). Regression analysis returned a parabola as the best fitting function without compromising simplicity and consistency with the global dataset. The R^2 of said equation is 0,994 and it is written as follows: $-4E\text{-}5x^2 + 0{,}0949x - 38{,}687$. The downwards facing parabola suggests future stagnation for our country, however, the result is purely linked to the mathematical entity of the analysis, and the implications section of this chapter will show why the future of PV cannot be forecasted this way in Italy. Since in the last few years the IC count has grown very slowly, or not at all, and the observations were just enough to consider the system minimally reliable, this trendline is statistically but not practically plausible. The fit is still excellent.
The lower observation number forced the author to use another method to verify the predictive capability of the trendlines used. The leave one out cross validation (LOOCV) method returned an impressive average percentage error of -3,534%. All ten regressions simulated with this method approximated the relationship to downwards facing parabolas, just like the original one, as a proof of consistency and solidity. Hence, H2 is considered,

statistically speaking, confirmed, thanks to the high fit of the original trendline to the dataset and the excellent predictive capabilities of the test functions, all very similar to the main one.

The measurement of the lag effect on the Italian dataset returned results which are very similar to the global one. The whole dataset has been used this time, since the column shifting procedure would have caused some observations to be lost in the process, thus making the results completely unreliable. Moreover, there is no issue in terms of reliability in using a dataset with static periods to measure the lag phenomenon. Lags of one to four years have been simulated once again; results will follow:

- The dataset with $\Delta t = 1$ returned $R^2 = 0{,}944$
- The dataset with $\Delta t = 2$ returned $R^2 = 0{,}889$
- The dataset with $\Delta t = 3$ returned $R^2 = 0{,}823$
- The dataset with $\Delta t = 4$ returned $R^2 = 0{,}757$

Just like the global scenario, the output does not allow us to confirm, neither reject the H3 hypothesis of the existence of this lag effect once again.

The following paragraph will put the statistical results in combination with the political economic shaping the sector in the next years, and extract insights from them from a practical point of view.

6.2 Managerial Implications and Insights

The investigation regarding the entity of the relationship between patent count and installed capacity in the PV industry analyzed in chapter 5 produced two main results: the confirmation of the existence of a correlation between the variables, and a model which has been proven to be effective at forecasting the future. This is the main point of attention in this section. Using patent data as proxies for the measurement of industry development and innovation is, as seen in the literature review section, a commonly accepted practice. Companies may find predictive models useful to evaluate the possible paths to follow and adapt their strategy accordingly. Patent data have the intrinsic advantage of being immune to bias and publicly accessible worldwide thus making them a powerful analytic metric. Government institutions could benefit from the results of this study too, since by incentivizing the production of new IP, among other levers, could be an effective way of developing the PV sector and meet the

objectives of international treaties, along with safeguarding the environment and increasing their energetic independence.
However, comparing the purely statistical results and the resulting trendline's equation to real world data could allow us to read the results with greater awareness about their effective possible applications and efficacy.
While the growth rate of both patenting activity and installed capacity still looks impressive according to the trendline found while testing H1 in the global scenario, we must also consider that many incentives came into play to safeguard and encourage the development of the sector, thus making such high growth perspectives realistic, at least for the next few years. From the IP point of view, treaties like PCT and TRIPS allowed inventions to be safeguarded all over the world and standardized the procedures and requirements. International and governmental organizations like the WIPO, EPO and USPTO are another warranty for new investors in renewables, who want to see their projects realized but at the same time reap profits with an adequate protection and set of rules. We have also seen how IP rights are proven growth drivers and metrics like patent count are synonyms of innovation. Technologies like PV strongly depend on them, mostly of trade secrets and patents.
On the environmental and political side, we have the global issue of climate change. Governments and international organizations have been setting goals in last decades to fight this phenomenon. The UNFCCC is a clear example of this, along with treaties like Kyoto and Paris, and the most recent 17 sustainable development goals by the UN, containing measures against global warming. Other energy centered programs like REPowerEU, the Green Deal and the IRA are an additional reason to believe in future growth of REs, and PV among them.

In light of the previously mentioned political economic factors, sustained growth is still likely the trajectory for the upcoming years.
The simulated polynomial function forecasting IC on a global basis, starting from patent count supposes continuous growth perpetually. This is clearly a sign that the predictive power of the model is not supposed to last forever because the variables cannot physically grow indefinitely.
Understanding the exact validity of the system in terms of time is not the objective of this research. Anyway, some factors can help at least in giving a general idea of it. Historical data about sector growth is the first instrument that could be used to assess it.

On average, PV installed capacity has grown by 39% each year from 2000 to 2020, while patent count relative to the PV industry went up by 28%. In the recent years though, a slight percentage growth decrease can be noticed, but we must consider that absolute values are still very high, since the industry has reached an advanced level of development and is not set to stop growing.
Given the context and the analyzed trendline, from the point of view of companies that both deal with research and PV installations and use, it might be useful to focus on R&D and still dedicate enough resources to the physical expansion of IC to optimize their growth. The optimal level of patenting activity will not be treated in this research but reaching it will give companies the best ratio between installed capacity, IP ownership and productive efficiency. Patenting activity can also be used to forecast IC with the goal of estimating the future saturation level of a market. Market targeting strategies might also get benefit from the awareness of the relationship between these metrics: companies could target a low IP local market with high growth potential to establish a presence in it and anticipate the competition. And just as businesses could try to identify the best compromise between investing in patenting activity or direct production, authorities could base incentive campaigns on such data. It has to specified that patent metrics are clearly not the only variables influencing the industry, a greater knowledge of the context is still necessary to take investing and policy decisions.

The lag effect analysis did not bring relevant discoveries to the table both in the global and the Italian scenario. Finding the existence of such phenomenon could have produced interesting insights on the forecast trendline, which should have been watched from a different point of view. The existence of a lag effect in fact could influence the decisions of companies and policymakers in light of the delay. The investments decisions change considering the technology diffusion timing, requiring more anticipation in case of a lag effect.

