Investigation of the effective factors in the adoption of photovoltaic systems in Iranian households using causal loop diagrams

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ABSTRACT

Supplying sustainable and clean energy is vital for any country. Therefore, policymakers throughout the world are looking to replace renewable resources. Accordingly, the electricity generation from solar energy by photovoltaic systems has been enhanced by governments due to its environmental and sustainability benefits in comparison with fossil energy resources. The home sector with a share of about 32% of electricity consumption is the second largest electricity consumer sector in Iran. Reducing electricity generated by fossil fuels in this sector contributes significantly to reducing Greenhouse Gasses emissions. However, the diffusion of photovoltaic systems technology in households is strongly influenced by their adoption to use. This research uses a system approach and is developed by the causal loop diagram. The aim was to investigate the diffusion of photovoltaic systems technology in Iranian households. Results demonstrate that the uptake of photovoltaic systems by households reflects an interplay between economic, social, political, technical, and demographic aspects. Furthermore, owing to the unstable policy in Iran, social capital can considerably affect the household's behavior and decision.

Keywords: Renewable energy, Photovoltaic systems, Diffusion of innovation, System dynamics, Social capital.

1. Introduction

Energy production is one of the most significant sources of greenhouse gas (GHG) emissions and accounts for approximately 37.5% of global carbon emissions. Due to the low cost of fossil fuels, they are frequently used to generate electricity, leading to an increase in pollution and ecosystem degradation. Therefore, governments and decision-makers are searching for ways to reduce the environmental impact of electricity generated from fossil fuels; one of the proposed solutions is the use of renewable energy [1]. On the one hand, the energy supply is crucial to the sustainability of the nation. Increasing energy demand, depleting natural resources, and climate change problems have prompted the transition to renewable energy sources. On the other hand, it is essential to focus on energy security to overcome issues that affect economic growth, environmental protection, and resource depletion; therefore, it is essential to create a stable society independent of fossil fuels [2]. In 2019, Iran's net electricity generation reached 306 terawatt hours, and 88% of it, was obtained from fossil fuel resources. Renewable electricity (except hydroelectricity) has a share of less than 1% of electricity generation [3]. In 2019, the household sector constituted about 32% of Iran's electricity consumption as the second largest electricity-consuming sector; so, the reduction of non-renewable electricity in this sector will have a significant contribution to reducing GHG emissions. One of the suitable options for establishing renewable energy in the home sector is the use of photovoltaic systems (PVS) [4]. Adoption of PVS technology by the household influences the PVS diffusion in society. Families as decision makers with a unique role in the transition to renewable energy, consider various aspects of PVS adoption; Hence, to establish effective policies, understanding the mechanism of PVS adoption by considering the consumers' heterogeneity and their social and environmental

interactions as well as comprehending the decision-making process and the practical characteristics of households, is important to facilitate the adoption of PVS [5-7]. A system dynamics approach(SD) is suitable for analyzing the relationship between critical variables affecting the adoption of PVS. The PVS adoption decision consists of a set of factors that are non-linearly dependent on each other. SD depicts the feedback and its effects on the behavior of the system over time [8]. This research presents the system elements of PVS adoption in the household sector in Iran. The main three objectives are (1) identifying variables, their roles, and relationships, related to PVS adoption in the household sector using the SD approach; (2) demonstrating the variables with a causal loop diagram (CLD) describing the pattern of PVS adoption; and (3) using the CLD to comprehend the dynamics of the system and role of policies and the social state on PVS adoption. According to the complexity of innovation diffusion in households' systems, feedback relationships between effective factors in the research, and the need to examine the system from a macro perspective for policy-making, this research presents an SD approach for policymakers to identify effective ways for PVS diffusion and the consequences of their decisions.

This paper is organized as follows. The following section is a review of the previous research about the adoption of PVS by households as well as innovation diffusion and the Bass model. The third section represents the conceptual model using CLDs. In this section, factors that affect PVS adoption are determined, and their relationships are shown by the generalized Bass diffusion model and CLDs, which are proposed for household PVS adoption in Iran. The last section entails a conclusion of this study and could be used in both practice and research.

