Master's Thesis of International Studies

Strategy for a Large Scale Introduction of Solar Energy in Turkmenistan

투르크메니스탄에 태양 에너지를 대규모로 도입하기 위한 전략

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Strategy for a Large Scale Introduction of Solar Energy in Turkmenistan

A thesis presented

By

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Abstract

Strategy for a large scale introduction of solar energy in Turkmenistan

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Regardless of Turkmenistan's abundant solar radiation and pressing energy needs, solar energy utilization is minimal. This draft outlines a complete strategy to advance solar energy adoption, starting with the creation of numerous small and medium-sized photovoltaic plants. By exploring various multi-purpose and specialized solar installations, the strategy addresses diverse energy demands while optimizing resources. Local assembly of solar panels and production of essential components are proposed to reduce investment costs and foster economic growth. The environmental benefits, such as reduced greenhouse gas emissions compared to diesel generators, are emphasized, highlighting solar energy's role in climate change mitigation. The integration of solar energy into existing infrastructure aims to enhance energy security and resilience. Strategic international partnerships and technology transfer initiatives are also recommended to accelerate Turkmenistan's transition to solar energy, positioning it as a regional leader in renewable energy adoption.

Key words: Solar Energy; Photovoltaic Plants; Renewable Energy; Climate Change Mitigation; Energy Security; Economic Growth.

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요약

투르크메니스탄에 태양 에너지를 대규모로 도입하기 위한 전략

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투르크메니스탄의 풍부한 태양 복사와 긴급한 에너지 수요에 관계없이 태양 에너지 사용량은 최소입니다. 이 초안은 수많은 중소 규모의 태양광 발전소의 창설을 시작으로 태양 에너지 채택을 촉진하기 위한 완전한 전략을 제시합니다. 다양한 다목적 및 전문 태양 광 설비를 탐색함으로써이 전략은 자원을 최적화하면서 다양한 에너지 요구를 해결합니다. 투자 비용을 줄이고 경제 성장을 촉진하기 위해 태양 전지판의 지역 조립과 필수 부품의 생산이 제안됩니다. 디젤 발전기에 비해 온실가스 배출량을 줄이는 것과 같은 환경적 이점이 강조되어 기후 변화 완화에 태양 에너지의 역할을 강조합니다. 태양 에너지를 기존 인프라에 통합하는 것은 에너지 안전과 회복력을 향상시키는 것을 목표로합니다. 투르크메니스탄의 태양 에너지로의 전환을 가속화하기 위해 전략적 국제 파트너십과 기술 이전 이니셔티브도 권장되며,재생 에너지 채택의 지역 리더로 자리매김합니다.

핵심 단어:태양 에너지;태양 광 발전소;신 재생 에너지;기후 변화 완화;에너지 보안;경제 성장. **학생 번호**:2023-25366

Table of content

1. Introduction

1.1. Context

Despite the abundant solar radiation in Turkmenistan and the urgent energy needs, the use of solar energy is in its initial stage. This document provides a detailed strategy to address this gap, starting with the creation of numerous affordable small and medium-sized photovoltaic plants throughout the country. By exploring different types of multi-purpose and specialized solar installations, the strategy aims to meet diverse energy needs while optimizing resource use. Moreover, it proposes measures to significantly reduce investment costs by facilitating the local assembly of solar panels and the production of connectors, electrical wiring and special batteries in Turkmenistan. This not only reduces costs, but also stimulates economic growth and job creation within the country. In addition, the environmental benefits of solar energy are highlighted, as photovoltaic solar panels produce much less greenhouse gases than traditional diesel generators, making a significant contribution to mitigating the effects of climate change. In addition, the strategy highlights the importance of integrating solar energy into existing energy infrastructure to enhance energy security and resilience to fluctuations in fuel prices and geopolitical uncertainty. Moreover, using the geographical advantages of Turkmenistan, such as vast desert territories suitable for the installation of solar installations, the strategy aims to maximize the potential of solar energy production. Through strategic partnerships with international organizations and technology transfer initiatives, Turkmenistan can further accelerate its transition to solar energy, positioning itself as a regional leader in the use of renewable energy sources. By combining these elements into a single strategy, Turkmenistan will be able to use its solar energy potential to sustainably meet energy needs and move towards a more environmentally friendly and sustainable future.

1.2. Motivation

As a citizen of Turkmenistan, I am deeply invested in the future trajectory of our nation, especially concerning our energy landscape. The challenges we face are multifaceted, from meeting growing energy demands to safeguarding our environment for future generations. It is within this context that the motivation to embrace solar energy integration resonates deeply with me. The potential of solar energy to transform Turkmenistan's energy sector is immense. With our abundant sunlight and vast open spaces, we possess a natural advantage that can be leveraged to enhance our energy security and economic prosperity. By harnessing solar power, we can reduce our dependence on finite fossil fuels, mitigating the risks associated with fluctuating fuel prices and geopolitical uncertainties. Moreover, since environmental stewardship is nowadays a necessity, the prospect of embracing solar energy is absolutely crucial for countries, especially developing countries. By transitioning to clean, renewable energy sources, we can reduce harmful emissions and combat climate change, ensuring a healthier and more sustainable future for ourselves and generations to come. However, the motivation to pursue solar energy integration goes beyond mere environmental and economic considerations. Indeed, it would also have consequences on the increasing of job opportunities, and on the fostering of technological innovation within Turkmenistan. In essence, the motivation to embrace solar energy integration is rooted in the perspective of development of Turkmenistan, of the bettering of its people’s conditions of living and of protection of the environment. By harnessing the power of the sun, we can chart a course regarding a more sustainable development for Turkmenistan—one where energy is abundant, clean, and accessible to all.

1.3. Purpose of the Research

The research aims to propose a strategy for the large-scale introduction of solar energy in Turkmenistan, recognizing the country's significant energy needs and ample potential for solar radiation. By emphasizing the deployment of small and medium-sized photovoltaic solar plants, the research explores their effectiveness in fulfilling various energy requirements, including irrigation, water pumping, and rural electrification. Additionally, the research investigates the economic viability of solar energy adoption, highlighting its potential to reduce reliance on expensive imported fuels and stabilize energy costs over time. Furthermore, it underscores the environmental benefits of solar energy, such as mitigating greenhouse gas emissions and contributing to climate change mitigation efforts. Moreover, the research examines strategies to lower investment costs by promoting local production of solar components, thereby enhancing economic self-reliance and creating new employment opportunities. In addition, the research considers the social impact of solar energy deployment, particularly in empowering local communities and improving access to electricity in remote areas. Through these analyses and discussions, the research aims to demonstrate that solar energy presents a sustainable, environmentally friendly, and financially feasible energy option for Turkmenistan and other Central Asian countries seeking to embrace renewable energy solutions.

2. Research Method

This paper explores the feasibility and potential strategies for implementing solar energy on a large scale in Turkmenistan. My research objectives, questions, and hypotheses serve as guiding principles throughout the study, enabling a structured investigation into this complex topic. To achieve comprehensive insights, I employed a qualitative approach. This approach allows me to triangulate findings and provide a nuanced understanding of the challenges and opportunities associated with solar energy adoption in Turkmenistan. Data collection is conducted through various sources, including an extensive review of existing literature, the estimation of several costs, and the design of two plans of action. By drawing from multiple sources, I captured a holistic view of the subject matter, considering technical, economic, political, social, and environmental dimensions.

2.1. The difficulty of collecting information

First and foremost, it is essential to emphasize that gathering reliable and accurate information on Turkmenistan is particularly challenging. This country publishes very little data online, and transparency across various sectors, especially in infrastructure development and governance, remains limited. This scarcity of information makes it almost impossible to conduct a comprehensive quantitative study, especially for an ambitious project like the large-scale installation of solar panels. Nevertheless, the increasing pressures from fossil fuel depletion, the consequences of climate change, and the urgent need for a transition toward more sustainable and environmentally friendly practices remain critical issues. Thus, it is necessary to address these challenges, even without robust quantitative data. As a result, I opted for a qualitative approach, developing two distinct action plans tailored to the country's context and specific needs, based on an in-depth analysis of existing scientific and technical literature on renewable energy.

2.2. The development of action plans

The development of action plans is therefore the chose solution in order to address what will be the main challenges of this study. They are based on the identification of common challenges faced by various countries that have undertaken similar energy transitions, while considering Turkmenistan's specific circumstances, where some of these difficulties are often more pronounced. Although there are no academic works or reports dealing specifically with the energy situation in this country, this comparative approach allows us to extract relevant insights and apply general recommendations adapted to the local context. In this way, it becomes possible to establish a solid foundation for proposing applicable solutions, although requiring ongoing adjustments. These two distinct action plans offer responses adapted to the identified challenges while providing a certain level of flexibility.