Lastly, the Italian dataset produced interesting results, since, strictly mathematically, stagnation is expected. However, taking into account the issues of the model like the lack of many observations and the fact that a brief stagnation brought the system to anticipate decline, the forecast trendline is not to be considered reliable for the author. The reasons of this statement can be found in economic prospects and the political outlook. As previously mentioned, government authorities are working on the expansion of all renewable energy sources. Moreover, the last observation in our analysis was already announcing a steep growth movement of the IC and patent count. Public policy measures are currently driving the sector, such as outright incentives and tax benefits. European Regulation 2022/2577 also contributed during the last months at reducing the bureaucratic procedures needed to develop renewable power plants.

Recent statistics prove that Italy surpassed 25GW of PV installed capacity in 2022 and 26GW in 2023 (Terna, 2023). This is additional proof that the industry is still growing fast in this country.

The realization of an effective approximation system linking patent counts to installed capacity in Italy will likely benefit both companies and authorities in the same ways it does in the case of global data, as an additional forecasting instrument available.

6.3 Limitations of the Study and Future Research

The main potential downfalls of this study are the relative lack of data, the impossibility of patent count variable to be weighted adequately and the presence of confounding factors.

Starting from the first point: the most robust dataset used, which is the global one, contained observations ranging from 2000 to 2020. 21 observations are still enough to create a reliable regression analysis, but having even more of them would have given a better image of the trend and increased the trendline's reality trueness. The Italian dataset on the other hand has the minimum number of observations needed for the study to be considered valid. This made the resulting model relatively weak and, as verified before and contrarily to the global one, not effective at predicting the future. Consistency among the data sources has been preserved, and this is one of the reasons why the two datasets, even if small, are reliable and all the entries of a single variable are gathered from the same source.

Future research could fill this gap by gathering longer historical series of data thanks to both more advanced resources, and the passing of time itself, which makes more data available. Especially in the case of the Italian scenario.

Another weakness is the characteristic of the patent count variable itself of not being possible to be weighed against the value and entity of the innovative step underlying each single patent document. Future analyses considering this element would be much more accurate if well performed, but patent evaluation is a resource intensive process which is also subject to non-unique results due to different evaluation methods chosen by the researchers.

Future studies analyzing the cause effect relationship between patent count and installed capacity could also bring to the table new instruments useful not just for forecasting events, but also to be used as potential levers by policymakers.

The literature review section contains the proof that patent count is not the only variable in play when it comes to influencing installed capacity. The consequence is that the resulting model cannot explain the variation of the dependent variable in a one-to-one scale, and part of the observed relationship might be influenced by chance. The other variables in play are for instance, the government policies, the climate of each country, economic metrics (GDP, financing rates, inflation, occupation), the resources available and their prices. A much more complex model considering multiple variables could return impressively accurate results, which would be both closer to the real-life scenario and powerful as predictive instruments.

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of Business and Management

Course of Management

Intellectual Property Rights and Renewable Energy Technologies: Patent Data as Proxies of Photovoltaic Industry Development

Prof. Massimiliano Granieri
SUPERVISOR

Prof. Ian Paul McCarthy
CO-SUPERVISOR

Niccolò Bagnara ID no. 747661
CANDIDATE

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Summary

1. Renewable Energy in 2023: Diffusion and Future Perspectives

1.1. Global Unsustainability Issue

Being aware of the causes and effects of climate change is necessary to appreciate the importance of renewable energy technologies (RETs) and their development.

According to the latest data published in the United Nations Climate report (2023), the biggest cause of global warming is attributed to the use of fossil fuels, which together contribute more than 75 percent of global greenhouse gas (GHG) emissions and about 90 percent of global carbon dioxide emissions (CO_2). CO_2 is naturally part of the air we breathe, and its presence inside the atmosphere is not bad per se: the problem is that this concentration is getting too high. This greenhouse gas traps the sun's heat, too much of it and we get climate change, with a series of cascading effects on our ecosystem and our everyday life.

Six main causes have been identified: first of all, among culprits of climate change, the UN mention the generation of power. The reason is that we are heavy users of coal, oil, and gas as sources of electricity. These sources, as mentioned before, have a negative impact on the environment. By giving a look at the reports regarding energy consumption, we can notice an upwards trend, with the major energy consumers being China (26%) and the US (15%). Deforestation is the second cause according to the UN. This is because plants absorb CO_2, which is then released into the air once it is destroyed for land exploitation activities. Food production also contributes to global warming for reasons that are linked to deforestation itself, the creation of monocultures, the transport of food products through very high emission boats and planes, the use of fertilizers, direct emissions related to livestock and finally the packaging of finished products. Livestock farming is a major source of pollution, requiring land, food and directly producing methane. Continuing with the causes of climate change, we have transport: whether sea, land, or air, private or public, most of it is still powered by non-renewable energy (UN, 2023). The manufacturing industry is also involved. Nonrenewable sources are the main providers of energy. Similar to the food industry, the lifestyle of an increasing number of more demanding consumers requires companies to produce substantial volumes, which must be supported by adequate flows of raw materials and energy. Another source of pollution is consumption related to the power supply of homes. Linked to the increase in the population and its needs in terms of comfort such as temperature control systems, connected devices and smart home technologies (UN, 2023).

Turning now to the consequences of climate change, one cannot help but briefly mention rising temperatures, storms, droughts, rising oceans, biodiversity loss, food shortages and related health risks. These phenomena in turn change our economy and will keep doing so.

