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Solar Power Technologies Growth in the United States, an Integrated Four Pillars Perspective

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Abstract: This paper examines solar power technologies growth in the United States (U.S.) considering the four pillars of the energy system: socio-cultural, policy, science & technology, and markets & companies. The study analyzed the growing use of Photovoltaic panels (PV) technology. The First Solar company was analyzed as a case study to understand the impact of the different energy pillars and challenges on PV technology in the U.S. As a general observation, it was found that solar power in the U.S. is an incredibly fast-growing technology. Solar power does however still only make up a relatively small fraction of the total power consumption in the U.S. - in 2020 of approximately 1.32%. Considering these two observations, solar power in the U.S. is currently in the middle of being a niche-technology and forming its own energy regime. The possibilities for solar power to grow further into a solid regime in the U.S. are supported by developments concerning the four pillars of the energy system. For the science and technology pillar we will focus on main technological developments and R&D. The markets-companies pillar will be discussed by considering the characteristics of main company First Solar and market developments. The social and cultural pillar will be explored by looking at the role of citizens, NGOs, and relevant cultural perspectives. For the policy pillar, we will focus on federal policy, some main policy instruments and implementation problems. Eventually this study explores two different scenarios of solar energy in the U.S: a business-as-usual scenario and a maximally optimistic scenario. In the first scenario solar power production will increase to about 5% by 2031 of the total power demand in the U.S. In the optimistic scenario it will be around 17% of the total power production in the U.S, an increase by a factor 3.4, depending on developments in the four pillars.

Keywords: Solar Energy in the U.S, Photovoltaic PV Technology, Energy Policy, Innovation, Citizens' Involvement, Energy Regime

1. Introduction

The United States (U.S.) is one of the most important countries in the world in terms of size, population, biophysical diversity, resources, economic output, agricultural, and industrial production or investments [1, 2].

The U.S is also one of the leading energy producers in the world and it was long the largest energy consumer until it was surpassed by China in the early of this century. Nowadays, the US relies on other countries for many sources of energy, especially petroleum products [3]. The total energy consumption in the US is 35.7 quadrillion Btu and about 67% of the total energy demands are covered by fossil fuel [4].

As shown in Figure 1, petroleum power plants provide about 35% of the U.S. electricity consumption, natural gas coming next with just less than 35%, nuclear and coal-fired power plants about 10% each, where renewable energy sources only provide less than 15% of the total demand [3]. Nevertheless, nowadays, the U.S. is leading a global transition to renewable energy technologies where it has some of the most effective solar, wind, geothermal, hydro and biomass technologies around the world [5]. This paper explores the future of renewable energy in the US. For practical reasons, this study will focus on solar energy technology, a technology with a strong growth potential. The main questions are "What is the future of solar energy in the

U.S. and what are the main relevant factors?"

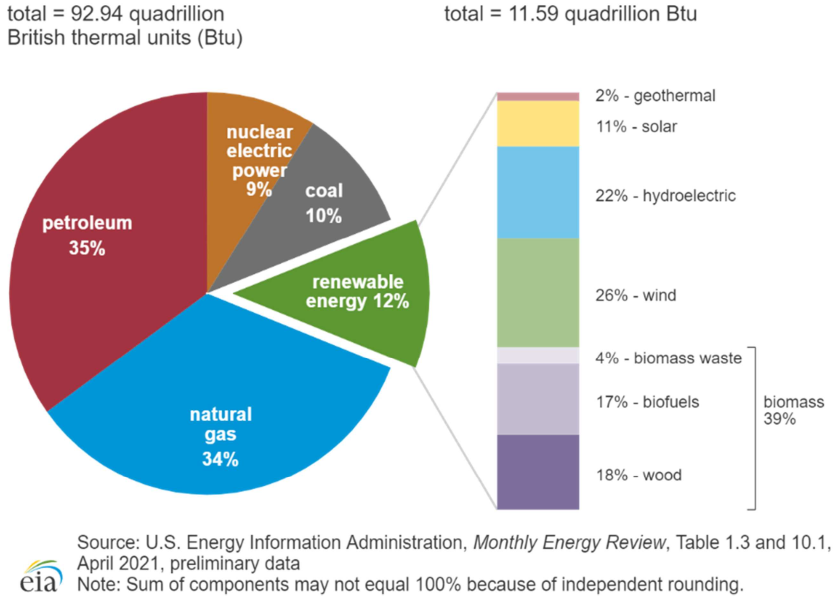

Figure 1. *U.S energy mix consumption.*

1.1. Solar Energy in the U.S.

The modern solar energy sector in the U.S. has started with the construction of the first practical silicon solar panel in 1954. The gas crisis in 1973 exposed the reliance on fossil fuels in the U.S., which caused the demand for alternative energy production by niche sectors. Nevertheless, the solar sector in the U.S. did stay a niche development in the 1980s and 1990s. A big game changer for solar energy in the U.S. was the 2009 stimulus package during the economic crisis at that time. This stimulus package brought subsidies for alternative energy. At the same time advances in technology and manufacturing made it easier to produce solar cells [6]. So, economic, political and improvements of solar technology together gave rise to the solar power sector.

Nowadays solar power is more affordable, more accessible and more prevalent in the U.S. than ever before. Growing from a production of 0.34 GW in 2008 to a capacity of 97.2 GW today. Now about 3% of the U.S. electricity production comes from photovoltaics (PV) and concentrating solar thermal power (CSP) [7]. The costs of installing PVs have greatly decreased in the past 10 years. The cost to install PVs has dropped by more than 70% compared to their price in 2010, while the number of installations kept increasing. This caused the solar power sector to expand into new markets and deploy thousands of systems in the U.S. [8]. This decrease in PV price was partially caused by favorable tax policies implemented to support the development of technologies for sustainable energy production [9]. For solar energy an investment tax credit (ITC) was implemented for the first time in 2005 when George W. Bush signed the energy policy act of 2005. This act established new sustainable fuel standards, among many other things as well [10]. This ITC paved the way for niche solar companies to become part of a larger energy regime resulting in an increase of 10000% of the U.S. solar industry [11].

In the U.S. the prospects for solar energy to become an even larger player are looking sunny, however not all parties are eager to welcome it. U.S. utilities have attempted to slow the growth of distributed generation (DG) solar energy by reversing policy support [12]. The demand for solar power is for a big part driven by a necessity for sustainable energy in general. However, analysts identified some drawbacks. For instance, PV panels installed for U.S. homes have a larger replacement cost than expected. Because of this there is a danger that the used panels might end up in landfills [13] which would conflict with the sustainable energy goals [14]. This might cause the demand and support for solar energy to decrease.

1.2. The Solar Energy System as an Upcoming Regime and Its Pillars

In this study the solidity of solar energy as an upcoming regime will be discussed. For our explorative study we will make use of a modified version of the so-called Multilevel Perspective (MLP) on transition. This popular frame distinguishes 'niche', 'regime' and 'landscape' and their interactions to analyze, understand and eventually stimulate the energy transition [15][1].

According to Geels (2011), transitions are results of interacting developments at three levels, the macro level ('landscape'), meso level ('regime') and micro level ('niche'). Here, landscape covers the political, social and cultural context, while niches are places where small scale innovations take place. Regimes are seen as semi-coherent sets of rules, actors and artifacts, which coordinate and link various elements of a socio-technology system. The energy

[1] Geels did not use the term pillar to characterize dimensions of a regime. This use of the term pillar was introduced and developed for the course Sustainability & Society of the Master Energy and Environmental Studies of the University of Groningen.

sector as a whole can be seen as a regime, but also substantial parts of it such as the coal sector can be considered a regime. In this paper we describe the solar sector as an – upcoming – regime and its relevant niches.