2.3. The impossibility of a quantified cost-benefit analysis

In parallel, despite extensive research, conducting a complete cost-benefit analysis proved difficult due to the lack of accessible information and limited transparency regarding economic and environmental data. Nonetheless, this study includes several estimates based on accessible online resources and elements from existing literature on similar projects. Although approximate, these estimates still provide benchmarks that offer an idea of the funding required for a project of this scale. The required amounts are naturally very high, given the ambitious nature of such an energy transition project. This is why two distinct approaches were considered: one short-term, with immediately achievable and lower-cost actions, and the other long-term, aiming for a more profound transition.

2.4. The utility of this research method

Although different in their timelines and scope, both options involve significant reforms, particularly in terms of governance and economic development. However, it is important to remember that this study alone cannot cover all the reforms and actions needed to achieve the set objectives. Instead, it provides an initial framework, a theoretical model that can later be refined and adjusted as new information becomes available and as the context evolves. In this sense, this study serves as a starting point for future initiatives, which must consider subsequent developments and the country's economic and political realities.

3. Literature review

3.1. Environmental impacts of large-scale solar power plants

Before studying how a strategy for a large scale introduction of solar energy could be implemented in Turkmenistan, it is important to highlight several aspects of such a project. First of all, it is clear that fossil fuels have dominated the energy supply, even more in the case of Turkmenistan, causing severe environmental issues such as climate change, land degradation, and pollution, as we are recalled by the article "*Environmental impacts of solar energy systems: A review*" (RABAIA, 2021). Shifting to a cleaner source of energy, like solar power, could therefore help the country reduce its dependency on fossil energies, and therefore its impact on the environment. Indeed, solar energy technologies significantly reduce CO2 and NOx emissions, helping to combat climate change through the reducing of greenhouse gas emissions (TSOUTSOS, 2005). They can also be used to reclaim and repurpose degraded land areas.

However, it is important to give more details about the environmental impacts of this strategy. Indeed, in the article titled "*Environmental impacts from the installation and operation of large-scale solar power plants*" (TURNEY, 2011), the authors provide a comprehensive analysis of the environmental impacts associated with large-scale solar power installations. First of all, they emphasize of course the existence of the many <u>environmental benefits of the use of solar power</u>. Solar power is presented as a more environmentally friendly alternative to traditional fossil fuel-based power generation. Their analysis includes various environmental impacts, categorizing them into beneficial, neutral, or detrimental relative to traditional power sources. Of the 32 environmental impacts identified, 22 are beneficial, 4 are neutral, and none are detrimental compared to traditional power generation. However, it has to be noted that they do not evaluate 6 remaining impacts that require further research to be fully understood. Moreover, they study the importance of <u>land occupation</u> metrics in order to compare the land use intensity of solar power plants with other power systems. It is found that solar power plants occupy less land per kWh of electricity generated than coal power plants, particularly for plant lifetimes exceeding approximately 25 years. They observe that the land transformation rate, which considers the extent and duration of land use changes, is also lower for solar power than for coal power for plant lifetimes beyond roughly 27 years. Then, they stress out the fact that the choice of location of solar power plants has environmental effects, that vary significantly depending on their location. For example, solar power installations in desert regions are shown to have more favorable environmental impacts due to higher solar insolation and the absence of significant wildlife. In contrast, installing solar power plants in forested areas results in higher CO_2 emissions due to vegetation clearing and reduced solar insolation from cloud cover. These emissions range between 16 and 86 g CO_2 per kWh, which is 2-4 times higher than in desert regions. Therefore, Turkmenistan appears indeed as an ideal location to implement such a strategy, since as we said before, its territory is largely covered by the Karakum desert. The environmental impact would be minimized. The authors also show in their study that all environmental impacts do not have the same level of impact, and they therefore assign priority levels to the various environmental impacts, with seven high-priority impacts, twelve moderate-priority impacts, and three low-priority impacts. They manage to show that the high-priority impacts are predominantly favorable for solar power as a replacement for traditional power generation, whereas neutral impacts are mostly of moderate priority, while detrimental impacts, although none were identified in this study, would be of low priority if they existed. This is therefore very encouraging for the implementation of this strategy, especially since one of its aim is the reducing of environmental impacts created by the production and use of fossil energies. Even though there is a need for further research, since six of the environmental impacts identified require additional research to be accurately classified, solar technology is still overall found to be much preferable to traditional means of power generation, even when considering wildlife and land use impacts. The study emphasizes that all high-priority impacts favor solar power displacing traditional power generation, and any detrimental impacts from solar power are of low priority. Since the article concludes that large-scale solar power plants offer substantial environmental benefits over traditional fossil fuel-based power generation, especially in regions with high solar insolation and low wildlife presence, such as deserts, to maximize environmental benefits and minimize adverse impacts, it seems that **the strategy of a large scale introduction of solar energy in Turkmenistan would indeed be a significant progress, in terms of environment at least**, and therefore of climate change mitigation. However, this analysis has to be completed with other dimensions of the impact that solar photovoltaic systems can have on the environment. Indeed, the authors mainly focused on the installation of the panels, but two other aspects are important, as shown in the article "*Environmental impacts of* *solar energy systems: A review*" (RABAIA, 2021) : the manufacturing, that induces energy and material consumption, and emissions from production processes; and the decommissioning, that generates waste, even though potential for recycling and reuse of materials. Another article, "*Environmental Impact of PV Systems: Effects of Energy Sources Used in Production of Solar Panels*" (BELOIN-SAINT-PIERRE, 2009), emphasized the significance of electricity source in the photovoltaic manufacturing: it shows that the choice of electricity source during the manufacturing process of PV modules significantly impacts the environmental footprint, particularly the CO2 equivalent emissions and the Energy Payback Time (EPBT). The authors therefore offer industrial recommendations that include the necessity for the photovoltaic industry to prioritize using renewable energy sources for module manufacturing to minimize environmental impacts, since choosing renewable energy sources presents a more immediate and effective solution than technological improvements themselves. Moreover, the use of toxic materials or hazardous substances like cadmium is also concerning (RABAIA, 2021), and there is therefore a **need for proper management and recycling**, including in the process of manufacturing, especially regarding a strategy that would encourage the production of the panels directly in Turkmenistan. Moreover, there is an important potential water use that has to be considered, since solar power plants may require significant water for cooling, especially in arid regions – in the case of Turkmenistan, the Karakum desert. The article "*Environmental impact of renewable energy source based electrical power plants: Solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic*" (RAHMAN, 2022) also reminds us that the maintenance of the solar panels can have an impact as well, since there are various electrochemical effects on soil caused by wastewater from solar photovoltaic plants. All these elements tend to show that there is a need for proper implementation strategies in order to mitigate the negative environmental impacts of solar energy technologies, which could include better site selection, improved technologies, and more stringent regulations.

3.2. Technical and technological challenges of large-scale solar power plants

However, the implementation of large-scale solar power plants still presents significant challenges in terms of forecasting, grid stability, and consumption management. If the rapid growth of global photovoltaic power generation, with significant increases in installed capacity worldwide, is expected to become a major source of electricity generation by 2050, it also means that further research need to be done about the challenges with grid integration, as shown in the article "*Key Operational Issues on the Integration of Large-Scale Solar Power Generation—A Literature Review*" (LI, 2020). The intermittency and variability of solar power pose indeed challenges for grid stability, necessitating accurate forecasting and flexible operational measures. The main factors that affect the photovoltaic generation and efficiency are of course physical factors, such as the efficiency of the modules themselves, electrical characteristics and the types of photovoltaic modules, but also external environmental factors, such as meteorological, climatic, and geographical factors, and human-related factors, that include scheduling constraints and maintenance practices. In order to reduce the potential negative impact of such factors, forecasting techniques, frequency regulation and measures to improve consumption of intermittent solar power are crucial. This means that the countries that implement such projects need **to take into account these factors**, and to make sure that they establish **effective protocols**, as well as a **sufficient level of training for officers assigned to supervision and maintenance**. Furthermore, they have to **foster further research and development efforts** in order to address these evolving challenges, and to enhance the efficiency and reliability of the technical solution that mitigate these challenges. This need for continuous technological development to maximize the efficiency and reliability of solar power systems is also highlighted by the article "*Large Scale Solar Power Plant in Nordic Conditions*" (KOSONEN, 2014). Even though this article focuses on the potential and feasibility of large-scale solar power plants in Nordic conditions, this necessity of further research is common to all the countries that implement large-scale solar power projects.