2. Literature review

2.1.Photovoltaic system synopsis

To assist the power grid, large-scale photovoltaic systems are being implemented [9]. Solar photovoltaic energy is the direct conversion of sunlight into electricity using an electronic device known as a solar cell. PVS panels capture solar radiation to generate electricity (PVS effect) via direct current [10]. Distributed generation is a small-scale electrical energy generation technology that can be either generative or renewable and is located close to the ultimate consumers. DG near to final consumers can bolster the grid's stability and improve the quality of the power system [11].

Sparrow (1977) examined socioeconomic factors influencing the adoption of solar energy in the United States. According to his research, distinctions in residential area have a significant effect on solar system attitudes and importance. In addition, Cesta and Decker (1978), by examining manufacturers, suppliers, and consumers, determined the practical factors that influence the adoption or non-adoption of solar systems, such as product price, level of government support, product quality, energy cost, and advertising of solar systems. To examine the effective factors in adoption, it is essential to consider the impact of the economic aspect and investment cost on the establishment of solar systems, as well as people's decisions and behaviors in adopting these systems. Additionally, it is necessary to consider the impact of commercial advertising and word of mouth on the adoption of innovative technologies. Understanding the level and status of adoption prior to the widespread diffusion of solar systems is preferable to demonstrating the technology [12]. due to the limitations of human experiments. Financial and investment considerations have a substantial impact on the adoption of PVS. However, this is not the only factor that influences the purchase and adoption of PVS. Awareness of environmental issues and technical and administrative obstacles should also be considered [13].

Many studies have been done in the field of PVS adoption by households in different countries. In a study in Japan, the initial installation cost, subsidy for the initial cost, the purchase price of excess electricity, the reduction in the annual energy cost, the annual reduction in CO_2 production, and the number of installed units were considered as essential factors for the adoption of PVS. The payment of households for PVS and the level of technology they are willing to use

were calculated, also the effect of changes in PVS and solar water heater characteristics were investigated. According to the results, applying policies that reduce the initial cost has a more important effect than the incentive tariff policy in PVS adoption [14]. Also, the impact of policies on the diffusion of renewable energy technologies has been investigated, focusing on the use of photovoltaic systems and their impact on the market and the amount of demand in the domestic sector of Colombia [6]. Effects of changes in the government's support plan on PVS diffusion are investigated in single-family and two-family Italian houses. This research assumed that the decision to adopt PVS is influenced by the investment payback period, environmental benefits of PVS, household income, and relationship with other factors. In order to calculate the investment payback period, variables such as investment costs, local radiation levels, government support, income from using PVS electricity produced by the household versus buying electricity from the grid, administrative costs, and maintenance costs have been taken into account. Under the results, applying the new feed-in tariff scheme in Italy, the growth rate of installed PVS is already exceeding the growth rate in the initial phase. However, the rate is slower than the adoption rate [15]. The success or lack thereof in the application of incentive tariffs of the existing policies is examined for the market of PVS and its diffusion on German villa houses. The implementation of incentive tariffs has led to a growth in the maturity level of PVS adoption. Government support is considered a variable, but it should be noted that the government support variable itself includes variables such as reliability, predictability, incentive tariffs, interest rate reduction in the purchase of PVS panels, or the length of the incentive tariff period. Based on the obtained results, applied policies are one of the critical factors for the transition to renewable energy, so they should be carefully examined and applied [16]. In a study in Iran, the impact of environmental, demographic, and knowledge factors regarding the performance of photovoltaic systems on the adoption of PVS are evaluated, taking into account the incentives of the Iranian government in the city of Tehran. Awareness about innovative products can reduce uncertainty about product performance and profitability. Therefore, training and raising awareness of renewable technologies, especially PVS, will make potential adopters adopt and increase the probability of adoption [17].

In Germany, renewable energy adoption has been advocated. Due to social cohesion supported by social security and labor welfare, political activism focused on energy and environmental issues, and consistent state intervention to balance socioeconomic inequities [18]. Germans do not face global and internal constraints; Sanctions are implemented to reduce welfare and security in the sanctioned society; This creates the possibility of being barred from using the technology of leading countries or facing technical barriers, resulting in a lack of access to mature green energy technologies and political instability. Inflation diminishes public confidence in the government and its policies. It is a crucial factor influencing the distribution of income inequality, the development of social anomalies, and the destruction of social capital. Additionally, a rise in the inflation rate causes fluctuations in other economic variables, thereby aggravating economic instability. Social capital is a set of pre-existing norms in the social system that increases the level of collaboration among society members and reduces the cost of exchanges and communication in the direction of cooperation and participation for the purpose of accumulating corporate assets. Social capital consists primarily of networks, trust, and norms, which influence the adoption of technologies by fostering greater accessibility and information search. In addition, the inflation rate variable is considered one of the indicators of instability. Iran's economic and political instability is viewed as an impediment to economic development and investment [19, 20]. In the residential sector, PV adoption is influenced by multiple factors. In Table 1 they are identified and summarized.

