ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

MODELING TURKEY'S SOLAR ENERGY POTENTIAL UNDER DIFFERENT CONDITIONS

Ph.D. THESIS

Veysel ÇOBAN

Department of Industrial Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

TÜRKİYE'NİN GÜNEŞ ENERJİSİ POTANSİYELİNİN FARKLI KOŞULLAR ALTINDA MODELLENMESİ

DOKTORA TEZİ

Veysel ÇOBAN
(507122108)

Endüstri Mühendisliği Anabilim Dalı

Endüstri Mühendisliği Programı

Tez Danışmanı: Doç. Dr. Sezi ÇEVİK ONAR

HAZİRAN 2018

Veysel Çoban, a Ph.D. student of ITU Graduate School of Science Engineering and Technology student ID 507122108, successfully defended the dissertation entitled “MODELING TURKEY'S SOLAR ENERGY POTENTIAL UNDER DIFFERENT CONDITIONS”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Doç. Dr. Sezi ÇEVİK ONAR** İstanbul Technical University	....
Jury Members :	**Prof.Dr. Seçkin POLAT** Istanbul Technical University	....
	Doç. Dr. Çağrı TOLGA Galatasaray University	....
	Doç. Dr. Başar ÖZTAYŞİ Istanbul Technical University	....
	Doç. Dr. Selçuk ÇEBİ Yildiz Technical University	....

Date of Submission : 22 May 2018
Date of Defense : 19 June 2018

To my wife Elif, and children Pelin Nisa and Ertuğrul Mete,

FOREWORD

The thesis aims to contribute to Turkey's efforts to increase solar energy capacity. The results obtained from these studies will help decision-makers to make more realistic decisions by considering the environmental, economic, social and technical conditions in the development process of solar energy systems in Turkey.

I would like to thank everyone who contributed to the studies that resulted in long efforts and endeavors. Especially, I would like to thank Assoc. Prof. Sezi Çevik Onar, who guided and helped me with her knowledge and experience in shaping and publishing my studies. Also, I would like to express my gratitude to Council of Higher Education (YOK) and the Supreme Turk State for the financial supports that have given under the Academic Member Training Program (OYP) in the realization and publication of the studies.

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Veysel ÇOBAN
(Research Assistant)

TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

MODELING TURKEY’S SOLAR ENERGY POTENTIAL UNDER DIFFERENT CONDITIONS

SUMMARY

Fossil-based energy sources are presented as primary energy supply in response to rising energy demand with increased population and industrialization. Carbon dioxide and harmful gases that are emitted to the environment in the energy conversion process of fossil energy sources accumulate in the atmosphere and cause the greenhouse effect. The greenhouse gases that cause global warming and climate changes reveal environmental, social and economic promises on a global scale. The world is turning to environmentally friendly renewable energy sources (hydro, wind, sun, geothermal, tidal, biomass) to eliminate the problems of fossil-based energy sources. The sun, which is the main source of the energies on earth (except tidal, nuclear, geothermal), is the most important renewable energy source. Solar energy systems require high-tech infrastructure and equipment, while simple and high-tech methods are used to obtain heat and electricity from the sun.

The high initial investment cost is the main disadvantage of solar energy systems and also prevents price competition with other energy systems. The competition conditions in the energy sector make it necessary for the solar energy systems to make the right decisions in the installation process. The correct identification and assessment of environmental, social, economic and technical conditions are required to make the right decisions. Experts that contribute to our work takes place in the energy sector, and academic and causal relationships between identified factors were evaluated taking into consideration Turkey and global conditions. In this study, Turkey's solar energy potential is modeled in different conditions to help decision makers in decision making processes. Factors affecting the production of renewable energies are defined, and the effects of wind and solar energy production are modeled with the Hesitant Cognitive Map. Many factors influence the energy sector, and these factors contain uncertainty in a dynamic feature, it is appropriate to develop modeling and calculations by fuzzy logic. Literature and expert opinions determined factors affecting the production and use of solar energy, and fuzzy cognitive maps modeled causal relationships between these factors. Models operated with different initial state scenarios are evaluated on the steady-state values and process movements of the factors.

As the initial study results show the significant effects of economic factors in the generation of solar energy, the study of the factors affecting the solar energy price has been defined as a new study title. Similarly, factors affecting the price of solar energy were determined by literature and expert opinions, and causal relationships between factors were evaluated linguistically based on the knowledge and experience of the experts. These studies provide information to decision-makers about the factors and the interactions of factors with each other in the solar energy plant installation and pricing decision-making process. In the last study of the thesis, the economic analysis of the solar power plant was examined using life cycle cost and leveled cost of

electricity methods. Pythagorean fuzzy clusters are referenced to incorporate the uncertainties contained in methods based on temporal effects into calculations. The values obtained from Pythagorean based LCC and LCOE calculations give information about the validity of the installation of solar energy systems and compare the solar energy system with other energy systems.

TÜRKİYE'NİN GÜNEŞ ENERJİSİ POTANSİYELİNİN FARKLI KOŞULLAR ALTINDA MODELLENMESİ

ÖZET

Nüfus artışı ve buna bağlı tüketim artışının sanayileşmeyi arttırması enerji talebinin sürekli bir artış göstermesine neden olmaktadır. Artan bu enerji talebini karşılamada fosil esaslı enerji kaynakları (petrol, kömür, doğalgaz) birincil kaynak olarak kullanılmaktadır. Fosil temelli kaynakların enerjiye dönüştürülmesi sürecinde çevreye saldıkları karbondioksit ve diğer zararlar atmosferde birikerek sera etkisine neden olmaktadır. Sera etkisi küresel ısınmaya ve iklim değişikliklerine neden olarak küresel boyutta çevresel, ekonomik ve sosyal sorunların ortaya çıkmasına neden olur. Fosil esaslı enerji kaynaklarının neden olduğu bu problemler bilinmesine rağmen sahip olduğu fiyat avantajı ve yaygın teknoloji uyumluluğu kullanımını engelleyememektedir. Bu durum çevreye duyarlı ve devletler tarafından desteklenen yenilenebilir enerji kaynaklarına (hidro, rüzgar, güneş, gelgit, jeotermal, biyokütle) yönelinmesini sağlamıştır.

Yenilenebilir enerji doğanın varlığı içinde yer alan enerji sirkülasyonunun kullanılabilir enerjiye dönüştürülmesi ile elde edilir. Bu enerji kaynaklarının sürekliliğinin olması ve kendilerini tekrarlamadıkları için bu adla çağrılırlar. Güneş yeryüzünde varolan enerjilerin esas kaynağı (nükleer, gelgit, jeotermal hariç) olmakla beraber doğrudan ısı, ışık ve elektrik elde edilmesinde de kullanılmaktadır. Güneş enerjisinden basit (güneş fırınları, pasif aydınlatma/ısınma) ve yüksek teknolojik (fotovoltaik, yoğunlaştırılmış güneş santralleri) yöntemler kullanılarak faydalanılır. Güneş enerjisinin elektriğe dönüştürülmesi sürecinde yer alan yüksek teknolojiye sahip ekipman ve bu ekipmanların kurulum maliyetlerinin yüksek olması güneş enerji santrallerinin devlet desteği ile doğru yer ve zamanda kurulma önemini doğurmuştur. Tez çalışmasında, güneş enerjisi sistemlerinin kurulumunda etkili olan faktörler literatür taraması ve uzman görüşleri ile belirlenerek aralarındaki nedensel ilişki tanımlanmıştır. Türkiye'deki akademik ve enerji sektöründen seçilen uzmanların bilgi ve tecrübelerine dayalı olarak değerlendirmeler dilsel olarak toplanmıştır. Türkiye koşulları ve küresel vizyon çerçevesinde yapılan dilsel değerlendirmelerdeki kararsızlık ve belirsizlikleri hesaplamalara dahil etmek için bulanık mantığa başvurulmuştur. Faktörler arasındaki nedensel ilişkilerin uzun dönem davranış ve durağan durum değerlerinin gözlenmesi için bilişsel haritalar kullanılmıştır. Çalışmamızda takip edilen basamaklar yayın akışına göre şu şekilde tanımlanabilir: yenilenebilir enerji sistemlerinin kararsız bulanık bilişsel harita ile modellenmesi, güneş enerjisi sistemlerinin bulanık bilişsel harita ile modellenmesi, güneş enerjisi üretim kapasitesinin kararsız bulanık bilişsel haritalar ile modellenmesi, güneş enerjisi fiyatlandırma sürecinin kararsız bulanık bilişsel harita ile analiz edilmesi ve güneş enerjisi tesisinin kurulumunun Pisagor bulanık mühendislik ekonomisi ile analiz edilmesi. Çalışmamız genelden özele doğru hareket ederek yenilenebilir enerji analizinden güneş enerjisi tesisinin kurulumunun ekonomik uygunluğunun ve diğer

enerji sistemleri ile karşılaştırılmasına indirgenmiştir. Tez çalışmasında gerçekleştirilen çalışmalar ve elde edilen sonuçlar yayın sırasına göre özetlenmektedir.

"Kararsız Bulanık Bilişsel Harita ile Yenilenebilir Enerji Kullanımının Modellenmesi" adlı yayında yenilenebilir enerji kaynakları incelenmiş ve rüzgar ve güneş enerjisi üretimini etkileyen dinamik faktörler tanımlanmıştır. Faktörler arasındaki nedensel ilişkiler uzmanlar tarafından dilsel olarak değerlendirilir ve Kararsız Bulanık Bilişsel Harita altında dilsel değerlendirmeler modellenir. Faktörlerin uzun dönemli etkileşimleri ve denge durum değerleri, faktörlerin farklı başlangıç durum senaryolarında gözlenir. Bu çalışmadan elde edilen sonuçlar, yenilenebilir enerji üretimini etkileyen faktörlerin belirlenmesini ve birbirleriyle etkileşimlerinin tanımlanmasını sağlar. Ayrıca, bu çalışmada güneş enerjisi üretimini etkileyen faktörler tanıtılmış ve çalışmalar için bulanık bilişsel harita tabanlı kararsız bulanık bilişsel harita modelinin geçerliliği doğrulanmıştır. "Bulanık Bilişsel Haritalarla Güneş Enerjisi Kullanımının Modellenmesi" adlı yayın, bulanık bilişsel harita temelinde güneş enerjisi üretim kapasitesinin modellenmesi ile ilgilidir. Bu çalışma, güneş enerjisinin üretimine odaklanmakta ve faktörler, önceki çalışmalardan elde edilen bulgulara göre tanımlanmaktadır. Model faktörler arasındaki nedensel ilişkiler, uzmanlar tarafından bilgi ve deneyimlerine göre dilsel olarak tanımlanır. Güneş enerjisi üretimini etkileyen faktörlerin etkileşimleri ve uzun dönem davranışları, başlangıç durum senaryoları altında bulanık bilişsel harita modeli ile gözlemlenmektedir. Güneş enerjisi üretimini etkileyen faktörler arasındaki nedensel ilişkilerin değerlendirme sürecinde karşılaşılan tanımlayıcı ve dilsel belirsizliklerin daha doğru bir şekilde birleştirilmesi için "Kararsız Bulanık Bilişsel Haritaları Kullanarak Güneş Enerjisi Üretim Kapasitesinin Analizi" çalışması gerçekleşmiştir. Bu çalışmada kullanılan faktörler, önceki çalışmada belirlenen faktörlere göre tanımlanmış ve faktörler arasındaki nedensel ilişkiler kararsız bulanık bilişsel harita modeli ile belirtilmiştir. Faktörler arasındaki nedensel ilişkiler uzmanların bilgi ve deneyimlerine dayanarak dilsel olarak değerlendirilmiş ve faktörlerin davranışları farklı başlangıç durum senaryolarına göre gözlemlenmiştir.

Önceki yayınlarda güneş enerjisi üretimini etkileyen faktörler tanımlanmış ve uzman değerlendirmeleri altındaki nedensel etkileşimleri bulanık bilişsel harita ve kararsız bulanık bilişsel harita modelleri ile incelenmiştir. "Karasız Bulanık Bilişsel Harita ile Güneş Enerjisi Fiyatlandırma Sürecinin Stratejik Analizi" çalışmasında, önceki yayınlarda açıklanan faktörler, güneş enerjisi fiyatını belirleyen faktörleri tanımlamak için özelleştirildi. Bu çalışmada, güneş enerjisi fiyatına etki eden kritik faktörler tanımlanmış ve bunlar arasındaki nedensel ilişkiler kararsız bulanık bilişsel harita modeli ile temsil edilmiştir. Faktörler arasındaki nedensel ilişkiler ve faktörlerin başlangıç durum değerleri, kararsız bulanık dilsel terimler kümesi kullanılarak uzmanların dilsel değerlendirmeleri ile tanımlanır. Elde edilen bilişsel model çeşitli başlangıç durum senaryolarını simüle etmek için kullanılır ve faktörlerin denge durum değerleri uzun vadede elde edilir.

"Güneş Enerjisi Fiyatlandırma Sürecinin Kararsız Bulanık Bilişsel Harita ile Stratejik Analizi" çalışması, güneş enerjisinin geliştirilmesinde enerji fiyatı ve ilgili ekonomik faktörlerin önemli bir rol oynadığını göstermiş ve güneş enerjisi santralinin kurulumunun ekonomik analizinin yapıldığı "Güneş Enerjisi Santrallerinin Pisagor Bulanık Mühendisliksel Analizi" çalışmamıza yöneltmiştir. Güneş enerjisi sistemleri, ekipman ve bu ekipmanların kurulumuna bağlı olarak yüksek bir başlangıç maliyetine sahip olduğu için ekonomik boyutta güneş enerjisi santralini doğru yere ve zamanda kurulması büyük öneme sahiptir. Enerji sistemlerin ekonomik değerlendirilmesinde ve karşılaştırılmasında yaygın olarak kullanılan yaşam döngüsü maliyeti ve seviyelendirilmiş enerji maliyeti yöntemleri, zamansal belirsizlik ve dinamizm içermektedir. Zamansal belirsizlikleri ve karar vericilerin fikirlerini ekonomik analizlere dahil edebilmek için Pisagor bulanık kümeler kullanılarak ekonomik analiz yöntemleri yeniden tanımlanmıştır. Önerilen Pisagor esaslı modeller yöntemleri, bulanık parametrelere sahip güneş enerjisi yatırımlar değerlerini hesaplamalara dahil etmeyi mümkün kılmaktadır. Farklı teknolojik özelliklere ve ekonomik koşullara sahip alternatif enerji sistemleri, önerilen Pisagor yaşam döngüsü maliyeti ve Pisagor seviyelendirilmiş enerji maliyeti yöntemleri kullanılarak daha doğru bir şekilde karşılaştırılabilmektedir. Bu yayında önerilen yeni Pisagor tabanlı ekonomik analiz yönteminin geçerliliği, literatürden elde edilen örnek bir uygulama ile doğrulanmıştır. Uygulanabilir olan Pisagor ekonomik analiz yöntemi ile Türkiye'de kurulacak herhangi bir güneş enerjisi santrali için kolaylıkla uygulanabilecektir.

1. INTRODUCTION

Population growth and developing industrialization cause to increase the energy usage and energy demand. The desire to improve the standards of life intensifies energy demands in specific regions on a local and global scale. The relationship between human development and electricity consumption shows that welfare level increases with energy use (Figure 1.1).

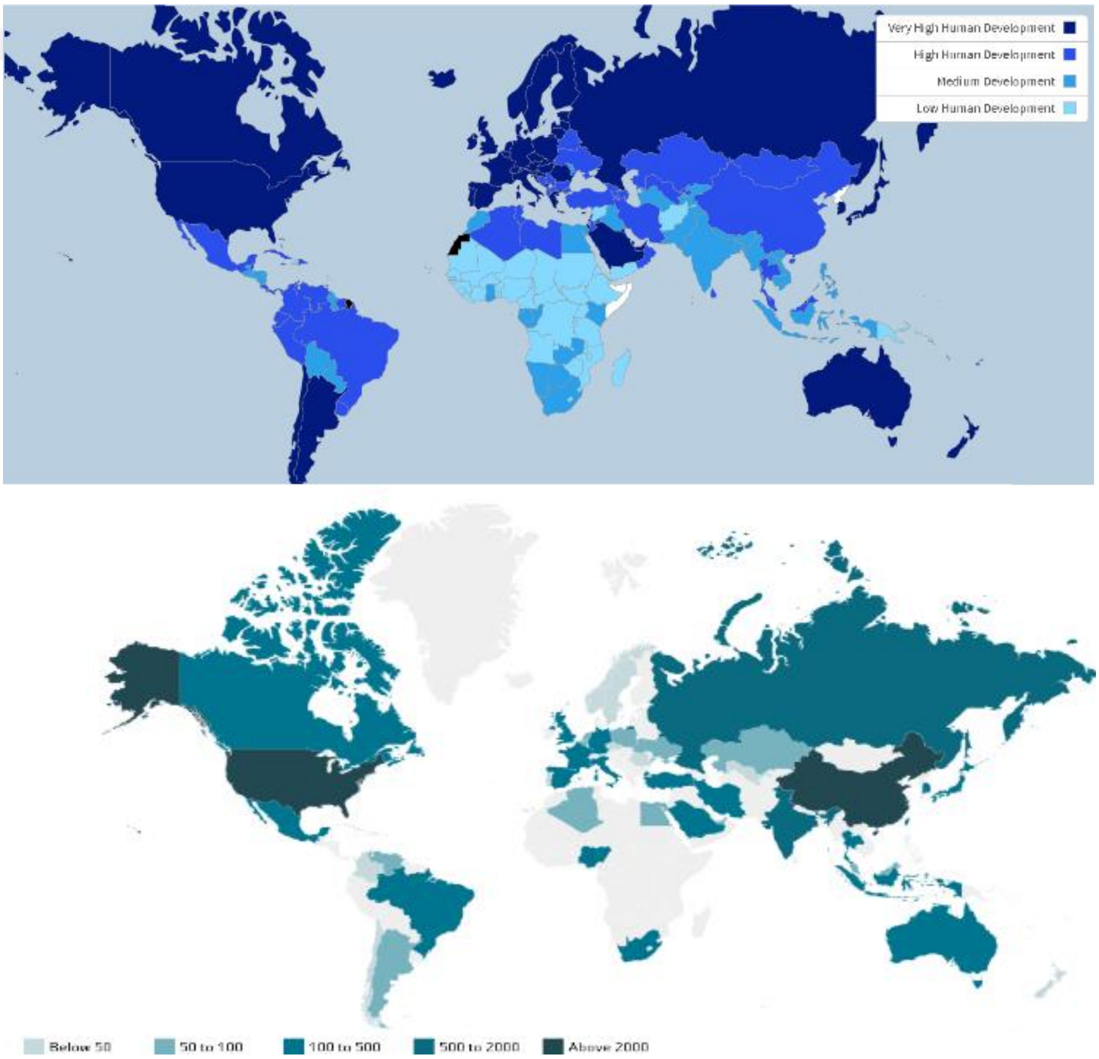


Figure 1.1 : Human development map (2016 data) (United Nations Development Programme, 2016) and electricity consumption map (2016) (Enerdata, 2017).

Kates (Kates, 2000) reveals the relation between energy consumption value and population, affluence and technology with the IPAT (Impact=population* affluence *technology) relationship formulation.

$$E = N * \left(\frac{\text{GDP}}{N}\right) * \left(\frac{E}{\text{GDP}}\right)$$

In equation E: energy consumption rate, N: World population, GSMH/N: World GDP per capita and E/GSMH: World energy intensity (GNP per capita energy consumption rate). The equation clearly shows that energy consumption increases with population and income increase (Figure 1.2).

The world population, which was about 6.1 billion in 2001, is expected to be 9.4 billion in 2050 with an annual increase of 0.9%. GNP per capita is $ 7,500 in 2001, with a yearly increase of 1.4% and is estimated at $ 15,000 for 2050. Since the annual increase in GNP is higher than the increase in energy consumption, the world energy intensity is predicted to be 0.20 W / ($ / year) in 2050 with an annual decrease of 0.8% from 0.294 W / ($ / year) in 2001. When the predicted factor values are set in the above equation, it is expected that the energy consumption rate of 13.5 TW in 2001 will increase to 27.6 TW in the year 2050 and 43 TW in the year 2100 (Tsao, Lewis, & Crabtree, 2006). These forecasts contain a high level of uncertainty due to the uncertainties in population, GNP, and energy intensity change rates.

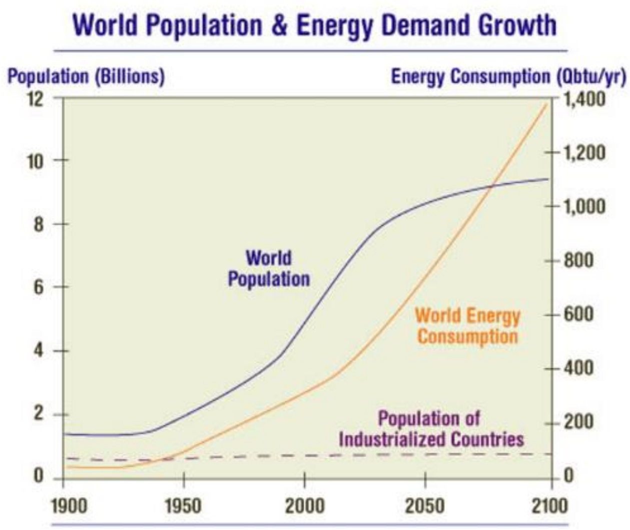


Figure 1.2 : The relationship between global population growth and energy demand growth (Energy Predicament, 2018).

According to the USA EIA data, world energy consumption is expected to be 1.6E + 14 kWh in 2012 and consumption is expected to increase by 1.4% annually with 1.85E

+ 14 kWh in 2020 and 2.4E + 14 kWh in 2040 (IEA, 2016b). According to the World Energy Council data for 2014, 40142 kWh / year and 31834 kWh / year consumption Kuwait and Qatar have the highest average per household electricity consumption. Cameroon and Nepal constitute the countries with the lowest electricity consumption with average electricity consumption per household of 509 kWh / year and 331 kWh / year (WEC, 2016). The average electricity consumption per household in the world is 4568 kWh / year per household, and Turkey's electricity consumption per household is 2339 kWh / year according to the same data. These values show that the increase in energy demand is positively affected by population growth and wealth growth.