Now consider the first of the impacts: global warming. This phenomenon does not occur uniformly in our globe, but is concentrated above all in the ocean (IPCC, UNEP, WMO).
More powerful and intense storms are another effect, linked in particular to temperatures.
The rise in temperature is also causing an increased risk of drought, which is becoming a problem especially in countries that are naturally poorer in water. This effect in turn causes problems for the agricultural sector, with the enlargement of the areas covered by deserts, the displacement of large masses of sand and the alteration of ecosystems (UN, 2023).
The rise of the oceans is also dependent on the increase in temperature: the waters rise not only because of the melting of the glaciers, but also because their volume increases with the increase in water temperature. Loss of biodiversity is the fifth of the consequences that we are going to consider: at the moment the loss of both terrestrial and aquatic animal and plant species is taking place at the highest rate ever, about a thousand times higher than any other value ever recorded. The lack of food presents an important issue and a challenge for the coming years as much as the production of energy: the sea absorbs pollutants thus becoming more acidic and inhospitable for many species, desert areas advance with consequences on crops and livestock that are supplied from those crops. The yield of crops decreases as nutrients in the soil decrease, of available water and increasing thermal stress (UN,2023). Health risks and poverty are linked to the climate change through the previously mentioned phenomenon of pollution, poor nutrition, droughts, and catastrophic natural events. People who live in countries made unhospitable by climate change are forced to spread across the globe, often in very precarious situations. The consequences are both physical and psychological (UN, 2023).

1.2. Political Outlook

Climate change is a global issue and cooperation is key to fight it.
The first international convention specifically created to address the negative effects of climate change is the United Nations Convention on Climate Change (UNFCCC), which entered into force in 1994. The UNFCCC has currently 197 Parties who agreed on its conditions, with the whole European Union counting as one. The convention is specifically constituted to reduce greenhouse gas emissions and it has paved the way for two of the most important treaties against climate change: Kyoto (1997) and Paris (2015). The Kyoto Protocol was adopted in 1997 and has been ratified during one of the annual Conventions of Parties (COP). It is a legally binding treaty stating that the Parties involved (currently 192) have “common but differentiated responsibilities and respective capabilities” meaning, as mentioned before, that every country should contribute to reduce emission based on its previous emission history and its resources.

The Paris Agreement is the successor of the Kyoto Protocol and was adopted in 2015 during the COP 21. This is the first universal agreement and sets the clear objective of limiting global warming to maximum 2 Celsius, with a more ambitious option to keep it around 1,5 degrees.

1.3. REPowerEU, Green Deal, IRA

The European Union has decided to promote the project with the objective to face the worldwide energy market disruptions caused by the Russian invasion of Ukraine and is intentioned to do so by diversifying its energy providers and investing heavily in renewable energy sources inside its boundaries.

The European Green Deal, presented in the end of 2019 for the first time, is a comprehensive policy framework involving the members of the Union, to reduce emissions of 55% compared to 1990 levels by 2030 and make the EU carbon neutral by 2050.

From the clean energy market point of view, this plan contained an objective of 40% of the overall energy production from renewables in 2030. The overall framework has also the objective of permanently reducing the energy consumption by eliminating waste and decarbonize the industrial sector as much as possible.

In 2022, the REPowerEU plan was approved, thus allowing member states to implement it into their individual recovery and resilience plans. During the Ukrainian conflict, energy prices have seen a huge increase: among the plans of the REPowerEU we have the reduction of them by internal production, and solar will be crucial. The EU Solar Energy Strategy is expected to create 320 new GW of solar photovoltaic by 2025, and 600 GW by 2030.

United States have also recently decided to address the issue of sustainability: the Inflation Reduction Act signed in 2022 by President Joe Biden has in fact the objective to fight inflation and climate change by investing in clean energy production and emission reduction. This is an ambitious plan with the ultimate goal of reducing carbon emissions of 40% by 2030, among other socially useful achievements to be made in the medical care field.

1.4. RE Technologies Overview

Countries are moving towards sustainability not just to become more independent from one another or to preserve the planet, but also because it is becoming more convenient thanks to the increasing costs of fossil fuels and to the refinement of the production processes of green power plants components. According to a study (IEA, 2022), the share of renewable electricity generation reached 28% worldwide in 2021, and following the information from the previously mentioned report, it is expected to reach 38% of the total in 2027. This rapid expansion is also boosted by favorable policies, regulations, and market reforms from the leading economies. Renewable energy sources are solar, wind, bioenergy, biofuels, geothermal, hydropower and

ocean. They can be replenished naturally and, differently from the nonrenewable ones, can be used continuously without being depleted. Each type of RES has its own corresponding RETs.
Solar PV systems use solar cells made from semiconductors to convert sunlight into electricity. These solar cells are arranged in modules connected with each other into a solar panel. Solar light hitting the panel is then converted into electricity, and it also works in cloudy environments. At the end of 2020 the capacity installed reached 710 GW, 125 GW more than the previous year, making it the fastest expanding renewable energy source (Irena, 2021). This capacity is set to triple over the next few years: by 1500 GW by 2027, thus exceeding both coal and gas, which are on the contrary slowing their expansion (IEA, 2022). Prices are also making it even more affordable since they fell by 93% in the period between 2010 and 2020 (IRENA).