Table 1- Causal loop diagram's list of 32 variables related to PVS adoption in the household sector

in Iran

Social aspect	Political aspect	Technical aspect	Management aspect	Economic aspect	Demographic aspect
Educational campaigns	Political stability	Companies that work with PVS	Business strategies	PVS Net Present Value	High income
Lack of knowledge	Economic stability	Quality of PVS system	Advertising	Capital cost	Education
Satisfied adopters	Feed-in tariffs	Efficiency	Incentive programs	Installation price	
Neighbors with PVS	Environmental issues	Panel energy	Operation and Maintenance fee	Payback Period	
Social capital	Low-interest rate policies for the purchase of PVS system	Solar resources	PVS after sale service		
Environmental concern	Subsidy policies for the purchase of PVS system	PVS complexity			
Public awareness					
Electricity supply reliability					

2.2. Conceptual framework

Innovation is an idea, activity, or object that a person or other adoption factors perceive as novel. In terms of human behavior, the passage of time since its first use or discovery is not very important in the objective novelty of the idea. However, the perceived novelty of the idea by the individuals determines their reactions to it. The newness aspect of an innovation may be based on knowledge, persuasion, or decision-making [21]. Therefore, generating solar electricity in the Iranian household sector has not been diffused, and seems novel to household vision. In this research, using PVS for distributed generation is considered an innovation.

The spread of rumors and advertisements, the adoption of innovation, and the growth of new products all have positive feedback on the diffusion of innovation, which means that those people who adopt the innovation infect others. This growth continues until the population of potential adopters is exhausted, and this reduction of the population reduces the adoption rate to zero and stops growth with negative feedback.

SD was developed in the 1950s by Forrester at MIT to use by engineers to find the main factors that determine the success and failure of companies [22]. SD is very suitable when dealing with complex systems with feedback relationships and long-term time horizons. This model allows the implementation of different policies to simulate the expected future [23]. Frank Bass proposed a model of innovation diffusion in which the adoption rate of an innovation depends on the population of adopters. The representation of this model using CLD is shown in Fig.1 This

model is widely used as one of the most popular product diffusion models in marketing, business, and technology management. According to the Bass model, at the beginning of the innovation entering the market, there are only potential adopters who are informed about the innovation through advertising and become adopters with the adoption rate. With the decline in the population of potential adopters, the share of advertising in innovation adoption is reduced, and the contribution of word-of-mouth advertising raises the adoption rate due to the growth in the population of adopters. Early adopters of PVS expose their friends, family, and acquaintances to the innovation they have purchased, and persuade them to buy it. Over time, adopters are in contact with potential adopters, and adopters create situations in which others imitate their behavior, beliefs, or purchases (the word-of-mouth loop in Fig.1), when the population of potential adopters decreases, the adoption rate reaches zero (market saturation circle in Fig.1) [5, 23].

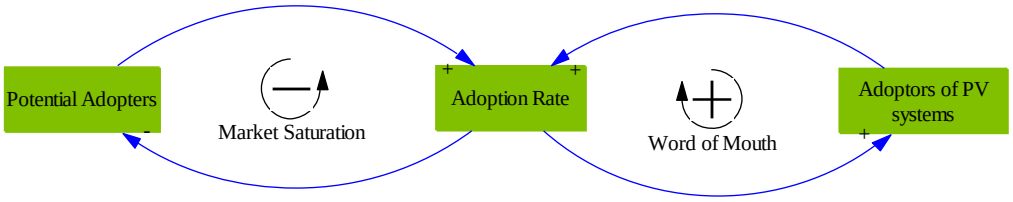

Figure 1. Bass innovation diffusion diagram

The literature review presents that despite the numerous studies conducted in the field of PVS innovation diffusion, there is not any research considering the social capital factor with all other aspects derived from the literature review, particularly in Iran with inflation and sanction problems. This article aims to fill the research gap by considering the impact of economic, social, political, technical, and demographic aspects on the adoption of PVS in the Iranian household sector with the SD approach and using the Bass model.