More generally, the main technological effort that has to be conducted short-term is the acquisition of technology. However, it is very important that this acquisition is led by the State, and oriented toward the development of the industry. In fact, scholars have shown that progress, for example social progress, is linked to the acquisition and the development of the industry of a country. In the article *Strategies for State-Led Social Transformation"* (KHAN, 2004) examines the necessity of state intervention in guiding economic transformation in developing countries, arguing that sustained growth requires more than enhancing market efficiency. The analysis continues with a discussion on whether the classical capitalist model is appropriate for today's late-developing countries. Early capitalist countries relied on the creation of a propertyless labor class competing in the market, which generated rapid productivity growth. However, late developers, faced with the challenge of catching up to advanced economies with already superior technologies, cannot rely on pure market mechanisms alone, as such an approach would likely result in low-technology production due to competitive constraints. Khan underscores that successful cases of economic catch-up, such as South Korea and Taiwan, illustrate the necessity of state intervention, not merely to enhance markets but to establish entirely new institutions and property rights arrangements suitable for accelerated productivity growth. In these contexts, the state was instrumental in facilitating technology acquisition and fostering the development of high-value-added industries. The document critiques the "good governance" framework dominant in mainstream economics, which posits that stable property rights, limited corruption, and democracy are the foundational conditions for capitalist growth. However, aiming at some of these dimensions is still important in the framework of the implementation of such a project, and it has to be studied a little bit later. Ultimately, the document argues that the development of effective state capabilities, especially in rent management and institutional restructuring, is crucial for developing countries to close the productivity gap and achieve sustainable growth. This analysis can therefore be used for environmental progress. Indeed, in the context of the implementation of a very ambitious project such as large-scale solar panels plant, the acquisition of technology, especially at the beginning, in order to catch up with the current technologies available, and to not waste time starting the research and development from scratch, is crucial. Therefore, it is important that the authorities seek to acquire technologies linked to solar panels, in order to implement the project, to foster research and development, and also to consider producing the panels in Turkmenistan – in a longer term perspective. In a broader perspective, it generally means that **the technological challenges need to be addressed by a global state-led strategy, that supervises and supports the acquisition of technologies and the creation and development of effective industries**.

3.3. Institutional barriers and their consequences

Even though the Turkmen authorities have several times declared themselves ready and willing to implement new types of energy production, and to actively engage in the environment protection and climate change mitigation, several obstacles need to be taken into account and overcome. Indeed, as shown in the article "*Barriers to Large-scale Solar Power in Tanzania*" (AHMED, 2019), several obstacles hinder the deployment of large-scale solar energy projects in developing countries. The study specifically focuses on Tanzania, but the profile of the country is very much similar to Turkmenistan's. Indeed, the Tanzanian power system heavily relies on fossil fuel-fired power plants. Therefore, some of the arguments and of the results of the study can be transposed to Turkmenistan's case. The study indeed aims to identify and analyze the barriers preventing the adoption of large-scale solar power in Tanzania in order to promote a sustainable energy transition. It uses a qualitative methodology, collecting primary data through 30 semi-structured interviews with key stakeholders from public institutions, private investors, civil society organizations, development partners, and financial institutions. A stakeholder-based approach is utilized to identify barriers based on the perceptions of different groups. The first main result is the omnipresence of institutional barriers. Indeed, there is an uncertainty around the government commitment towards large-scale solar projects, leading to uncertainty and hesitation among potential investors. Decision-makers often perceive solar power as unsuitable for large-scale electricity generation, favoring traditional fossil fuel-based methods, and decisions made by the utility and regulatory bodies are often influenced by political considerations, undermining stable and predictable policy environments necessary for large-scale investments. Moreover, the business environment is not conducive to private investment in large-scale solar projects due to bureaucratic hurdles and lack of incentives. This creates an uncertain business environment, and this raises the **necessity for the authorities to encourage a more stable environment, through more transparency, and a strong legal and financial framework**. Indeed, this financial risk is also associated to a situation of a rather closed economy and authoritarian regime that induces higher risks of non-payment, and of political risk for investors – especially foreign investors. Moreover, the taxes on import are very important, which makes the investment very risky. This is why the strategy that will be studied in this paper will try to offer alternatives to an "all-import" strategy, with the analysis of the possibility to produce, at least partly, the solar power plants in Turkmenistan. Finally, the authors emphasize the technological barriers that are inherent to the developing situation of the country. Indeed, there is first a lack of comprehensive data and studies to support the development of large-scale solar power projects, making it difficult to plan and implement these projects effectively in such countries. There is also a scarcity of locally qualified personnel to support the deployment and maintenance of large-scale solar technologies. This is why the implementation of such a large-scale strategy has to be done alongside a broader policy of training and education, as well as of incentives for partnerships abroad, that could even eventually lead to transfers of technology. The strategy displayed in this paper will therefore take into account the **importance of education and of international partnerships**. The authors show for example that in the case of Tanzania, European development partners and other international entities are supportive of renewable energy projects, providing potential technical and financial assistance, and in fact, that most large-scale power projects are financed, at least partly, by international financial institutions.

3.4. Public acceptance and support

Besides the institutional, financial and technical difficulties that need to be overcome in order to implement the strategy, it is also necessary to gain the support of the public opinion. Indeed, the population is a key-actor to make this strategy successful, since it relies on the participation of the local industry, the local businesses and the work-force, and also since large investment have to be done, and need to be understood in order to be accepted. The article titled "*Public attitudes regarding large-scale solar energy development in the U.S.*" (CARLISLE, 2015) explores public opinions and factors influencing support or opposition to utility-scale solar energy projects. The country studied in this article is the United States, but some of its conclusion can be transposed in the case of Turkmenistan. However, some other elements need to be analyzed carefully. First of all, the authors observe a <u>general support for solar energy among the population</u>. The article notes indeed that the majority of Americans support solar energy development due to its potential to mitigate climate change and reduce dependence on fossil fuels. However, the current energy structure in Turkmenistan is very advantageous to the population, since the energy is very cheap or almost free. Indeed, it is produced by the large amount of fossil materials that the country has, and **the change to solar power energy might create skepticism among the population**, especially if large public investment are needed. The people might fear an increasing of the energy prices. Therefore, it will be essential in order to implement this strategy to also spread **awareness** in the population of the benefits of power solar system, and to have enough **transparency** on the investments and prices. This should be in fact included in the broader education policies, particularly with awareness about climate change, its consequences on the country, the population and the necessity to preserve the environment. Then, the authors highlight several factors that influence public attitudes toward large-scale solar energy development. For example, the perception of the government's commitment for the benefit of the population, the perception of low-cost leases for solar facilities, the belief that solar energy is more expensive than other forms of electricity, the trust in solar energy developers, or even the concerns about property value impacts play an important role. Overall, the study enhances the fact that public attitudes towards solar energy can vary significantly based on proximity to the proposed project. People are generally supportive of solar projects, but this support can wane if the project is planned for their local area, often due to concerns about direct impacts such as property value and environmental effects. Therefore, understanding the factors that influence public attitudes towards utility-scale solar development is crucial for policymakers and developers. By **addressing concerns related to environmental impacts, property values, and ensuring transparent communication about the benefits and costs**, it may be possible to **enhance public support for these projects**, including in the case of Turkmenistan.

Besides the support from the overall population, the article "*Community acceptance of large-scale solar energy installations in developing countries: Evidence from Morocco*" (HANGER, 2016) also shows that the local community acceptance is crucial. The study explores indeed the factors that influence the local community acceptance of large-scale concentrated solar power (CSP) projects, with a focus on the Noor I project in Ouarzazate, Morocco. The authors conducted 232 face-to-face interviews with local residents in order to assess their attitudes towards the project and identify key drivers of acceptance, that is necessary for the success of the implementation. They try to identify if the "not-in-my-backyard" (NIMBY) syndrome, often cited in the context of infrastructure projects in developed countries – as seen just before with the example of the USA -, is relevant in the context of a developing country. They also explore several potential drivers of acceptance, that include expected socio-economic and environmental impacts, procedural and distributive justice, and trust in the institutions involved. In terms of results, this research found that community acceptance of the Noor I CSP project is almost universal. Solar power is perceived positively, mainly because it is seen as environmentally friendly. This high level of acceptance contrasts therefore largely with experiences in Europe and North America, where renewable energy projects often face significant local opposition. However, the authors also observed that the perceived level of knowledge about the project among the local population is very low. There is a positive correlation between this low level of knowledge and the high acceptance rate, suggesting that greater awareness might alter perceptions. Therefore, it seems that in the context of a developing country, like Turkmenistan, it is indeed **necessary to implement broader educational policies about the benefits of an energetic transition**. Additionally, the authors noted that there are high expectations regarding job creation and electricity prices, which could lead to future dissatisfaction if not met. This is why transparency and clear projections are also crucial in the process of the project's implementation, in order to make it successful in the long term. Even if the Moroccan context is different from Turkmenistan's, the study points out that several socio-cultural factors influence community acceptance, such as the presence of patriarchal and authoritarian institutions. If these factors distinguish the Moroccan context from those of European and North American countries, it can be more or less transposed in the MENA region and in Central Asia. The findings of this study can therefore be very useful for Turkmenistan. Indeed, policymakers and project developers need to **manage expectations and provide more information** to the local community to maintain high levels of acceptance. **Addressing issues of procedural justice and ensuring that the perceived benefits, such as job creation, are realized** will also be crucial for the long-term success of large-scale solar power projects in such countries.