Today, fossil fuels are used as the primary energy source in meeting this growing energy demand. Fossil fuels (coal, natural gas, petroleum) are expected to meet about 90% of today's energy demand and to meet about 80% of energy demand in the future (EIA, 2016). If traditional energy consumption habits go parallel to the rate of increase in energy consumption, carbon dioxide emissions will increase, and climatic and environmental problems associated with it will increase (Viswanathan, 2016). The problematic relationship between energy and climate is a significant problem for humanity regarding energy production and consumption. Nearly a billion people are deprived of modern energy services even today. The fact that the world population will reach about 2.6 billion in 2050 indicates that the interest in energy and ecological systems will grow even more (Wegertseder, Lund, Mikkola, & Alvarado, 2016). Despite the uncertainties, in the long run, it is inevitable that population growth and consumption habits related to GNP will increase energy consumption (Viswanathan, 2016).

The compatibility of modern technology with fossil fuels, easily be transported to desired locations and at a relatively low price against other sources of energy has led to the widespread use of fossil fuels. Despite these advantages, fossil fuels cause carbon dioxide and other greenhouse gases (methane, nitrous oxide, fluorous gases) to spread when burned, that is when they enter the energy conversion process (Figure 1.3). These gases cause the ozone layer to be thinned, causing harmful radiation (ultraviolet rays, UV-B and UV-C) to reach the earth. These harmful rays disturb the food chain and ecological order and put the lives of humanity, plants and sea creatures in danger.

Greenhouse gases harm directly to the health of the community and the environment as well as to absorb the radiation released from the earth, causing the surface temperature to rise and the harmful gases falling to the earth as acid rain, damaging the ecological system. The increase of the earth's temperature dissolves glaciers and causes climatic changes that put the living conditions of the earth in the hazard. The main reason for the greenhouse effect is the density of carbon dioxide in the atmosphere. The carbon dioxide concentration value reached 371 ppm in 2001 and 395 ppm in 2016 from 280 ppm (parts per million) in 1750 (Keeling & Whorf, 2002). This situation necessitates a shift towards C-neutral (carbon-free) energy sources to control the level of carbon dioxide in the atmosphere (Viswanathan, 2016). The CO_2 release rate should be limited to 1-2 GtC / year so that the atmospheric CO_2 concentration can be stabilized in the long run (Keeling & Whorf, 2002). Almost all of the energy needs to be met from the zero-carbon-density (C-neutral, non-CO_2-releasing) sources of energy in order to achieve this balance along with the increase in energy consumption rate in the long run (Hoffert, Frei, & Narayanan, 1988). In this case, approximately 15 TW in 2050 and 30 TW C-neutral energy sources in 2100 will be needed (Tsao et al., 2006).

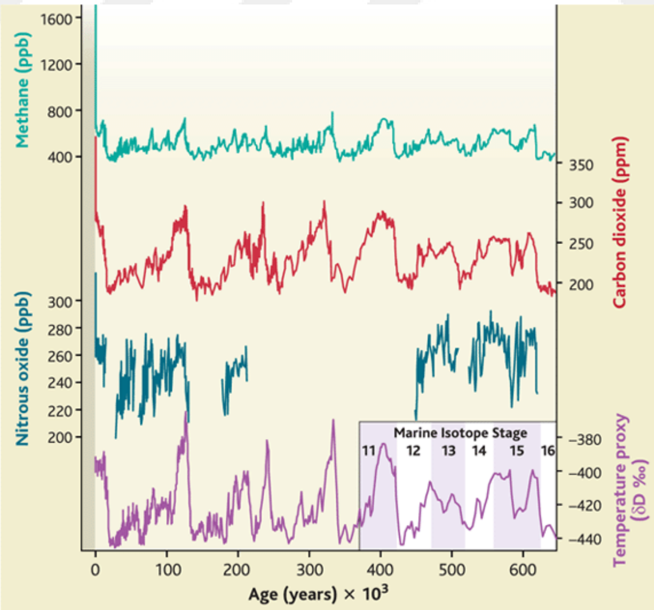


Figure 1.3 : Change of greenhouse gases (Brook, 2018).

The strong balance established between greenhouse gases and global warming has deteriorated over the last two centuries. The main reason is that the 85% of the global energy consumed together with the increasing World population is met from the fossil fuels and the corresponding increase in CO_2 level (Figure 1.4).

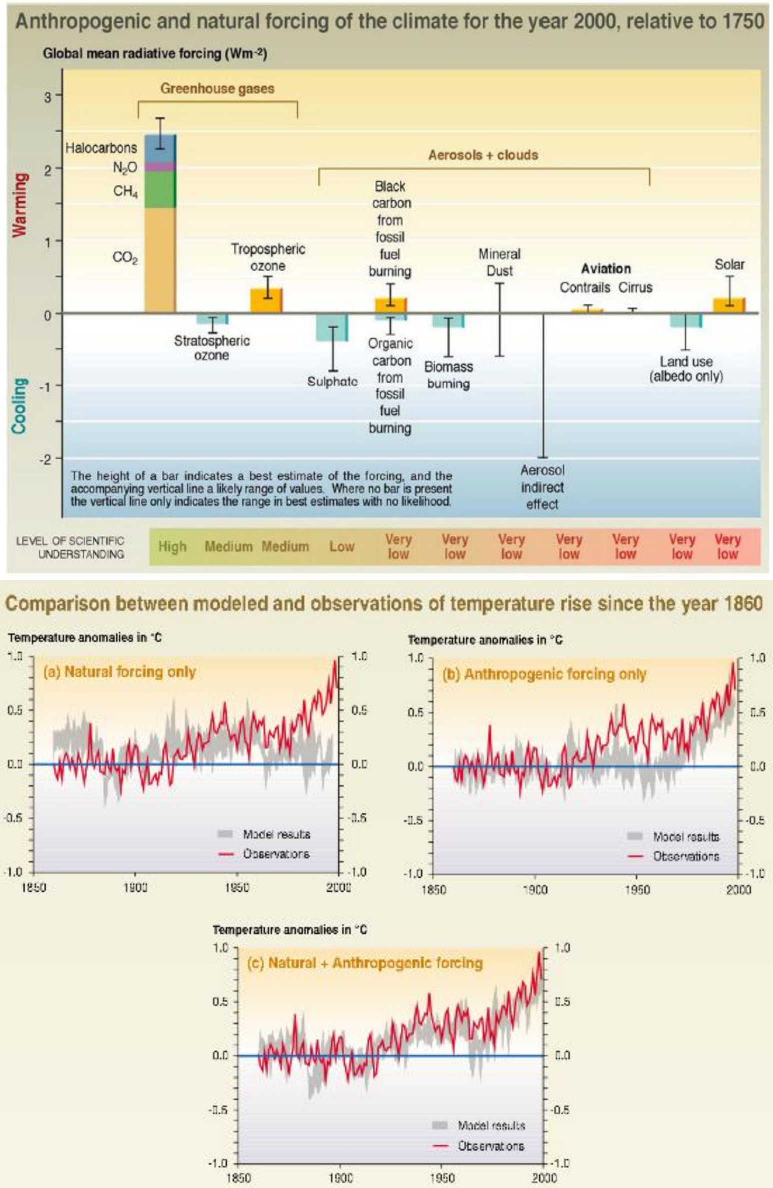


Figure 1.4 : Human-caused and natural factors that cause climatic change and change in global warming (IPCC, 2001).

Human activities change the intensity of the atmospheric composition which causes the absorption and scattering of solar radiation. It has been observed that this change, which is also seen in greenhouse gases, has caused global warming in the past 50 years (Harward Library, 2001). The accumulation of human-based greenhouse gases in the atmosphere increases the surface air temperature and sub-surface ocean temperature (National Research Council (NRC), 2001).

Also, the presence of fossil-based energy resources in particular underground regions causes price uncertainties on a global scale and economic injustice among countries. These situations require humanity to turn to new energy sources for a habitable world at the social, economic and environmental level (Figure 1.5).

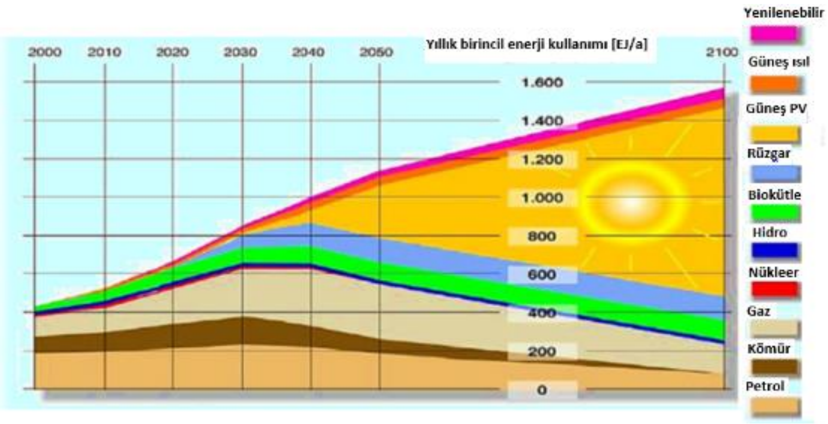


Figure 1.5 : The world's energy consumption diversity between 2000-2100 (German Solar Association (GAS), 2017).

Renewable energy constitutes the most critical part of this energy trend and is mainly utilized in meeting electricity and heat demand. Renewable energy is fed from natural sources such as the sun, wind, wave, tide, and geothermal, and does not cause any emissions that will harm the environment. For example, an annual generation of a PV system with an energy production capacity of 2 kW, an annual output of 3,600 kWh of electricity, will prevent the consumption of coal for energy generation and pollutant emissions of approximately 2268 kg (5000 pounds) (U.S. Energy Information Administration (EIA), 2016). Countries benefit from renewable energy sources without any influence other than their position in the world. Renewable energy sources with the C-neutral feature have an important share in solar and wind production, with the potential to generate 15 TW of energy. Only the sun has the potential to produce the full 15W of energy with its technological advancement (Viswanathan, 2016). Renewable energy sources contribute to socio-economic progress by helping countries to recover from fossil fuel dependence and to improve local new sectors and job opportunities. In Germany, the solar energy sector has created 150,000 jobs in 2010 and is expected to earn € 55-75 billion in the PV sector in 2030 (German Solar Association (GAS), 2017).

According to the U.S. Energy Information Administration (EIA) data, renewable energy is the fastest growing energy source with an annual average increase of 2.6% (U.S. Energy Information Administration (EIA), 2016). Renewable energy, which meets 12% of world energy consumption in 2016, is expected to reach 16-17% in 2040. In addition to these advantages, the most significant challenge is the storage of the generated energy and the transport to the places where it is needed. The cost of batteries used in solar systems reduces revenues and increases system tariff costs

(Mulder et al., 2013). Solar energy systems that maximize electricity generation with high solar energy efficiency in the sunshine period can reach competitive levels by lowering electricity market prices. Yearly and daily changes in the world location cause solar radiation to be cut off and the competitive advantage not to be sustained. In this case, the cost concerns in front of environmental sensitivity cannot prevent the use of fossil fuels (Olcay, 2018).

The sun forms the source of all the energies that exist and will exist on Earth (except nuclear, tidal, and geothermal). The solar energy transferred by food and water through photosynthesis has turned into fossil fuels by the end of the centuries. Climates formed by the rotation of the earth around the sun cause seasonal and regional temperature differences in the sea and black and create winds and sea waves. Movement differences in land and sea provide wind and wave energy. Energy can also be obtained directly from the sun with indirect ways. In addition to traditional and straightforward technology methods such as hot water acquisition and cooking, photovoltaic (PV) and concentrated solar power (CSP) with advanced technology are utilized for high efficiency from solar energy. In summary, the main reasons why solar energy has an important place among renewable energy sources are as follows; The sun's source is unlimited, the distribution of the solar source overlaps with increasing human energy demand, and the sun is a source of renewable energy that does not release carbon.

1.1 Meaning and Importance of Thesis

Turkey mainly meet rising energy demand from fossil fuels (%87.6, 2015 (International Energy Agency, 2016)) for its growing economy and a population of about 81 million by the year December 31, 2017. Turkey which has limited fossil energy sources is dependent on foreign energy, and this causes economic uncertainty. Turkey's external dependence on energy can be explained as follows: Turkey imports about 74% of the total energy demand in 2013. Turkey located in the front row for fossil fuel imports in the countries of the world (natural gas in the 5th, 8th coal, petroleum 13th). Turkey meets 43% of primary energy consumption from the third country and meets 27% from only a country (Enerji Günlüğü, 2014).

Energy imports, which have been declining since 2011, accounted for $ 37.9 billion (18.3%) of total imports of $ 207.2 billion in 2015. The Table 1.1 shows the expenditure of energy imports Turkey and reveals the level of the energy dependence of the Turkish economy (Turkish Statistical Institute (TUIK), 2015).

Table 1.1 : Turkey general energy data (1990-2013) (T.C. Enerji ve Tabii Kaynaklar Bakanlığı, 2015).

	1990	2013	Change
Total energy demand (million toe)	52,9	120,29	%127,39 (increase)
Total domestic production (million toe)	25,6	31,94	%24,78 (increase)
Total energy imports (million toe)	30,9	96,29	%211,62 (increase)
Demand coverage rate of domestic production	48%	%28,5	%40,63 (decrease)

Imports of crude oil increased about 43% in 2015. Instabilities and uncertainties in fossil energy sources damage Turkey's economy (1974, 1980 oil crisis).

Table 1.2 : Turkey's energy imports (2005-2011) (TUIK, 2016; TUIK, 2015)) .

Years	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Total Imports ($ billion)	116.8	139.6	170.1	202	141	185.6	240.9	236.6	251.7	242.2	207.2
Energy Imports ($ billion)	21.2	28.8	33.9	48.3	29.9	38.5	54.1	60.1	55.9	54.9	37.8
Energy Imp. / Total Imp. (%)	18.2	20.6	19.9	23.9	21.2	20.7	22.5	25.4	22.2	22.7	18.2
Crude Oil Import (million tons)	23.4	23.8	23.5	21.9	14.2	16.9	18.1	19.5	18.6	17.5	25.1

The direct and indirect ways of obtaining energy from the sun, which is the main source of renewable energy resources, are becoming widespread and the share of this production in energy production is increasing rapidly. Significant advances in the installation of renewable energy systems and their technological development seen in Turkey parallel to these developments in the world.

Turkey has all the renewable energy sources (except tidal) due to its position on the earth, and strategic plans are developed to obtain heat and electricity based on these resources (T.C. Enerji ve Tabii Kaynaklar Bakanlığı (ETKB), 2015). The governments have developed strategies to use the high renewable energy potentials, and the share of renewable energy resources in electricity generation has been determined to be at least 30% as a target for 2023 (T.C. Enerji ve Tabii Kaynaklar Bakanlığı (ETKB), 2015). Until 2023, 36,000 MW of hydroelectric power, 20,000 MW of wind energy, 1,000 MWe of geothermal energy, 1,000 MWe of biomass and at least 5,000 MW of solar power are targeted to be installed (T.C. Enerji ve Tabii Kaynaklar Bakanlığı (ETKB), 2016). These targets have triggered the research and development activities to ensure the renewable energies, especially solar energy, are effectively obtained and used for Turkey.

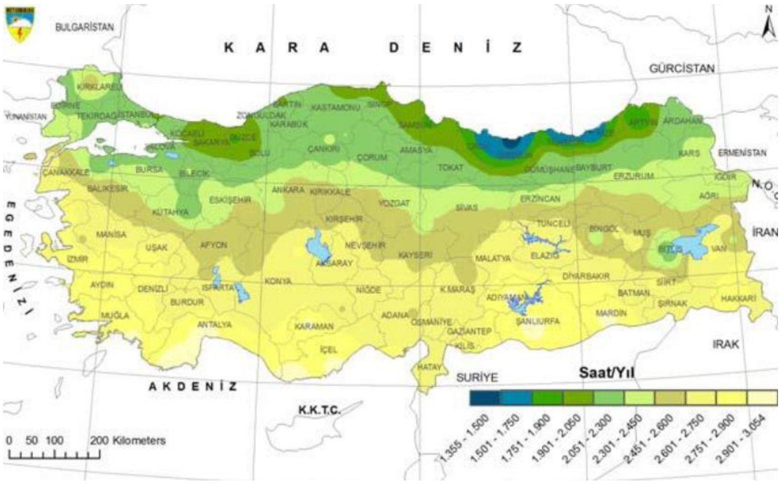


Figure 1.6 : Turkey's total annual sunshine duration map (Meteoroloji Genel Müdürlüğü (MGM), 2011).

The solar energy reaching the earth is also significantly dependent on the amount of radiation coming to earth, as well as the height of the system above sea level. As we move from north to south latitudes at the same altitude solar energy increases by 1.7-1.9% on a yearly basis and every 1000 meters above the same latitude increases the amount of energy by 9-11% in Turkey (Olcay, 2018). Turkey has a very high solar energy potential (Figure 1.6) with a daily average of 7.5 hours of sunshine per day and a total of 2737 hours of sunshine per year (Germany - average 1600 hours/year) (T.C. Enerji ve Tabii Kaynaklar Bakanlığı (ETKB), 2015). Southeast Anatolia region has the highest sunshine duration of 2993 hours per year, and lowest sunshine duration is calculated in the Black Sea region with 1971 hours/year. Water vapor intensity in the atmosphere and high latitude decrease the sunshine duration and the sunshine effect value of the Black Sea region. The annual total solar energy and average daily solar energy reaching Turkey have been identified as 1527 kWh/m^2 and 4.2 kWh/m^2, respectively (T.C. Enerji ve Tabii Kaynaklar Bakanlığı (ETKB), 2015).

Table 1.3 : Turkey's renewable energy potential (T.C. Enerji ve Tabii Kaynaklar Bakanlığı (ETKB), 2015).

Energy Type	Potential
Hydroelectric	160000 GWs/year
Wind	48000 MW
Sun	1520 kWs/m2- year
Geothermal	31500 MWt
Biomass	100018 MWh
Biogas	17500-23260 MWs

Regional differences cause to be differentiated on the interest and investment in solar energy. In Germany, the solar energy coming from the square meters per year varies between 1000-1300 kWh (Figure 1.7). The fact that this value is 1527 kWh in Turkey revealed that Turkey has a high solar energy potential (Figure 1.8) (Yenilenebilir Enerji Genel Müdürlüğü (ETKB), 2018).

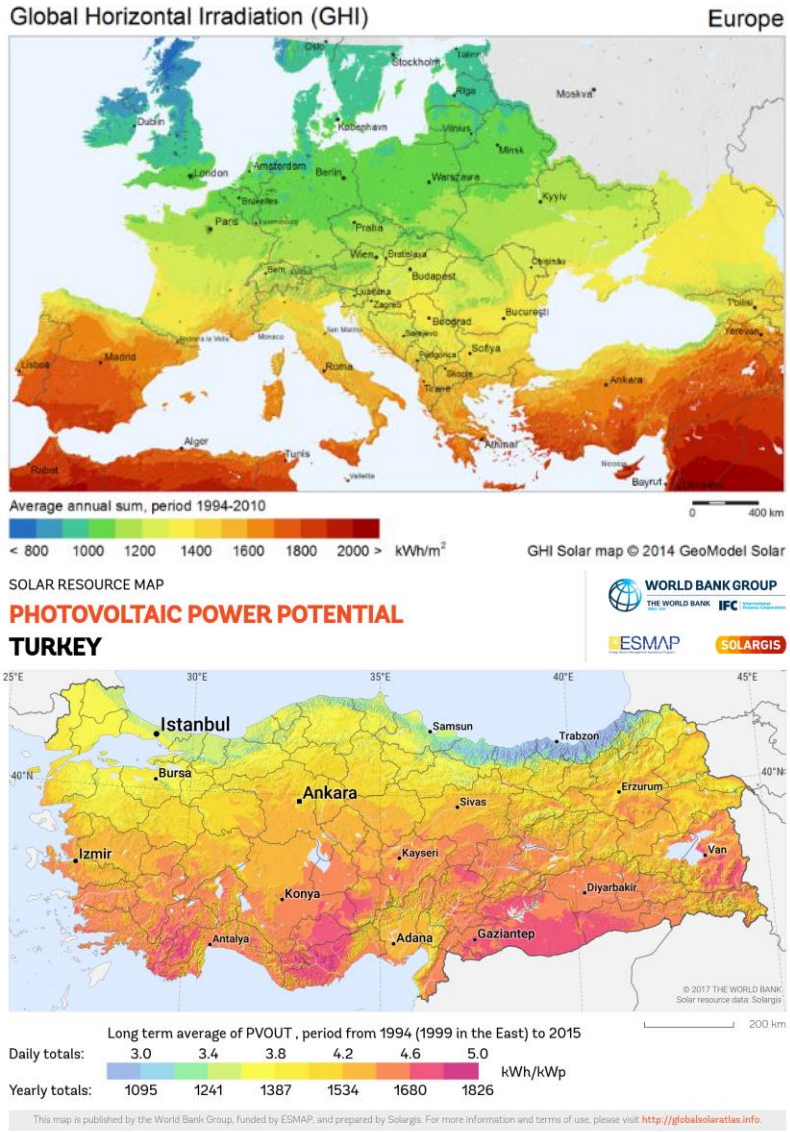


Figure 1.7 : European solar radiation map (SOLARGIS, 2017b).

Turkey, which didn’t have the MW level solar power in 2013, has reached installed capacity of 300 MW in 2015 and also aims to reach installed capacity 1,800 MW and 3,000 MW of solar energy for the years 2017 and 2019 respectively (T.C. Enerji ve Tabii Kaynaklar Bakanlığı (ETKB), 2015). As of 2016, the number of solar power plants is 1045, and total installed power of 832.5 MW is reached (T.C. Enerji ve Tabii Kaynaklar Bakanlığı (ETKB), 2017).