The solidity of a regime can be determined by looking at its various dimensions or pillars. Geels (2011) distinguishes six of them: market and/or user preference, science, culture, technology, policy and industry. Here we will take market and industry together, as well as science and technology. Culture will be extended by society, because of the importance of societal processes, i.c. civil society. So we will explore four pillars of the regime: socio-culture, policy, science/technology and market/companies. These pillars can already be related to some examples of innovations in solar power mentioned in this introduction. Policies include for instance the federal investment tax credit that supports solar power. The technology development of solar power has increased its efficiency and its solidity for companies and markets.

The socio-cultural pillar is connected to the role and perspectives of citizens and civil society organizations (cso's) and NGOs. In the following chapters the pillars will be operationalized further. Our analysis is based on a quick scan of available relevant scientific literature, gray literature and websites of main actors. Making use of the four pillars we will explore the future of the solar power regime in the U.S in the final sections of this paper. In the following chapters we will discuss the various technologies, the role of companies and markets, citizens and their perspectives and policy.

2. Science and Technology

2.1. Solar Technologies in the U.S.

The sun is a valuable resource of power, and it is the most productive source of energy on the earth. However, worldwide consumption of energy is expected to continue increasing at 5% annually [16]. As shown in Figure 2 relying on solar energy technologies will be the only choice that would satisfy the global future energy demand [17].

Solar energy technologies are beneficial and play a significant part in today's markets as they would reduce the electricity bills and the use of power generated from fossil fuels such as natural gas which are detrimental to the environment [18]. The electricity generated from the sun is free and no operating or maintenance costs are needed; the only main cost is the initial budget spent on installing the solar technologies [19]. Solar energy can be utilized in various applications.

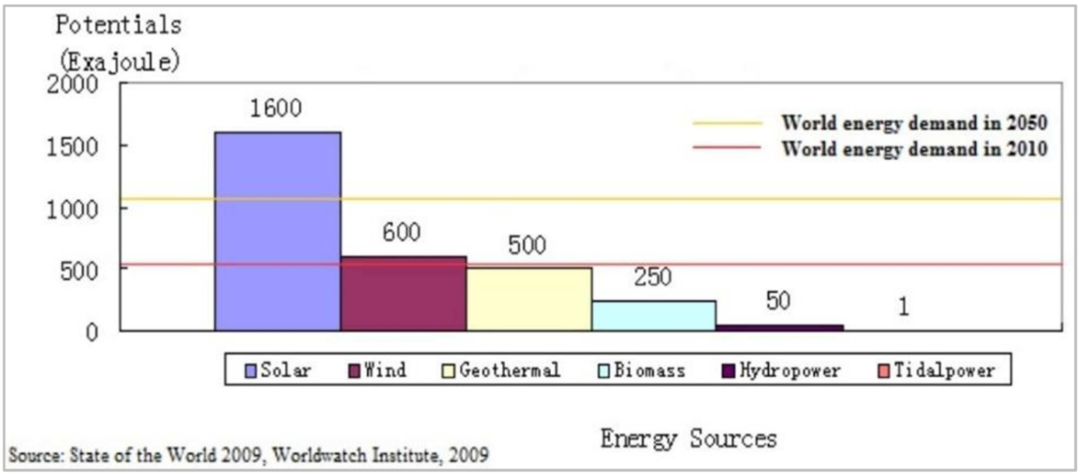

Figure 2. *The Potential for RES (Base on Today's Technology level).*

2.1.1. The Main Solar Power Technologies in the U.S.

There are three main technologies for harnessing and utilizing solar energy [20].

Solar Photovoltaic (PV) Panels convert sunlight directly into electricity. In the second quarter of 2021 the U.S. alone installed approximately 5.7 gigawatts (GWdc) of solar PV capacity, bringing its total capacity to 108.7 GWdc, which is enough to power 19 million American homes. The U.S. has officially surpassed 3 million installations across all market segments, as shown in Figure 2.

Concentrating Solar Power (CSP) technology uses mirrors to concentrate the energy from the sun to drive electrical turbines to create electricity (see Figure 3). Currently, there are about 1,815 megawatts (MWac) of CSP plants in operation in the U.S. Solar Heating and

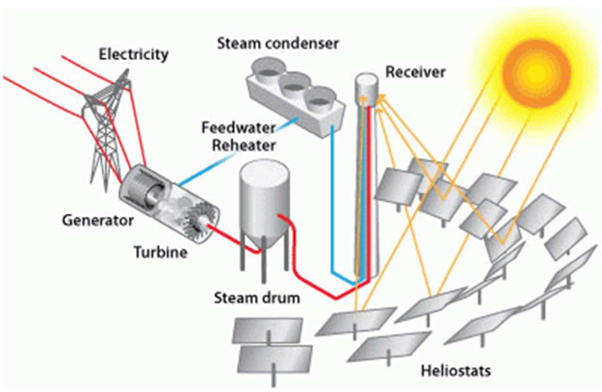

Figure 3. *Concentrating Solar Power (CSP) [89].*

Cooling (SHC) technology directly collects solar radiation to provide hot water for daily use, swimming pool heating for residential or commercial, space heating & cooling, and industrial applications. The payback period for this technology is 3-6 years and there are no extra operating costs for these. In 2010, about 70000 solar heating & swimming pool heating units were installed in the U.S. [20]. Overall, there are some other applications for solar energy such as water desalination and crop drying, but the use of these technologies is limited and Solar Photovoltaic (PV) Panels were and are still the most popular solar applications and many companies around the world are investing on the R&D of solar energy technologies.

2.1.2. R&D of Solar Technologies in the U.S.

In 1954 the first PV cells were developed at Bell Labs, then in the 1970s, the emerging companies in California started the R&D of solar energy technologies. However, many companies failed to materialize largely because the technology was inefficient and too expensive, thus the use of solar power as a direct source of power was limited and it was not competitive with conventional energy resources such as coal. The efficiency of the first model's PV was relatively small, initially 4% and later 11% [21]. In the last decades, with worldwide concerns of Greenhouse Gases (GHG), and the increasing demand for energy consumption, many companies have advanced in the R&D of solar energy technologies and the efficiency of solar PV panels has increased to 17% [23]. The U.S. solar energy markets are rapidly maturing across the country, as solar power is now economically competitive with conventional energy sources in most states and it has made considerable progress in terms of solar energy technology [24].