3. Research method

Regarding energy demand growth, the need for sustainable energy, and environmental concerns, the use of renewable energies, specifically solar energy, has been gaining prominence. Thus, the present research aims to study, draw, and analyze the PVS adoption CLD in the Iranian household sector. As the household sector in Iran takes second place in electricity consumption, this sector is selected for the case study. Fig.2 depicts the proposed methodology architecture.

As demonstrated in Fig.2, the proposed methodology begins with identifying influential variables in PVS adoption, which are described in the literature review and Table 1. In order to investigate the current situation of PVS in Iran, including the companies involved in PVS production and installation and their performance, existing government incentives and restrictions, and the supportive laws as well as social behaviors towards these systems, an interview was conducted with experts in the field of renewable energy, especially solar energy. Part of the relationships and variables in this investigation have been obtained from these interviews. Furthermore, the interactions among variables are illustrated using CLDs. The Bass model shown in Fig.1 is generalized by incorporating the identified influential variables on PVS adoption detected from previous research and interviews. The CLD determines the Bass innovation diffusion by considering and categorizing it into the six primary aspects, including economic, management, political, social, technical, and demographic (summarized in Table 1.). Thereafter, the interactions are analyzed, and some suggestions are advised according to Iran’s status.

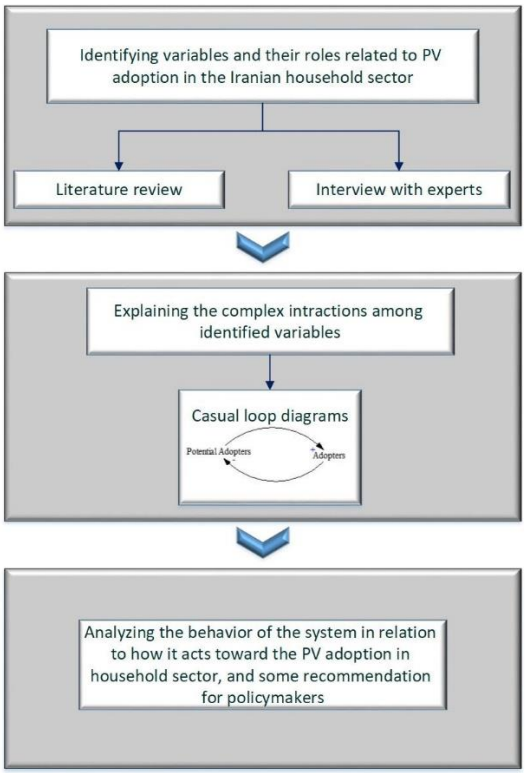

Figure 2. The architecture of methodological steps undertaken in this research

3.1. Policy effect on PV adoption

According to Fig.3, economic stability provides a context for easier planning and reduces public discontent. Inappropriate and uncoordinated government policies cause economic instability. Moreover, investment decisions are highly dependent on economic stability. Investment decisions are made in a stable status [24]. In a society with frequent changes in policies, investors need time to be convinced of the permanence and stability of economic policies; Because they cannot change the decisions they have made about their capital at the same time as the government turns away from its policies [25]. As a result, increasing political and economic stability raises social capital. Considering and implementing policies such as payment of purchase subsidies and low-interest rate loans will reduce the amount of initial capital required to purchase PVS and, as a result, reduce the investment payback period.

Furthermore, the Iran Ministry of Energy contracts a 20-year long-term commitment with a feed-in tariff for the purchase of solar electricity from household distributed generation. PVS in houses is on-grid and has different electric meters. Thus, each adopter's house has two electric meters and households do not consume solar power they produce in their house immediately. Furthermore, the government also guarantees that the amount paid will increase with the inflation rise [26]. In this way, the amount of household income and the amount of the net present value will raise.