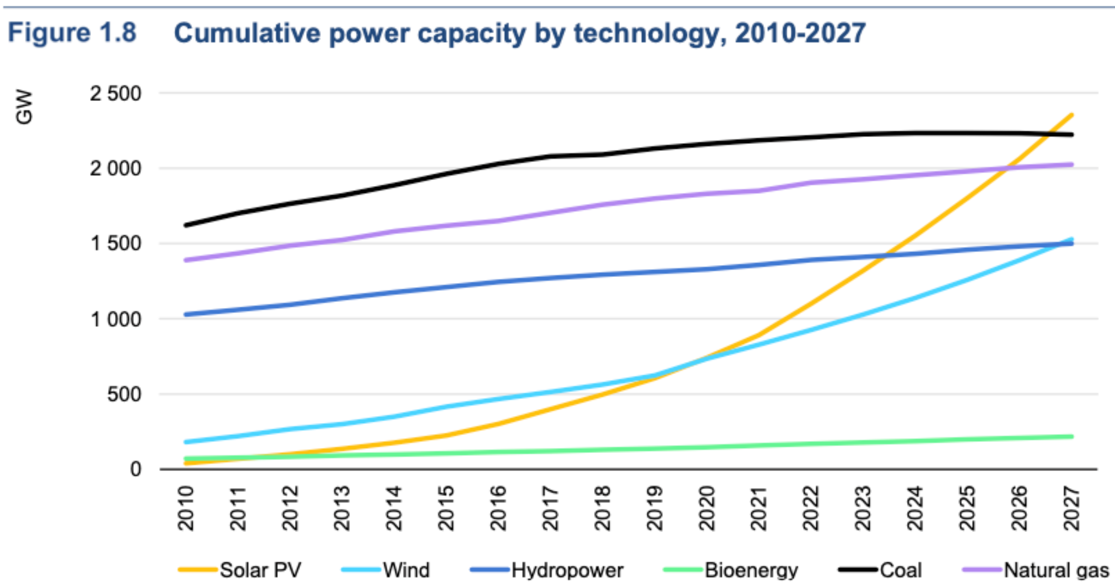

Table 1: Cumulative power capacity by technology (IEA, 2022)

Hydropower tech allows the harnessing of falling or running water to generate electricity. In 2021, hydropower contributed to the total installed renewable energy capacity by around 1,2 TW over a total of around 3,1 TW (Statista, 2023, REN21, 2022). China is the leader.
Wind energy converts the kinetic power of wind in electricity by using onshore and offshore turbine. In the last twenty years the technology has seen an increase of more than 100%, reaching around 750 GW of installed capacity in 2021 (Statista, 2023, GWEC, 2022).
Ocean energy uses the power of the ocean to generate electricity. Water columns, oscillating converters, overtopping converters, semipermeable membranes are examples of hydro RETs.

Traditional bioenergy technologies are energy production systems that imply the use of biomass (organic matter deriving from plants or animals) to produce energy through a variety of different methods, such as gasification, pyrolysis, combustion, and anaerobic digestion.
Biofuel technologies on the other hand employ biomasses in order to produce biofuel, which is in turn used to fill compatible transportation vehicles.
Bioenergy currently covers around 10% of the total primary energy supply worldwide, and it is expected to remain constant in the next years as percentage (Statista, 2022, Bohlsen, 2020).
Geothermal energy is generated by the heath located beneath the Earth surface. The main advantages are that the energy input is constant, emissions are low, does not use much land and it is cost efficient. Moreover, initial costs are high since plants are expensive and so is drilling. Because of the lack of adequate policies and high resource exploration risks, this RET is expected to only increase by 6 GW of total installed capacity by 2027 (IEA, 2022).

1.5. Focus on Photovoltaic Technologies

As seen in the previous chapter, solar PV is set to be the most important technology worldwide in the energy transition and it will be the growth leader in sustainable energy along with wind energy in the next years (IEA, 2022). Its expansion will be driven particularly thanks to the REPowerEU and the Inflation Reduction Act, along with the 14th Five Year Plan from China.
The first time the photovoltaic effect was observed was 1839, when the French physicist Alexandre Becquerel. In 1877 in fact, a professor called Adams and his student Richard Day created the first device of this kind using selenium, for an overall efficiency of just 0,5%. The real breakthrough though happened in 1939, when Russel Ohl replaced selenium with silicon. In 1958, NASA launched a program where they were used as a power source, and a few months later, Sputnik-3 was equipped a photovoltaic panel and launched by the Russian space agency.
In the 70s, a Comsat employee successfully increased efficiency of panels by 50% and left the company to found one of his own called Solarex. The oil crisis furtherly increased the interest for photovoltaic technology. Polycrhistalline silicon and amorphous silicon replaced the monocrystalline silicon because of cheaper production costs. Continuous incremental innovation brought the widespread diffusion of silicon-based cells with wafer-based ones.

2. IP Rights and Renewable Energy Technology: Literature review

2.1. IP Rights Brief Overview and Legal Framework

Intellectual property (IP) is a form of protection of newly generated knowledge volved at encouraging innovation by the means of exclusion. Intangible assets are the object of IP protection, covering aesthetic creations, inventions, domain names, plant varieties and commercial names (Granieri, 2022). This kind of property enables the owner to exploit it in two different ways, which can in many cases be complementary: direct use and indirect use.

Direct use implies the utilization of the creation. The second use is based on licensing of the IP to third parties. Diverse forms of protection have been instituted to preserve knowledge creation: the most important ones are patents, trademarks, copyrights, and trade secrets.

Patents are form of protection awarded at a national level, however, the coordination among countries is strong in this matter and many international treaties ensure inventors the safeguard of their work. The Paris Convention for Protection of Industrial Property is the first example of an international attempt to coordinate the discipline. The rationale of the agreement was providing applicants the same IP protection in each participating country, thus harmonizing the framework. The Patent Cooperation Treaty (PCT) is another relevant agreement signed in 1970. This time the objective was the procedure.

An important institution treating patents is the European Patent Office (EPO). created in 1973 with the Munich Convention. the Office issued the European Patent Convention (EPC), a framework which harmonizes procedures and administrative activities. The next important convention in temporal order is the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS), signed in 1994. The treaty was part of a set of agreements by the World Trade Organization (WTO). Patents in particular have now to be granted by parties, given that the underlying invention is useful, non-obvious and new.

Another relevant treaty is the Patent Law Treaty (PLT), which came into force in 2005. The intent was to standardize and streamline patent procedures, but also clearly stating substantive patent law rules. In order to qualify for protection, the patentable object must have three attributes: novelty, inventive step, and industrial application, as stated by the EPC.