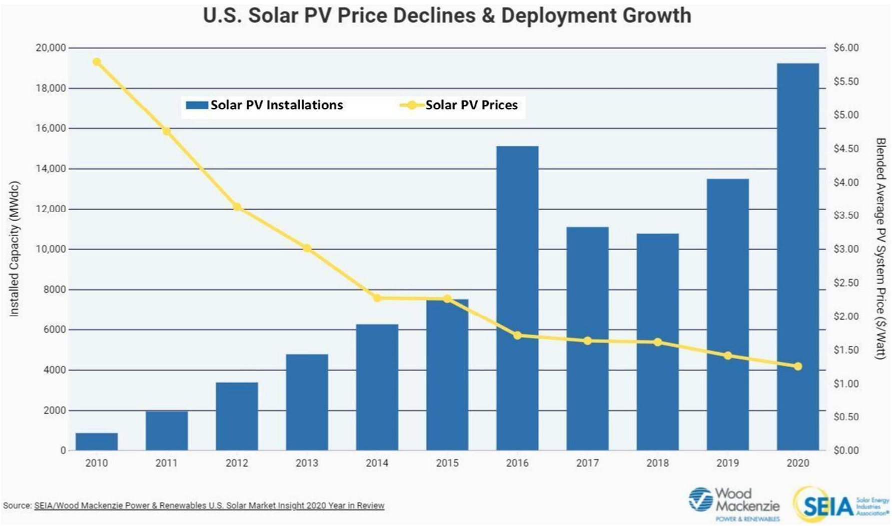

Figure 4. *The average cost of solar PV panels in the U.S.*

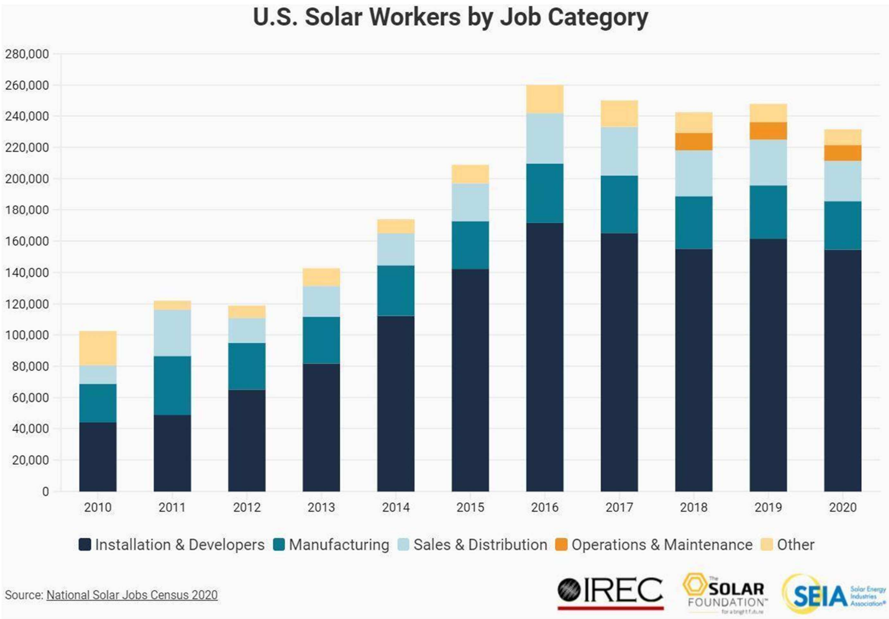

Figure 5. *U.S. Solar Employees by Job Category.*

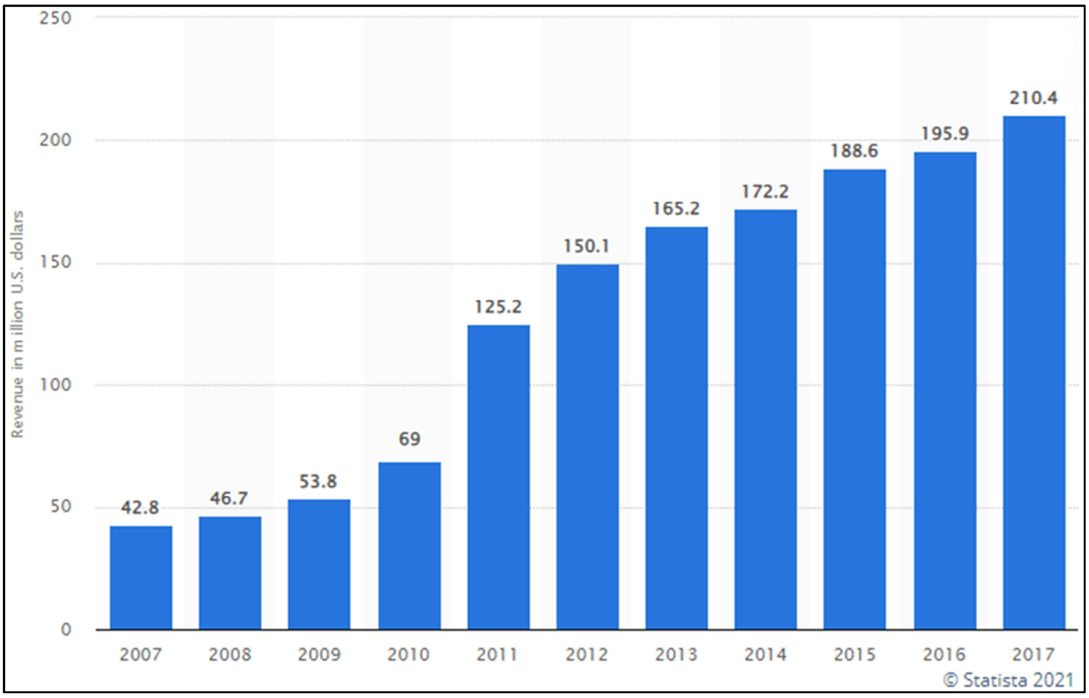

Figure 6. *Revenue of the Solar Power Industry in the U.S.*

Obviously, R&D and engineering played a significant role in the transition to solar energy technologies not only in the U.S. but also around the world [22]. In the current R&D and internationally competitive market, solar energy technologies have become more affordable, and accessible than ever before. Figure 4. shows the drop of the average cost of solar PV panels in the U.S. and increase of the installation capacity [25].

In 2020, the solar industry generated about $25 billion in private investment in the U.S. economy and about 230,000 Americans work in the solar industry, Figure 5 and 6 illustrate the development of the U.S. solar energy industry in terms of workers' job categories and yearly revenue. It is clear that the majority work as installation and developers also the revenue significantly increased between the period 2007 and 2017 from 42.2 to 210 million U.S. dollars, this indicates that the solar industry is the initial phase of R&D and the U.S. government aspire to increase the dependence on solar energy to 40% by 2035 [51]. Nowadays, many U.S. companies such as First Solar are working in the R&D of new designs and more efficient PV.

2.2. Technology and R&D at the Company Level: First Solar

To describe technology developments at the company level we will focus on First Solar. It is one of the leading companies in this sector, not only in the U.S. but also around the world [26]. It is a manufacturer and provider of one of the best and cheapest models of large-scale solar PV. It was founded in 1990 and went public in 2006 [28]. First Solar has a net income of $ 469 Million (2021) and total assets of $ 7.414 Million (2021) [27]. First Solar is developing its rigid thin-film solar PV panels from cadmium telluride (CdTe) as a semiconductor instead of expensive silicon chips (Figure 7). In 2017, the efficiency of First Solar produced CdTe-panels was 14% with a reported cost of $0.59 per watt [28]. The low cost of its models has been the key to its success [29].

First Solar has its own R&D department, since it manufactures for instance its own PV solar modules. First Solar even mentions that: "No company invests more in R&D advancing our technology to rapidly increase our energy yield, lower LCOE and provide stable grid integration" [30]. As such it is a good example of an innovation that combines the introduction of new goods, new methods of production, opening of new markets, new sources of supply and carrying out of new organizational structures. [31].

The main technological advancements that First Solar presents are its PV solar modules. Its modules are regularly updated in terms of energy production, efficiency and durability. First Solar is able to recycle its PV modules in such a way that 90% of the components can be recovered. This makes it possible for First Solar to reuse the same materials, which is a new method of production [32]. The advancements of its solar panels and the recycling of their materials directly connect on how sustainability is linked to innovation in First Solar: it is already taken into account in the concept development stage. Sustainability is therefore an important factor for First Solar. Further improvement of PV modules can be defined to be an incremental innovation because the technology for PV modules already exists, as well as the markets. The recycling systems created by First Solar could be seen more as an architectural innovation, because it asks for new knowledge and it opens new sorts of markets [33].