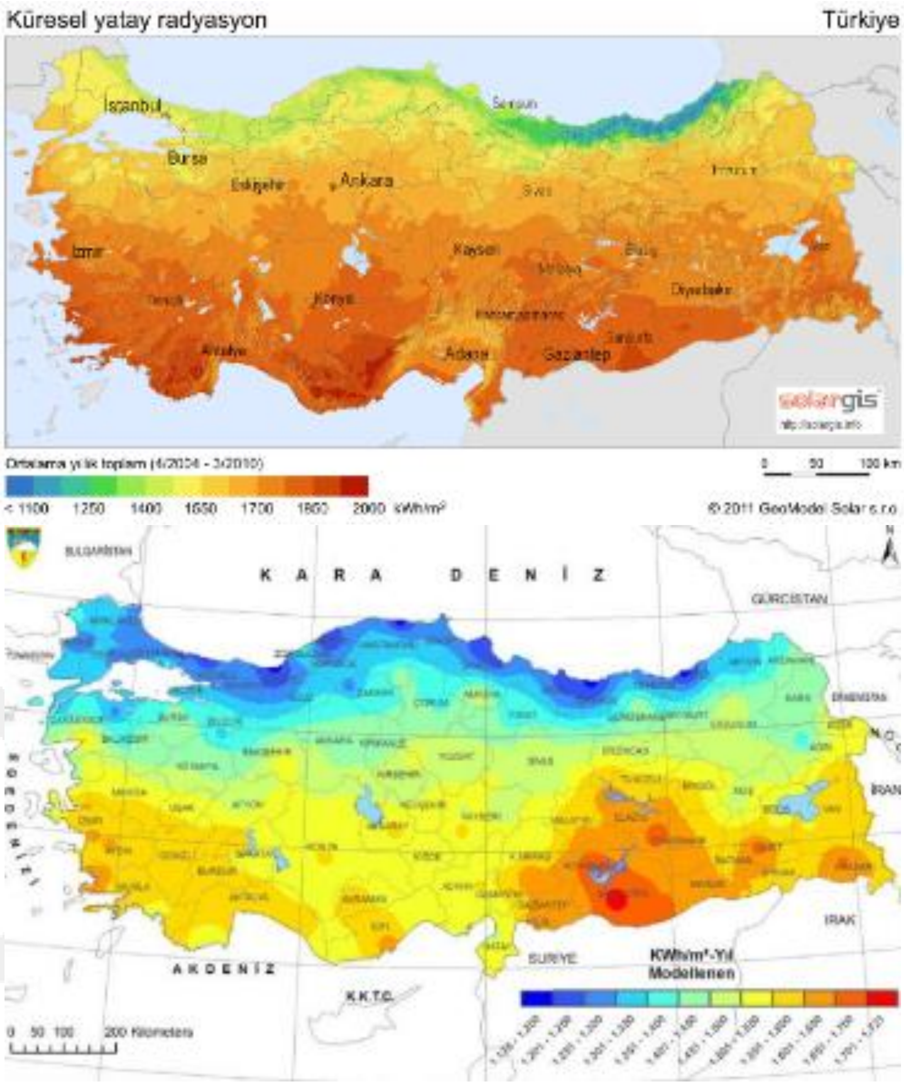


Figure 1.8 : Turkey's solar radiation map (SOLARGIS, 2017a; Yenilenebilir Enerji Genel Müdürlüğü (ETKB), 2018).

Solar energy, which is 0.95% of installed power based on renewable energy sources in 2015, is targeted to be increased to 4.5% in 2017 and 6.5% in 2019 (T.C. Enerji ve Tabii Kaynaklar Bakanlığı (ETKB), 2017). As of March 2016, Turkey reached 388 MW grid-connected solar power installed capacity that meets 0.22% of Turkey's electricity needs. The value of the installed capacity is expected to reach 3,360 MW in the first quarter by 2016 and meets 1.85% of Turkey's electricity needs (T.C. Enerji ve Tabii Kaynaklar Bakanlığı (ETKB), 2017).

Although Turkey has high solar energy potential, it is insufficient to convert this solar energy potential into usable energy. Results to be obtained from the theses study will increase awareness of Turkey's solar energy potential and help entrepreneurs and administrators to perform more effective investment decisions.

1.2 Purpose and Scope of the Thesis

Main obstacles encountered in the use of solar energy potential in Turkey can be defined as regulatory and bureaucratic processes; inadequacy of network connection and transmission network, lack of human resources to solve technical problems and economic difficulties to meet high installation costs. Lack of strategy for the correct assessment of Turkey's solar energy potential is the leading cause of these problems.

Countries (Germany, America, China, India, Spain, UK) that directed to exploit renewable energy sources have developed policies and strategies for the use of renewable energy and reveal their potential. The incentives presented in the framework of these action plans have led to lower costs and increased investment in renewable energies. While new investments in renewable energies in 2004 amounted to $ 45E + 9 (billion) and total renewable power capacity was 800GW, total investments in power increased to $ 232E + 9 in 2013 and $ 270E + 9 in 2014, bringing the total power capacity to 1578 GW and 1712 GW respectively (Renewable Energy Policy Network for the 21st Century (REN21), 2015). The hydropower from renewable energy power sources has the largest share (62%) with 1055 GW capacity in 2014, while the solar energy capacity of 177 GW photovoltaic and 4.4 GW CSP constituted 11% share with a total of 181.4 GW in the same period (T.C. Enerji ve Tabii Kaynaklar Bakanlığı (ETKB), 2015). The policies put into practice are aimed at replacing the fossil-based energy of renewable energy and supporting domestic production.

Incentive programs are applied to expand the renewable energy plants in Turkey. Domestic production of mechanical and electronic components used in power generation facilities operating before December 31, 2020 is supported. Additional domestic production support is given to the fixed price guarantee tariff (feed-in-tariff) for 5 years from the date that the plant for electricity generated in these facilities enters into operation (T.C. Resmi Gazete, 2011). Incentives for domestic manufacturing of solar energy based on facilities in Turkey are given in Table 1.4.

Including two kinds of licensed and unlicensed production of electricity from solar energy made in Turkey are expected to follow specific legal procedures. Licensed production is carried out by commercial companies for an installed capacity of more than 1MW. Companies that have to measure solar radiation for a year make license applications every year in October (the first GES license application started in 2012.).

Unlicensed producers are not obliged to be a company, and unlicensed solar energy production is carried out by real and legal persons. Unlicensed facilities are defined as facilities with an installed power capacity of 1 MW or less, using the entire generated energy without giving it to the transmission and distribution system, or selling it to the government at fixed prices and having no measurement obligation (T.C. Resmi Gazete, 2011).

Table 1.4 : Domestic contributions for solar energy production facilities (T.C. Resmi Gazete, 2011).

Facility Type	Domestic Manufacturing	Domestic Contribution (US $ cent/kWh)
Production plant based on PV solar energy	PV panel integration and solar structural manufacturing	0.8
	PV modules	1.3
	PV module forming cells	3.5
	Inventors	0.6
	Material that focuses solar radiation on the PV module	0.5
Production plant based on CSP solar energy	Radiation collection tube	2.4
	Reflective surface plate	0.6
	Solar tracking system	0.6
	Mechanical part of the heat energy storage system	1.3
	Mechanical assembly of the steam generator in the head	2.4
	Stirling motor	1.3
	Panel integration and solar panel structural mechanics	0.6

The country's ignorance of rapid capacity growth and technological developments, along with incentives and financial support for the development of the renewable energy industry, has led to serious burdens on the country's economies. Countries with insufficient resources have had to regulate or abolish incentives for renewal of their policies and renewable energies.

The main purposes of the thesis are to provide a realistic solar energy vision to political actors and entrepreneurs whose determine the solar energy investments in Turkey and to incorporate future uncertainties into account in the decision-making process. For this purpose, it is aimed to present the most suitable technology (photovoltaic, PV and concentrated solar power, CSP) by evaluating the solar energy resources that best suit the country's position and physical conditions in the world.

1.3 Original Value

The study takes into account the improved conditions in Turkey, but the models developed on this condition will guide decision makers for installation of solar energy systems on a global scale. The study involves evaluating the technical, economic, social, political and environmental data used in the establishment of solar energy systems in a single model. The technical and economic feasibility of PV and CSP systems is evaluated according to the solar energy potentials of the region of interest. In the process of developing solar energy systems, taking into account the technical and economic dimensions as well as the long-term social, political and environmental dimensions have critical importance in the decision-making process. The inclusion of these evaluation headings and sub-factors in the models is intended to achieve more realistic results.

It is planned to obtain linguistic expressions by applying to the experience and knowledge of sectoral and academic experts for evaluations of the solar energy system to be applied on the social dimension. At this stage, it is planned to use linguistic fuzzy sets to remove the uncertainty and complexity of verbal expressions. Thus the expressions will be more clearly defined and can be converted into numerical values to be included in the overall evaluation.

In summary, literature and Turkey and other countries with sectoral analysis that hinder the development of solar energy and supporting fundamental factors and related technical parameters, economic, social and environmental terms are defined. These factors will be evaluated with decision-making approaches, and a unique model will be given to help establish the most suitable PV and CSP systems.

1.4 Common Effect

The main decisive factor that leads to renewable resources from traditional methods (fossil sources) is a cost in achieving energy. Exhaustion of limited fossil energy sources reveals that fuel prices will increase in the future. Today, the abundance of fossil energy sources enables fossil fuel prices to be low and causes fossil fuels to be preferred as primary energy source despite environmental damages. Under these conditions, ensuring price advantage has critical importance to provide a competitive advantage to renewable energy sources and expand the use of renewable energy.

Solar energy that has an essential place among renewable energy sources with its abundance and accessibility must have a cost advantage in order to spread its use. Determining the most suitable locations and conditions to promote the use of solar energy systems (PV/CSP), which require a high initial cost, will provide price advantage against competitors. Turkey's solar energy installation conditions are evaluated by the technical, economic, social and environmental factors. The installation and decision-making process of solar energy systems in Turkey is carried out by considering the long-term behavior of these factors.

The decision making process is shortened, and high productivity and long-term social and environmental gains are obtained by considering the appropriate data. Solar energy prices will be able to compete with fossil and other renewable energy prices with obtained method advantages and legal incentives. These advantages, which will enable consumers to obtain cheaper energy, are expected to direct investors to the installation of solar energy systems and significantly reduce energy dependency on the outside.

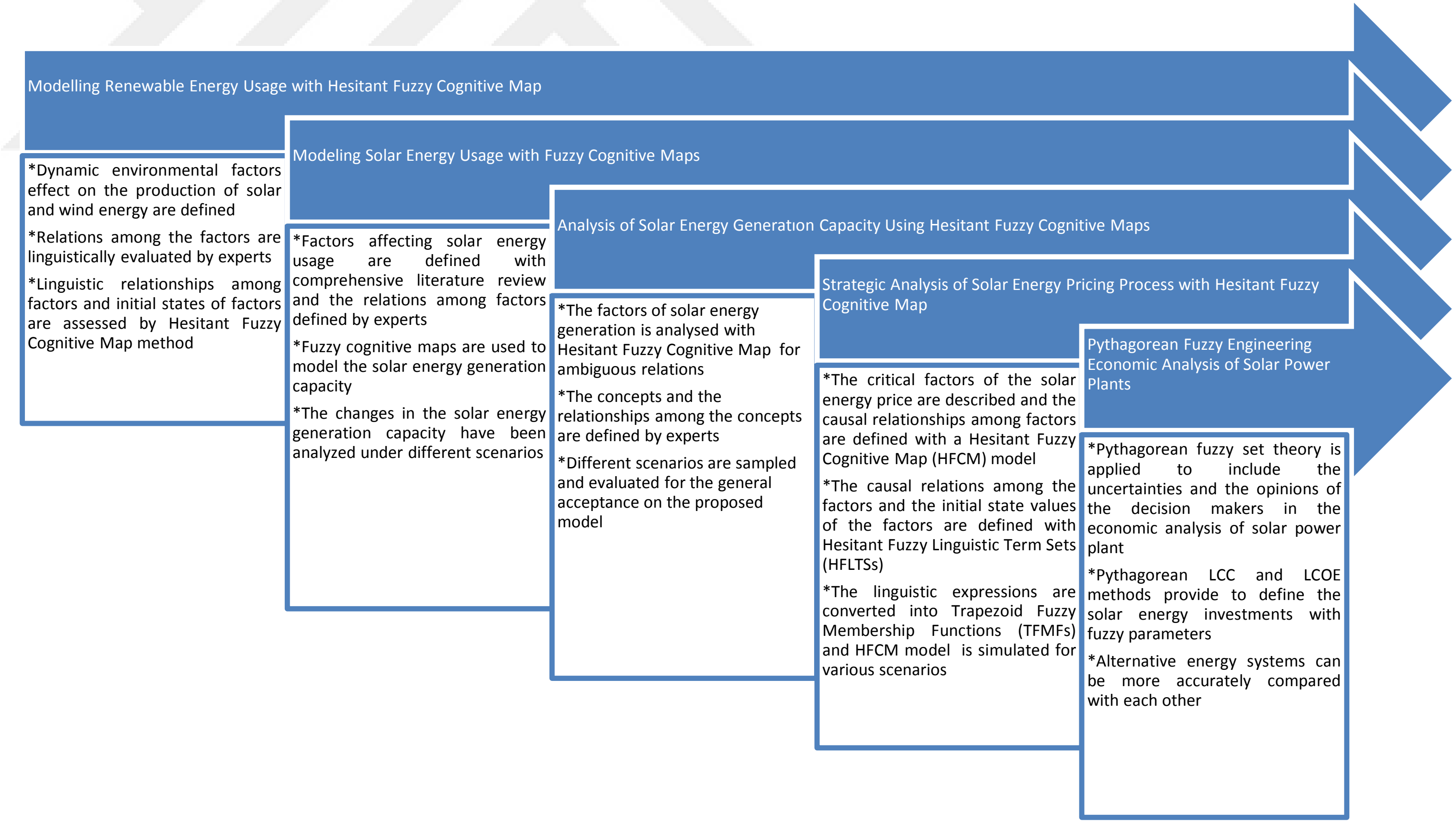
1.5 Publications and Their Relations with Each Other

Publications are designed to reach individual evaluations in order to model Turkey's solar energy potential under different conditions that are defined as factors or concepts. Renewable energy sources are examined, and dynamic factors are affecting the generation of wind and solar energy are defined in the publication "Modeling Renewable Energy Usage with Hesitant Fuzzy Cognitive Map." Causal relationships between factors are assessed linguistically by experts, and linguistic evaluation is modeled under the Hesitant Fuzzy Cognitive Map. The interactions and the equilibrium state values of the factors in the long term are observed in the different initial state scenarios of the factors. The results obtained from this study provide the determination of the factors affecting renewable energy production and the identification of their interactions with each other. Also, factors affecting solar energy production were introduced, and validity of the FCM-based HFCM model was observed for the studies. The publication "Modeling Solar Energy Usage with Fuzzy Cognitive Maps" concerns the modeling of solar energy production capacity by FCM. This study focuses on the production of solar energy, and the factors are identified according to findings from the previous study. Causal relationships between factors are defined linguistically by experts according to their knowledge and experience. The interactions of the factors affecting solar energy production and their long-term behaviors are observed with the FCM model under the initial state scenario. The "Analysis of Solar Energy Generation Capacity Using Hesitant Fuzzy Cognitive Maps " study was carried out to more accurately incorporate the descriptive and linguistic uncertainties encountered in the evaluation process of causal relationships between the factors affecting solar energy production. The factors used in this study are defined based on the factors determined in the previous study and the causal relationships between the factors are related through the HFCM model. The causal relationships among the factors were assessed linguistically based on the knowledge and experience of the experts, and the behavior of the factors was observed according to the different initial state scenarios.

In previous publications, the factors affecting the solar energy production were defined, and their causal interactions under the expert evaluations were examined with FCM and HFCM models. In the "Strategic Analysis of Solar Energy Pricing Process with Hesitant Fuzzy Cognitive Map" study, the factors described in previous publications were customized to define the factors that determine solar energy price. In this study, the critical factors for the solar energy price are defined, and the causal relationships among them are represented with a Hesitant Fuzzy Cognitive Map (HFCM) model. The causal relations among the factors and the initial state values of the factors are defined with the linguistic evaluations of the experts by using Hesitant Fuzzy Linguistic Term Sets (HFLTSs). The obtained HFCM model is used for simulating various scenarios, and the equilibrium state values of the factors are obtained in the long term. The study "Strategic Analysis of Solar Energy Pricing Process with Hesitant Fuzzy Cognitive Map" showed that energy price has an important role in the production of solar energy and the economic analysis of installation of the solar energy plant was carried out with the study "Pythagorean Fuzzy Engineering Economic Analysis of Solar Power Plants." Because solar energy systems have a high initial cost based on the equipment and installation of equipment, the decision to install the solar power plant in the right place and on time should be given correctly. The Life-Cycle Cost (LCC) and Levelized Cost of Energy (LCOE) methods used in the evaluation and comparison of systems involve temporal uncertainty and dynamism. LCC and LCOE methods have been redefined with Pythagorean fuzzy sets in order to incorporate temporal uncertainties and the opinions of the decision makers into economic analyzes. The proposed Pythagorean LCC and LCOE methods enable dealing with the solar energy investments with fuzzy parameters. Alternative energy systems with different technological features and economic conditions can be more accurately compared using the Pythagorean LCC and Pythagorean LCOE method.

Publications have been developed to build on the sectoral and academic expert opinion in Turkey. Assessments made by the experts under Turkey conditions and global approach were operated under the defined models and the results obtained were globally generalized in the publications. The validity of the new Pythagorean based economic analysis method described in the publication "Pythagorean Fuzzy Engineering Economic Analysis of Solar Power Plants" has been verified by a sample application obtained from the literature. Applicable Pythagorean economic analysis method can be readily applied to any solar power plant to be established in Turkey. Relationships between publications are shown in Figure 1.9.

Figure 1.9 : Relations among publications.



2. MODELLING RENEWABLE ENERGY USAGE WITH HESITANT FUZZY COGNITIVE MAP*

The energy obtained from infinite natural sources such as wind power, hydropower, solar energy, geothermal energy, biomass, tidal power and wave power are called renewable energy. In the last two decades, renewable energy has become a serious energy source. Between the years 1990 and 2014, total renewable electricity generation enlarged by 191 % (European Commission, 2016). Europe's 28 % of overall electricity generation is obtained from renewable energy in 2014 (European Commission, 2016). Although hydropower plants have the highest renewable energy generation capacity, wind and solar power generation capacities are significantly increasing in the recent years. Figure 2.1 shows the share of energy from renewable sources in gross final consumption of energy in 2011.

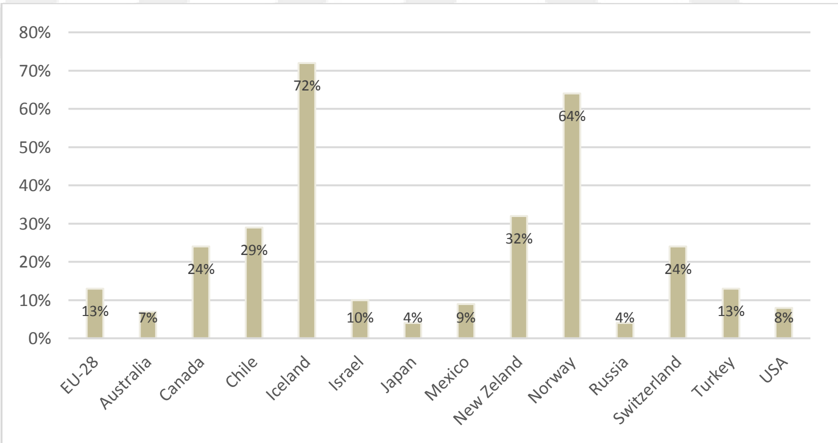


Figure 2.1 : The share of energy from renewable sources (European Commission, 2016).

Among the renewable energy sources, solar power has the highest increase capacity. In 2014, solar power generation capacity increased by 14.1 % compared with 2013 (European Commission, 2016). Although there is a significant increase in the installed capacity of solar energy sources, the percentage of solar energy in the total installed capacity is still limited. Understanding and modeling the solar energy capacity can

* This chapter is based on the paper Çoban, Veysel, and Sezi Çevik Onar. "Modeling renewable energy usage with hesitant Fuzzy cognitive map." *Complex & Intelligent Systems* 3, no. 3 (2017): 155-166.

enhance the solar energy production. The factors and the relations among the solar energy generation are uncertain, complex and vague. Fuzzy cognitive maps are excellent tools for dealing with complexity and ambiguity inherent in modeling problems (Kyriakarakos, Dounis, Arvanitis, & Papadakis, 2017). Hesitant fuzzy sets are the extensions of fuzzy sets where more than one membership value of an element can be defined (Torra, 2010; Torra & Narukawa, 2009). Hesitant fuzzy sets and hesitant linguistic term sets enable better expressing the experts' evaluations (Axelrod, 1976; Torra, 2010; Lofti Asker Zadeh, 1965). In this study, hesitant fuzzy cognitive maps are used for modeling solar energy generation capacity.

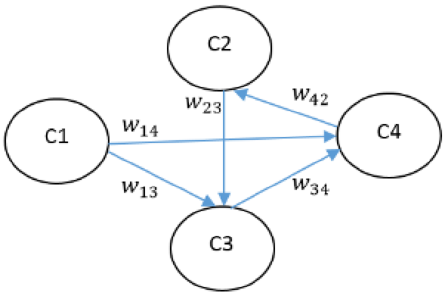
In general, this study examines the dynamic behavior of factors whose behavior is unclear during the installation phase of renewable energy systems. In this way, the relationships between the factors are determined linguistically by expert opinions and the behavior of the factors and the general system can be observed. This model can be differentiated according to the opinions of experts which vary according to economic, social, political and environmental conditions.