2.2. The Debate on IP Rights as Growth Drivers in RE Technologies

The debate among scholars about IP being beneficial or detrimental to the development of the underlying technologies is till open, and different lines of thought have emerged during the years. Strong IP protection encourages investments, boosts the efficiency and efficacy of R&D departments in companies (Hall et al., 2010) and amplifies knowledge diffusion through licensing agreements (Ockwell et al. 2010). On the other hand, exclusion through IP, according to literature causes the loss opportunities of improvement of existing inventions for the fear of infringements (Bessen & Meurer, 2009), the excessive increase of prices of patented technologies (Lerner & Tirole, 2003), market concentration (Murray & stern, 2007), and impossibility of market entry for SMEs due to sometimes prohibitive patenting and enforcement costs. Diverse studies about IP and PV technologies demonstrate that this specific RET has characteristics in line with the rest of the industry when it comes to IP influence. The next papers will serve as proof of this statement, thus implying that such characteristics, which are related to patent data in some studies could be used as a basis to start from when trying to generalize the application of the relations at the center of this thesis.

The link between IP protection and higher profits for inventors is in fact observed in the PV sector too. These higher profits serve, again, as an additional incentive to innovate even more and expand the diffusion of the technology itself. According to the literature, it can be noticed that PV technologies which are protected by IP can serve as collateral for loans to be reinvested in the practical realization of the projects themselves. Licensing to developing countries is a real thing in PV too, well as patent thickets. Compulsory licensing is, according to the book, one of many solutions proposed to fight climate change.

3. Conceptual Framework

3.1. Research Question

As we know, patent procedure generally precedes the realization of the technology itself, in order to protect it. It must also be said that, as we will see in the next literature, installed capacity depends on many other factors than patent counts, and inside the IP world itself tools like trade secrets play a crucial role, with the drawback of not being accurately quantifiable.

H1. Cumulated global patent count in the PV industry is correlated with global cumulated PV capacity installed.

H2. Cumulated Italian patent count in the PV industry is correlated with Italian cumulated PV capacity installed.

H3. A lag effect affects the previous relationships.

3.2. Previous Studies and Hypotheses

According to the previously conducted studies, patent count is one of the most effective proxies to measure innovation in a specific sector. Now, it has to be said that the choice of patent count and installed capacity for our study have a precise meaning. The result of policy decisions, the sentiment of the investors, safety regulations and the intrinsic characteristics of each economic system or country have an effect on the patent landscape, which, in turn, influences the development of technologies. The last step in this system of cause-effect relations, from the point of view of IP and RETs, is the measurement of the effective installed capacity or, alternatively, energy consumption or production. Installed capacity has therefore been chosen by the author over energy consumption, since it better reflects the potential of energy production in the future, and it is less affected by events like for instance, a pandemic in the case of consumption, and climate conditions in the case of production. Harnoff et al. underline the role of patents in innovation: the authors consider patents as boosters for R&D and hence a good element to encourage new inventions. The choice of the independent variable in this last case lays its bases on a study by Griliches (1990), who observed how patent count is positively correlated with R&D

spending, thus making it a perfect proxy for innovative activity, independently from the industry. “Effects of policies on patenting in wind-power technologies” (Schleich et al., 2017) shows that patenting activity is positively correlated with R&D expenses and the installed capacity in the analyzed countries. In particular, policies related to the achievement of certain total capacity thresholds tend to encourage patenting activity, which in turn contributes to the effective development of the wind energy power plants. Another important discovery for this study consists in the findings by Zheng et al. (2021): the researchers used patent count to measure innovation level and have conducted a study about how this metric has a positive impact on renewable power generated on a certain territory and the provinces surrounding it. Since power generated is physically dependent on installed capacity, the hypotheses of this study strongly rely on this research.

4. Research Methodology and Model Creation

4.1. Data Collection and Elaboration

The data regarding the patents have been retrieved thanks to the International Renewable Energy Agency’s (IRENA) portal, in a section dedicated to International Standards and Patents in Renewable Energy (INSPIRE). Statista has been chosen as information provider for the installed capacity metrics across the last twenty years.

4.2. Patent Landscape and Market Data

A quick overview of the market and the patent landscape in the photovoltaic industry is necessary as an introduction for the next paragraph: it will work as a framework from which useful insights will be extracted. First of all, we can start from the total amount of primary energy covered by renewable sources around the globe. The situation is drastically different depending on the country. Most countries don’t even reach the 50% level of total energy production from renewable sources. Globally, the energy market is still largely dominated by fossil fuels, with more than 80% of the energy consumption coming from them. Oil is still the most important among them, followed by coal and gas. Hydroelectric energy is on the other hand the greatest contributor among the renewable energy sources to the energy mix.

Moving on to the situation in Italy, since this country will be compared in the following patent focused analysis, we can notice from the graphic that by 2021, 18% of primary share was satisfied by renewables, with a population of 60M. Moreover, Italy is the third largest producer of renewable energy in Europe. The geographical conformation of the country is in fact a valuable resource in this case: the north being excellent fit for hydropower, the south for photovoltaic, the center-south for wind farms and some regions for geothermal energy too. While our country is a leader in hydroelectric, the other renewables are still very important. Photovoltaic, for instance, has seen a rapid growth in the last few years thanks to the steep decrease of the levelized cost of energy by more than 80% in a decade. Sustainable sources satisfy more than a third of the 320-Terawatt hours of electricity needed yearly in this country. 42% of the total comes from hydro, 20% of it is produced with photovoltaic, and 16% with wind power. Another reason why photovoltaic is so relevant in Italy is the value of investments dedicated to it in the last years. In fact, PV technologies have received the greatest amount of invested money among renewables in 2021. Public support to the sustainability cause, major improvements in existing technologies, the emerging of new inventions related to energy and enabling tech, more and more private organization focused on the theme all contributed to the flourishing of the industry.

Let's now give a look at the main players in the RE industry. As for April 2023, the pure renewable energy company with the highest market capitalization is NextEra Energy Inc, with $ 159B. The Spanish Iberdrola takes the second place, followed by the Danish Orsted.

China is the most active issuer of patents, followed by USA, Japan, Korea, Germany, Canada, and Australia. Although, while reading these data, we must consider that number of patents is not directly proportional to the effective magnitude of innovation happening in a country, since other factors such as policy may encourage filing of many different patent documents even for small inventions. The most popular application of PV technologies is in the power generation sector. The building sector takes a smaller percentage: 12%. Waste sector patents, make up for the rest.