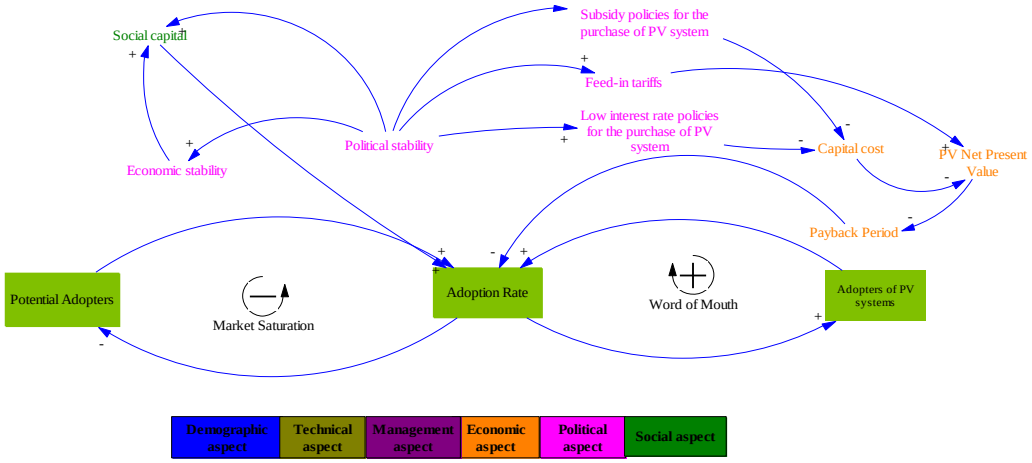

Figure 3. The effect of the country's political status on the PVS adoption

3.2. PVS-involved companies influence PVS adoption

As shown in Fig.4, as the number of PVS adopters rises, so does the number of businesses pursuing PVS. Meanwhile, the companies seek to develop the quality of PVS to attract more customers (according to the interview conducted with experts active in the production and installing solar panels, companies import solar panel cells from other countries, and the production of solar panels in Iran includes the assembly of different PVS parts, so an increase in the quality of panels means enhancing the quality of its imported parts and equipment), with the quality improvement, the amount of energy produced by the number of panels increases; As a result, the income from the sale of solar electricity rises, which causes a decrease in the investment payback period and the adoption rate increases (R3). As time passes and the number of PVS adopters enhances, the technologies of PVS installation and its maintenance equipment grow and mature. So, the related costs decrease, and as a result, the net present value of PVS rises, which has a positive effect on the adoption rate (R1 and R2).

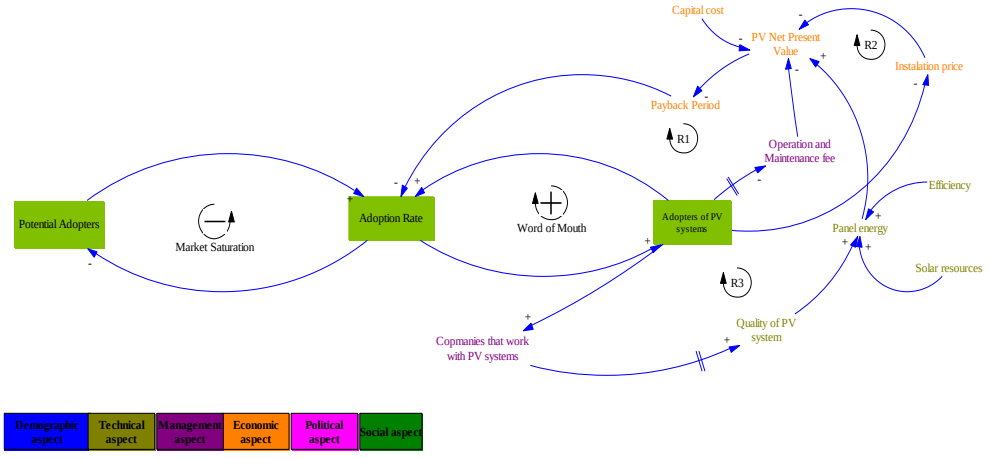

Figure 4. The effect of enhancing the quality and reducing side costs on the PVS adoption

The rise in PVS adopters and demand results in an increase in the number of PVS-active businesses. Consequently, businesses enhance their business strategies to remain competitive on the market. In addition, they devise after-sales services and incentive programs to attract new customers, as well as to increase customer satisfaction and retain their current customers. These enhancements result in an increase in PVS quality (R4 in Fig.5) and adopter satisfaction;

consequently, social capital increases, which increases the adoption rate (R5 and R6). Additionally, these companies advertise to introduce their organization and PVS. These advertisements raise public awareness of PVS and its benefits and encourage its purchase. The adoption rate then increases as social capital grows (R7). The corresponding CLDs are shown in Fig.5.