2.1 Fuzzy Cognitive Map

Fuzzy Cognitive Map (FCM) that is an extension and combination of the cognitive map (Axelrod, 1976) and fuzzy logic (Kahraman, Kaymak, & Yazici, 2016; Lofti Asker Zadeh, 1965) was introduced by Kosko (Kosko, 1986). Direct or indirect causal and fuzzy (non-binary) relationships between concepts are represented in the FCM. Fuzzy causal relations among concepts are generated by consulting the experts or general literature reviews. The fuzziness of these sources stems from the uncertain, complex and dynamic environments and decision factors in it (Groumpos, 2010; Michael, 2010). FCM can be shown in a symbolical form with concepts or factors (nodes) and connections or causal relationships (arcs/edges). Connections represent the interactive causality among concepts that it reflects the dynamic relationships in systems. Edges that are shown with a directed arrows are weighted by using signed fuzzy values in the interval [-1, 1] (Kosko, 1986; Papageorgiou, 2013).

Concepts (factors) and causal relationships among them can be modeled as a map for a visual expression of a system whose parts are schematically showed with nodes (C_i) and weighted edges (w_{ij}) where are represented with three states as $w_{ij} < 0$ negative causality, $w_{ij} > 0$ positive causality, and $w_{ij} = 0$ no relation. The sign of the causal relationship causes an increase or decrease in the activation level of a concept within each iteration.

Concepts do not influence itself that means there is no self-loop in the model. The visual expression of the model can be transformed into mathematical form as an adjacency matrix which indicates the relationships among nodes with fuzzy values. These fuzzy values represent the weights of the relationships and the initial weights of all interactive combinations among the nodes in FCM are shown with a weight matrix (W) which is a $n \ x \ n$ matrix and whose diagonal values are zero $(w_{ii} = 0)$ due to no-self loops. A sample FCM is drawn with four concepts (C_1, C_2, C_3, C_4) and 5 directed and weighted edges is shown in Figure 2.2.



$$W = \begin{bmatrix} 0 & 0 & w_{13} & w_{14} \\ 0 & 0 & w_{23} & 0 \\ 0 & 0 & 0 & w_{34} \\ 0 & w_{42} & 0 & 0 \end{bmatrix}$$

Figure 2.2 : Graphical representation of FCM and its weighted matrix form.

Time-dependent states of concepts in the FCM are described with an activation level (A_i^t) which represents the presence of a related concept in the system by using [0, 1] interval values. The activation levels of all concepts of the FCM in time t is shown in a state vector as $A^t = [A_1^t, A_2^t, \dots, A_n^t]$ and the initial state vector is symbolized as A^0.

Initial state values of concepts and weight values of connections are defined by experts' assessments or literature reviews that also represent the scholars' assessments in written form (Dickerson & Kosko, 1994). These fuzzy evaluations become starting points for FCM operations and new state values of concepts are calculated with consecutive iterations (McCulloch & Pitts, 1943) as follows;

$$A_i^{t+1} = f\left(\sum_{j=1}^{n} A_j^t \, w_{ij} + A_i^t\right). \tag{2.1}$$

According to Equation (2.1) for concept i, C_i; total causal effects of other concepts on the C_i is calculated by time dependent iterative operations and using threshold function, $f(.)$, which transforms the new state values in the $[0, 1]$ or $[-1, 1]$ intervals that change according to threshold function type. A_i^{t+1} represents the new state values of concept C_i at time $t+1$ after the first iteration from time t.

Although there are commonly used four different threshold functions that are bivalent, trivalent, sigmoid, and hyperbolic functions; sigmoid and hyperbolic threshold functions which are continuous transformation functions and have an ability to transform the iterative state values into the fuzzy representation form in the $[0, 1]$ or $[-1, 1]$ interval are frequently used in FCM studies.

Sigmoid function (Equation 2.2) is a continuous transformation function and are used to transforms the sum of the weights and state values in the $[0, 1]$ interval. This property provides it to be commonly used in the FCMs.

$$f(x) = \frac{1}{1+e^{-\delta x}} \tag{2.2}$$

Hyperbolic Tangent function (Equation 2.3) is also a continuous transformation function (sigmoid-shaped function) and transforms the sum of the weights and state values in the $[-1, 1]$ interval. By this way, inverse relations between concepts and negative state values can obviously be observed and interpreted in FCMs.

$$f(x) = \tanh(\delta x) = \frac{e^{\delta x} - e^{-\delta x}}{e^{\delta x} + e^{-\delta x}} \tag{2.3}$$

Where e is a Euler number and δ is a positive parameter (δ>0) that draws the function curve. x is the activation level of a concept at related time (sum of weighted state values and activation level of the previous time). After these threshold operations, new state values and activation level are obtained that they are convenient to fuzzy form.

Delta (δ) is a previously defined constant value that determines the shape of the function such as large delta values ($\delta \geq 10$) produce discrete functions and small values ($0 < \delta \leq 1$) produce linear functions. Specific delta values can be defined for each different study such that it should be fit with the study content and also reflect the researchers' findings obviously (Papageorgiou, 2013).

Iteration process for activation levels is updated until to the converged steady-state values that are measured based on the limit value. Limit values can be defined based on the iteration number or the difference between last two state values such as $A^{t+1} - A^t \leq f$ (general acceptance is $f = 0.001$).

FCM is an important analyzing and decision-making tool that has an ability to obviously reflects the complex, dynamic, and uncertain real world problems visually and matrix form. Causal relationships among concepts in the FCM can be observed and made an inference for a long term circumstances. The realistic and simple tool in the analyzing and decision making of the uncertain real world problems. Therefore, FCMs have been applied in many different scientific fields such as strategic planning (Ferreira, Ferreira, Fernandes, Meidutė-Kavaliauskienė, & Jalali, 2017), environmental management (Pacilly, Groot, Hofstede, Schaap, & Bueren, 2016), and decision-making (Froelich & Salmeron, 2016).

2.2 Hesitant Fuzzy Cognitive Map (HFCM)

Evaluations in real-world conditions do not only base on numbers such that they also expressed with the linguistic assessments (natural language) such as words and sentences (Lofti Asker Zadeh, 1965). Linguistic evaluation expressions (high, medium, low) that are shaped by personal perceptions, knowledge, and experience cannot give an exact assessment of numbers and they include uncertainty and hesitancy. However, these evaluations are highly fit to human nature such that people can easily express themselves and naturally judge in the decision states.

But it appears that linguistic terms also include the hesitancy in the evaluation processes where experts cannot directly define their opinions by only using one assessment word such as low, very high, medium. Torra (Torra, 2010) proposed a solution step for this problem by defining “Hesitant Fuzzy Sets (HFSs)” that explain the set of values for a membership of a single element and enable experts to comment on the concepts and relationships among them.

The Hesitant Fuzzy Linguistic Term Sets (HFLTS) presented as an extension of HFSs by Rodriguez et al. (Rodriguez, Martinez, & Herrera, 2012) reveals as an ordered finite subset of the consecutive linguistic term set. Experts overcome their challenges about hesitancy among several linguistic values by using HFLTS that is an ordered finite subset of consecutive linguistic terms of linguistic term sets (Rodriguez et al., 2012). For example, a sample HFLTS $\mathrm{H_s} = \{\, \mathrm{s_2}\text{: low}, \mathrm{s_3}\text{: medium}, \mathrm{s_4} : \text{high}\}$ can be defined by using linguistic term set S ={nothing, very low, low, medium, high, very high, perfect}. Basic mathematical operations and notations of HFLTS based on the linguistic term set S can be shown as follows (Rodriguez et al., 2012):

- The bounds and complement of the HFLTS ,H_S;

$$\text{Upper bound } H_{S^+} = max(s_i) = s_j, s_i \in H_s \text{ and } s_i \leq s_j \; \forall_i;$$

$$\text{Lower bound } H_{S^-} = min(s_i) = s_j, s_i \in H_s \text{ and } s_i \geq s_j \; \forall_i;$$

- The basic operations of the HFLTSs (H_s, H_s^1, H_s^2) that are complement, union and intersection;

$$H_s^c = S - H_s = \{s_i | s_i \in S \text{ and } s_i \text{ not } \in H_s\} \text{ and } (H_s^c)^c = H_s$$

$$H_s^1 \cup H_s^2 = \{s_i | s_i \in H_s^1 \text{ or } s_i \in H_s^2\}$$

$$H_s^1 \cap H_s^2 = \{s_i | s_i \in H_s^1 \text{ and } s_i \in H_s^2\}$$

New values that are obtained after these basic operations also will be a HFLTS. Experts can comment on real-world problems and events by using comparative linguistic expressions. These type hesitant linguistic expressions and linguistic terms in a natural language can be generated by using context-free grammar that is shown as G_H. A context-free grammar G_H is defined based on the 4-tuple (V_N, V_T, I, P), where V_N is a set of nonterminal symbols such as primary term, composite term; V_T is a set of terminal symbols such greater than, lower than; I is the starting symbol and an element of V_N; and the production rules, P are defined based on the extension of the Backus-Naur Form (Rodriguez et al., 2012).

For example; "at least medium", "greater than low", "lower than high", and "between low and very high" hesitant linguistic expressions are described by context-free grammar, G_H. Linguistic expressions are more flexible and natural for experts in order to evaluate the hesitant circumstances.

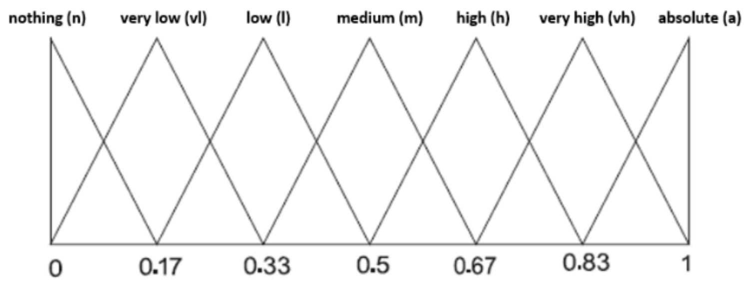


Figure 2.3 : The linguistic term set $S = \{s_1, s_2, \dots, s_6\}$.

Linguistic expression defined according to context-free grammar should be transformed into the HFLTS by transformation functions, E_{G_H} (Rodriguez et al., 2012).

These transformation process provides to use the linguistic expressions in the computation and evaluation processes. For example;

- $E_{G_H}(s_i) = \{s_i | s_i \in S\}$
- $E_{G_H}(at\ most\ s_i) = \{s_j | s_j \in S\ and\ s_j \leq s_i\}$
- $E_{G_H}(at\ least\ s_i) = \{s_j | s_j \in S\ and\ s_j \geq s_i\}$
- $E_{G_H}(lower\ than\ s_i) = \{s_j | s_j \in S\ and\ s_j < s_i\}$
- $E_{G_H}(greater\ than\ s_i) = \{s_j | s_j \in S\ and\ s_j > s_i\}$
- $E_{G_H}(between\ s_i\ and\ s_j) = \{s_k | s_k \in S\ and\ s_i \leq s_k \leq s_j\}$

where S ={s_0: nothing, s_1: very low, s_2: low, s_3: medium, s_4 : high, s_5 : very high, s_6 : absolute} is the linguistic terms set. For example, according to linguistic term set S ={ nothing, very low, low, medium, high, very high, perfect} is the transformation of linguistic expressions "*at least medium", "greater than high"* and *"between medium and very high"* into HFLTS can be shown as :

- $E_{G_H}(at\ least\ medium) = \{\ medium, high, very\ high, absolute\}$
- $E_{G_H}(greater\ than\ high) = \{\ very\ high, absolute\}$
- $E_{G_H}(between\ medium\ and\ very\ high) = \{medium, high, very\ high\}$

The set of information is aggregated to obtain a unique datum by using aggregation operators such as mean, arithmetic mean, weighted arithmetic mean, and OWA operator (Yager, 1988) that are as follows:

$$Arithmetic\ mean\ (a_1, a_2, \ldots, a_n) = \sum_{i=1}^{n} \frac{a_i}{n} \quad (3.4)$$

$$Weighted\ mean\ (a_1, a_2, \ldots, a_n) = \sum_{i=1}^{n} w_i * a_i \quad (3.5)$$

where w_i is the weight of i-th information source (w_i).

$$Ordered\ Weighted\ Averaging\ (OWA)(a_1, a_2, \ldots, a_n) = \sum_{i=1}^{n} w_i * b_i \quad (3.6)$$

where b_i is the i-th largest element of the aggregated objects $a_1, a_2, \ldots, a_n$ and their permutation values are ordered from the largest to the lowest. w_i is an element of the aggregated weight vector $W = (w_1, w_2, \ldots, w_3)^T$ and represents the weight of the ordered i-th data in the interval [0,1]. All weights in W that can be measured by different ways such as average, max, and min are aggregated by using summation formulation as $\sum_{i=1}^{n} w_i = 1$ (Pacilly et al., 2016). To represent the optimism and pessimistic degree of the OWA operator, the orness method is used (Pacilly et al., 2016) as;

$$orness(W) = \frac{1}{n-1}\sum_{i=1}^{n} w_i * (n-i) \tag{3.7}$$

where orness value is positive and smaller than 1 where it is defined as optimistic OWA operator that closes to one and defined as pessimistic OWA operators that close to zero (Yager, 1993).

The OWA operator has been widely used aggregation operator in computational intelligence, especially fuzzy logic, with its ability to aggregate and model the linguistic expressions. OWA aggregation operator is used to aggregate the fuzzy membership functions of the linguistic terms of the HFLTS and the trapezoidal fuzzy membership function is obtained for the fuzzy envelope (H. Liu & Rodríguez, 2014; Yager, 1988). OWA weights that are used in OWA operation reflect the differentiation of the importance of the linguistic terms that it proceeds from the hesitation among linguistic expressions.

HFLTSs obtained by transformation of linguistic term sets are easily compared and computed by enveloping method which developed by Rodríguez et al. (Rodriguez et al., 2012). HFLTS is described by using envelope method within linguistic interval whose upper and lower bounds are shown as (H_{S^+}) and (H_{S^-}) respectively. Envelope of HFLTS, $env(H_S)$, is represented as within these bounds as follow;

$$env(H_S) = [H_{S^-}, H_{S^+}], \quad H_{S^-} \leq H_{S^+} \tag{3.8}$$

For instance, HFLTS, $H_s = \{medium, high, very\ high\}$ that is the linguistic expression of “between medium and very high” is enveloped as env(H_S)= [medium, very high] where linguistic term sets is S={nothing, very low, low, medium, high, very high, absolute}. HFLTS is aggregated with using OWA aggregation operator based on fuzzy membership functions of the linguistic terms and obtained a new HFLTS to achieve a fuzzy envelope of HFLTS (H. Liu & Rodríguez, 2014; Yager, 1988).

The trapezoidal fuzzy membership function is accepted as a useful tool for defining and representing the weights of the causal relationships among factors. These causal relations can be defined by linguistic values that involve the uncertainty and hesitancy and can be transformed to the fuzzy numbers by representing triangular, trapezoidal, sigmoid, Gaussian functions (Delgado, Herrera, Herrera-Viedma, & Martinez, 1998).Trapezoidal fuzzy membership function, $\tilde{A}$= (a, b, c, d), is used in this study to define the fuzzy envelope of the HFLTS whose values are transformed from linguistic terms (Figure 2.3).

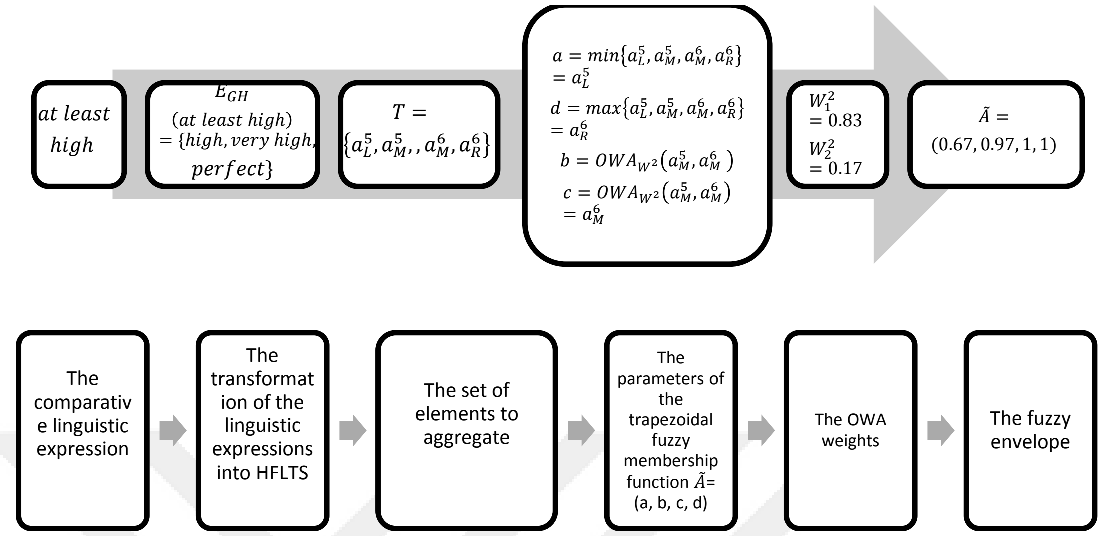
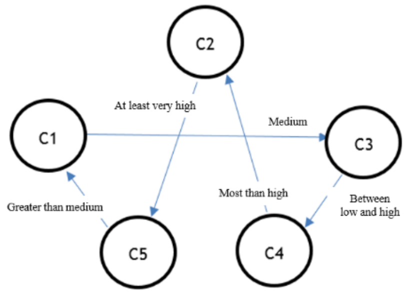


Figure 2.4 : Sample fuzzy envelope generation process.

After these core knowledge and definitions, the HFCM operation flow process (Figure 2.4) can be summarized as follows:

- HFCM consists of concepts and weighted edges among concepts that can be defined by experts with their linguistic expressions. A context-free grammar is used to generate the linguistic evaluations such as at most high, between very low and medium, and lower than very high.
- Linguistic evaluations that define the causal relations among concepts are transformed to HFLTS according to the linguistic term set.
- A trapezoidal fuzzy membership function is obtained by aggregating the fuzzy membership functions of the linguistic terms of the HFLTS.
- Trapezoidal fuzzy membership functions are transformed within the $[-1, 1]$ interval by weighted average defuzzification method and adjacency matrix of the concepts is accepted as a weight matrix (W) of the HFCM.
- Initial state vector of the concepts is iterated in the activation function for each time step. Activation levels in the related time calculated under the hyperbolic tangent threshold function until the state value of each concept converges to its steady state equilibrium.

HFCM (Figure 2.5) utilizes the hesitant fuzzy linguistic terms sets (HFLTS) that experts can easily and freely express their hesitant and uncertain judgments on the relationships between the factors. HFCM is more realistic and flexible than the traditional fuzzy cognitive maps because of its ability to reflect experts' knowledge and experiences that are expressed by hesitant linguistic values.



	C1	C2	C3	C4	C5
C1			{medium}		
C2					{very high, perfect}
C3				{low, medium, high}	
C4		{very high, perfect}			
C5	{high, very high, perfect}				

Figure 2.5 : A sample HFCM and HFLTS matrix.

2.3 Modelling Renewable Energy Usage Based on HFCMs

The energy that is generated from natural sources such as sun, wind, wave, and geothermal is called the renewable energy. Although there are many alternative renewable energy sources, only some of them are available for investors because of their constrained conditions such as regulation, incentive, costs, and energy demand. In this study, the factors that affect and/ or are affected by generated solar and wind energy capacities will be defined and the causal relationships among them will be observed in HFCM. In this way, basic reasons (factors) that affect the solar and wind generated energy capacities will be able to define and the new perspectives and visions will be provided to investors for their long-term investments.

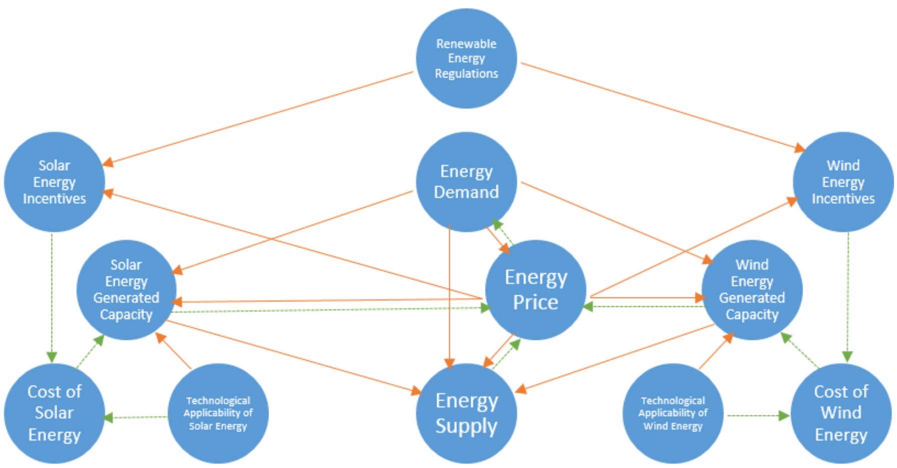


Figure 2.6 : Graphical representation of the relational HFCM.

In this study, the model is defined and the causal relationships are designed based on solar and wind energy generation. Solar (SEGC) and the wind (WEGC) energy generated capacity are basic factors in the energy generation system and refer the total amount of energy that is produced from new constituted solar and wind energy systems.

Cost of solar (COSE)/ wind (COWE) energy, technological applicability for solar (TASE)/ wind (TAWE) energy and solar (SEI)/ wind (WEI) energy incentive factors directly affect the amount of the new generated solar and wind energy capacities and also have indirect effects on the other global factors. The cost of energy systems refers the total amount of cost that stem from investment cost, production, transmission and distribution costs. Technological applicability for energy systems represents the applicability of solar and wind energy technologies under the given geological, physical, and operational conditions for generation and distribution of the solar and wind energy. Other auxiliary factors around the solar and wind energy generations are an incentive and any type of governmental supports that encourage users and investors to direct the solar and wind energy usage and investments. Solar and wind energy incentive are monetary (e.g. zero-interest loan, tax relief, feed-in-tariff) or non-monetary (e.g. law, regulation, policies) encouragement programs whose special purposes are to increase the use of solar and wind energy-efficient equipment and reduce non-renewable energy usage.