3.5. Research questions

Given the literature on the subject, it is clear that the strategy of a large scale introduction of solar energy in Turkmenistan would represent a significant progress, especially in terms of environment, and therefore of climate change mitigation. However, there are other challenges that need to be taken into account. Therefore, **to what extent is the implementation of proper sub-strategies needed, in order to address the other challenges?**

Moreover, the large scale introduction of solar energy in Turkmenistan also creates challenges in terms of governance. Indeed, there is first a need for proper management, that goes from the manufacturing of the panels to the maintenance. This includes recycling, as well as the establishment of effective protocols. But it also means that at the institutional level, there is a necessity for the authorities to ensure transparency, and a strong legal and financial framework, in order to guarantee a secure business environment. It is also important to foster international partnerships, with incentives for partnerships abroad, that could even eventually lead to transfers of technology, and at least that could encourage supportive development partners of renewable energy projects, providing potential technical and financial assistance[1]. In consequence, **what governance changes need to be done in order to address these challenges and to implement a successful long-term strategy?**

Finally, the strategy cannot be a success without a strong education and training focus. Indeed, the persons that will work on the manufacturing, the installation, the supervision and the maintenance need to get a sufficient level of training. More broadly, it is essential to sensibilize the population to the importance of climate change mitigation. Since the change to solar power energy might create skepticism among the population, especially if large public investment are needed, it is essential to also spread awareness about the benefits of power solar system for the environment, the society and the energy security of the country. This education policy goes along with the fostering of further research and development efforts in order to address the evolving challenges, and to enhance the efficiency and reliability of the technical solutions that mitigate

[1] For example, organizations like the International Finance Corporation, which is part of the World Bank Group, "helps manufacturers implement and finance strategies aimed at decarbonizing their operations [… and] focuses on initiatives that promote energy efficiency, renewable and alternative energy, emerging technologies, and resource efficiency". See "Decarbonization and Sustainability", IFC, online

these challenges. Therefore, **what measures would be recommended for the Turkmen authorities in order to ensure a long-term improving of education, training, research and development?**

4. Plans of action

Setting up such a project requires a precise and detailed action plan, which takes into account the whole process, from the acquisition of the solar panels to their maintenance, including the preparation of the installation sites and the sale of the energy produced.

It is therefore first necessary to separate the two potential action plans: the first would involve acquiring solar panels abroad, then transporting and installing them in Turkmenistan, while the second would require the creation of an entire industry chain to produce the solar panels directly in Turkmenistan. Indeed, as Turkmenistan is still a relatively closed country to international trade, any imports of foreign products, especially when they are equipped with cutting-edge technology, involve significant costs in terms of customs and taxes. Both action plans therefore have the merit of being explored.

4.1. First plan : import of panels

The first plan of action therefore involves importing solar panels from abroad. However, before looking at this part of the large-scale introduction of solar energy in Turkmenistan, it is necessary to consider the details preceding the actual acquisition of these panels. First and foremost, it is important to identify the political and administrative authorities responsible for such a project. The Ministries of Energy and of Agriculture and Environmental Protection are the first to be involved. The Ministry of Energy obviously manages the production and distribution of electricity throughout the country, and is a key player in the changes sought by the authorities as part of the new energy policies promoting clean electricity. For its part, the Ministry of Agriculture and Environmental Protection manages the distribution and use of land (for the production of agricultural products), and must therefore take part in discussions about the land to be chosen for the project. Its portfolio of missions also includes strengthening the country's economy and improving living conditions for the population. By seeking to strengthen Turkmenistan's energy and economic independence, and limit the pollution generated by the exploitation and use of hydrocarbons, the project falls completely within its remit.

It would therefore be necessary to set up an interministerial commission comprising officials from the Ministry of Energy and the Ministry of Agriculture and Environmental Protection. This commission should report to the President. In fact, a project of this scale in a strict presidential system cannot be designed or carried out without the clear approval and support of the President. In addition to this supervision, the commission would have to report occasionally on the progress of the project, in particular to the Mejlis, the unicameral assembly that holds legislative power in Turkmenistan and represents the citizens. In fact, the Mejlis can pass laws, and approves laws passed by the President, as well as the state budget. Its role is therefore crucial, both in terms of ensuring a degree of transparency about the project in the eyes of the public, but also in terms of having the legislative support needed for the changes and innovations brought about by the implementation of the project.

Once the inter-ministerial commission has been set up, it should produce an estimate of the costs involved in implementing the project, and make recommendations on the energy prices that should be set for national consumption. In setting this price, the commission will have to take into account the fact that this energy transition will necessarily be costly, and that the budget cannot be balanced in either the short or medium term. It will therefore be necessary to look at a price that is acceptable to the population, in order to guarantee their support for such a project - and through this, the support of the Mejlis.

The report on the estimated costs of the project will then have to be examined and approved by the Mejlis, and then also by the Chairman. Once this stage has been validated, the committee should propose at least two different suppliers of solar panels, with prices in line with the validated budget. The main countries producing solar panels are China, the United States, France, Germany and South Korea. However, for reasons of economic competitiveness, as well as geographical proximity - which is particularly important when it comes to the cost of transporting panels to Turkmenistan - Chinese manufacturers are the most attractive producers. China is a key global producer, with several manufacturers. The first one is LONGi Solar. Stepping onto the solar scene in 2000, LONGi Solar has risen to prominence as a Chinese solar trailblazer. A subsidiary of LONGi Group, it reigns supreme as the world's premier manufacturer of mono-crystalline silicon wafers. With a workforce of 60,000 and an astounding brand valuation of over 84 billion dollars, they're an undeniable powerhouse. Yet, their impact doesn't stop at sheer size. LONGi Solar has been a driving force behind innovative solar solutions, showcasing cutting-edge PERC technology in their panels. This innovation is pivotal, drastically reducing energy loss and maximizing solar energy conversion. Their standout product line features half-cut cell panels, pushing efficiency to even greater heights. Then, there is Trina Solar. With a history dating back to 1997, Trina Solar Co., Ltd. shines as another heavyweight in the solar manufacturing arena. Engaged deeply in PV panel R&D, sales, power station products, and energy cloud platforms, the innovation prowess of the company is evident in the 25 world records it has set or broken in PV cell conversion efficiency and panel output power. By April 2022, the Chinese company achieved a remarkable feat, shipping PV panels equivalent to a staggering 100GW – an environmental achievement akin to planting a whopping 7.4 billion trees! Homeowners find a trustworthy solar ally in Trina Solar, thanks to their exceptional product quality, enduring presence, strong financial health, and panel efficiencies ranging from 19.9% to 20.6%. Moreover, the manufacturer Jinko Solar could also be an interesting candidate for the project. Emerging from Shanghai in 2006 as a wafer manufacturer, Jinko Solar Holding Co., Ltd. has seamlessly evolved into a renowned Chinese solar panel producer and has been listed on the New York Stock Exchange since 2010. The company reach spans across utility, commercial, and residential sectors in numerous countries. With shipments surpassing 100GW, Jinko Solar has solidified its reputation, serving a vast customer base of over 3000 clients across 160 countries. Their entry into the high-performance realm was marked by the introduction of the Tiger panel series, built on the foundation of high-purity N-type cells – a testament to their commitment to pushing the boundaries of solar efficiency. Finally, another main competitor on the Chinese market is JA Solar. Indeed, JA Solar Technology Co Ltd emerged in 2005 from the heart of Beijing and has since become a big player in crafting and spreading silicon wafers, solar cells, and solar panels. Stretching its influence from China to Vietnam and Malaysia, their reach is truly global, making waves in 135 countries and regions. Innovation shines through their Deep Blue panel series, where the 3.0 lineup embraces cutting-edge cell tech, and the 4.0X series places bold bets on top-notch N-type silicon. The chosen supplier will therefore probably be chosen among these four main manufacturers of the Chinese market.