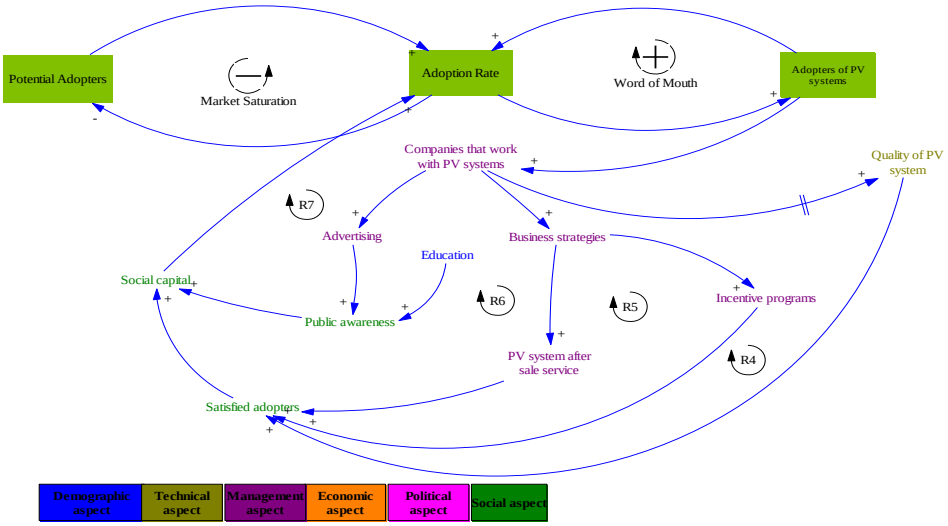

Figure 5. Investigating how active companies in the field of PVS influence its adoption

3.3. The consequences of social behavior and the benefits of its changing

PVS adopters with roles in social networks such as neighborhood have a direct impact on social capital. By encouraging and introducing their PVS to the entourage, they reinforce the word-of-mouth cycle. Consequently, with an increase in the number of residents who have PVS, social capital and the adoption rate increase (R11).

In Iran, pervasive power outages and blackouts have occurred in recent years, especially in 2021 and during the warm seasons when the need for electrical cooling devices increases and causes peak consumption, causing discontent and criticism. It has impacted numerous individuals and caused numerous problems for citizens [27]. By injecting the solar electricity generated by a household into the grid, the issues associated with a sustainable electricity supply have been resolved, and households will have access to energy throughout the year. As a result of bringing this issue to the public's attention, households incline to purchase PVS to provide dependable electricity (R10). As the number of adopters increases, the perception of PVS's complexity (the complexity of PVS perceived by potential adopters) decreases, resulting in an increase in the number of satisfied adopters, which has a positive impact on social capital and the adoption rate (R9). Also, decreasing the population of potential adopters and increasing the number of adopters reduces the dearth of knowledge about PVS in society through the household word-of-mouth loop. The conduct of educational campaigns is also highly effective for advancing knowledge.

As long as poverty exists in human societies, the protection of the environment and natural resources will face significant opposition from the poor, and it will be impossible to implement environmental protection policies and programs so long as the fundamental needs of the poor are not met. Perhaps the Maslow's Hierarchy of Needs principles can be applied to the connection between these two phenomena. The importance of preserving the environment for future generations diminishes as survival becomes more important in the present, and meeting the requirements of the present becomes more important . As a result, an increase in the proportion of the population with incomes above the poverty line would enable this society to move beyond

issues of subsistence to address other issues, such as environmental concerns (if there are environmental issues), and they would be motivated to increase environmental awareness in order to address these issues. Increasing knowledge increases public awareness in society. Also, education has a significant impact on the level of awareness of individuals. By heightening community awareness and establishing social and environmental norms in social networks, social capital multiplies and has a positive impact on adoption rates (R8). The loops are depicted in Fig. 6.