The remaining factors in the model that are renewable energy regulation (RER), energy demand (ED), energy price (EP), and energy supply (ES) can be defined as common factors because they have global impacts on the model. Renewable energy regulation reflects the state policies either to support the green energies or to continue to use the fossil-based energy sources. These policies will have important causal and direct effects on the solar and wind energy incentive and other related factors. Energy demand represents a number of energy requirements of the people in order to maintain their daily activities such as heating, transportation, cooking, and production. Energy price is the amount of payment for energy which is used or will be used from conventional or renewable sources. Energy supply meets the total amount of energy which will be produced by all types of energy sources in the future. Figure 2.6 represents the concepts and causal relationships among them such that positive relationships are showed with solid lines and negative relationships are showed with dotted lines. Different scenarios are simulated to observe the impact of possible changes and steady state of the system after the iteration process in HFCM. The following procedures are followed in each of these scenarios.

Table 2.1 : Linguistic relationship matrix.

	SEGC	COSE	TASE	SEI	WEGC	COWE	TAWE	WEI	RER	ED	EP	ES
SEGC											Negative between l m	Positive between vl l
COSE	Negative at least vh											
TASE	Positive between h a	Negative greater that h										
SEI		Negative greater than vh										
WEGC											Negative between l m	Positive between l h
COWE					Negative at least vh							
TAWE					Positive between h a	Negative greater than vh						
WEI						Negative greater than h						
RER				Positive greater that h				Positive greater than h				
ED	Positive at least vh				Positive at least vh						Positive between m h	Positive at least h
EP	Positive between h vh			Positive lower than m	Positive between h vh			Positive lower than m		Negative lower than m		Positive at least h
ES											Negative greater than h	

First of all, experts express their evaluations about the relationships among concepts with linguistic statements (Table 2.1). The effects of a factor on the other factors were expressed as “negative” or “positive” and the degree of the effect by using comparative linguistic expressions such as positive at least high and negative between medium and very high. For example, causal relationship between *wind energy incentive* and *cost of wind energy* was linguistically defined as *negative greater than high* in Table 2.1.

These linguistic expressions are transformed into HFLTS that are used to obtain the trapezoidal fuzzy membership functions by using OWA operations. Trapezoidal fuzzy membership functions are defuzzified with the weighted average method and transformed into numeric values as weight matrix (Table 2.2) and initial state vectors. The activation levels of the concepts in time t and a state vector of the HFCM model is iterated under the threshold function until the HFCM reaches its steady state equilibrium.

Table 2.2 : Weight matrix.

	SEGC	COSE	TASE	SEI	WEGC	COWE	TAWE	WEI	RER	ED	EP	ES
SEGC											-0.138	0.057
COSE	-0.936											
TASE	0.838	-0.936										
SEI		-0.972										
WEGC											-0.416	0.534
COWE					-0.936							
TAWE					0.838	-0.972						
WEI						-0.936						
RER				0.936				0.936				
ED	-0.936				0.936						0.583	0.867
EP	0.750			0.133	0.750			0.133		-0.133		0.867
ES											-0.602	

2.4 Sample Cases

a. An example for the existence of one concept in model

In this scenario, renewable energy regulation factor is activated that means governments increase their interest in developing renewable energies and support their usage and investments. Other concepts are accepted as a stable in the initial state of the system that means there is no direct impact on their current status. Initial state vector is represented as $A^0 = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ ]$ and changes of the concepts and their converged values are observed in the iteration process.

The results of the simulation for sample case (Figure 2.7) can be listed as follow:

1. First reactions seem as increase evenly of the solar and wind energy incentive that are directly affected by renewable energy regulation. Increasing effects in the energy incentive cause to reduce the interest of the governments in the renewable energies in order to regulate the general energy supply and prices in their countries.
2. Increasing incentive in the solar and wind energy cause to reduce their costs and increase their investments and new generated capacities. So far, no change is observed in the energy price, energy supply, and energy demand because of long path lengths among these concepts that it causes long reaction time. Afterward, increasing solar and wind energy capacities raise energy supply and reduce energy prices that cause to increase energy consumption and energy demand at the low rates. At these periods, causal interactions among concepts increase and rapid changes can be observed for their rates in the dynamic system.

3. Renewable energy regulation does not cause any change in the technological applicability of the solar and wind energy during the iteration process because of their closed form and transmitter properties that mean they are not affected by any other factors in the system.

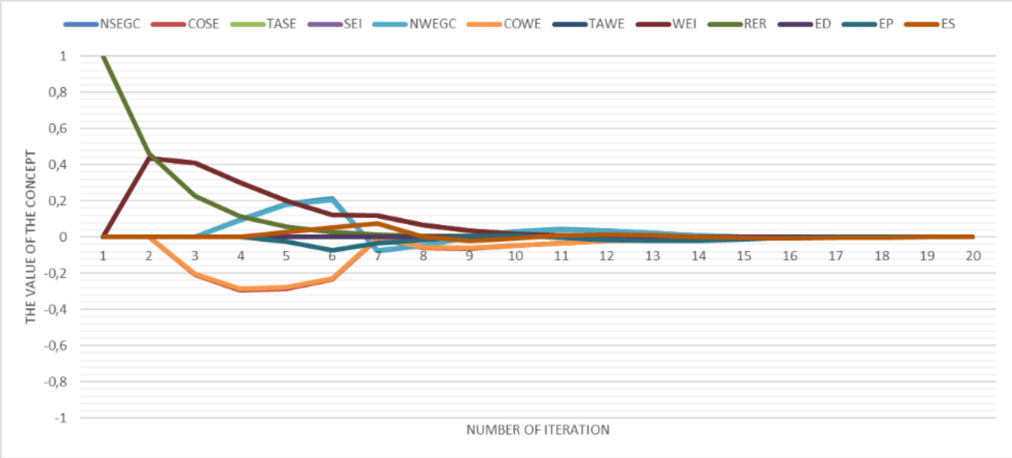


Figure 2.7 : The graphical result of the HFCM simulation for the existence of one concept in the model.

4. Renewable energy regulation loses its influence in the medium term and reaches zero steady value. This circumstance causes to decrease of the incentive and decrease of the decay rate of the cost of solar and wind energies. As a domino effect, new solar and wind energy generation capacities and energy supply start to decrease that it causes to the increase of the energy price and the decrease in the energy demand. Concepts except for technical applicability for solar and wind energy reflect fluctuating motions as decrease and increase. At the final state in the convergence zone, they reach to the zero steady values that mean there will be no change in their state.

b. An example for a combination of concepts in model

The scenario is planned in which the cost of solar and wind energy systems is reduced by improvement in the solar and wind energy technologies and increasing research and development investments. Also, scenario includes the decrease of the renewable energy regulation that reflects the disinterest of the government on the green energy and increase of the technical applicability of solar and wind energy at the same period. By this scenario, transmitter concepts that are renewable energy regulation, the technical ability of solar and wind energy are included in the system at the same time. Initial state vector of the scenario is defined as $A^0 = [0 - 1\ 1\ 0\ 0 - 1\ 1\ 0\ 1\ 0\ 0\ 0\ ]$ and their time dependent changes are observed in the iteration process.

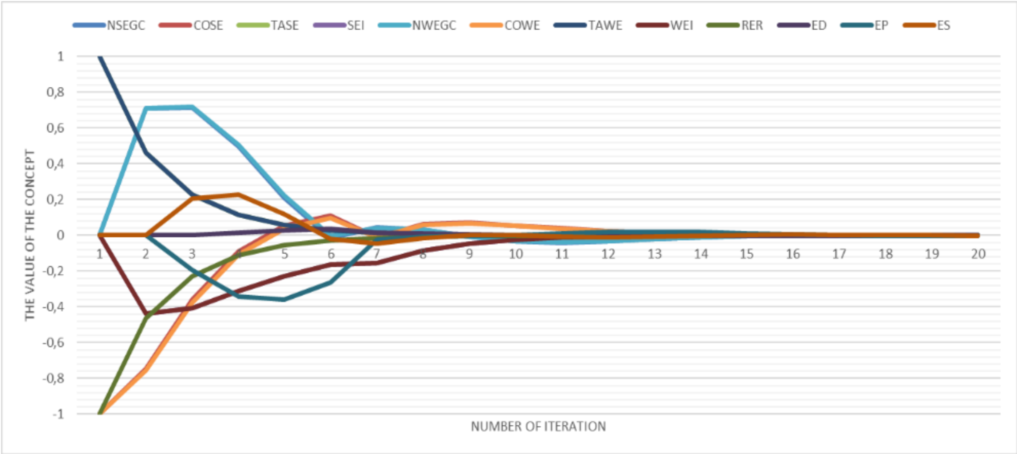


Figure 2.8 : Graphical result of the HFCM simulation for a combination of concepts.

The results of the simulation for sample case (Figure 2.8) can be listed as follow:

1. Firstly, new solar and wind energy generation capacities increase with high rates and solar and wind energy incentive starts to decrease and continue to decrease during the iteration process that it arises from disinterest of governments on green energy by decreasing renewable energy regulation. Initial active concepts do not protect their impacts whose values reduce in the first reaction. No change is observed in the energy demand, energy supply, and energy price because of their global properties and long path lengths with active concepts.
2. Increasing solar and wind energy generation capacities cause to the increase of energy supply and reduce of the energy price that also increases the energy consumption and energy demand. Increase in the cost of solar and wind energy in the medium period cause the decrease of the new generated solar and wind energy capacities and the energy supply. This energy bottleneck indicates that energy price will rise and energy demand will reduce in the same period. Energy supply, demand and price and new solar and wind energy generation capacities factors converge to steady state at zero value in small fluctuations.
3. Active factors in the initial state lose their effects on the other factors during the iteration process. Decreasing investments and new generation capacities of the solar and wind energies stimulate governments to take precaution for supporting these concepts by regulation and incentive. Also, decreasing cost of solar and wind energy systems are balanced by incentive and general energy demand and prices. Technical applicability for solar and wind energy are limited by solar and wind energy systems, so their positive active initial values decrease and reach steady states at zero values.

4. At this scenario, all concepts get involved in the model as active and they causally interact with each other. All concepts, except technical applicability of solar and wind energy that decrease along iterations, increase and decrease during the iteration process and converge to zero values at the steady state.

c. An example for the existence of all concepts in model

System is modeled based on the positive availability of all concepts and their initial states are defined as $A^0 = [1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1]$. Although all concepts are positively existence in the model, system include some opposite interacts among concepts such as increase of the cost of systems will cause to decrease of the new generation capacities of the solar and wind energy system. The solar and wind energy generation based model reaches steady state at zero level which means system is at the balance and there will be no change in the long term. Results of the model can be listed as follows (Figure 2.9):

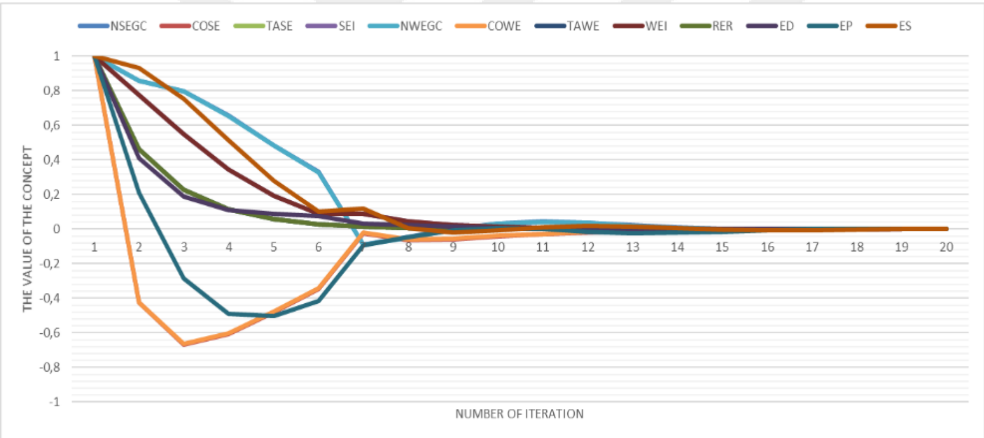


Figure 2.9 : Graphical result of the HFCM simulation for the existence of all concepts.

1. The cost of solar and wind energy factors changes their signs from positive to negative at the first reaction that it stems from increasing supporting policies such as incentive and regulation. Cost reductions and increasing incentive in solar and wind energy systems cause increases in new capacity of solar and wind energy and energy supply and decreases in energy price that will stimulate the energy consumption in the short term. Technical applicability for solar and wind energy decrease during the iterations and reach the steady state in the medium term that it arises from technical limitations such as infrastructure, distance from energy grids, technical knowledge and new investments. Generally, concepts in the model

rapidly decline and converge to their steady state in order to balance the system by causal reactions.

2. Increasing energy price is reduced by increasing solar and wind energy capacities that are supported by incentive and regulation which surpass increasing cost factors for solar and wind generations. When incentive and regulation lose their impacts on the cost of solar and wind energies at the medium period, new generated energy capacities of solar and wind systems decrease in a few iterations but then they recover their increasing state. This state stems from increasing solar and wind energy capacities that cause the increase in energy demand and reduce of energy price and profits such that model reacts to balance the system by decreasing supports (incentive and regulation) on solar and wind energies.
3. All concepts in the system converge to steady state at the zero level after 20 iterations. The steady state of the solar and wind energy generation system reflects the balance of model that means any concepts will not change their state in the long term. Energy supply and energy price concepts are lastly converged to their steady values because of their long decaying times resulting from long path lengths.

2.5 Conclusion

Renewable energy is an important alternative to conventional energy whose sources are finite and becoming expensive in time. The tendency to the renewable energy increases the importance of the determining right energy generation technology in a dynamic environment. In order to deal with this kind of complex problems in the energy sector, we applied the new HFCMs model that is an extension of hesitant fuzzy sets and fuzzy cognitive map.

In this study, the causal relationships among concepts in solar and wind energy generation are described by linguistic term sets that help expert to express their evaluations with natural language. These linguistic terms are transformed into trapezoidal fuzzy membership functions by using HFLTS and OWA operations. Trapezoidal fuzzy membership functions are defuzzified with the weighted average method and transformed to [-1, 1] interval as a weight matrix. Weight matrix and the initial state of the factors are included the iteration process within hyperbolic tangent threshold function in Equation 2.3 until convergence. Converge values represent the steady state of the factors in the model.

In the sample applications, three scenarios are designed according to the current situation of the solar and wind energy systems and verified the accuracy of the theoretical energy model and the usability of the new generated HFCM tool. Simulation processes show that incentive and regulation that refer the support and international obligation of governments have the most important impact on new solar and wind energy generation capacities. However, technical applicability for solar and wind systems that are transmitter factors have a less important impact on new green energy systems. Simulation results also show that the affecting and being affected of the transmitter (renewable energy regulations and technical applicability for solar and wind energy) and global concepts (energy demand, energy supply, and energy price) take a long time because of their long path lengths within concepts.

In the future research, solar and wind energy systems can be divided in their special fields and investigated their main factors by using HFCM as modeling and simulation tool. Factors for new solar and wind energy generation systems can be extended by reviewing the literature or applying wide experts' knowledge that can be expressed by using linguistic definitions. Also, future studies can include the improvement of FCM and HFCM simulation models that are useful tools to analysis real life systems and represent the linguistic expression of experts in the models.

3. MODELING SOLAR ENERGY USAGE WITH FUZZY COGNITIVE MAPS[*]

Energy is a scare resource and has been important for over several centuries. Fossil fuels are the main energy resources. Fossil fuels are known to be one of the major contributors to the greenhouse effect that heat earth, disrupt its energy balance and cause climate change (United State Environmental Protection Agency (USEPA), 2016). Renewable energy resources are considered as the alternative for fossil fuels. Usage of renewable energy resources has been increased over the last two decades since they cause less damage to the environment. The renewable energy resources such as wind, solar, geothermal and tidal energy are starting to get global attention on almost any level possible.

Solar energy was the only source of energy until fossil fuels has been discovered (Silvi, 2008). Over the last century, using solar power to generate energy has been considered many times but due to the relatively high costs and low efficiency, these attempts were not successful until the last decade. Electricity generated from solar sources are not considerably significant when it comes to comparing with other sources of electricity but solar energy investments are increasing. Solar energy is widely being considered as a reliable source of electricity generation. According to British Petroleum, the world has added 40.2GW of solar power generating capacity which results in total of 180GW. Total installed base of solar electricity generation capacity has quadrupled in the past four years. In 2014, solar generation capacity grew by 38% (BP, 2017). According to Renewable Energy Policy Network, total installed capacity of solar energy reached 177GW of photovoltaics and 4.4GW of concentrated solar power systems (Renewable Energy Policy Network for the 21st Century (REN21), 2015). Germany is the number one country when it comes to solar electricity consumption

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[*] This chapter is based on the book chapter Çoban, Veysel, and Sezi Çevik Onar. "Modelling solar energy usage with fuzzy cognitive maps." In *Intelligence Systems in Environmental Management: Theory and Applications*, pp. 159-187. Springer, Cham, 2017.

with 18.8% of global total. Germany is being followed by China (15.7%), Italy (12.7%), Japan (10.4%), and United States of America (10%) (BP, 2017).

The usage of solar energy depends on several factors such as incentives provided by government, physical conditions, and energy prices. Germany is the world leader in deploying renewable energy to the grid. Germany investing heavily on renewable energy and eliminating nuclear (Renewable Energy Policy Network for the 21st Century (REN21), 2015). Germany has a successful energy policy provided by using feed-in-tariff mechanisms, revised ownership structure and reduced dependence on fossil fuels (Renewable Energy Policy Network for the 21st Century (REN21), 2015). Although many countries focus on solar energy, solar energy usage is still limited and remain very low compared to its potential. Defining the factors that affect solar energy usage and the relations among them will show the ways to increase solar energy usage. These factors are complex and the relations between them are ambiguous. Fuzzy cognitive maps are excellent tools for modelling such complexity and ambiguity. In this chapter, fuzzy cognitive maps are used for modelling solar energy generation capacity. The factors and the relations among the factors are revealed based on both a comprehensive literature review and experts' opinions.

3.1 Renewable Energy

Energy is the key factor in the generation of social and economic life for all countries in world. The historical developments of the industrialization and urbanization of the countries have been reflecting a strong relationship with their energy consumption. The general tendency of the countries to the industrialization has caused to increase the energy demand and consumption all around the world. While energy demand of the European Union is expected to increase by 0.5 %/ year, energy demands of the Asia countries are expected to increase by 3%/ year such that the average expecting energy demand of the world is 1.8%/ year in the period from 2000 to 2030 (World Energy Council (WEC), 2016).

The energy is provided by two inverse channels that are named as a renewable and a non-renewable source that is the conventional and primary energy sources. Non-renewable energy sources based on consumption of fossil fuels such as are coal, oil, natural gas release air-pollutant gases (CO_2, NO_x) that have adverse effects on the environment and human health with the greenhouse effect. Increasing trend of the fossil fuel consumption in the period from 2007 to 2030 (International Energy Agency (IEA), 2017) is likely to lead to global warming, climate change and increases in human damages. On the other side, fossil fuel energy sources are finite and becoming scarce that this causes to increase energy prices and decrease economic developments. The world's increasing energy demand based on industrialization and population growth causes countries to tend to the alternative energy sources that will be different from rapidly depleting fossil fuel energy sources.

Renewable energy that generates the energy from infinite natural sources such as sun, water, wind, geothermal heat is one of the alternative energy sources. Renewable energies that do not use any other production processes have some important advantages against the fossil fuel sources such as using domestic resources, not emitting air-pollutant gases, providing sustainable and safety energy, and decreasing greenhouse effect. Also, they cause to increase of the economic activities by decreasing energy prices and providing new businesses in energy sector. For these reasons, governments from different regions around the world tend to develop their renewable energy technologies and utilize from their renewable energy sources. Therefore, the developing the renewable energy technologies and utilizing from renewable energy sources are having critical importance for the sustainable economic development and social wealth of all countries.

Based on the definition of the renewable energy used by the UK government, renewable energy technologies can be divided into eight classes as: solar photovoltaic, micro-wind, micro-hydro, large-scale wind, large-scale hydro, energy from waste, landfill gas and biomass (Kahraman, Kaya, & Cebi, 2009). These differences among the renewable energy technologies reflect the different requirements based on economic, ecologic, technical, and social in order to efficiently utilize from different renewable energy sources. In order to install the most suitable renewable energy alternative that affects the economic growth and social wealth of the countries, many factors are defined according to their specific properties and the relationships among them are evaluated by experts. In this aims, governments can provide economic, social and political supports such as incentives, regulations, and international treaties.

3.2 Solar Energy

When world's energy demand is increasing with improving industry and growing population, conventional energy supply methods based on fossil fuel will remain incapable because of their non-renewable and finite sources. Besides, the scarcity of the fossil based energy sources triggers the irregular change and rise of the energy price that cause the unstable economies and social unrests. Therefore, the world tend toward the alternative energy supply sources such as sun, wind, geothermal that are called as renewable sources and their efficiently obtaining methods by improving new technologies (Ameta & Ameta, 2015; Mackay, 2015). Improving new technologies in the alternative energy methods and their spreading among society cause to decrease of the cost of energy production and energy price that affect economic and social conditions.

Sun is the primary and origin source of many renewable energies such as solar, wind, and wave by provided atmospheric movements and ecologic formations. Solar energy generated by sun can also be accepted as a basic and the most important energy source among alternatives against the threats of the fossil fuel resources depletion. Solar energy is used in heating, enlightenment, and electricity with its modern technologies such as solar heating, photo-voltaic, concentrated solar power (Ameta & Ameta, 2015). It has some advantages and disadvantages compared with renewable and fossil based energy sources that they affect the selection of the solar energy sources by investors.

Solar energy has an environmental sensitivity such that it does not emit any waste, air-pollutant and greenhouse gases, and noise, but it has the indirect effects on environment with its production materials like cadmium telluride. Although its initial costs for purchasing and constructing that consist of solar panels, wiring, inverter, and batteries are fairly high such that governments try to encourage the investors by incentives such as feed-in tariff and regulations, it has not any production cost and has a little maintenance cost with providing long term warranties and services (Kalogirou, 2014).