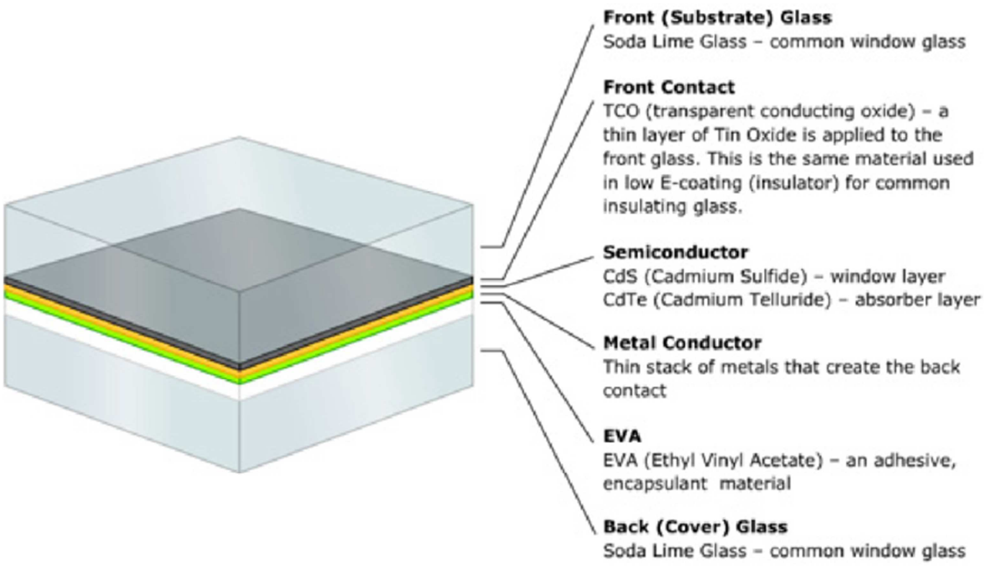

Figure 7. *U.S. First Solar (PV) Construction [90].*

As shown in Figure 8, the growing energy demand [36], and the changing perception of the public worldwide regarding climate change and sustainability [37] pose a big opportunity for First Solar.

2.3. Conclusions Science and Technology Pillar

Clearly, at least three technologies developed and reached a stage of maturity, the CST technology, the SHC technology and the improved PV technology. Especially the cadmium telluride thin-film solar PV panels turned out to be successful. Another innovation of First Solar, recycling of panels, is a step forward, too. R&D efforts seem to go on. One of the challenges is to meet the demand of integrated solar storage options at various scales to improve security of supply of solar energy [34].

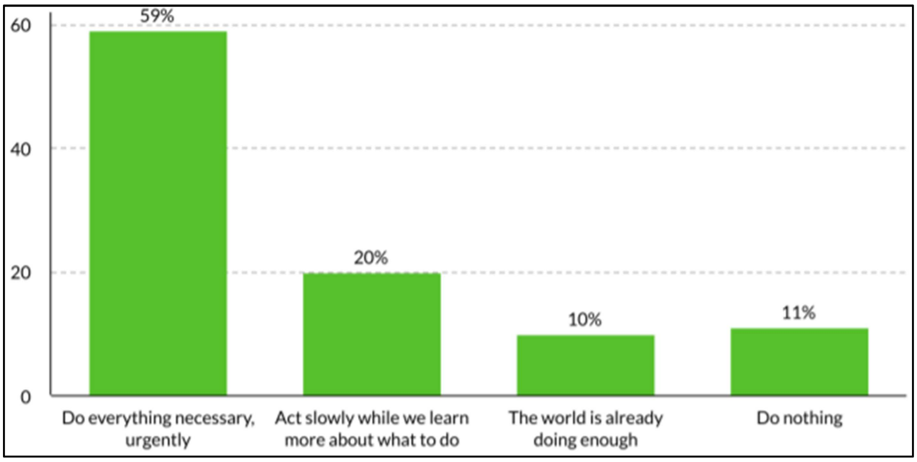

Figure 8. *Urgency of Response among People Who Believe in the Climate Emergency [91].*

3. Markets and Companies: First Solar

For the analysis of the markets and role of companies we will again focus on First Solar. For the analysis of this company and its position in the solar sector we will make use of some well-known analytic tools from business analysis and management [35]. Porter's Five Forces model will be used to analyze the company's position compared to competing companies and products. For an internal analysis of the company McKinsey's 7 S Framework will be applied. The macro-environmental factors will be assessed by using a PESTEL frame, finally to give an integrated assessment of the company's potential SWOT analysis will be used.

3.1. Competition: Porter's Five Forces

According to Porter's Five Forces model, key elements – called forces - for the competitive position of a company are substitutes, buyers, entrants, suppliers and rivals.

First Solar is part of a strong supply chain, including reliable raw material suppliers. Costs of raw materials may rise however, and as a result the power of suppliers, too. In addition, mining of toxic cadmium, which is needed for the thin-film modules, can be a problem.

Substitutes can be other forms of sustainable energy production, such as wind energy or different techniques of using solar energy, for example the already mentioned concentrated solar thermal (CST) energy and solar heating and cooling systems (SHC). Indeed, some companies are specialized in other types of sustainable energy production or in CST and SHC. Maybe more cost effective and more efficient alternatives for cadmium telluride will be developed. Important issue to note is that the availability of required raw materials may decrease.

Buyers of PV modules are mainly interested in producing their own electricity in a sustainable fashion. This can range from individuals to companies. First Solar however focuses mainly on PVs for corporations and on utility scale, and as a consequence, main buyers are electricity producing companies and governments. Although First Solar has a strong dealer community, strengths of local distributors may grow if competition increases.

Potential entrants could be other companies that want to deliver solar energy technologies for corporations or other sustainable energy production techniques in general, but in this case primarily other PV-module producing companies, since those would be entering the same market as First Solar.

First Solar works together with many other companies for its materials, components and structures, as well as services and it also recycles most of its own raw materials [38].

As First Solar is one of the U.S. companies for solar energy and it provides PV modules on a global basis, main rivals are other PV module producing companies in and outside the U.S. These are often large (multinational) companies that specialize in producing and installing PV modules. Other rivals could be companies that provide services to produce electricity to governments and companies [39]. This may result in a big roster of potential competitors or rivals.

In conclusion the pull of the potential entrants force is relatively small because First Solar is already a big name with many global contacts, but the company can however be heavily affected by substitutes, buyers and suppliers forces. The number of buyers and substitute energy producers are expected to increase, because of the growing energy demand worldwide [36]. This could also mean that the buyers and suppliers of First Solar will be scattered across other companies, since all companies will then have to produce more energy. This in turn could make it more difficult for First Solar to obtain materials and thus damage the company.

3.2. Organizational Strength: 7 S Framework

In McKinsey's 7 S Framework seven characteristics of the internal organization constitute the internal capacity of a company, structure, style, system, staff, skills, strategy and shared values. First Solar has a traditional hierarchical structure and management style with an executive management led by a CEO and a board of directors, governing manufacturing plants and sales and support offices around the globe [40, 41]. The system (procedures) is formal. First Solar has a highly skilled staff as a result of several training and learning programs [42]. while the company as a whole has a solid track record of developing and distributing new products. The values of First Solar are properly reflected by this quote from its website: "First Solar knows that clean affordable solar electricity is an essential part of the worldwide energy mix. That's why First Solar leads the way with the lowest carbon footprint, lowest water usage and fastest energy payback of any PV technology" [30]. The strategy of the company is to become leading in sustainable cost-effective solar panel development and production, worldwide. Key is the design, manufacturing and sale of their own cadmium telluride solar PV modules, for specific markets. In addition, the company provides solar power systems, including project development, services and finances. Although the finances of the company have not been discussed yet, these are of course a relevant factor as well. Based on the available information, we conclude that the financial situation of First Solar is solid enough.