Once the producers have been selected, presented and validated, the interministerial commission will have to choose a freight company to transport the panels purchased in China to Turkmenistan, and more specifically to the chosen sites. To keep costs down, it would be preferable to choose a Turkmen company rather than a Chinese one, especially as the difficulties of the terrain will be better known by the national company. Terne Logistics in particular is one of the country's leading companies. It has a global reach, which means that this company handles cargo transportation all over the world, leveraging a developed network of representative offices globally. It also ensures the expertise of a qualified team of specialists who ensure the safe delivery of goods, including special goods as solar panels. Moreover, the company includes trucking, sea freight, air freight and rail transportation. And indeed, the panels could be transported by air freight from China to the capital city Ashgabat, then by rail transportation to the area where they will be installed, and then by trucks in order to reach the furthest places of installation.

At the same time, the inter-ministerial commission will have to prepare a provisional map of the land chosen for the installation of the solar panels. These maps will also need to include the roads and possibly railways that will need to be built to enable the panels to be transported to the chosen sites. The role of the Ministry of Agriculture will be particularly important, as it will be responsible for selecting the land to ensure that it does not deprive the country of potential agricultural resources, but also land whose environment will allow the panels to function optimally, without damaging them prematurely.

For the preparation of the land, the Ministry of Agriculture should be overseeing the process. The process involves extensive land grading and soil stabilization to ensure a stable foundation for the solar arrays. Heavy machinery, including bulldozers and tractors, will be needed in order to level the terrain, while engineers assess the soil composition to ensure its suitability for supporting the panels. Existing irrigation systems could be carefully modified in order to maintain the area's agricultural integrity while accommodating the new infrastructure. Additionally, measures such as planting windbreaks of native vegetation should be implemented in order to protect the installations from the region's characteristic desert winds. This effort represents a significant intersection of agricultural land management and modern energy technology, and would highlight the Ministry’s role in facilitating a transition to sustainable energy production.

The inter-ministerial commission will then have to issue a national call for tenders to find a company that can build the roads and/or railways required for the installation. It will also have to issue a call for tenders to find a company to install the collateral electrical infrastructure needed to ensure the success of the project. The company will need to implement transmission lines, which are required to connect the solar farm to the grid, but also substations, which are necessary to step up the voltage for efficient long-distance transmission, and inverters, which convert the electricity generated by solar panels into electricity for use on the grid.

At the same time, the commission will have to create a national public company in which the government is the majority shareholder, in order to recruit the necessary number of workers and engineers to implement the project. Given the scale of the project, it is possible that the company thus created will need to recruit staff both in Turkmenistan and in other countries (in particular Uzbekistan and Kazakhstan, where solar panel installation projects are also being carried out). The company will need to select a number of engineers and project managers to supervise the project alongside the commission, and act as its liaison on the ground. A large number of electricians will also be employed, of course, to take care of the electrical connections and ensure that the new systems are perfectly integrated into the existing infrastructure. Finally, several hundred installation workers will need to be recruited to assemble the solar panels, connect them together and ensure that they are properly aligned. Given the large number of installers required, the interministerial commission will have to prepare accelerated training cycles to rapidly train the workers employed by the company. General workers will also be required, for tasks such as preparing the panels and installation sites, and providing assistance during the installation process. In addition to these staff, the company will need to employ safety officers, who will assist the project managers in ensuring that all safety and installation protocols are followed. In total, around 500 staff will be needed on the installation site, and around fifty to liaise with the commission and the project managers.

In addition to installation, the company set up by the commission will be used to employ the staff needed for maintenance. As with the installation team, there will be electricians and general workers to cover maintenance tasks such as cleaning the panels, inspection and minor repairs. The team should be made up of at least fifty people.

The Ministry of Energy, in accordance with the laws and the framework given by the Mejlis, and under the validation of the President, determines the pricing strategy for the electricity generated by the newly installed solar panels. The pricing model takes into account several factors, including production costs, regional energy demand, and the potential for both domestic consumption and export. Given Turkmenistan's strategic location and expected production of solar energy, a portion of the generated electricity would be expected to be transmitted to neighboring countries via high-voltage transmission lines, contributing to the regional energy market. The inter-ministerial commission should therefore create a plan for the implementation of these transmission lines, and follow the same process than for the provisional map for the implementation of solar panels. For domestic use, tiered pricing may be applied to ensure affordability for local consumers while maintaining financial viability for large-scale industrial clients.

To manage energy storage and distribution, advanced battery storage systems are being considered to store excess energy generated during peak sunlight hours. These storage solutions will help regulate supply during periods of lower solar output, ensuring a steady and reliable energy flow. Additionally, investments in infrastructure, including new substations and grid upgrades, are being planned to accommodate the increased load and optimize the integration of renewable energy into the national grid. These measures are part of a broader strategy to establish Turkmenistan as a key player in regional renewable energy markets, while also ensuring energy security and stability at home.

4.2. Second plan : national production of panels

We began by looking at the steps that would need to be taken to set up such a project, on the assumption that the solar panels would be purchased abroad, in this case in China. However, with a view to making the country even more independent in terms of energy, and therefore energy security, we also need to think about the possibility, or at least the cost, of producing the solar panels in question on home soil.

Indeed, although the prices of panels produced in China are very competitive - which is largely due to supply outstripping demand for the time being[2] - it should not be forgotten that many countries are beginning to take an increasing interest in solar energy, and that demand could

[2] "Wholesale prices plummeted by almost half last year and have fallen another 25 percent this year. Chinese manufacturers are competing for customers by cutting prices far below their costs, and still keep building more factories. The price slashing has taken a severe toll on China's solar companies. Stock prices of its five biggest makers of panels and other equipment have halved in the past 12 months." In Bradsher Keith, (2024) "China Rules Solar Energy, but Its Industry at Home Is in Trouble", The New York Times, July 25, 2024, online

increase significantly over the next few years. It is therefore possible that, in response to a shock in demand, supply prices could rise drastically, including in Chinese production. What's more, China may in a few years' time want to increase its own requirements in terms of solar panels, and may therefore seek to redirect its production to its domestic market. It is therefore important, for reasons of energy security as well as medium- and long-term economic logic, to consider a solution that includes the production of solar panels on Chinese soil.

However, while this solution may seem obvious, it presents a number of challenges, in fact many more than the solution of importing the panels. Of course, the first and main difference in terms of costs is to the benefit of Turkmenistan, which would not need to pay as much in transport costs to bring the panels from China - as explained in the first action plan - and which would also not have the problem of customs duties. Of course, in the case of imports, we could advocate a sectoral reduction in customs duties, specifically aimed at solar panels, in order to boost import capacity and the attractiveness of Chinese industries exporting their panels to Turkmenistan. However, these tariffs could probably never be reduced to zero, and would continue to represent a certain cost.

To produce solar panels in Turkmenistan, given that no other Central Asian country has yet been able to launch such production, a number of challenges need to be addressed - and this without the option of building on an existing model. First of all, we need to define the requirements for such production. The infrastructure needed for production (factories, machinery and production lines), raw materials, technologies and patents (and therefore everything to do with intellectual property in this area), but also human capital, i.e. the ability to recruit a sufficient number of trained staff, and first and foremost, effective governance. In fact, it is crucial for the development of a new industry sector to have a clear governance structure that is supported by the political authorities - in particular to obtain support in financial and economic terms, since the political sphere can play a facilitating role, particularly in terms of the development of the sector, through incentives or a favourable legal regime.

It is therefore important in the context of this second action plan that the Ministry of Energy and the Ministry of Industry and Construction Production of Turkmenistan work together, possibly through a joint commission, to define the main lines of development of a new industrial sector, that of solar panel production. In a country like Turkmenistan, the most effective way of developing this sector would probably be the state-supported creation of large companies, at least half of whose capital would be held by the state (i.e. they would be public companies). For the other half of the capital of these new companies, it would be necessary to envisage an incentive for the participation of large fortunes - in particular large fortunes from the hydrocarbon industry, which would therefore allow, at the same time as a de facto energy transition, a transition in terms of investment and profitability. More generally, this would make national capital less dependent on international oil and gas prices, and thus stabilise the economy by diversifying activities. The big oil and gas fortunes could, for example, benefit from tax rebates on their investment in the development of the solar panel industry, or incentives in kind, which is very common there. It is also possible to open up this participation in the capital to foreign companies or individuals, but it is important, in the interests of economic and energy independence, to keep a certain percentage within the country, in order to see significant economic spin-offs from these investments in Turkmenistan in the long term. With the capital raised, the construction of the necessary infrastructure, as well as machinery and production lines, could be launched, with a procedure that would always involve invitations to tender, followed by facilitation of the conditions of activity for the companies chosen.

Once these companies have been set up, the joint commission should facilitate the launch of industrial activity by doing several things. Firstly, by giving these industries access to patents, which the State could, for example, help to acquire, both for the panels themselves and for the manufacturing technologies. In this context, technical partnerships could also be envisaged with developed industrial countries offering development aid, for example in Europe, but also with Japan or South Korea.