Improvements in solar energy technology that is cooperate with nanotechnology, chemistry, and physic give hope to decrease the initial costs and increase the efficiency of the solar energy production. Availability of the solar technology that consists of technical infrastructure such as distance to grid and land usage that solar panels need to use a lot of space and weather conditions like number of cloudy and rainy days affect the feasibility and efficiency of the solar energy sources (Kalogirou, 2013; Mackay, 2015).

Table 3.1 : Factors related to installing solar energy sources.

Factors	Definitions
Energy Demand (ED)	The requirement for energy as an input to provide products and/or services (International Energy Agency (EIA), 2016a).
Energy Price (EP)	The amount of money or consideration-in-kind for which an energy is bought, sold, or offered for sale. There is an inverse relation between non-renewable energy cost and attraction of renewable energy investments (M. Zhang, Zhou, & Zhou, 2014).
Energy Supply (ES)	Energy made available for future disposition. Supply can be considered and measured from the point of view of the energy provider or the receiver (International Energy Agency (EIA), 2016a).
Availability of Alternative Renewable Energies (AARE)	Energy resources that are naturally replenishing but flow-limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time. Renewable energy resources include biomass, hydro, geothermal, solar, wind, ocean thermal, wave action, and tidal action. The availability of renewable energy sources shall be governed by the physical capabilities of these sources and by limitations imposed by local or global regulatory agencies.
New Solar Energy Generation Capacity (NSEC)	The amount of energy that is generated with the process of producing energy by transforming solar energy; also, the amount of energy produced, expressed in kilowatt-hours for electric (International Energy Agency (EIA), 2016a).
Cost of Solar Energy (CSE)	The total cost of producing and/or transmitting solar energy above some previously determined base cost. The cost of solar energy has a declining trend rapidly in the last decades, but its cost is still higher than the cost of conventional energy technologies (Adaramola, 2014).
Solar Energy Incentives (SEI)	The programs that offers monetary or non-monetary awards to encourage producers to buy energy-efficient equipment and to participate in programs designed to reduce energy usage. Examples of incentives are zero or low-interest loans, rebates, and direct installation of low cost measures. Renewable energy development policies which are consist of law, supportive policies (tax relief, subsidized loans, feed-in tariff) and development plans complement each other and support the generation of new renewable energy (M. Zhang et al., 2014).
Technical Applicability of Solar Technology (TAST)	The feasibility of the solar technologies that are usable in the given geological and operational conditions for production, processing, and sales of the solar energy (Bogetoft & Olesen, 2007).
Regulations (RG)	The governmental function of controlling or directing energy entities through the process of rulemaking and adjudication. In some conditions, laws and regulations could constrain or release the deployment of solar energy (Adaramola, 2014).
Global Treaties (GT) – Kyoto Protocol	A written statement signed by two or more parties that specifies the terms for controlling energy. The Kyoto Protocol sets binding greenhouse gas emissions targets for countries that sign and ratify the agreement. The gases covered under the Protocol include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons (HFCs), per fluorocarbons (PFCs) and sulfur hexafluoride. The clean development mechanism (CDM) of the Kyoto Protocol has a very small role in solar energy generation among the renewable energy technologies because of its weak cost competitiveness (Adaramola, 2014).

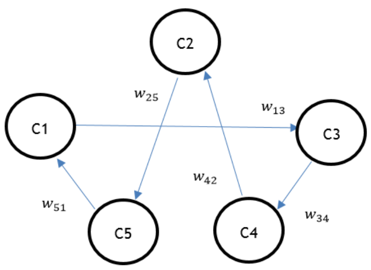
In this study, we define the factors (Table 3.1) that affect and are affected by "New Solar Energy Generation Capacity" that are based on their advantages and disadvantages against alternative renewable energies and fossil based energy sources. This study aims to verify the basic factors and ascertain their effects on the solar energy sources that they reflect the main tendencies of the investors.

3.3 Fuzzy Cognitive Maps

Axelrod (Axelrod, 1976) introduced the Cognitive Map (CM) as a directed graph that is presented to visually model causal relationships (direct or indirect – hidden relationships) among concepts. Causal relationships are defined with binary numeric (crisp) values in CM that can be defined as Crisp Cognitive Maps (CCMs). An extension of the CMs with representing the causal relationships by linguistic values instead of the binary values were introduced as Fuzzy Cognitive Maps (FCMs) by Kosko (Kosko, 1986). FCMs are used as a tool in describing the degree of the relationship between concepts in linguistic terms (fuzzy numbers).

FCMs have been applied in many different scientific fields such as strategic planning (Diffenbach, 1982), environmental management (Özesmi & Özesmi, 2004), and decision making (W.-R. Zhang, Chen, & Bezdek, 1989). FCMs represent knowledge in a symbolic form for the modelling complex and dynamic systems. FCMs consist of concepts (nodes) and connections (arcs/ edges) that represent the strengths of the interactions among concepts and show the dynamism of the system. Causal relationships among the concepts are modelled in directed graph with feedback and weighted in the interval [-1, 1] as positive, negative or neutral (Kosko, 1986) by fuzzy numbers. Signed weighted edges connect the concept and represent the causal relationship among the concepts.

Nodes and weighted edges in graphic display are assigned the concepts (C_i) and relationships among concepts (w_{ij}) respectively. Initially experts' suggested weights of all the interconnections among the concepts in FCMs are shown in the weight matrix (W). There is no self-loops (no concept connects itself) in FCMs, so the diagonal of the matrix is defined as zero ($w_{ii} = 0$). A simple FCMs is drawn with five concepts (C_1, C_2, C_3, C_4, C_5) and five directed weighted edges and its weighted matrix is shown in Figure 3.1.



$$W = \begin{bmatrix} 0 & 0 & w_{13} & 0 & 0 \\ 0 & 0 & 0 & 0 & w_{25} \\ 0 & 0 & 0 & w_{34} & 0 \\ 0 & w_{42} & 0 & 0 & 0 \\ w_{51} & 0 & 0 & 0 & 0 \end{bmatrix}$$

Figure 3.1 : A simple FCMs and its weight matrix.

Concepts, cause-effect connections among them and initial state of system are determined by expert(s). Initial state values of the concepts and edges can be obtained from the knowledge and experiments of the expert(s), simulation results or recorded data. Concepts are also described with their activation level in the related time as A_i^t that is defined in the interval [0, 1] as a degree of presence of a given concept in the system. The initial state vector A^0 can be defined as binary or rational values such as respectively: $A^0 = [0\ 1\ 0\ 0\ 1\ 0\ 0\ 1\ 0\ 0\ ]$, $A^0 = [0.42, 0.16, 0.34, 0.66, 0.35, 0.41]$.

The expert can define the causal relationships between concepts in FCMs with linguistic statements that allow to experts to express their knowledge naturally and easily. The experts' linguistic expressions used in to evaluate the causality among factors include the sign and size of the influence such as positive high, negative medium, and positive very high that can be described within triangular membership functions of the fuzzy sets (Figure 3.2). Linguistic variables are transformed (defuzzified) in the [-1, 1] interval as a crisp value by different defuzzification methods such as Weighted Average Method, Center of Gravity. Crisp values transformed from linguistic evaluations are defined as a weight matrix of the concepts in FCM and used to calculate the new state of the system. In this study, negative/ positive very very low, very low, low, medium, high, very high, and very very high linguistic terms are used as a linguistic variable in order to define the causal relationships around the "installing solar energy" and applied to triangular fuzzy membership function in order to transform them into crisp values.

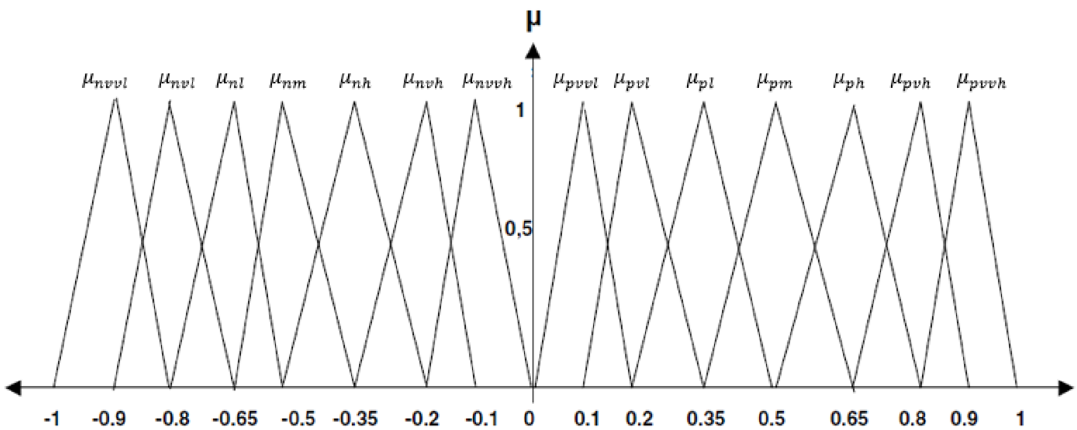


Figure 3.2 : Triangular membership functions of the linguistic variables (Xirogiannis, Glykas, & Staikouras, 2010).

Feedback mechanism in FCMs that represents the butterfly effect among concepts provides a dynamic system. Operations in FCMs start with defining the initial value (current state) of each concept based on the experts' evaluations, and then concepts (factors or nodes) interact with each other until an equilibrium point (Kosko, 1997). The activation levels of all concepts of the FCMs in time t is showed in an initial state vector as $A^t = [A_1^t, A_2^t, \dots, A_n^t]$. The new values of concepts at the new time step is calculated as;

$$A_i^{t+1} = f\left(\sum_{j=1}^{n} A_j^t \, w_{ij} + A_i^t \right) \tag{3.1}$$

In the equation, the previous state value (A_i^t) of concept C_i and the total causal effects of other concepts on the concept C_i (weighted activation sum of C_i) are summed and used in the $f(.)$ transformation (threshold) function. The thresholds function is used to transform the weighted activation sum $\left(\sum_{j=1}^{n} A_j^{t-1} w_{ji} + A_i^{t-1}\right)$ to the interval $[0, 1]$ or $[-1, 1]$ and determines the activation level of each concept. The most commonly used threshold functions which sigmoid and hyperbolic tangent functions are continuous transformation functions are shown below (Haykin, 1994; Tsadiras, 2008):

1. Bivalent (step) function: This function transforms the activation level of each concept to 1 (activated) or 0 (inactivated) and obtained a binary FCMs.

$$f(x) = \begin{cases} 0, & x \leq 0 \\ 1, & x \geq 0 \end{cases} \tag{3.2}$$

2. Trivalent function: This function defines the activation levels in three part as -1, 0, and 1 and these values refer the decreasing, remain stable and increasing of the concept respectively.

$$f(x) = \begin{cases} -1, x \leq -0.5 \\ 0, -0.5 < 0 < 0.5 \\ 1, x \geq 0.5 \end{cases} \tag{3.3}$$

3. Sigmoid function: This function is commonly used function in the FCM that transforms the sum of the weights in the interval $[0, 1]$. Logistic function is the special case of the sigmoid function that δ parameter in sigmoid function is accepted as 1.

$$f(x) = \frac{1}{1+e^{-\delta x}} \tag{3.4}$$

Logistic function: $f(x) = \frac{1}{1+e^{-x}}$ (3.5)

4. Hyperbolic Tangent function: This function transforms the sum of the weights in the interval $[-1, 1]$ whose initial state vector can include the negative state.

$$f(x) = tanh(\delta x) = \frac{e^{\delta x} - e^{-\delta x}}{e^{\delta x} + e^{-\delta x}} \quad (3.6)$$

where x is the activation level of concept at related time. Parameter δ is the positive real number that is used to determine the shape of the function curve. Delta value (δ) is the problem-specific parameter and might be defined by researcher. When delta value takes large values as $\delta \geq 10$, the sigmoid function closes to the discrete function and activation levels are defined in the interval (0, 1). If delta value is defines with smaller values such as $\delta \leq 1$, the sigmoid function resembles to a linear function. If scholar wants to define a good degree of fuzzification in the interval $[0, 1]$, delta value should be defined closer to 5 (Bueno & Salmeron, 2009).

Activation level that is the value assigned to each concept is updated until convergence at a steady state. The concepts whose edge values are different from zero have an effect on the updating process of the activation level from A^t to A^{t+1}. In order to stop the iteration (updating), a limit value can be defined as $A^{t+1} - A^t \leq e$ that can be change according to study type and generally it is accepted as 0.001. Fixed-point equilibrium, limit cycle and chaotic behavior are another states that terminate the iterations (Dickerson & Kosko, 1994; Kosko, 1997; Tsadiras & Margaritis, 1997).

Causal and interactive relationships among concepts within different aspects define the dynamic fuzzy system. Relationships represent the experts' knowledge and experience with linguistic or numerical values. FCMs are realistic and simple tool in the analyzing and decision making of the uncertain real world problems such as social, managerial, biological, economical, and energy problems.

3.4 Application

In this study, we defined the nine different factors around the "New Solar Energy Generation Capacity" and their causal relationships in the systems are graphically represented with FCMs that also analyzed the strengths of factors. The weight of the relationships are linguistically described by experts and defined as weight matrix.

The basic factor of the system is the New Solar Energy Generation Capacity (NSEC) and the other factors can be named as affecting factors that have effects on basic factor.

The weights between the factors are defined according to importance level of relationships by experts who work academically in the field of renewable and solar energy.

Table 3.2 : Linguistic terms of the causal relationships among the concepts.

	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
Energy Demand (ED)		VH			H					
Energy Price (EP)	NM		VH		VVH					
Energy Supply (ES)		NVH					NM			
Availability of Alternative Renewable Energies (AARE)			H							
New Solar Energy Generation Capacity (NSEC)			H							
Cost of Solar Energy (CSE)					NVVH					
Solar Energy Incentives (SEI)				M		NVH				
Technical Applicability of Solar Technology (TAST)					M	NVH				
Regulations (RG)							VVH			
Global Treaties (GT)									M	

The effect of a specific factor on the other factors was determined by using linguistic terms, very low, low, medium low, medium, medium high, high, and very high in the interval [-1,1] as "negative" or "positive" (Figure 3.2). Dotted lines in the constructed FCM represent a negative causality, where the solid lines represent a positive causality among the relevant factors. For example, relationship degree between "Energy Price" and "New Solar Energy Generation Capacity" was linguistically defined as "Positive Very Very High" by experts' consensus. Table 3.2 represents the relationship degrees (i.e., the relationship matrix) among the factors affecting Installing Solar Energy. Then, these linguistic terms were transformed into numerical values by using the fuzzy membership functions given in the Center of Gravity (also called Center of Area) defuzzification method (Figure 3.3) by using Equation 3.1 that the weights of the relationships (Table 3.3) are obtained in the [-1,1] crisp interval (Lee, 1990; Sugeno, 1985).

$$\boldsymbol{z}^* = \frac{\int \boldsymbol{u}_{\underline{c}}(\boldsymbol{z})\cdot \boldsymbol{z}\, \boldsymbol{dz}}{\int \boldsymbol{u}_{\underline{c}}(\boldsymbol{z})\boldsymbol{dz}} \tag{3.7}$$

where $\int$ denotes an algebraic integration.

Figure 3.3 : Centroid defuzzification method.

There are 31 connections in FCM based on the installing solar energy that consists of 10 different factors whose two are transmitters and eight are ordinary factors. Direction degrees of the causal relationships among factors can be expressed as in-degree that directs into a node and out-degree that directs out from a node.

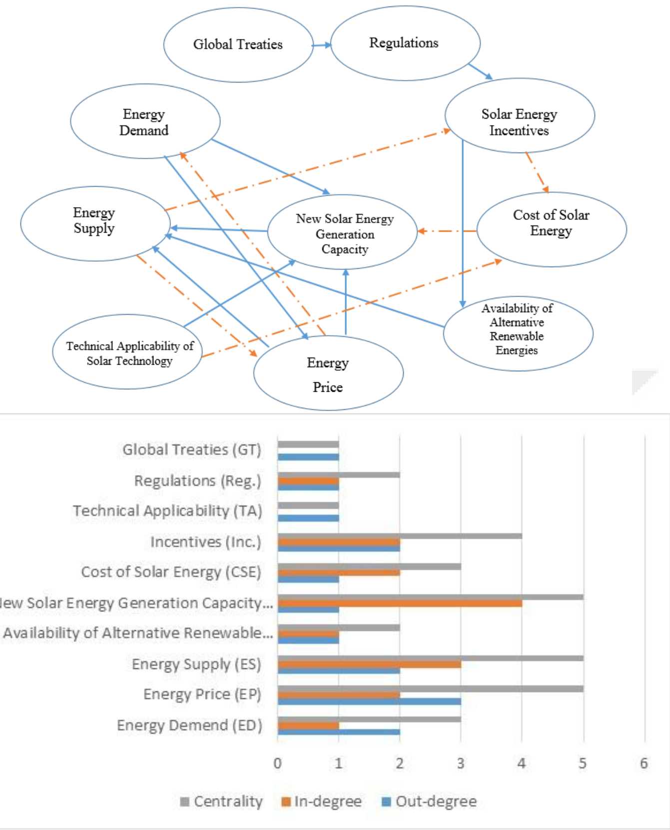


Figure 3.4 : Fuzzy cognitive map of Solar Energy Usage (Graphical representation of the relational fuzzy cognitive map) and In-degree, out-degree, and centrality values of factors.

The other concept is centrality value that is measured with summation of the in- and out- degree of a node and reflects the importance of factors on the map (Figure 3.4). Figure 3.4 shows that Energy Price, Energy Supply, and New Solar Energy Generation Capacity are a central factor of the map with five total degrees and it is followed by Incentives with four degree values. Also New Solar Energy Generation Capacity is an receiver factor and Global Treaties are transmitter factors of the FCM.

In this study, FCM model was simulated under different scenarios with initial state of the system in order to evaluate the effects of the possible changes of the factors in the system. Scenarios were design based on the existence or lack of the specific factors in the system in the initial state vector; and behavior of the system was observed in the last state after the consecutive iterations. In this way, factors at each new states can be represented graphically and the active, inactive, influential and ineffective factors can be determined by observing the last state vector in the system. And then changes are observed whether the system converged towards a steady state and made a decision about factors in FCM.

Table 3.3 : Weight matrix of the linguistic relationships among concepts after using CoG defuzzification method.

	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
ED		VH			H					
EP	NM		VH		VVH					
ES		NVH					NM			
AARE			H							
NSEC			H							
CSE					NVVH					
SEI				M		NVH				
TAST					M	NVH				
RG							VVH			
GT									M	

	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
ED		0.738			0.650					
EP	-0.500		0.650		0.900					
ES		-0.738					-0.500			
AARE			0.650							
NSEC			0.650							
CSE					-0.900					
SEI				0.500		-0.738				
TAST					0.500	-0.738				
RG							0.900			
GT									0.500	

First of all, initial state vector, A^0, was represented and then multiplied by the weight matrix that was defined by experts' common views about the relationships among factors ($A_i^{t+1} = f\left(\sum_{j=1}^{n} A_j^t\, w_{ij} + A_i^t\right) A_i^{t+1} = f\left(\sum_{j=1}^{n} A_j^t\, w_{ij} + A_i^t\right)$

). In the following iterations, calculated state vector was added to the multiplied values and the hyperbolic tangent function with λ=0.50 were used to recalculate an outcome new state vector at the each iterations. A Lambda value reflects the shape of the changes of the new state values in the hyperbolic tangent functions, therefore lambda (λ) was selected as 0.50 in order to see clearly the changes at the each iteration. The iterations were terminated when the difference between the two calculated new state vectors was smaller than or equal to 0.0001 (i.e., $A^{t+1} - A^t \leq 0.0001$). The last state vector also called as the final states or steady state vector of the factors (A^l).

Scenarios based on the initial state were designed as the existence or lack of one or more specific factors in the system that include the worst, best and random cases whose notations are shown as “1”, “0” or “-1”; for example if there is any incentive provided by governments and energy prices are decreasing, initial state vector will be defined as $A^0 = [0 - 1\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ ]$ that “0” values represents the inactive factors. After that FCM is operated and new states of the concepts are observed at each iteration and reached at the last state in time. In the new solar energy generation capacity model that reflects the real life conditions can be expected to converge at the steady states that represents the long term predictions of the concepts in the system.

Case 1. Existence of only one factor

In this case, one specific factor that is thought as a key concept of the solar energy generation model was accepted to exist in the system and other factors were accepted as lack.