All in all, first solar has a strong position, but functions in a highly competitive market. To stay competitive the company should continuously improve its PV modules and systems.

3.3. External Environment: PESTEL Analysis

To assess the external environment of First Solar, we will use the PESTEL frame, which includes political, economic, social, technological, environmental/ethical and legal aspects.

First Solar is a company that operates globally and therefore it depends on policies from many countries. In many countries, however, governments subsidize and encourage renewable energy. The dependence on subsidies may be a problem. The specific political situation in the USA will be discussed in the policy section of this paper. If it comes to the economy, the growth of the GDP in the U.S. is expected to grow until 2026. The rate of growth is however expected to decline over time, depending on for instance the war in Ukraine [43]. The market situation in other parts of the world is uncertain. Regarding the social aspects, the situation for the company is positive. The number of consumers that prefer sustainable energy over fossil fuels is expected to grow worldwide. Therefore the number of consumers for PV modules, and thus also First Solar consumers, is also expected to increase, especially among the Millennial generation in the US.

As we discussed in the previous section, compared to other PV technologies, the modules of First Solar are the most attractive ones on the market, but ongoing research at other companies and research institutes may result in a third generation of PV modules [42, 44]. Both environmental and ethical arguments support the First Solar strategy while the US has relevant national and federal laws about the production of electricity [45].

In conclusion, the external environment seems to be supportive, although national policies and geopolitical developments may affect the position of First Solar.

3.4. Weighing of the Factors: SWOT Analysis

To weigh the various factors concerning competitors, companies' capacity and quality and external factors a

SWOT (Strengths, Weaknesses, Opportunities and Threats) is carried out.

For First Solar the biggest strengths are its R&D, its own technology, its organization, its global network, its supply and distribution networks and its market position. The main weaknesses are its dependency on many other companies for production and its focus on specific raw materials, technologies and markets.

The main opportunities for First Solar are the growing demand for electricity worldwide, and to produce energy more sustainable. Threats to First Solar are other solar power techniques such as CST and SHC, and more in particular new types of solar panels, as well as new policies. Also other sources of renewable energy can be threats for the market position of First Solar and it could also pose competition for the acquiring of materials and third-party services to produce PV modules therefore decrease the production rate of PV modules for them.

3.5. Conclusions Markets and Companies' Pillar

Clearly the market for solar energy is growing, the domestic market in the US and outside the US. Ongoing R&D and political support will stimulate further growth. A large, multinational company such as First Solar can exist and grow, just as a few other large solar panel companies. In addition other technology-based products are or will be developed and produced.

4. Citizens and Cultural Perspectives

4.1. Citizens' Organizations

Effective participation of citizens and NGOs in innovation and policy making is essential to increase the transition to renewables, including solar energy, but at the same time it is a challenge [46].

Citizens have at least four options to influence the speed and character of energy transition: by voting for politicians in favor of energy transition, by purchasing renewables, by participating in political procedures or open innovation trajectories or by organizing themselves in civil society organizations (CSO's) or NGOs. This section focuses on these organizations as they have played a substantial role in environmental governance for a long time [47].

Currently about 20-40 Million US citizens are members of environmental NGOs, but together they receive less than 2% of charitable donations [48].

Citizens, civil society organizations and NGO's can create pressures that unsettle incumbent energy regimes in the context of sustainable energy transitions, while others provide niche types of sustainable energy service. These organizations aim to empower citizens and open new cultural perspectives, i.c. on sustainability and energy. At present, renewable experts agree that achieving zero or low carbon energy transition will not be possible without citizens participating in innovation [49]. Nowadays the majority of U.S. citizens have become climate-aware and have a much better understanding of climate change than in the past, thus one may expect a greater level of willingness to participate in solar energy transition [50]. For sure, in the U.S. the growth of solar panels installed has been growing quite rapidly throughout the years as can be seen in Figure 10.

The aim of the U.S. government to increase the use and power generation of solar energy from 3% to about 40% of the total electricity consumption by the year 2035 [51] asks for more governmental efforts in implementing new policies in cooperation with local stakeholders and NGOs. The U.S. government introduced tax credits on solar energy installation costs, but citizens are still locked out of the direct decision-making processes of the energy transition. The government established the National Community Solar Partnership, however, to expand the access to affordable solar to all U.S. households and enable communities to understand the meaningful advantage of solar energy, such as reducing the energy burden, higher resilience, and the development of workforce [52].

Several NGOs in the U.S. help to promote the use of renewable energy sources and solar power in particular. Most large environmental NGOs focus on changes on a global scale, and in most cases not on energy, however. Friends of the Earth United States (FoE US) for instance, aims to realize a clean, low-carbon economy globally and to stimulate electricity production from wind and solar energy sources worldwide [52]. The main resources of FoE US are its large global network with partners around the world and its large number of members worldwide (2 million) together with its database of resources on all kinds of topics related to sustainability [54]. FoE U.S. advocates for a more sustainable economy in the U.S. via campaigns, demonstrations and lobbying at banks and government institutions. [55]

Another example of a cso is Solar United Neighbors (SUN) [56]. SUN is a young (2017) organization that only operates inside the U.S. Its goal is to stimulate a more clean and equitable energy system by founding solar energy cooperatives in a way that local communities in the U.S. can benefit from. Its main resource is its large database of information on everything solar panel related. SUN uses this knowledge to support the installation of solar panels and the solar industry in general. They also advocate for policies in the U.S. that would allow for an even better growth of the solar power regime in the U.S. Thanks to SUN at least 53 MW of solar was installed and more than 30.000 people joined an energy cooperative. Citizens-owned energy cooperatives have a long tradition in the US and umbrella organization Touchstone Energy Cooperatives unites 40 million members. These older cooperatives do not focus on renewables exclusively, although 88% of them offer electricity generated from renewable sources and most of them stimulate solar energy actively [57].

Interestingly, also the largest mine workers union supports the energy transition [58].

4.2. Citizens and Worldviews

Whether sustainability citizens and their organizations may be successful depends on their resources and organization, but also on their visions or perspectives and the way these can be connected to – other- perspectives among citizens [59].

A common way to assess these cultural perspectives is to look at worldviews, ethics and risks perceptions. Environmental scientists distinguish four worldviews: traditional, modern, post-modern and integrative, which can be found in the US and other western countries [60].

First, these worldviews and their relevance for solar energy will be discussed.

Since adherents of the traditional worldview strongly believe in traditions and religion, it might be difficult to accept a new technology in the form of solar power. On the other hand, in this view humans are seen as nature's stewards and must therefore take good care of it. The use of solar power, or more sustainable energy sources in other words, is then a method to indeed take better care of nature. Another point in favor of solar power for the traditionalists could come from their strong beliefs in solidarity and service to others. If the use of solar power could improve living conditions for others, then it might be a good thing to do for the traditionalists. Therefore, if these traditionalist citizens can be convinced that solar power can be used to benefit community members, then they might more easily accept solar energy.

Since the modernist is normally an individualist and believes that nature may be exploited to benefit him or her selves, he or she. will not prefer solar power at first glance, as it is not better for the individual than energy from fossil fuels. On the other hand, modernists do believe in solutions provided by science. So if the modernist could be convinced that a changing climate is indeed a problem, then they might also accept solar panels as a solution to that, since it is a scientific tool to battle climate change.