4.3. Model Shaping and Research Methods

The temporal precedence logic suggests that patent count comes first in the cause affect relation, since patents are usually filed before the technology is put on the market. This will be the independent variable in the model. Regression analysis will be used to assess the entity of the relation between the variables. Test regressions will be used to estimate the predictive capabilities of resulting models with training datasets. High fit of the resulting function (at least R^2 higher than 0,70) with the dataset, along with high predictive capabilities of the model (at least 10% or less average percentage error) will be considered enough to prove the existence of a correlation.

The lag effect will be investigated by using the R^2 of the best fitting function in case of nonlinear relation, and with Pearson in case of a linear one. A significantly lower fit of lagged datasets will be considered as a proof of nonexistence of the phenomenon, while the opposite results will be enough to confirm it.

Table 11 contains the global dataset, with the cumulated PV installed capacity on one column, measured in GW, and cumulated PV patent count on the other. Table 14 contains the same kind of data, this time exclusively for the Italian scenario.

Year	Cumulated PV Installed Capacity Worldwide (GW)	PV cumulated Patent Count Worldwide
2000	1.288	3.813
2001	1.615	7.782
2002	2.069	11.610
2003	2.635	15.981
2004	3.723	20.997
2005	5.112	26.992
2006	6.660	34.428
2007	9.183	44.748
2008	15.844	59.466
2009	23.185	81.099
2010	40.336	108.670
2011	70.469	138.880
2012	100.504	168.622
2013	138.856	195.325
2014	178.391	223.134
2015	229.300	252.842
2016	306.500	287.414
2017	404.500	325.066
2018	509.300	364.025
2019	633.700	397.691
2020	772.200	430.925

Table 11, own elaboration

Year	Cumulated PV Installed Capacity Italy (GW)	PV cumulated Patent Count Italy
2000	0,02	8
2001	0,02	15
2002	0,02	25
2003	0,03	37
2004	0,03	51
2005	0,04	68
2006	0,04	93
2007	0,11	155
2008	0,48	241
2009	1,26	409
2010	3,59	588
2011	13,13	790
2012	16,79	940
2013	18,18	1.024
2014	18,59	1.027
2015	18,90	1.063
2016	19,28	1.124
2017	19,68	1.182
2018	20,11	1.233
2019	20,87	1.264

Table 14, own elaboration

5. Results

5.1. Key findings and Effectiveness

Testing H1 - Global Scenario - The regression analysis tool available on Excel has been applied to the dataset in order to show what is the relationship between the two variables and, subsequently, calculate the predictive potential of the resulting function and its error margin. by looking at the graph (image 4), we can see how the first eight predicted points (in red) through which the straight dotted line passes are negative.

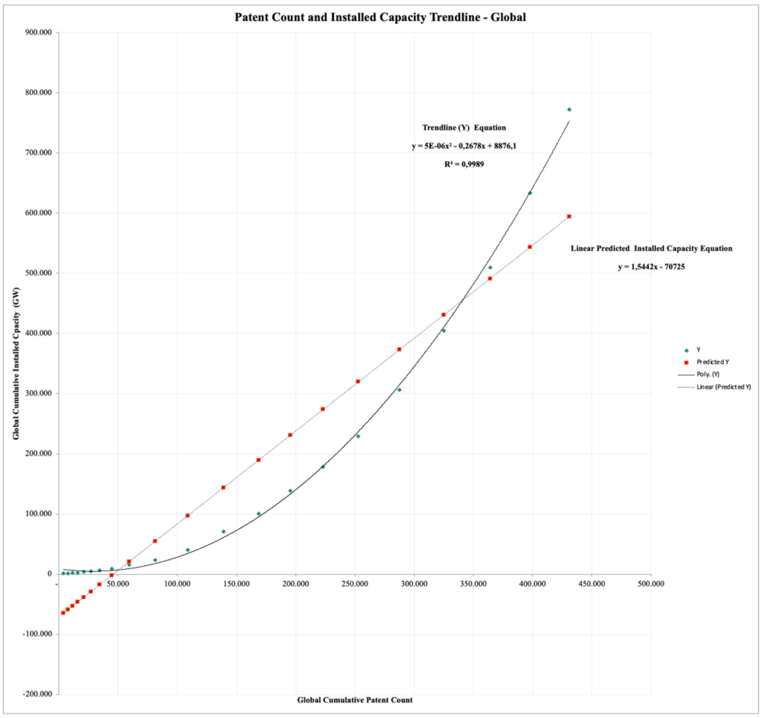

Image 4, PV cumulated patent count and IC worldwide, 2000-2020, own elaboration

The result shows that the relation cannot be approximated to a linear function. The outcome is a parabola graph resumed by the following equation: $y = 5E\text{-}6x^2 – 0{,}2678x + 8876{,}1 + e$. A very high value of R^2 is the proof of the previous choice, with $R^2 = 0{,}999$.

Then last five points of the dataset were eliminated, and the rest used to make a prediction and verifying how good is our function, like a training dataset. Regression analysis was used, and a polynomial function of order two was chosen once again. The high R^2 value of *0,999*.

Year	Test Function Estimated IC (GW)	Original Function Estimated IC (GW)	Real IC Value (GW)	% Error Test Function
2000	2.219	7.928	1.288	
2001	2.313	7.095	1.615	
2002	2.522	6.441	2.069	
2003	2.904	5.873	2.635	
2004	3.531	5.457	3.723	
2005	4.545	5.290	5.112	
2006	6.201	5.583	6.660	
2007	9.233	6.905	9.183	
2008	15.032	10.632	15.844	
2009	26.700	20.043	23.185	
2010	46.997	38.820	40.336	
2011	76.219	68.122	70.469	
2012	112.121	105.886	100.504	
2013	150.383	147.327	138.856	
2014	196.294	198.065	178.391	
2015	252.175	260.810	229.300	
2016	326.094	344.941	306.500	6,393%
2017	417.476	450.163	404.500	3,208%
2018	523.969	573.961	509.300	2,880%
2019	625.774	693.165	633.700	-1,251%
2020	735.166	821.956	772.200	-4,796%

Table 17, global test function error measurement, own elaboration

The percentage error has been calculated for the test function on the last five points (Table 17), and the average value is equal to 1,287% for the test function. The value is low, thus showing the accuracy of the function at predicting the future. Hence, H1 is accepted.