As well as obtaining and making patents available, the authorities need to launch training programmes. Turkmenistan's Ministry of Education could be given responsibility for developing training programmes, whether through training visits abroad, by recruiting international teams to come to Turkmenistan specifically to train workers, or by setting up professional conversion training courses for workers already qualified in related fields. This training phase is crucial, because as with the installation of solar panels, panel production requires a certain minimum level of knowledge.

In addition to these aspects, it is important that the joint committee looks into ways of facilitating the arrival of the raw materials needed for solar panel production in the country. The main raw materials needed for this production are silicon, metal and glass. Although their extent is not fully known, it seems that Turkmenistan has large reserves of copper and iron, which are crucial for electricity (MINING SEE, 2024). It is therefore possible to envisage increased extraction of these materials. What's more, glass production requires large quantities of sand, which is also readily available in the country. It therefore seems that the main material to be imported is silicon. It is a nonmetallic chemical element in the carbon family (BRITANNICA, 2024), and for the time being, silicon is mainly produced in China (production volume estimated at 6.6 million metric tons in 2023 – (JAGANMOHAN, 2024)) and Russia (second largest producer, but nowhere near the Chinese production volumes). Turkmenistan's strategic geographical location means that it can consider importing silicon from China or Russia. The joint commission will therefore have to negotiate with the two countries in order to define which country will be able to meet Turkmenistan's needs in terms of volumes, but also in terms of purchase price. For transport, the same solutions can be envisaged as those already mentioned in the first action plan.

Once all these elements are in place, it will be possible to start producing solar panels. However, because of the high initial investment costs, it is difficult to say at what level of production these investments will become profitable. In fact, this strategy needs to be established for the particularly long term, because in the immediate and short term, importing Chinese solar panels, despite transport costs and taxes and customs duties, will remain more attractive.

Once the panels have been produced, the plan of action is no different from the first, in terms of choosing the land on which to install them, preparing the land, installing them and maintaining them.

However, projections in terms of costs are possible, although it is not possible to obtain exact figures. The orders of magnitude presented in *3.6. Cost projection* should enable a first decisive approach to the implementation of these action plans.

4.3. Synthesis of the main axis of the plans of action

Establishing large-scale solar plants in Turkmenistan requires a significant initial investment in infrastructure. The country also needs to develop the necessary infrastructure for the transmission, distribution, and storage of solar energy. In addition, training and capacity building are essential to ensure the effective operation and maintenance of the system. Identifying suitable land areas for solar installations is another crucial step, which must be done carefully to avoid disrupting ecosystems or agricultural activities. Furthermore, integrating solar power into the existing energy grid demands careful planning and coordination. Finally, investment costs can be reduced by promoting local production and assembly, including assembling solar panels and manufacturing connectors, wiring, and specialized accumulators within the country.

4.4. Current prospects to be deepened

The 100 MW solar park and the hybrid wind-solar project represent significant advancements in Turkmenistan's efforts to deploy solar energy (SANTOS, 2022). Additionally, ongoing collaboration with international partners can further accelerate the adoption of solar energy in the country.

5. Estimations for the large-scale introduction of solar energy in Turkmenistan

In Turkmenistan, despite abundant solar radiation, the adoption of solar energy is still in its early stages. To overcome this deficit, a strategy can be developed, starting with the establishment of numerous affordable small and medium-sized photovoltaic solar plants. By locally assembling solar panels and producing essential components within Turkmenistan, investment costs can be significantly reduced. Furthermore, photovoltaic solar panels emit far fewer greenhouse gases than diesel generators, making them a valuable contributor to climate change mitigation. As the country embarks on large-scale solar projects, it aims to tap into its solar potential and achieve a cleaner energy future.

5.1. Current Situation

As of now, Turkmenistan has no installed solar capacity. The country's total renewable energy capacity in 2021 was 2 MW, all from hydroelectric power (IRENA, 2017 & 2024). Turkmenistan receives over 3,000 hours of sunshine per year in some regions, with an average of 300 sunny days annually[3], which represents an enormous solar potential.

5.2. Recent Developments

Recently, several projects around solar energy are implemented in the country. First of all, a 100 MW Solar Park: Turkmenenergo (the state power corporation) and Abu Dhabi-based renewable energy developer Masdar are jointly developing a 100 MW solar park in Turkmenistan (MASDAR, 2022). But also a 10 MW Hybrid Wind-Solar Project: another project involves a 10 MW hybrid wind-solar park, with 3 MW of solar capacity. This plant is located near the recently completed artificial lake Altyn Asyr (SANTOS, 2022).

[3] Climate Change Knowledge Portal, "Current Climate, Turkmenistan", Climate Change Knowledge Portal, online

5.3. Benefits

5.3.1. Positive impact on the environment

Solar panels have a significant positive impact on the environment, primarily by reducing greenhouse gas emissions. When solar panels convert sunlight into electricity, they operate without emitting CO_2 or other harmful greenhouse gases, unlike fossil fuel-based power sources. Over the course of their operational lifetime, solar panels produce a fraction of the emissions that traditional energy sources generate, helping mitigate the effects of climate change. Additionally, solar power requires almost no water to generate electricity, unlike coal or nuclear power plants that consume large amounts of water in their cooling processes. This water conservation aspect not only preserves vital water resources but also protects local ecosystems that could be impacted by high water usage in power generation. By reducing reliance on fossil fuels, solar energy also significantly decreases the release of air pollutants, such as sulfur dioxide, nitrogen oxides, and particulate matter, which are common byproducts of burning fossil fuels. Cleaner air resulting from reduced fossil fuel use directly benefits public health, potentially lowering healthcare costs by reducing respiratory and cardiovascular diseases associated with air pollution. Through these combined effects, solar power represents a cleaner, more sustainable approach to energy that supports both environmental and public health.

However, given that electricity is for now free in Turkmenistan, it would be difficult to change this long-standing situation. Indeed, it is in general difficult to implement a negative change in terms of costs of living for the population, even though it is related to an improvement in terms of environment. It would be perceived as an unfair decision, and the risks of a non-acceptance of the implementation of the project by the population. However, we have seen that the success of this type of project is also linked to the integration of the population in the decision-making, or at least to the fact that authorities make sure that the ins and outs of the project are understood and accepted by the population.

5.3.2. Surplus energy selling

Selling surplus solar energy to neighboring countries can offer multiple benefits for the exporting nation, strengthening its economy, boosting regional cooperation, and enhancing its role as an energy leader. Economically, selling excess solar energy can become a new revenue stream, allowing the exporting country to profit from energy that would otherwise go unused. This added revenue can support the nation's green economy initiatives, help finance further renewable energy projects, or reduce reliance on more polluting energy sources.

Energy exports can also strengthen political and economic ties between neighboring countries, promoting regional stability and collaboration. When a country sells its surplus solar energy to its neighbors, it not only contributes to regional energy security but also helps balance energy supply during times of high demand, like heat waves or droughts, when fossil fuel production may be constrained. In doing so, the exporting country can establish itself as a renewable energy hub, positioning itself as a regional leader in clean energy and innovation. This leadership role can foster partnerships, technological exchanges, and even cooperative research initiatives, further advancing the clean energy goals of all involved nations.

Additionally, exporting solar energy enables a country to diversify its export base, reducing its dependence on traditional commodities or industrial goods. This diversification can make the exporting nation more resilient to global market shifts while fostering green energy jobs, expertise, and technology domestically. Finally, by exporting clean energy, the nation actively contributes to the global fight against climate change, as it helps neighboring countries reduce their dependence on fossil fuels, lowering the region's overall carbon emissions and environmental impact. This approach strengthens the exporting country's reputation as a proactive, environmentally responsible state and underscores its commitment to sustainability on an international scale.

Even though the electricity prices are very low in the neighboring countries: 0,05$ per kWh in Kazakhstan[4], 0,023$ per kWh in Uzbekistan[5] and 0,057$ per kWh in Afghanistan[6], if the production is large enough in Turkmenistan, export through the grid could still become important

[4] Global Petrol Prices, "Kazakhstan electricity prices", online
[5] Global Petrol Prices, "Uzbekistan electricity prices", online
[6] Global Petrol Prices, "Afghanistan electricity prices", online

in a long term perspective. Iran is also a neighboring country, but the electricity prices are so low there that it makes it almost impossible to consider the implementation of such import: 0,002$ per kWh[7]. Indeed, given the costs of implementation of the needed infrastructure to export the produced electricity, it would be too long to amortise the initial investment. Moreover, it is important to note that all these countries have very low electricity prices thanks to an important oil production, and state subsidies. In a perspective in which they would also start implementing more durable and environmental-friendly energy policies, the offer of importing energy produced by solar panels from Turkmenistan could become a real landmark. Indeed, it could help them to their own transition, and implement it gradually, while already using a cleaner source of energy.