The post-modernists are characterized by their intense relativism, but also their ability to acknowledge multiple perspectives on reality combined with a concern for the wellbeing of the environment. For these reasons it seems straightforward to believe that the post-modernist will hardly have many difficulties with the use of solar power. They believe that it could be used adjacent to other energy sources and since solar power improves the wellbeing of the environment it fits well into the thinking ideology of the post-modernist.

The integrative or integral worldview is defined as a combination of the three previously mentioned worldviews. Adherents try to bridge opposite positions such as economy and ecology, right and left policy or science and spirituality. The worldview is characterized by a global commitment. This would probably stimulate the need for solar power because adherents want to improve the environment for the greater good.

Empirical research shows that in reality postmodernists and integrationists displayed significantly more concern about climate change as well as more sustainable behaviors, compared with modernists and traditionalists [60].

Together with more general worldviews, ethical considerations and risks perceptions influence citizens' public perspectives on renewables. For that reason we will discuss some ethical dilemmas and risks concerning solar energy.

Compared to many other countries there is more than enough empty space to install large solar panel parks in the US so here solar panels seem to be almost dilemma free.

The main problem originates from the acquisition of the raw materials for PV panels. The mining and the chemical separation often cause polluting emissions, but the true ethical dilemma comes from the forced labor and bad working conditions in the mines for these raw materials [61]. For the production of solar panels polysilicon is required [62]. This polysilicon is mostly produced in China, since China produces 89% of the global polysilicon supply [63]. The mining in China is assumed to be performed for a significant share by Uygur people that are held in detention camps, although China itself will not confirm this. If the Uygur people are indeed forced to mine for polysilicon this can be regarded as a form of slave labor. This then poses an ethical dilemma for solar energy. What is now more important: a more sustainable energy mix in the U.S. or the human rights of the Uygur people in China?

From a deontological point of view (judging an action if it is morally right or wrong) the action that Uygur people in China are forced to work for acquiring the raw materials for solar panels is wrong because it violates the right of autonomy of people. So, following this way of reasoning, import of raw materials from China to produce U.S. solar panels has to stop.

Using a utilitarian point of view (to choose the option that provides the best sum of positive and negative consequences) may lead to another conclusion. Basically, the way of utilitarian thinking is that the needs of the many outweigh the needs of the few. Climate change will affect most people in the world, including a lot of people in the U.S. Solar power could play a big role in solving this. If then, in order to produce these PV cells, some people have to suffer, that would be a smaller need compared to climate change. Therefore, in a utilitarian approach, one would deal with this dilemma by saying that the import of raw materials from China has to continue to produce U.S. solar panels.

In general ethical dilemmas are not only related to environmental risks but also to social and economic issues, and are rooted in cultural contexts [64]. Identifying and assessing relevant risks and their perceptions as well regulatory frameworks may help policy makers and other stakeholders to develop proper mechanisms to eradicate barriers for solar energy investments [65]. One way of assessing this is calculating death rates and environmental impacts. All energy sources have negative effects on human life and the natural environment but differ enormously in size as shown in Figure 9, fossil fuels are the most dangerous, while solar energy is the safest and cleanest source of power [66]. This is certainly not the only way to look at risks, however, risks are also related to unstable electricity prices and emanating from adverse changes in financial and economic conditions, such as interest rate and inflation, which affect the cash flow of electricity production [66], or supply shortages. This, too, may affect citizens' perspectives on renewables and solar energy in particular. This may also be true for health issues concerning workers in the solar energy industry, such as electrocution or thermal burns [67] and unexpected changes to the policies or government regulations.

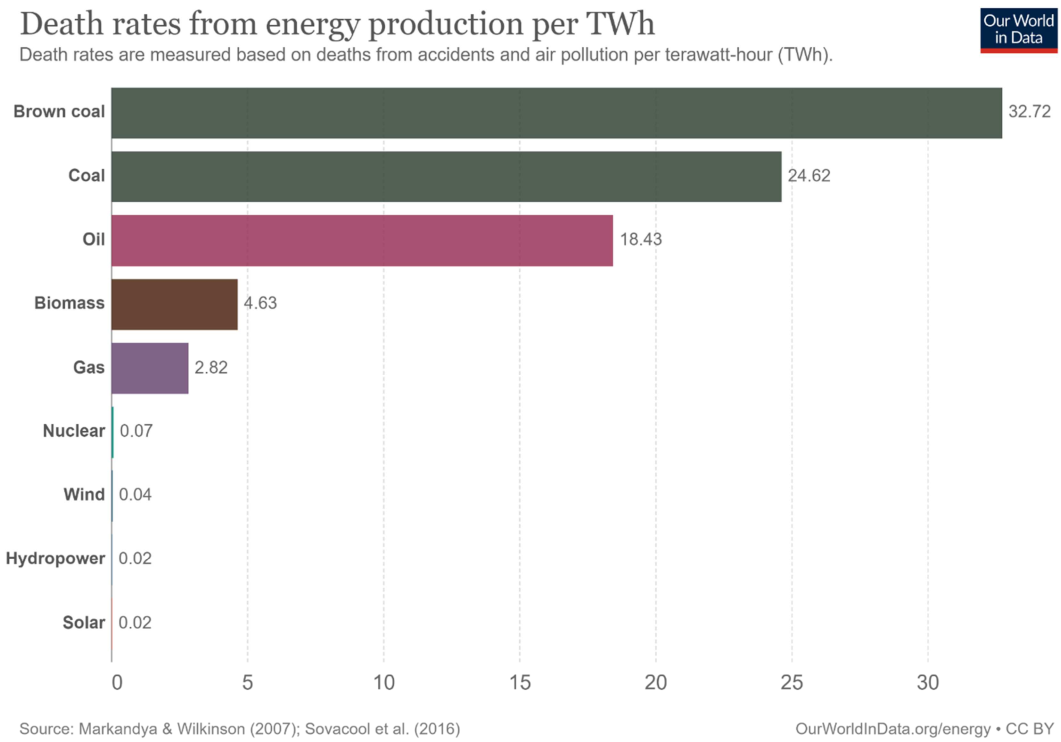

Figure 9. *Death rates from energy Production Per TWH [92].*

4.3. Conclusion Socio-Cultural Pillar

Overall, citizens and perspectives seem to change in favor of solar energy NGOs and old and new types of energy cooperatives, such as Friends of the Earth, SUN and Touchstone Energy Cooperatives strive towards more implementation of local solar power in American society, supported by the government. The worldviews of U.S. citizens can be seen to have some alignment with the sustainable evolution of the energy system that solar power can provide. Solar power also provides society with a very safe alternative to electricity production in terms of health risks for workers and users of solar power. There are however some risks connected to investing in solar power and meeting electricity demands. This could turn people away from using solar power too easily. Some ethical dilemmas remain. Acquiring materials for producing PV panels could also be a reason for citizens to be wary of solar power. In the end however we do believe that for most citizens the incentives to switch to solar power for the U.S. will outweigh the risks and dilemmas associated with it. Therefore, the socio-cultural pillar seems to be solid.

5. Solar Energy Policy in the U.S.

The market of solar energy in the U.S. has grown rapidly in recent decades, mainly due to the supportive governmental policies and R&D of its technologies [68, 69].