Testing H3 - Global Scenario - In order to do this, the dataset has been manipulated by shifting the IC value by one, two, three and then four periods, thus obtaining the inputs for the regression analyses with Δt ranging from one to four years. To calculate the existence of a lag effect, the lagged datasets' regression analyses should return parabolas with R^2 values that are higher than the one of the original non-lagged datasets. The results are: for $\Delta t = 1$, $R^2 = 0{,}998$; for $\Delta t = 2$, $R^2 = 0{,}996$; for $\Delta t = 3$, $R^2 = 0{,}994$ for $\Delta t = 4$; $R^2 = 0{,}995$. Which, compared to the R^2 of the original dataset, equal to 0,999, show that it we cannot confirm the presence of a lag effect, neither to reject it.

Testing H2 – Italian Scenario - Data from 2010 to 2019 have been used to obtain the regression and its trendline. This way the analysis can focus on the effective development stage, without the slow technology testing phase influencing the results. Once again, the best fit trendline was found to be the polynomial, with an R^2 of 0,994 and an equation written as follows: $y = -4E\text{-}5x^2 + 0{,}0949x – 38{,}687 + e$. The parabola was chosen also to keep consistency with the previously obtained trendline for the global dataset, and compared to the linear approximation, it also showed a better fit, measured by it high R^2 versus the same metric of the linear, equal to *0,8838* (image 6).

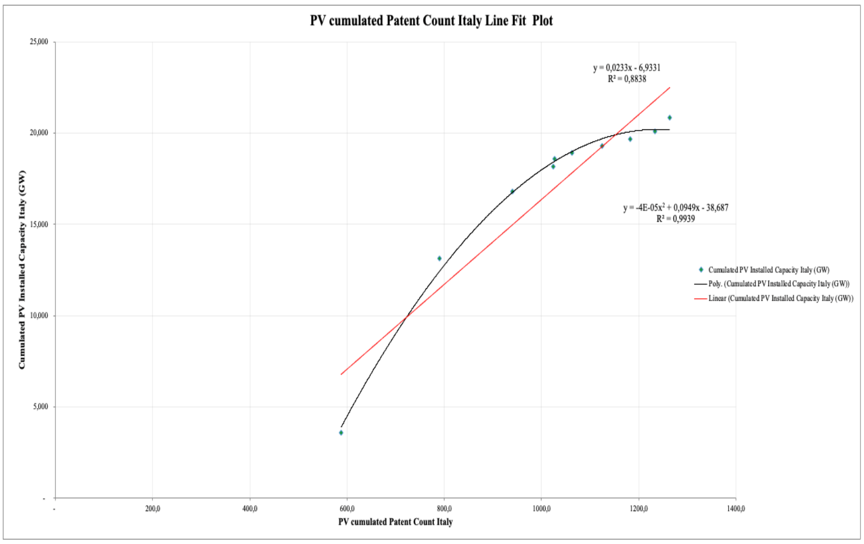

Image 6, regression analysis, PV cumulated patent count and IC Italy, 2000-2019, own elaboration

It can be noticed that the graph in this case is a downwards facing parabola, and the vertex can be found in the same location of the last observation. Meaning that, according to this function, a descending trend is expected, like a sort of market saturation/decline. While the diminishing of installed capacity is in reality very unlikely, considering the existing policies and the whole plans to increase the use of renewable energy, from a statistical point of view this is justified by the very slow growth/stagnation of the last few years. This same stagnation brought the dataset to depict the relationship this way, and the model to predict future decline.

The next step at this point is measuring how well the model approximates the results and predicts the future, by calculating the average percentage error of both the original trendline and a test trendline, generated with a partial dataset. This time though, generating a test trendline with a total number of points which is very low: 10 in fact, would not produce reliable outputs, considering that we would have to split the dataset in half to train the model. Hence, another method can be used: a cross validation method called 'leave one out cross validation' (LOOCV). Ten regression analyses have been run on excel, each one trained with nine values out of ten, each one excluding a different observation. Table 18 shows the results of the test, along with the various equations returned by the software. The result is an average percentage error of -3,534%. Once again, the result is satisfying, since conventionally, a value under 10% is considered good. This means that the dataset used in the analysis is effective at making predictions. As for H1, H2 can be confirmed too: the high fit of the trendline at representing the dataset along with the efficacy of the latter at predicting unknown values are enough to prove that patent counts affect IC in the Italian scenario.

ITALIAN SCENARIO

Year	Year Out in LOOCV	LOOCV Function	LOOCV Function Cumul. IC estimate (GW)	Cumul. IC Real Value (GW)	Percentage Error
2010	2010	$y = -3E-05x^2 + 0,0678x - 24,377$	5,117	3,590	42,535%
2011	2011	$y = -4E-05x^2 + 0,093x - 38,262$	10,244	13,130	-21,980%
2012	2012	$y = -4E-05x^2 + 0,0946x - 38,579$	15,001	16,790	-10,655%
2013	2013	$y = -4E-05x^2 + 0,096x - 39,164$	17,197	18,180	-5,407%
2014	2014	$y = -4E-05x^2 + 0,0943x - 38,42$	16,237	18,590	-12,658%
2015	2015	$y = -4E-05x^2 + 0,0953x - 38,854$	17,251	18,900	-8,724%
2016	2016	$y = -4E-05x^2 + 0,0956x - 39,012$	17,907	19,280	-7,119%
2017	2017	$y = -4E-05x^2 + 0,0956x - 39,012$	18,102	19,680	-8,017%
2018	2018	$y = -4E-05x^2 + 0,0943x - 38,472$	16,988	20,110	-15,523%
2019	2019	$y = -4E-05x^2 + 0,1019x - 41,476$	23,418	20,870	12,208%