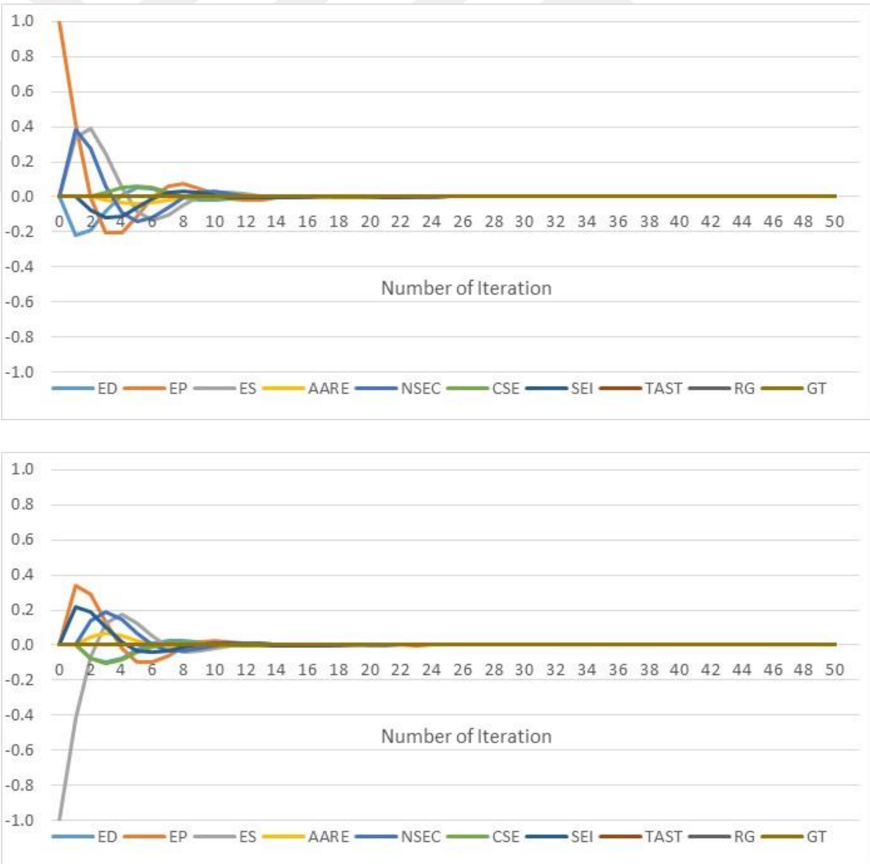


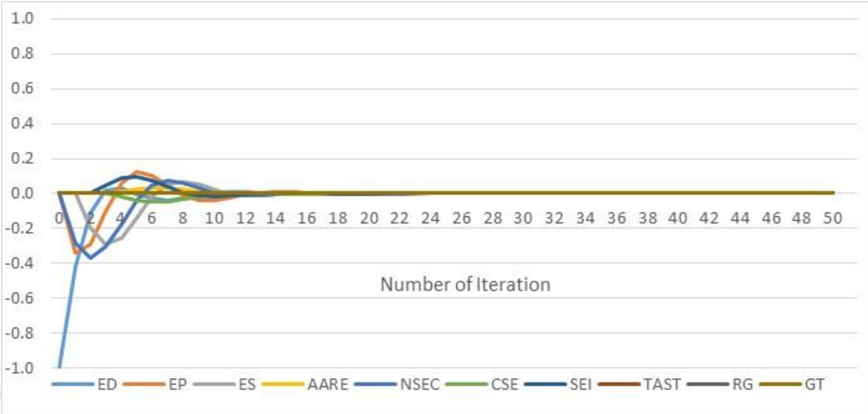
Figure 3.5 : Sample result of the FCM simulation process for increase of the energy price and decrease of the energy supply.

So, based on these assumptions, “energy price”, “energy supply”,”energy demand”, “global treaties” such as Kyoto Treaty, and “technical applicability of solar technology" are accepted as the trigger factors and the influences of their individual existence was observed in the system. For example, the "energy price" was accepted to increase in the model that is defined as "1" and other factors were accepted as ineffective that was defined as "0" in the initial state like $A^0 = [0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$. Also the worst scenarios can be defined based on the existence of the individual factor in the system such as decreasing of the energy supplies that was showed as "-1" in the initial state like $A^0 = [0\ 0 - 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$ (Figure 3.5).

In this case, four different scenarios were designed and observed the behaviors of the concepts at each iteration and the convergence states were evaluated according to initial state of the system.

i. **Scenario 1. 1:** In this worst scenario, it is accepted that energy demand was decreasing that can be based on the change of the nations' or households' energy using habits by governmental regulations, energy price, environmental laws, environmental sensitivity and many other different and latent effects. Initial state is defined as $A^0 = [-1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$ and reached the following results (Figure 3.6):
   - **a.** The first reaction of the system was decreasing the energy price that also affected the decrease of the new solar energy generations and energy supply.
   - **b.** After the first reaction, energy demand was started to increase by decreasing of the energy price, but energy supply did not react suddenly and availability of alternative renewable energies and solar energy incentives were started to increase that it caused to decrease the cost of solar energy. In this period new solar energy generation capacity was continued to decrease that can be based on the reaction time, bureaucratic procedures or distrust to the sector.
   - **c.** While solar energy incentives were increasing and cost of solar energy was decreasing, new solar energy generation capacity started to increase at the following iterations (i.e. time periods). At the same period, availability of alternative renewable energies, energy supply and energy demand increased while energy price was decreasing. When energy price was decreasing, market directed to the balancing strategies that include the decrease of the solar energy incentives that caused to

increase of the cost of solar energy and decrease the new solar energy generation capacity, and also the decrease of the availability of alternative renewable energy caused to decrease of the energy supply and increase energy price that decreased the energy demand.



Iterations	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
0	-1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
1	-0.421899	-0.338591	0.000000	0.000000	-0.284434	0.000000	0.000000	0.000000	0.000000	0.000000
2	-0.113185	-0.292305	-0.199825	0.000000	-0.370092	0.000000	0.000000	0.000000	0.000000	0.000000
3	0.014835	-0.100655	-0.292420	0.000000	-0.307726	0.000000	0.044930	0.000000	0.000000	0.000000
4	0.029314	0.062930	-0.251562	0.010109	-0.173141	-0.015837	0.085802	0.000000	0.000000	0.000000
5	-0.000968	0.126644	-0.137824	0.023850	-0.037421	-0.037354	0.094926	0.000000	0.000000	0.000000
6	-0.028922	0.104845	-0.021345	0.032080	0.049257	-0.050228	0.073594	0.000000	0.000000	0.000000
7	-0.036589	0.044480	0.051099	0.030985	0.076362	-0.048506	0.037902	0.000000	0.000000	0.000000
8	-0.026467	-0.010893	0.069958	0.022467	0.061243	-0.035174	0.005559	0.000000	0.000000	0.000000
9	-0.009459	-0.038872	0.052079	0.011360	0.029643	-0.017786	-0.013238	0.000000	0.000000	0.000000
10	0.004490	-0.039165	0.021723	0.002134	0.002033	-0.003337	-0.017673	0.000000	0.000000	0.000000
11	0.010832	-0.023694	-0.002811	-0.003016	-0.012282	0.004728	-0.012840	0.000000	0.000000	0.000000
12	0.010205	-0.005853	-0.014091	-0.004246	-0.013869	0.006654	-0.005145	0.000000	0.000000	0.000000
13	0.005909	0.005931	-0.013702	-0.003069	-0.008321	0.004808	0.000855	0.000000	0.000000	0.000000
14	0.001325	0.009581	-0.007407	-0.001188	-0.001561	0.001862	0.003468	0.000000	0.000000	0.000000
15	-0.001560	0.007389	-0.000760	0.000245	0.002811	-0.000384	0.003227	0.000000	0.000000	0.000000

Figure 3.6 : The result of the FCM simulation process for the scenario 1.1 and a sample part of the iterations**.**

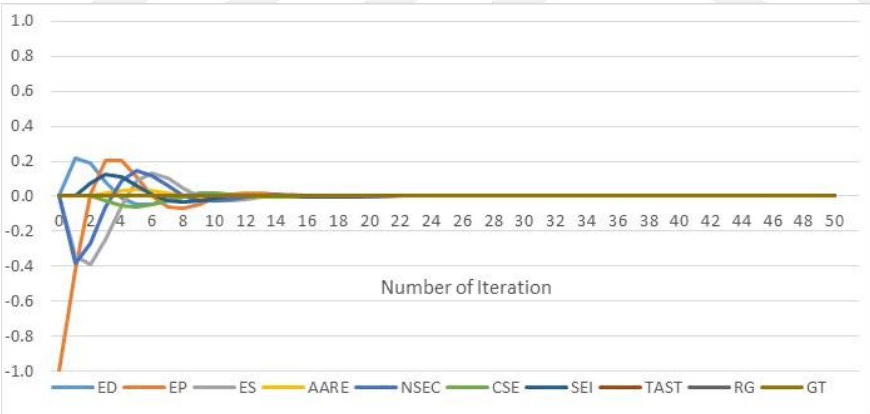
d. System repeated the similar balancing policies in the short time periods and converged the steady state that all factors reached an equilibrium point “0”. It means that energy demand will be reached an equilibrium for supplying energy in the long term and governments will not change their politics about solar energy incentives that do not depend any global treaties, regulations and technical applicability of solar technology.

e. Technical applicability of solar technology, regulations, and global treaties did not reflect any changes that they stay ineffective during each iteration because of technical applicability of solar technology and global treaties are transmitter factors and the regulations are only affected by global treaties that stay on hold in the system.

ii. **Scenario 1. 2:** Another worst scenario is that energy price was decreasing that can be based on the increasing energy supply, decreasing energy demand, falling cost of the energy technologies and energy sources and also many other different and latent effects. Initial state of this scenario was defined as $A^0 = [0 -1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$ and reached the following results (Figure 3.7):

a. Firstly, decrease of the energy price affected the energy supply and new solar energy generation capacity as negatively and energy demand as positively. The other factors stayed as a neutral that protect their stable state. Similar to the previous case, technical applicability of solar technology, regulations, and global treaties did not reflect any changes that they stay ineffective during each iteration until reaching the convergence.

b. Increasing energy demands and decreasing energy supply activated the increase of the energy prices that positively triggered the availability of alternative renewable energies and the solar energy incentives that caused to decrease the cost of solar energy, but new solar energy generation capacity did not give a reaction at the beginning.



Iterations	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
0	0.000000	-1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
1	0.221278	-0.421899	-0.338591	0.000000	-0.384219	0.000000	0.000000	0.000000	0.000000	0.000000
2	0.192086	0.007499	-0.391414	0.000000	-0.272020	0.000000	0.076036	0.000000	0.000000	0.000000
3	0.084549	0.206065	-0.247792	0.017106	-0.063102	-0.026796	0.121679	0.000000	0.000000	0.000000
4	-0.008317	0.206851	-0.052274	0.035061	0.090396	-0.054895	0.110061	0.000000	0.000000	0.000000
5	-0.050242	0.108153	0.085876	0.040519	0.143260	-0.063414	0.061212	0.000000	0.000000	0.000000
6	-0.046909	0.000687	0.129787	0.031995	0.118694	-0.050072	0.008223	0.000000	0.000000	0.000000
7	-0.021260	-0.061897	0.102363	0.016247	0.060176	-0.025426	-0.025496	0.000000	0.000000	0.000000
8	0.004360	-0.071310	0.046565	0.001574	0.006090	-0.002454	-0.034491	0.000000	0.000000	0.000000
9	0.018005	-0.046932	-0.001941	-0.007052	-0.023867	0.011053	-0.025992	0.000000	0.000000	0.000000
10	0.018660	-0.014088	-0.026454	-0.009021	-0.028950	0.014135	-0.011259	0.000000	0.000000	0.000000
11	0.011566	0.009563	-0.027970	-0.006593	-0.018998	0.010329	0.000886	0.000000	0.000000	0.000000
12	0.003053	0.018238	-0.016699	-0.002768	-0.005476	0.004336	0.006692	0.000000	0.000000	0.000000
13	-0.002730	0.015168	-0.003497	0.000260	0.004059	-0.000408	0.006768	0.000000	0.000000	0.000000
14	-0.004641	0.007096	0.005036	0.001640	0.007336	-0.002569	0.003833	0.000000	0.000000	0.000000
15	-0.003685	-0.000218	0.007393	0.001600	0.005858	-0.002507	0.000591	0.000000	0.000000	0.000000

Figure 3.7 : The result of the FCM simulation process for the scenario 1.2 and a sample part of the iterations.

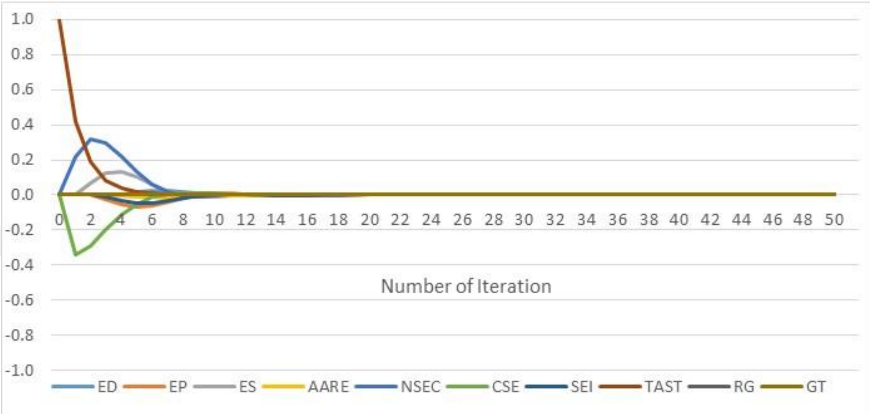
c. At the following iterations, availability of alternative energies decreased and increasing solar energy incentives caused to decrease the cost of solar energy and increase the new solar energy generation capacity. Increasing new energy generation capacities also increased the energy supply, but these increases did not directly affect the energy price that continued to increase while the energy demand was decreasing at the same period.

d. System exhibited the balancing movements with floating steps based on the small changes. This balancing movements covered all concepts except technical applicability of solar technology, regulations and global treaties. At the steady state, the system converged to equilibrium zero point after the 50 iterations that it reflects no change in the concepts. If any policies that are related the regulations, technical applicability of solar technology, and global treaties are not developed by governments in the system, there will not be any change in the solar energy incentive, cost of solar energy and new solar energy generation capacity.

iii. **Scenario 1. 3:** This scenario that is positive and looks at the bright side of the system was accepted the existence of the technical applicability of the solar technology in the systems. Technical applicability of solar technology reflects the locational state of the solar energy generation and changes from country to country. It is a transmitter concept that is not affected by another concept in the model. Its existence in the system was defined in the initial state as $A^0 = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0]$ and reached the following results (Figure 3.8):

a. Existence of the technical applicability of the solar technology influenced the cost of the solar energy negatively and new solar energy generation capacity positively at the beginning of the iterations. At the same time, the technical applicability of the solar technology started to continuous decrease until to reach the zero point at the steady state. Its basic reasons can be the decreasing available lands for new solar energy generation and the increasing cost of the land usage. In spite of the "zero" technical applicability of solar technology, seeing small increase in the new solar energy generation capacity indicates its relationship with the cost of the land usage.

b. At the beginning of the iterations; solar energy incentive, availability of alternative renewable energy, energy supply, energy price and energy demand did not give any reaction immediately because of the indirect effects of the decreasing cost of the solar energy and increasing generation of the new solar energy whose influences took the time in the system. Regulations and global treaties stayed stable during the 50 iteration because of their transmitter properties.



Iterations	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
0	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000	0.000000	0.000000
1	0.000000	0.000000	0.000000	0.000000	0.221278	-0.338591	0.000000	0.421899	0.000000	0.000000
2	0.000000	0.000000	0.064634	0.000000	0.319986	-0.292305	0.000000	0.187606	0.000000	0.000000
3	0.000000	-0.022779	0.122069	0.000000	0.295506	-0.195134	-0.014542	0.084223	0.000000	0.000000
4	0.005125	-0.053230	0.132552	-0.003272	0.218168	-0.111902	-0.033996	0.037882	0.000000	0.000000
5	0.014282	-0.068763	0.103372	-0.009121	0.131200	-0.051680	-0.045092	0.017045	0.000000	0.000000
6	0.021895	-0.062267	0.057921	-0.014249	0.060062	-0.013369	-0.043522	0.007670	0.000000	0.000000
7	0.023858	-0.040697	0.017514	-0.016203	0.015353	0.006622	-0.032606	0.003452	0.000000	0.000000
8	0.019890	-0.016076	-0.006713	-0.014627	-0.004500	0.013256	-0.018611	0.001553	0.000000	0.000000
9	0.012567	0.002144	-0.014281	-0.010769	-0.007737	0.011978	-0.006864	0.000699	0.000000	0.000000
10	0.005173	0.010428	-0.011083	-0.006391	-0.003631	0.007563	0.000124	0.000315	0.000000	0.000000
11	-0.000019	0.010423	-0.004243	-0.002848	0.001110	0.003249	0.002550	0.000142	0.000000	0.000000
12	-0.002353	0.006179	0.001256	-0.000708	0.003431	0.000513	0.002102	0.000064	0.000000	0.000000
13	-0.002449	0.001508	0.003540	0.000154	0.003165	-0.000532	0.000663	0.000029	0.000000	0.000000
14	-0.001442	-0.001433	0.003096	0.000219	0.001541	-0.000483	-0.000498	0.000013	0.000000	0.000000
15	-0.000326	-0.002244	0.001403	-0.000014	-0.000110	-0.000047	-0.000921	0.000006	0.000000	0.000000

Figure 3.8 : The result of the FCM simulation process for the scenario 1.3 and a sample part of the iterations.

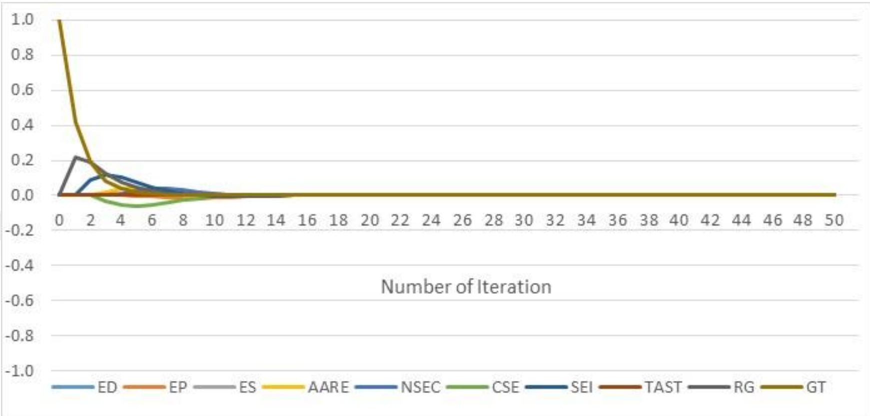
a. At the following iterations, solar energy incentives decreased but cost of solar energy decreased and new solar energy capacity increased through the support of the technical applicability on the solar energy. By using these advantages, solar energy substituted the alternative renewable energies and increased the energy supply, decreased energy price and increased the energy demand at the same period. Decreasing influence of the technical applicability of solar technology triggered the incentives on the solar energy that continued the similar effects on the system. When incentives were withdrawn and technical applicability continued to decrease, cost of solar energy started to increase and new solar energy generation capacities started to decrease whose place at the energy supply was partially filled by alternative renewable energies. But main balance between the energy supply and energy demand were provided by energy price whose increase decreased the energy demand in the model.

b. At the last period, all concepts converged to the zero value that reflects the stability of the system. There will not be any change (increase or decrease) in the states of the concepts. For example, governments will not provide any regulations, incentives; while the cost of the solar energy and energy price are not changing, it is accepted that energy demand and energy supply will not change any time; while energy demand and energy supply are not changing, there will not be any requirements in order to generate the new solar energy and alternative renewable energies.

iv. **Scenario 1. 4:** The other positive scenario is the existence of the global treaties in the solar energy generation model. Global treaties that include the binding rules accepted by all countries around the world have an important influence on the governments about their energy generation politics that are shown with regulations and legislations. For example, Kyoto protocol that is an international treaty and struggles with global warming by reducing greenhouse effects forces the governments to direct the renewable energies in order to decrease the global greenhouse gas emissions. If there is any global treaties related to energy generation, its existence in the system is defined in the initial state as $A^0 = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1]$ and we reached the following results (Figure 3.9):

a. The effects of the global treaties on the other concepts were not observed in the short period such that technical applicability of solar technology that is transmitter concept stayed stable as zero. The first reaction was observed positively on the regulation that was designed by governments according the binding targets. The last reaction of the global treaties was observed on the energy demand because of the shortest path length (6) between these two concepts.

b. Global treaties that forces the governments to direct the renewable energy increased the regulations about solar energy and solar energy incentives that they decreased the cost of solar energy and increased the new solar energy generation capacity and availability of alternative renewable energies. At this initial period, while the effect of the global treaties was decreasing, any changes were not observed in the energy supply, energy demand and energy price.



Iterations	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
0	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
1	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.221278	0.421899
2	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.089379	0.000000	0.192086	0.187606
3	0.000000	0.000000	0.000000	0.020107	0.000000	-0.031496	0.117471	0.000000	0.127945	0.084223
4	0.000000	0.000000	0.005881	0.035464	0.012755	-0.055524	0.104299	0.000000	0.076376	0.037882
5	0.000000	-0.002073	0.016749	0.039406	0.028220	-0.061673	0.076394	0.000000	0.042867	0.017045
6	0.000466	-0.006837	0.026580	0.034907	0.036820	-0.054627	0.047933	0.000000	0.023121	0.007670
7	0.001748	-0.012281	0.030522	0.026487	0.036045	-0.041455	0.024948	0.000000	0.012130	0.003452
8	0.003550	-0.015668	0.027689	0.017531	0.028539	-0.027442	0.009271	0.000000	0.006235	0.001553
9	0.005123	-0.015558	0.020410	0.009975	0.018647	-0.015616	0.000467	0.000000	0.003155	0.000699
10	0.005806	-0.012389	0.012071	0.004594	0.009913	-0.007192	-0.003104	0.000000	0.001577	0.000315
11	0.005400	-0.007784	0.005308	0.001369	0.004054	-0.002142	-0.003474	0.000000	0.000780	0.000142
12	0.004181	-0.003470	0.001231	-0.000166	0.001119	0.000261	-0.002442	0.000000	0.000383	0.000064
13	0.002662	-0.000522	-0.000391	-0.000624	0.000216	0.000978	-0.001221	0.000000	0.000187	0.000029
14	0.001315	0.000841	-0.000479	-0.000555	0.000268	0.000870	-0.000386	0.000000	0.000090	0.000013
15	0.000403	0.001011	-0.000003	-0.000337	0.000494	0.000528	-0.000029	0.000000	0.000044	0.000006

Figure 3.9 : The result of the FCM simulation process for the scenario 1.2 and a sample part of the iterations.

c. At the balancing period, when the influences of the global treaties and regulations decreased that they caused to decrease the solar energy incentives and increase cost of solar energy, new solar energy generation capacity continued to increase with low rates and availability of alternative solar energies decreased low rates. Energy generation with solar and alternative renewable energies increased the energy supply that caused to decrease the energy price and increase energy demand.