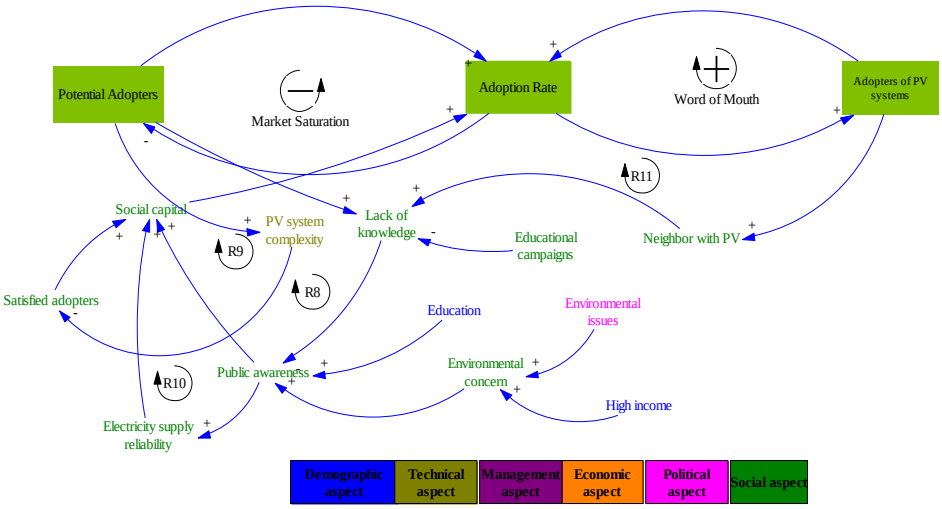

Figure 6. Investigating social factors influencing the PVS adoption

Finally, all CLDs are shown together in Fig.7.

4. Conclusion

This study investigates the factors that influence PVS adoption. Due to the political and economic instability in Iran, only government feed-in tariffs do not encourage households to invest in solar cells. By providing financial incentives such as subsidies and low-interest financing the government can reduce the initial investment required by households to purchase PVS. Moreover, the creation of social norms and environmental concern in people through increased advertising and educational campaigns encourages society to utilize PVS. It should be considered that development in PVS quality, proper after-sales service and maintenance, and determining the business strategies of companies active in this field are highly effective in enhancing the satisfaction of PVS adopters; satisfied adopters are very influential in encouraging other members of society to use PVS systems.

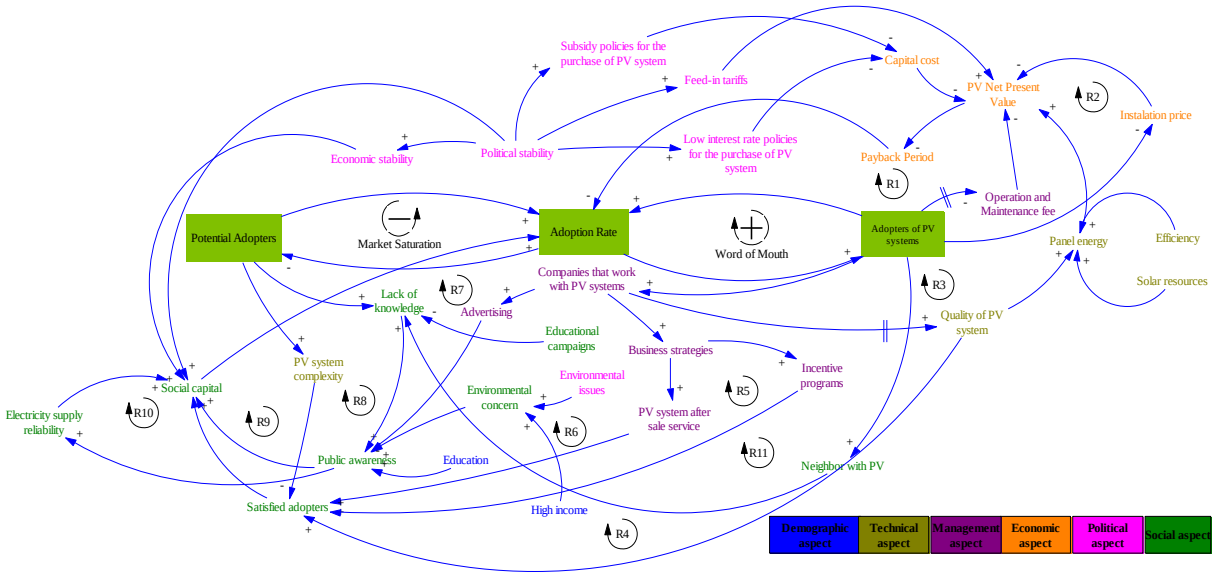

Figure 7- the finalized CLD of the PVS adoption in the Iranian household

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