5.4. Cost projection

5.4.1. Installation cost[8]

1 hectare (10 000 m²) = 5,000 panels (2m²/panel)

- Installation cost ≈ 1,464 $/kWp (AYER, 2024)
- Functioning cost ≈ 13 ct/kWh[9]
- 1 panel (used in large-scale solar farms) = 3 kWp, or 3,000 kWh
- Price for 1 panel:
    - Installation cost ≈ 4,489 $
    - Functioning cost ≈ 390 $
    - Total ≈ 4,879 $
- **Price for 1 hectare (5 000 panels) ≈ 24,395 thousands $**
- **Price for 1 000 hectares ≈ 24,395 millions $**

[7] Global Petrol Prices, "Iran electricity prices", online
[8] All these costs are estimations driven from several websites online.
[9] This cost is a simplification, but the installation of a solar power farm induces several costs beyond the installation, that are summarized in the following article: Rodriguez Laura (2021), "Breaking down solar farm costs: Free template inside", RatedPower, online

5.4.2. Import cost

- Economic cost:
  - Transportation cost (import) ≈ 600 to 3,000 $/panel[10]
- Financial costs:
  - Custom ≈ 5 to 10% of the price of 1 panel ≈ 224 to 449 $/panel[11]
  - Taxes ≈ 15 to 20% of the price of 1 panel ≈ 673 to 898 $/panel[12]
- Total ≈ 1,497 to 4,347 $/panel
- **Import cost for 1 hectare (5 000 panels) ≈ 7,485 to 21,735 thousands $**
- **Import cost for 1 000 hectares ≈ 7,485 to 21,735 million $**

5.4.3. Local production cost

The cost of producing a solar panel can vary widely based on several factors, including the type of solar panel, the scale of production, location, labor costs, and the current prices of raw materials. However, as of recent data, the cost to produce a solar panel generally includes the following components[13]:

- **Materials**: The primary materials used in solar panels are silicon wafers, encapsulation materials (such as EVA), glass, aluminum framing, and junction boxes. Silicon, being the most expensive component, has a significant impact on the overall cost.

- **Manufacturing Costs**: This includes costs associated with the manufacturing process, such as energy consumption, labor, equipment depreciation, and factory overheads.

- **Research and Development**: Investment in improving technology, increasing efficiency, and reducing costs through innovation.

[10] These costs of import are estimations based on the costs in other countries. It is to be thought that the panels would be imported from China, since it is the closes producer of panels to Turkmenistan, and also because China produces 74% of solar photovoltaic module production worldwide (date of 2018). See ShipHub, "Photovoltaic panels", ShipHub, online
[11] Tax Code of Turkmenistan (2004), available online
[12] *Ibidem*
[13] For an extensive analysis of the PV supply chains and the main segments of the manufacturing process, see IEA (2022), "Solar PV Global Supply Chains, An IEA Special Report", IEA Website, online

- **Shipping and Logistics**: Costs related to transporting the raw materials to the manufacturing site and shipping the finished panels to their final destination.

- **Economies of Scale**: Larger manufacturers can often produce panels at a lower cost due to economies of scale.

Given these factors, as of the most recent estimates (2023), the cost to produce a standard monocrystalline solar panel is typically around $0.30 to $0.40 per watt[14]. Since an average solar panel has a capacity of about 300 to 350 watts, the cost to produce one solar panel would be approximately:

$$\text{Cost per panel} = \text{Panel capacity (watts)} \times \text{Cost per watt}$$

Using an average panel capacity of 300 watts and an average cost of $0.35[15] per watt:

$$\text{Cost per panel} = 300\ \text{watts} \times 0.35\ \$/\text{watt} = 105\ \$$$

Therefore, the cost to produce one solar panel is roughly $90 to $120. For 5000 panels, the price of local production would be 525,000 $.

Even though there is an important investment that needs to be made in Turkmenistan in order to create the necessary infrastructures to produce the panels, **it is expected that the cost per panel will be consequently reduced, compared to the imported price**. Moreover, the impact of economies of scale has to be considered as something that would also lower the cost of production, even though it is hard to quantify before the implementation of the strategy (NREL, N.d.).

Building a solar panel manufacturing facility involves several significant costs, including land acquisition, construction of the plant, purchase of manufacturing equipment, staffing, and operational expenses. The total investment required can vary based on the size of the facility, location, production capacity, and the level of automation.

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[14] This estimation is driven from the prices on the market, see Jude Tamara (2024), "How Much Do Solar Panels Cost in 2024? (Expert Reviewed)", This Old House, online

[15] Price estimated on the basis of the retail prices for individuals. Indeed, as it would be a massive order, made by a public client (the Government of Turkmenistan), we can estimate that the wholesale price would be around 30% of the retail prices, and examples of these retail prices can be found in Bailey Elliot, "Cost of Monocrystalline Solar Panels: An In-Depth Guide and Analysis", *Solvoltaics online*, August 9, 2023, online

Here's a breakdown of the key cost components:

- **Land Acquisition and Preparation**: The cost of land varies greatly depending on location. Industrial land prices can range from $50,000 to $500,000 per acre[16].
- **Construction Costs**: This includes the cost of building the factory, which can range from $100 to $200 per square foot. For a medium-sized factory of around 50,000 square feet, the construction cost might be between $5 million and $10 million (RYZHKOV, 2024).
- **Manufacturing Equipment**: The cost of machinery and equipment for solar panel production (e.g., ingot and wafer production equipment, cell processing machines, panel assembly lines) is significant. Depending on the scale, this can range from $10 million to $50 million or more (RYZHKOV, 2024).
- **Utilities and Infrastructure**: Adequate power supply, water, and other utilities are necessary. The cost can be around $1 million to $5 million depending on the infrastructure requirements (RYZHKOV, 2024).
- **Staffing and Training**: Hiring and training skilled workers, engineers, and management staff. Annual salaries and training costs might amount to $2 million to $5 million (RYZHKOV, 2024).
- **Licensing and Compliance**: Costs for obtaining necessary permits, complying with local regulations, and environmental assessments. This could range from $500,000 to $2 million.
- **Operational Costs**: Initial operational costs including raw materials, initial working capital, and other expenses can be around $2 million to $5 million (RYZHKOV, 2024).

Based on these components, the total cost to build a solar panel manufacturing facility can range from $20 million to $80 million for a medium-sized plant with moderate production capacity. Here's an example estimate for a mid-sized facility[17]:

- **Land Acquisition and Preparation**: $1 million
- **Construction Costs**: $10 million
- **Manufacturing Equipment**: $30 million

[16] This estimation is based on the market overview of the International Trade Administration, see International Trade Administration, "Turkmenistan – Country Commercial Guide", Official Website of the International Trade Administration, online
[17] This estimation is based on the average data found in Ryzhkov Alex (2024), "Cost Analysis for Launching a Solar Panel Business", FinModersLab, online

- **Utilities and Infrastructure**: $4 million
- **Staffing and Training**: $3 million
- **Licensing and Compliance**: $1 million
- **Operational Costs**: $3 million

Total Estimated Cost: 52 million $

These figures are rough estimates and actual costs can vary based on specific project details and local conditions. Additionally, larger-scale facilities or those incorporating advanced automation and high production capacities could see significantly higher initial investments. However, given the current situation in Turkmenistan, the strategy should first aim at implementing a medium-sized facility with moderate production capacity.

Given these elements, we can easily compare the price of production of the panels to the price of import. Indeed, the global price of production of the panels include the initial infrastructure investment (52 million $) as well as the unit production cost. Logically, the more panels are produced, the more the initial investment will be amortized.

As a reminder, these were the prices with import:

- Cost (price, installation and functioning) ≈ 4,879 $
- Import ≈ 1,497 to 4,347 $/panel
- Maximum total: 9,226 $/panel

With an initial investment of 52 million $, here are the prices of production. It is therefore clear that for 5 000 panels, import is more interesting than local production. However, 5 000 panels only concern 1 hectare. For a large-scale strategy with several hectares, it is therefore sure that local production will be cheaper than import, since as shown on the following graphic, the cost per panel has an important tendency to decrease. Considering that important economies of scale will be induced by the production, we can estimate that the average cost of production of the panels will make the local manufacturing more interesting than the import.