In general, success of policy depends on the quality of its implementation [70]. So not only the aims of policy counts, but also the quality of the policy instruments, and the willingness of governmental and non-governmental actors to cooperate. Community Net Energy Metering (NEM) or shared solar legislation, was one of the effective policy interventions in the U.S. which enables various electric utility customers to share the costs and benefits of ownership in a local solar PV installation. Another vital policy is the Investment Tax Credit or Federal Tax Credit (ITC) for solar energy policy which was designed to help the adoption of solar energy technologies. ITC provides 30% of the total installation costs, and this applies for both commercial and residential regimes, and the cap on their value is unlimited [71]. In addition, the U.S. federal government has implemented the renewable electricity production tax credit (PTC), which provides additional recovery costs per kilowatt-hour (kWh) for electricity generated from renewable sources. Another policy is the Renewable Portfolio Standard (RPS), a regulatory mandate to increase the production of energy from renewable sources such as solar and wind [72]. The majority of the 50 U.S. states have some forms of RPS programs [68]. The federal RPS called Renewable Electricity Standard (RES) requires electric utilities to generate a certain percentage of their produced electricity from renewable energy sources [63]. Although ITC-policy could be considered as a financial intervention, it was a vital piece of legislation which helped the U.S government to create enormous jobs in the solar energy industry. Yet the reliance on solar energy and its technologies has not yet reached its full potential as a clean energy source for the U.S, and tremendous efforts still need to be made to advance the deployment of solar technologies [71]. Although the U.S. current nationwide installed capacity from solar energy is more than 100 gigawatts (GW) (see Figure 10), which is enough to power 19 million houses, the installed solar capacity only covers about 3% of the U.S. total demand [74].

Recently, however, President Joe Biden set a course for the U.S to increase the clean energy investment in solar and other renewable energy technologies [14].

The Department of Energy expects that by 2050 solar energy could generate up to more than 45% of the U.S electricity supply [75]. Achieving such ambitious goals requires far greater acceleration and sustainable deployment than the U.S. has ever achieved, even if the cost of solar panels drops dramatically. Installing solar panels with such capacity will require an enormous area of around 11.5 million acres (0.5% of the total area of the U.S).

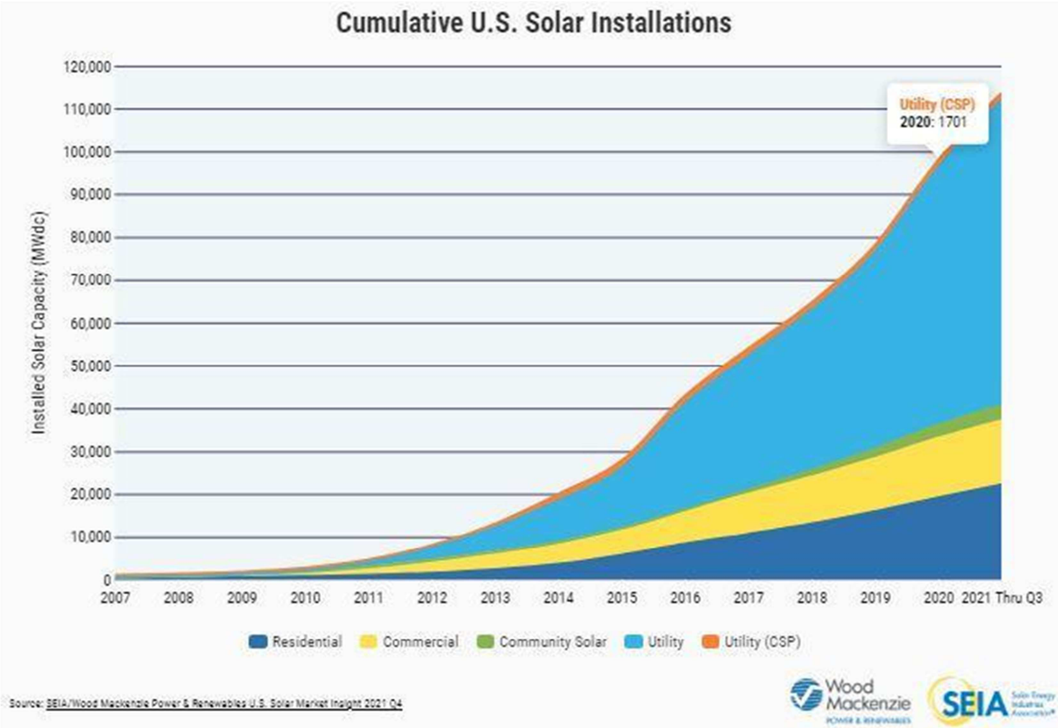

Figure 10. *Cumulative U.S. Solar Installation.*

5.1. Development of US Solar Energy Policy in Brief

For effective policy, involvement of many actors is required, but coordination of the state is crucial [76]. The implementation of Net Energy Metering and the Investment Tax Credit (ITC) was essential and supportive federal policy to make the U.S solar technologies market grow rapidly [77].

However, it took decades before major federal renewable energy legislation was enacted [78], partly due to opposition from Republican politicians. In the early 2000s, the global demand for oil had been increasing and put a pressure on domestic natural gas to meet increasing demand. This was one of the main reasons in 2005 for president George W. Bush to announce a comprehensive national energy policy [78]. The global pressure on the U.S. to mitigate climate change stimulated design and a new energy policy, in particular the Kyoto Protocol [79]. In the same year of Bush' announcement the ITC was established by enacting the federal Energy Policy Act [80].

The resulting financial incentives and tax reduction motivated commercial and public parties to fully consider the investment on solar energy technologies.

5.2. The Main Solar Energy Policy Instruments

In the introduction of this section three major policies regarding solar power in the U.S. were introduced, the ITC for PVs, the PTC for renewable energy and the RPS for electricity generation by sustainable sources. The policy instruments used to implement do differ for these different policies. The ITC is primarily an economic policy instrument. By practically reducing the costs of installing solar panels, the government hopes to influence the behavior of energy consumers. So that energy consumers would now rather choose solar power instead of other (fossil fuel) energy sources. The PTC is an economic policy instrument as well, because costs of producing sustainable energy are partially recovered. However, a difference with the ITC is that the PTC is not directed towards the behavior of consumers (of energy), but towards the behavior of energy producers. The PTC policy is then aimed at persuading energy producers to use more sustainable energy sources, such as solar power. The RPS policy aims to regulate an increase of the energy produced by solar and wind energy. It is a legal policy instrument since it requires utilities to perform this action according to government rules.

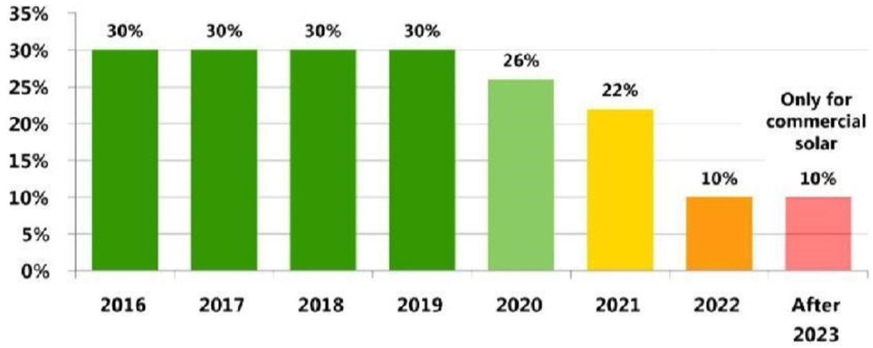

Figure 11. *ITC Extensions [93].*

As shown in Figure 11 the ITC was originally implemented in 2005 and over the years has been extended several times. However, in 2018, when the policy was again extended, Congress had to decide on the extension of the ITC, which made the future of the ITC not certain [81]. Since the PTC has also been renewed several times [82] and the targets of the RPS will be reviewed and, if necessary, changed every three years [83], getting permission from Congress is also an important hurdle for the PTC and RPS policies. The goals and methods of all three policies are clearly stated, so all of them have a low amount of ambiguity, although according to the National Regulatory Research Institute, some goals of the RPS policy conflict with other sustainable energy policies [84].