Table 18, model prediction error measurement with LOOCV, Italy, own elaboration

Testing H3 – Italian Scenario - Lastly, the lag effect has been analyzed in the Italian case too. The same range of Δt values have been applied: from 1 to 4. The whole Italian dataset has been considered this time, since furtherly cutting it would have made the results completely unreliable. Moreover, there is no issue in measuring the lag effect of a relationship containing some periods of stasis. By running four regressions, the resulting parabolas returned: for the dataset with Δt = 1, R^2 = 0,952; for Δt = 2, R^2 = 0,918; for Δt = 3, R^2 = 0,869, for Δt = 4, R^2 = 0,838. The R^2 of 0,978 related to the original equation is still the highest, but like in the previous case, all of the four results coming from lagged datasets show high values for said metric. H3 cannot be confirmed, and the null H03 for the Italian case cannot be rejected.

6. Conclusions

6.1. Summary of findings

Global cumulated PV patent count is correlated with global cumulated PV installed capacity, the same goes for the Italian scenario. The global trendline has a good predictive capacity and is consistent with the future perspectives of the industry, while the Italian one lacks this last attribute from a practical point of view, although being valid from the statistical one. Presence of a lag effect cannot be confirmed, neither rejected in both scenarios.

6.2. Managerial Implications and Insights

Companies may find predictive models useful to evaluate the possible paths to follow and adapt their strategy accordingly. Patent data have the intrinsic advantage of being immune to bias and publicly accessible worldwide thus making them a powerful analytic metric. Government institutions could benefit from the results of this study too, since by incentivizing the production of new IP, among other levers, could be an effective way of developing the PV sector and meet the objectives of international treaties, along with safeguarding the environment and increasing their energetic independence. From the IP point of view, treaties like PCT and TRIPS allowed inventions to be safeguarded all over the world and standardized the procedures and requirements.

International and governmental organizations like the WIPO, EPO and USPTO are another warranty for new investors in renewables, who want to see their projects realized but at the same time reap profits with an adequate protection and set of rules. we have the global issue of climate change. Governments and international organizations have been setting goals in last decades to fight this phenomenon. The UNFCCC is a clear example of this, along with treaties like Kyoto and Paris, and the most recent 17 sustainable development goals by the UN, containing measures against global warming. Other energy centered programs like REPowerEU, the Green Deal and the IRA are an additional reason to believe in future growth of REs, and PV among them.
In light of the previously mentioned political economic factors, sustained growth is still likely the trajectory for the upcoming years. The simulated polynomial function forecasting IC on a global basis, starting from patent count supposes continuous growth perpetually. This is clearly a sign that the predictive power of the model is not supposed to last forever because the variables cannot physically grow indefinitely. On average, PV installed capacity has grown by 39% each year from 2000 to 2020, while patent count relative to the PV industry went up by 28%. In the recent years though, a slight percentage growth decrease can be noticed, but we must consider that absolute values are still very high, since the industry has reached an advanced level of development and is not set to stop growing. The optimal level of patenting activity will not be treated in this research but reaching it will give companies the best ratio between installed capacity, IP ownership and productive efficiency. Patenting activity can also be used to forecast IC with the goal of estimating the future saturation level of a market. Market targeting strategies might also get benefit from the awareness of the relationship between these metrics: companies could target a low IP local market with high growth potential to establish a presence in it and anticipate the competition. And just as businesses could try to identify the best compromise between investing in patenting activity or direct production, authorities could base incentive campaigns on such data. The lag effect analysis did not bring relevant discoveries to the table both in the global and the Italian scenario. the Italian dataset produced interesting results, since, strictly mathematically, stagnation is expected. However, taking into account the issues of the model like the lack of many observations and the fact that a brief stagnation brought the system to anticipate decline, the forecast trendline is not to be considered reliable for the author. The reasons of this statement can be found in economic prospects and the political outlook. As previously mentioned, government authorities are working on the expansion of all renewable energy sources. Moreover, the last observation in our analysis was already announcing a steep growth movement of the IC and patent count. Public policy measures are currently driving the sector, such as outright incentives and tax benefits. Recent statistics prove that Italy surpassed

25GW of PV installed capacity in 2022 and 26GW in 2023 (Terna, 2023). This is additional proof that the industry is still growing fast in this country.

6.3. Limitations of the Study and future research

The main potential downfalls of this study are the relative lack of data, the impossibility of patent count variable to be weighted adequately and the presence of confounding factors. 21 observations are still enough to create a reliable regression analysis, but having even more of them would have given a better image of the trend and increased the trendline's reality trueness. The Italian dataset on the other hand has the minimum number of observations needed for the study to be considered valid. This made the resulting model relatively weak and not effective at predicting the future. Future research could fill this gap by gathering longer historical series of data thanks to both more advanced resources, and the passing of time itself, which makes more data available. Especially in the case of the Italian scenario.

Another weakness is the characteristic of the patent count variable itself of not being possible to be weighed against the value and entity of the innovative step underlying each single patent document. Future analyses considering this element would be much more accurate if well performed, but patent evaluation is a resource intensive process which is also subject to non-unique results due to different evaluation methods chosen by the researchers.

Studies investigating the cause effect relationship between the same variables contained in this document could open to interesting applications, allowing policymakers to leverage either investments in installation or in patenting activities to reach their goals in terms of sustainability. The literature states that patent count is not the only variable in play when it comes to influencing installed capacity. The consequence is that the resulting model cannot explain the variation of the dependent variable in a one-to-one scale, and part of the observed relationship might be influenced by chance. The other variables in play are for instance, the government policies, the climate of each country, economic metrics (GDP, financing rates, inflation, occupation), the resources available and their prices.

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