Number of panels	Fixed cost in $ (infrastructure implementation investment)	Price in $ of production/panel	Total cost in $	Cost/panel in $ (price of production + infrastructure implementation investment)
500	52,000,000	105	52,052,500	104,105
1,000	52,000,000	105	52,105,000	52,105
1,500	52,000,000	105	52,157,500	34,772
2,000	52,000,000	105	52,210,000	26,105
2,500	52,000,000	105	52,262,500	20,905
3,000	52,000,000	105	52,315,000	17,438
3,500	52,000,000	105	52,367,500	14,962
4,000	52,000,000	105	52,420,000	13,105
4,500	52,000,000	105	52,472,500	11,661
5,000	52,000,000	105	52,525,000	10,505

Figure 1 *- Table of estimated costs of production and investment*

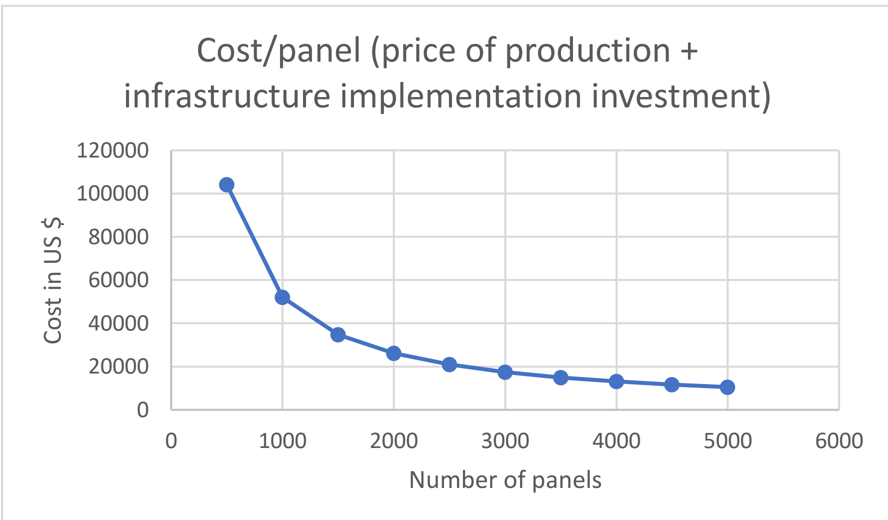

Figure 2 *- Graph of the estimated cost/panel in $ including the cost of production and the infrastructure fixed investment*

6. Results

This research highlights the remarkable potential of solar energy in Turkmenistan, driven by the country's extensive sunlight exposure and the urgent need for sustainable energy solutions. With its vast desert areas receiving high solar irradiance, Turkmenistan has a natural advantage for generating solar power. However, the journey toward adopting solar energy on a large scale is fraught with numerous obstacles. The study reveals challenges ranging from regulatory barriers, such as a lack of clear policies supporting renewable energy, to infrastructure limitations, which include an aging power grid that is ill-equipped for new energy sources. Financial hurdles are also significant, with limited access to capital for large-scale projects, and public perception issues add to the complexities, as renewable energy awareness and acceptance are still relatively low. Overcoming these barriers will require a comprehensive, strategic approach, involving substantial policy reform, infrastructure upgrades, financial incentives, and public awareness initiatives.

The challenges to overcome are numerous and span multiple areas, including governance, imports, training, production, and more. This means that, as demonstrated in this study, a single strategy is not sufficient. It is essential to address these various challenges by creating tailored sub-strategies that can tackle the governance, energy, and social issues associated with implementing such a solar park.

To effectively address the various setbacks encountered, including technical challenges like grid integration and efficient storage solutions, a new, robust system for renewable energy development is essential. The lack of a structured legal and regulatory framework for renewable energy presents one of the largest hurdles. Without supportive policies, such as feed-in tariffs or tax incentives, there is little incentive for private investment, which is crucial for such capital-intensive projects. Additionally, infrastructure investments must focus not only on solar installations but also on strengthening the power grid and improving energy storage capacities, ensuring that the generated solar power can be efficiently distributed and utilized. By building this foundational framework, Turkmenistan has the opportunity to increase energy security, cut carbon emissions significantly, and stimulate economic growth through job creation in both the renewable energy and ancillary industries, such as manufacturing, installation, and maintenance of solar infrastructure.

In terms of governance, the action plans outline the need to establish commissions and, above all, to create stronger connections between ministries to ensure better institutional coordination. This process should be overseen by the highest levels of the State, given the scope and strategic importance of the project. These initiatives and changes are absolutely essential for the project's long-term success. Governance is, in fact, a critical element that underpins all other aspects of the project. It also plays a key role in ensuring the project's efficiency, acceptance, and understanding by the local population.

In the short term, this research suggests that importing solar panels from China could be an immediate and cost-effective solution. Given China's expertise and competitive pricing in solar technology, importing these panels offers Turkmenistan a way to quickly meet some of its energy demands with minimal initial investment. However, while importing panels is a practical solution, it comes with its own set of challenges. High transportation costs, customs duties, and logistical complexities must be managed carefully to avoid inflating the overall project cost. Additionally, relying heavily on imports raises concerns about long-term energy security and dependency on foreign markets.

In the long run, domestic production of solar panels appears to be a more sustainable and economically advantageous option. Although initial investment in manufacturing infrastructure, skilled workforce training, and sourcing raw materials is high, local production could significantly reduce costs over time and decrease reliance on imports. Establishing a domestic solar manufacturing sector could also have far-reaching economic benefits, spurring job creation and technological innovation, while building a local knowledge base in renewable energy technologies. By investing in domestic production, Turkmenistan could retain more of the economic value generated from solar projects within the country, supporting the national economy and making renewable energy more affordable for local consumers. Additionally, developing this sector could open doors for Turkmenistan to become a regional exporter of solar technology, further diversifying its economy and reducing its reliance on fossil fuels.

The study also brings to light several key obstacles that hinder the widespread adoption of solar power in Turkmenistan. Regulatory hurdles remain a significant issue, as there is currently no cohesive renewable energy policy that encourages investment or provides incentives for the private sector to participate in solar projects. Infrastructure limitations are equally challenging, as the country's existing power grid lacks the capacity to integrate large amounts of intermittent solar energy, requiring upgrades in transmission and storage capabilities. Furthermore, public support varies, influenced by factors such as limited awareness about renewable energy benefits and a cultural attachment to the country's traditional reliance on fossil fuels. For solar energy to gain broader acceptance, it is crucial to foster public understanding and highlight the long-term benefits of clean energy.

This research identifies several potential pathways to address these challenges, emphasizing the need for strategic partnerships with international organizations, foreign governments, and private sector entities that can bring both expertise and financial resources to the table. Knowledge transfer is essential, allowing Turkmenistan to leverage best practices from countries with more established renewable energy sectors, particularly in areas like grid management and policy design. Establishing a supportive legal framework is also critical, as it would enable a more favorable environment for private investment, streamline approval processes for renewable projects, and offer tax breaks or other incentives to reduce upfront costs. Engaging both the public and private sectors is vital to creating a collaborative ecosystem that can sustain the renewable energy transition.

By addressing these issues through a combination of immediate import strategies and long-term domestic production goals, Turkmenistan has a unique opportunity to secure its energy independence, reduce greenhouse gas emissions, and foster economic growth. Successfully navigating these challenges could position Turkmenistan as a leader in renewable energy within Central Asia, demonstrating the country's commitment to sustainable development and potentially serving as a model for other countries in the region facing similar challenges.

7. Conclusion

In conclusion, the favorable conditions for large-scale exploitation of PV solar energy in Central Asia present a transformative opportunity for Turkmenistan and its neighboring countries. The demonstrated feasibility and cost-effectiveness of small and medium-sized PV solar stations compared to diesel generators underscore the potential for rapid adoption and deployment of solar energy technologies. However, realizing this potential requires concerted efforts in capacity building, knowledge transfer, and hands-on learning initiatives within Turkmenistan and across Central Asia. By investing in training programs and fostering a culture of innovation, it would be possible to unlock the full benefits of solar energy, not only in terms of energy independence but also in driving agricultural development towards ecologically cleaner practices and enhancing the productivity of smaller and medium-sized enterprises, particularly in areas with limited access to public power supply. Furthermore, the localization of PV solar technology component production holds promise for creating high-tech employment opportunities and reducing investment costs for solar energy users in Turkmenistan. This not only fosters economic growth but also strengthens the resilience and self-reliance of the country's energy sector. Importantly, the large-scale adoption of PV solar energy will make a significant contribution to environmental conservation and climate change mitigation efforts in Central Asia. By reducing reliance on fossil fuels and mitigating greenhouse gas emissions, solar energy emerges as a vital tool in safeguarding the region's fragile ecosystems and securing a sustainable future for generations to come. Therefore, embracing PV solar energy is not only a pragmatic choice for meeting energy needs but also a moral imperative for safeguarding the environment and ensuring the well-being of present and future generations in Turkmenistan and beyond.

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