So, according to Matland's theory of policy implementation [70], despite low ambiguity, implementation of these policies can face problems, because of uncertainties at the Congress level.

5.3. Governmental Actors

The U.S. government has actively (and successfully) made an attempt to increase the solar power share in the total energy production in the U.S. In the previous decade the installation of solar power installations has increased by an average of 42% per year. This is due to strong federal policies such as the ITC [85]. The applications of solar power are also maintained by a policy framework at the local, state and federal level [86]. So the U.S. government primarily contributes to the implementation of solar power. However, there are some examples in which governmental institutions are countering the implementation of solar power. For instance, energy utilities based on fossil fuels may fear that the rise of solar power will threaten their business model. Because of this, throughout the United States, these energy utilities use their money and position to influence policymakers so that it becomes harder for businesses and homeowners to implement solar power [87]. The energy utilities have worked against pro-solar policies in various states with varying degrees of success. An example is that in Ohio a mega-utility was allegedly involved in a 61-million-dollar bribery of the local government with the consequence that there is now an anti-solar law in place that removes state incentives for sustainable energy development [87]. So implementation problems may also rise because of lack of cooperation by governmental institutions.

5.4. Conclusion on Policy Pillar

All in all, solar policy in the US seems to be rather successful, because of governmental aims and policy instruments. Main policies, the ITC, PTC and RPS have been implemented quite well and result in the development of sustainable energies and especially solar. So on first sight it seems that there is little change necessary for these policies. Solar industry umbrella SEIA predicts that if all the policy instruments stay in place as they are, solar power will generate approximately 14% of all the electricity in the U.S. [74]. However, the Biden administration aims for solar power to generate 45% of the U.S. electricity by 2050 [51, 75]. This requires not only ambitious specific aims, but also excellent implementation. This would ask for less political debate and hurdles at Congress level, less resistance at state levels and streamlining of energy policies, avoiding conflicting goals. The policies discussed in this chapter all worked via economic and legal policy instruments, but if the U.S. government wants to reach a larger share of solar power before 2050, more communicative instruments could also be considered. These new communicative policies could perhaps provide an extra stimulus for people to consider taking up solar panels or other forms of solar energy.

6. Integration of Pillars in 2 Scenario's

In this paper we discussed developments of solar power in the US via the four pillars of the energy system. As a general observation it was found that solar power in the U.S. is an incredibly fast-growing technology, as can be seen in Figure 10. According to Figure 1, solar power does however still only make up a relatively small fraction of the total power consumption in the U.S. Because of these two observations we believe that solar power in the U.S. is now in between being a niche-technology and forming its own solar energy regime in the socio-technological energy landscape.

The possibilities for solar power to grow into an actual regime in the U.S. are supported by each of the four pillars of the energy system. In this final section two different scenarios will be presented. A business-as-usual scenario and a maximally optimistic scenario.

6.1. Business-as-Usual

First of all, it is predicted by SEIA that, if all current and planned policies will not change until 2031, that solar power will produce approximately 11% of the total electricity production in the U.S. [74]. This means that the assumption is made that 8 years from now there will still be a government in place that prioritizes sustainable energy goals. Also the important policy instruments such as the ITC, PTC and RPS should be kept in place as they are. So the growth of solar power is basically expected to continue via the trend that it has now. This would also mean that there would be no significant acceleration in technological developments by R&D departments, no significant acceleration in the changing of the support of U.S. citizens and no significant acceleration of the social and governmental influence that environmental NGOs have.

According to EIA in 2020 a total of 95 qBtu was produced in the U.S. If the ratio of solar power and geothermal is assumed to be the same as for consumption that is shown in Figure 1, then solar power makes up approximately 1.27 qBtu. Using this number in combination with the fact that solar power made up 3% of the total electricity production in the U.S. in 2020 [74], we can approximate the total electricity production in the U.S. in 2020 to be equal to 42.3 qBtu. However we can approximate, again from EIA [74], that the electricity production in the U.S. will have increased by about 10% in 2031. So that means that instead of 42.3 qBtu, now 46.5 qBtu of electricity will be produced. Another report from EIA mentions that in 2031 the total energy production in the U.S. will have increased to a number of 109.5 qBtu [88]. It can then be calculated that in this scenario solar power will produce about 5% of the total power demand in the U.S.

6.2. Maximally Optimistic

In the maximally optimistic scenario another reasoning is used. In this scenario we take the goal of the U.S. government to produce 45% of total electricity production by 2050 [75] as a starting point. This means that 40% of all electricity should be produced by solar power in 2030. We will assume this number of 40% for the maximally optimistic scenario in 1931. This scenario can only be reached if the advancements in all sectors connecting to solar power grow faster than SEIA expects [74]. R&D departments for example should help to reduce the costs of producing and installing solar power even more combined with keeping the electricity prices low. New generation PV panels should be developed fast, as well as integrated systems. This requires close cooperation of companies and research institutes. Political struggles between Republicans and Democrats on renewables or bad coordination of governmental policy at different levels should be avoided. NGOs and governments using splendid communicative policy instruments could also be a key factor in making sure that people are willing to invest in solar power and work in jobs connected to solar power. With this combined effort the grid could be decarbonized a lot quicker and then solar power could fill up that newly shaped hole in the socio-technological landscape.

The calculation of the share of U.S. power production that solar power now holds is in principle the same as the one portrayed in the previous scenario. Only in this scenario 11% total electricity production will increase to 40% electricity production. This in turn will then result in solar power making up about 17% of the total power production in the U.S. Compared to the business-as-usual scenario this is an increase of a factor 3.4.

7. Discussion and Conclusion

Our main questions were what the future of solar energy in the US can be, and what relevant factors are.

Without doubt the future is sunny, but it depends on various factors how sunny it will be. Even in our Business as Usual scenario solar power has increased, but it is still small compared to what fossil fuels contribute nowadays. And even this scenario has some uncertainties, such as the political developments. In our Maximally Optimistic scenario solar has increased much more, so much in fact that it provides a significant portion of all energy produced in the U.S. Therefore, in this scenario, solar power has truly grown out to be a respected energy regime in the socio-technological energy landscape of the U.S. But it is uncertain if this scenario will come true. For this scenario the assumption is made that innovations for solar power through the four different pillars all excel even more in the future. However, as we have seen throughout this paper, these pillars are not independent. Niche and regime developments mean strengthening of the ties of what we called pillars. Strong interactions exist between government and companies (by subsidies, legislation, taxes, lobby etc.). Technology is improved by both governmental and industrial R&D, while technology may influence markets strongly. Governmental and civil society institutions work together and interact in various ways. The more interactions and interdependencies, the more stable niches and regimes will be. Nevertheless each of the pillars should have a minimum stability. The Maximally Optimistic scenario requires that governmental policies remain stable, while elections may be a disturbing factor. It also requires further successful innovations and smooth implementation. So although this scenario looks promising for the U.S. we do not directly expect all goals to be fulfilled.

We suggest investigating this further. We are fully aware of the limitations of our study. Within our timeframe we were not able to conduct an in-depth study of all elements we discussed. We did not explore all relevant solar technologies for instance, or value chains, or developments at state levels. We did not look at other main solar companies and we only considered a few NGOs.

Despite these limitations, we think our main conclusions will not change. The future of solar energy in the US looks promising, but the level of growth depends on the way socio-cultural, policy, market and company related and science-technical factors develop and interact.

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