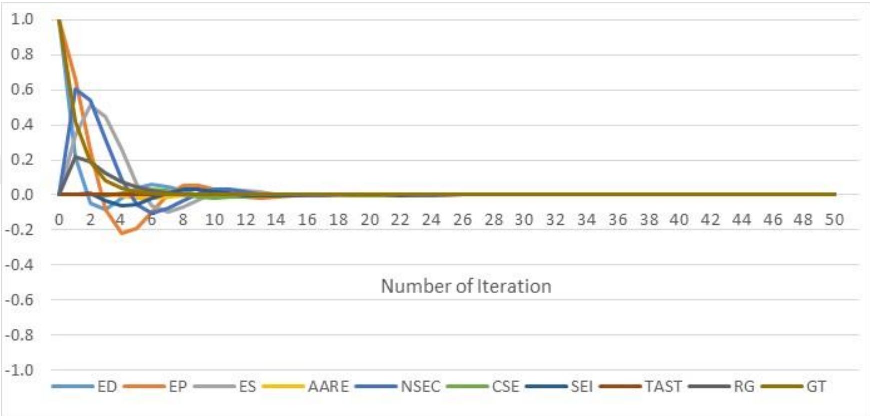
d. The long term period showed that all concepts converged to the zero values at the steady state that means system reached to the balance and there will not be any change in the system. Disappear of the global treaties reflects that all binding target in the treaties that were executed through the regulations or legislations were carried out by governments. It is clear that treaties and regulations have an important influence on the renewable energy generations through incentives and cost.

Case 2. Combination of the concepts

In this case, some specific factors whose combinations were accepted as an important contribution to the new solar energy generation capacity were defined as positive and negative that represent the increase and decrease of the concepts in the system respectively. Concepts in the combinations were selected according to the real life problems that were defined by experts' knowledge and experiences. Scenarios that were described according to frequently encountered problems in the real life included the inverse combinations like the increase and decrease of the concepts at the same time. The number of concepts in each combination were not limited and the three most important ones among combinations that were defined in each scenario by experts were specially selected in order to evaluate the new solar energy generation capacity in long term. In this context, the behaviors of the concepts in three different scenarios were iterated 50 times and their steady state values were evaluated according to their initial state values.

i. **Scenario 2. 1:** Despite the scenario is seen as a positive, it includes the worst and best state in same time. It is accepted that while energy demand and energy price were increasing, global treaties such as Kyoto Protocol, Vienna Convention for the Protection of the Ozone Layer, and U.S.-Canada Air Quality Agreement were increased all around the world at the same time. This scenario includes the encounter between global environmental sensitivity and energy tendency and its initial state is defined as $A^0 = [1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1]$ and reached the following results (Figure 3.10):

a. The model tended to decrease the impact of the existence concepts in the system. The highest reduction occurred in energy demand (78%) and lowest reduction was observed in energy price (34%) such that reduction of the global treaties (58%) stayed in the medium levels. Availability of alternative renewable energies, solar energy incentives, technical applicability of solar energy and cost of solar energy did not give any reaction, while regulations, new solar energy generation capacity and energy supply increased in the first iteration. New solar energy generation capacity was the highest increasing concept that is highly affected by regulations and affected the energy supply by generated solar energy.



Iterations	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
0	1.000000	1.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	1.000000
1	0.221278	0.665432	0.338591	0.000000	0.602779	0.000000	0.000000	0.000000	0.221278	0.421899
2	-0.050105	0.252510	0.510380	0.000000	0.540933	0.000000	0.013434	0.000000	0.192086	0.187606
3	-0.079196	-0.083745	0.443761	0.003023	0.319447	-0.004735	-0.030985	0.000000	0.127945	0.084223
4	-0.016794	-0.218449	0.258495	-0.005611	0.088356	0.008791	-0.061893	0.000000	0.076376	0.037882
5	0.041570	-0.192894	0.063437	-0.016449	-0.057122	0.025767	-0.055025	0.000000	0.042867	0.017045
6	0.062028	-0.094230	-0.060893	-0.019780	-0.101750	0.030982	-0.021670	0.000000	0.023121	0.007670
7	0.049075	0.000926	-0.095870	-0.013776	-0.078195	0.021577	0.013313	0.000000	0.012130	0.003452
8	0.021872	0.051464	-0.069604	-0.003204	-0.029189	0.005017	0.032463	0.000000	0.006235	0.001553
9	-0.001737	0.055348	-0.022652	0.005862	0.012073	-0.009185	0.032782	0.000000	0.003155	0.000699
10	-0.013234	0.032268	0.014562	0.010014	0.031051	-0.015688	0.021123	0.000000	0.001577	0.000315
11	-0.013215	0.004722	0.029930	0.009259	0.029515	-0.014505	0.006868	0.000000	0.000780	0.000142
12	-0.007009	-0.013083	0.026468	0.005712	0.017202	-0.008948	-0.003328	0.000000	0.000383	0.000064
13	-0.000210	-0.017686	0.014000	0.001822	0.004016	-0.002853	-0.007297	0.000000	0.000187	0.000029
14	0.003885	-0.012967	0.001773	-0.000822	-0.004262	0.001288	-0.006358	0.000000	0.000090	0.000013
15	0.004666	-0.005091	-0.005260	-0.001801	-0.006555	0.002821	-0.003224	0.000000	0.000044	0.000006

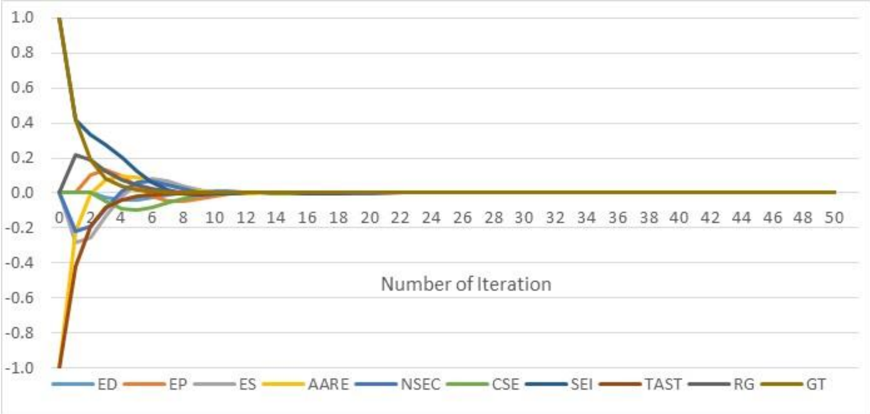
Figure 3.10 : The result of the FCM simulation process for the scenario 2.1 and a sample part of the iterations.

b. Increasing global treaties and regulations started to show their effects on the energy cost and energy price through increases of the availability of alternative renewable energies and new solar energy generation capacities in the medium period. Results showed that increase in the new solar energy generation capacity did not directly affected by solar energy incentives that indicated the decreasing trend and cost of solar energy that indicated the increasing trend in the same period. Increased energy supply by generating the alternative renewable energies and solar energy decreased energy price and increased energy demand. Technical applicability of solar energy that is transmitter concept also stay stable at zero value in the middle term and protect its position during 50 iterations.

c. Global treaties and regulations protected their positive effects until reaching a convergence at a steady state. However, other factors different from technical applicability of solar energy changed their position from positive to negative or vice versa in order to balance the system in the long term. These concepts did not reflect the direct and parallel reactions with other concepts at the same time. For example, while solar energy incentives were increasing in some periods, cost of solar energy increased or decreased in same periods. At the long term with 50 iterations, concepts reached their steady stable value “zero” at the convergence state that represents the occurrence of no changes as increase or decrease in the model.

ii. **Scenario 2. 2:** Scenario was designed based on the increasing and decreasing of some specific concepts in the system. Similar to the scenario 2.1, experts defined the supportive and preventive factors of the new energy generation within converse conditions. Increasing of the solar energy incentives and global treaties were accepted as the supportive factors that were used to develop the new renewable energy capacities, and on the other hand decreasing of the availability of alternative energies and technical applicability of solar energy were accepted as the preventive factors that were used to represent the nonexistence of availabilities of the new renewable energy generation in the system. Initial state of the scenario is defined as $A^0 = [0\ 0\ 0 - 1\ 0\ 0\ 1 - 1\ \ 0\ 1]$ and the following results were obtained (Figure 3.11):

a. Selected factors protected their sign but lose their influence in the short term. The highest decrease was observed on the availability of alternative renewable energies factor that can be based on the increasing number and effects of the related factors in the system. In this period, cost of solar energy and energy demand protected their situations as staying stable, while regulations and energy price increased and new solar energy generation capacity decreased in spite of solar energy incentives were increasing with low rate.



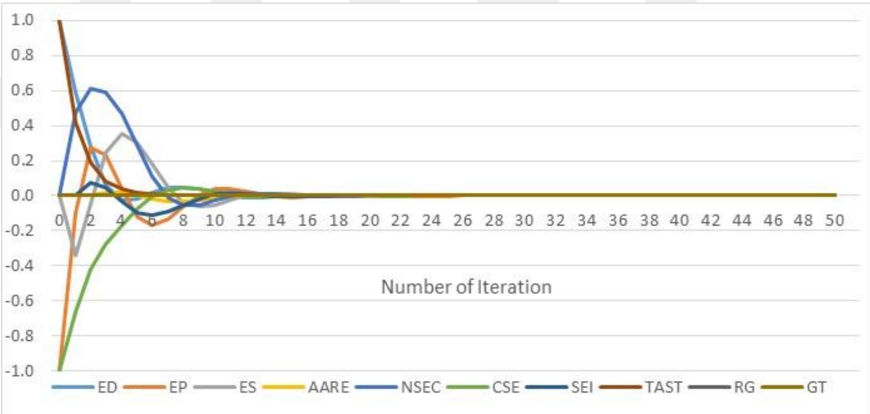
Iterations	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
0	0.000000	0.000000	0.000000	-1.000000	0.000000	0.000000	1.000000	-1.000000	0.000000	1.000000
1	0.000000	0.000000	-0.284434	-0.221278	-0.221278	0.000000	0.421899	-0.421899	0.221278	0.421899
2	0.000000	0.099928	-0.251903	-0.004648	-0.192086	0.000000	0.330572	-0.187606	0.192086	0.187606
3	-0.022480	0.132971	-0.134850	0.072161	-0.087951	-0.050353	0.275892	-0.084223	0.127945	0.084223
4	-0.040013	0.099121	-0.018426	0.094268	0.009142	-0.089978	0.203432	-0.037882	0.076376	0.037882
5	-0.040286	0.036978	0.056834	0.087965	0.060398	-0.098526	0.125951	-0.017045	0.042867	0.017045
6	-0.026443	-0.017593	0.081823	0.067819	0.066342	-0.082538	0.061174	-0.007670	0.023121	0.007670
7	-0.007941	-0.046048	0.069747	0.044254	0.046662	-0.055944	0.018480	-0.003452	0.012130	0.003452
8	0.006787	-0.048070	0.041723	0.024068	0.021903	-0.030463	-0.002465	-0.001553	0.006235	0.001553
9	0.013869	-0.033933	0.015276	0.010276	0.004361	-0.012291	-0.007971	-0.000699	0.003155	0.000699
10	0.013875	-0.015765	-0.000806	0.002830	-0.002903	-0.002475	-0.005746	-0.000315	0.001577	0.000315
11	0.009791	-0.001919	-0.005941	-0.000019	-0.002701	0.001023	-0.001766	-0.000142	0.000780	0.000142
12	0.004837	0.004682	-0.004145	-0.000406	0.000425	0.001133	0.000858	-0.000064	0.000383	0.000064
13	0.001123	0.005273	-0.000210	0.000010	0.003029	0.000230	0.001474	-0.000029	0.000187	0.000029
14	-0.000681	0.002843	0.002654	0.000336	0.003728	-0.000406	0.000786	-0.000013	0.000090	0.000013
15	-0.000946	0.000104	0.003385	0.000328	0.002791	-0.000455	-0.000207	-0.000006	0.000044	0.000006

Figure 3.11 : The result of the FCM simulation process for the scenario 2.2 and a sample part of the iterations.

b. The sign of the availability of alternative renewable energies factor changed from negative to positive that means that availabilities for generating new renewable energies started to rise in the medium term. Other initial factors protected their signs but lost their influence slowly in this period. Increasing solar energy incentives started to show its effects on the cost of solar energy that decreased in time and also increased the new solar energy generation capacity. Increase of the new solar and alternative energy generation by provided positive conditions increased the energy supply. Increasing energy supply did not decrease the energy price in the first step, but following steps energy demand decreased and they reflected their common influences on the energy price as decrease.

c. In the long term, firstly technical applicability of solar technology and global treaties lost their influences, while solar energy incentives that is supported by energy supply and regulations protected its influence on the other factors until convergence. Factors exhibited the converse properties during 50 iterations such as energy price increased or decreased in some period while energy demand and energy supply were decreasing at the same time. This property reflects the complexity and dynamism of the system that is also indicate the real life model. The model reached an equilibrium point at "zero" that represents the stability of the factors after the 50 iterations.

iii. **Scenario 2. 3:** In this scenario, we focused only in-degree factors of the new solar energy generation capacity that are energy price, technical applicability of solar technology, energy demand and cost of solar energy. Initial state vector was designed to support the increase of the new solar energy generation capacity in the long term. Therefore, it was accepted that energy demand and technical applicability of solar technology were increasing, and energy price and cost of solar energy were decreasing in the system. Initial state of the scenario was defined as $A^0 = [1 - 1\ 0\ 0\ 0 - 1\ 0 1\ \ 0\ 0]$ and we reached the following results (Figure 3.12):



Iterations	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
0	1.000000	-1.000000	0.000000	0.000000	0.000000	-1.000000	0.000000	1.000000	0.000000	0.000000
1	0.588259	-0.097192	-0.338591	0.000000	0.475768	-0.665432	0.000000	0.421899	0.000000	0.000000
2	0.278989	0.275659	-0.047428	0.000000	0.611445	-0.420389	0.076036	0.187606	0.000000	0.000000
3	0.063436	0.234654	0.249308	0.017106	0.592081	-0.274855	0.044857	0.084223	0.000000	0.000000
4	-0.024246	0.040053	0.356693	0.017789	0.470173	-0.167590	-0.035893	0.037882	0.000000	0.000000
5	-0.019920	-0.115736	0.307117	-0.000071	0.288661	-0.075970	-0.096110	0.017045	0.000000	0.000000
6	0.017075	-0.165817	0.179841	-0.021653	0.111337	-0.006316	-0.111881	0.007670	0.000000	0.000000
7	0.044962	-0.131231	0.048672	-0.034903	-0.007776	0.033879	-0.090562	0.003452	0.000000	0.000000
8	0.049719	-0.060289	-0.036823	-0.036067	-0.056381	0.045920	-0.051658	0.001553	0.000000	0.000000
9	0.035923	0.003376	-0.064772	-0.027846	-0.053442	0.038307	-0.014960	0.000699	0.000000	0.000000
10	0.015404	0.036998	-0.051688	-0.015895	-0.027524	0.022261	0.007842	0.000315	0.000000	0.000000
11	-0.001392	0.040277	-0.022914	-0.005388	-0.001841	0.007142	0.015157	0.000142	0.000000	0.000000
12	-0.009689	0.025706	0.001772	0.000986	0.012215	-0.002179	0.011976	0.000064	0.000000	0.000000
13	-0.010143	0.007528	0.013719	0.003138	0.013969	-0.005224	0.004991	0.000029	0.000000	0.000000
14	-0.006258	-0.005024	0.013830	0.002535	0.008490	-0.004120	-0.000841	0.000013	0.000000	0.000000
15	-0.001686	-0.009342	0.007677	0.000952	0.001627	-0.001562	-0.003490	0.000006	0.000000	0.000000

Figure 3.12 : The result of the FCM simulation process for the scenario 2.3 and a sample part of the iterations.

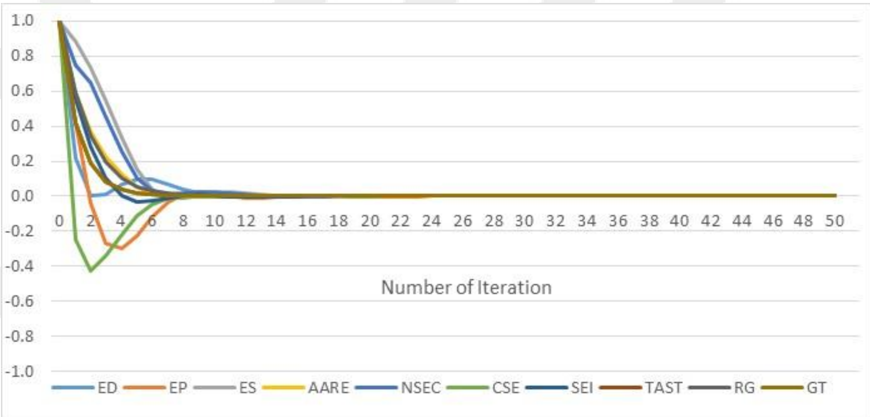
a. At the first period of the iterations, existence factors in initial state protected their positions within their signs but they decreased their influence whose the highest decrease was observed in energy price (91%). Global treaties, regulations, solar energy incentives and availability of alternative renewable energies were stayed stable at the same time. Also, global treaties and regulations that are transmitter factors did not change their stable position during 50 iterations. As it is expected that new solar energy generation capacity started to increase and reflected the highest increase among the factors in the system. At the following iterations of the first period, increasing solar energy incentives and technical applicability of solar technology increased the availability of alternative renewable energies and decreased the solar energy cost, and increasing energy demand did not meet by energy supply with new energy generations that it caused to increase the energy price.

b. Technical applicability of solar technology, new solar energy generation capacity and energy supply continued to have a positive effect, when cost of solar energy and solar energy incentives continued to have a negative effect at the medium term. Solar energy incentives and energy demand changed their position from positive (increasing) to negative (decreasing) according to their first period positions. While energy price had a high influence on the other factors in the system; energy demand, cost of solar energy and technical applicability of solar technology continued to lost their influences. Availability of alternative renewable energies started this period with rising (positive) influence on the system, but at the following iterations, its influence changed from positive to negative in time.

c. In the long term, technical applicability of the solar technology was firstly and energy price lastly reached an equilibrium point. Activation levels of the concepts fluctuated around the equilibrium value "zero" in order to balance the system, and at the end they reached their steady state values "zero" with decreasing rates. Zero equilibrium value of the model represents the stability of the system that there is not any factor that can activate the system. New solar energy generation capacity also reached to zero value that represents the sufficiency of the existent solar energy capacity and needlessness of the new solar energy generation in the system.

Case 3. Existence of all factors

This case represents the positively existence (i.e. increase) of all concepts in the systems whose initial state was defined as $A^0 = [1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1]$. Although it included some opposite factors such as an increase of the energy demand and energy price at the same time, it was accepted that extreme conditions could be possible in any systems. We expected that the system would reach an equilibrium zero point that represents the stable balancing state of the concepts in the long term. Reached results during the 50 iterations as follow (Figure 3.13):



Iterations	ED	EP	ES	AARE	NSEC	CSE	SEI	TAST	RG	GT
0	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
1	0.221278	0.421899	0.882620	0.588259	0.747604	-0.249613	0.558052	0.421899	0.588259	0.421899
2	0.004648	-0.043241	0.733674	0.371600	0.645786	-0.428256	0.282852	0.187606	0.344900	0.187606
3	0.011820	-0.269607	0.545882	0.226846	0.454300	-0.343937	0.101540	0.084223	0.194891	0.084223
4	0.065885	-0.300055	0.336238	0.124281	0.251437	-0.216759	0.001801	0.037882	0.106249	0.037882
5	0.096856	-0.226336	0.154196	0.056272	0.106798	-0.111070	-0.031802	0.017045	0.056276	0.017045
6	0.094230	-0.121461	0.037285	0.018165	0.033529	-0.044750	-0.026207	0.007670	0.029151	0.007670
7	0.069620	-0.034570	-0.010915	0.002278	0.013308	-0.013602	-0.008376	0.003452	0.014843	0.003452
8	0.039087	0.012831	-0.012539	-0.000860	0.018634	-0.004385	0.004698	0.001553	0.007456	0.001553
9	0.014701	0.023968	0.004080	0.000670	0.027134	-0.004177	0.007955	0.000699	0.003705	0.000699
10	0.001223	0.014528	0.018415	0.002091	0.028059	-0.004930	0.004162	0.000315	0.001824	0.000315
11	-0.002719	0.000478	0.022223	0.001878	0.020932	-0.003796	-0.001532	0.000142	0.000892	0.000142
12	-0.001331	-0.008577	0.016839	0.000500	0.010387	-0.001218	-0.005328	0.000064	0.000433	0.000064
13	0.001331	-0.010264	0.007739	-0.000974	0.001319	0.001308	-0.006011	0.000029	0.000209	0.000029
14	0.002908	-0.006877	-0.000035	-0.001791	-0.003697	0.002697	-0.004361	0.000013	0.000101	0.000013
15	0.002856	-0.002057	-0.004045	-0.001787	-0.004688	0.002747	-0.001914	0.000006	0.000048	0.000006

Figure 3.13 : The result of the FCM simulation process for the scenario 3 and a sample part of the iterations.

a. At the first iteration, increase rate of the concepts was decreased but stay positive, except at the cost of solar energy whose increase turn to negative state that represents the decrease of the cost in the solar energy generation. The cost of solar energy was directly affected by solar energy incentive and technical applicability and also increasing regulations and energy supply had an indirect impact on the cost of solar energy. Increasing incentives and availabilities for new renewable energies and solar energy caused to heavy increase in new energy generations and energy supply against the energy demand that also negatively affected the energy prices. At the same period, we observed the rapid decline of the global treaties and technical applicability of solar technology at same rate and also they reached to the steady state in a short time due to their transmitter properties.

b. The system reacted against the decreasing energy price and turn to natural regulations in itself. In this way, regulations and solar energy incentives were diminished in time that it caused to increase of the cost of solar energy and decrease of the availability of alternative energies and new solar energy generation capacities. Decreasing in the new energy generation also decreased the total energy supply that increased the energy price and decreased the energy demand. In this period, the system tended to the new cycle that transformed the system towards the balancing period.

c. The concepts in the system converged to unique zero values for 50 iterations. Steady state of the model represents the stability at zero values that means that concepts in the system neither will increase nor decrease in the long term. The latest converged concept was energy price that was followed respectively by energy supply, energy demand, and new solar energy generation capacity whose directly affecting factors that are solar energy incentives and cost of solar energy were also included in the latest converged concepts.

3.5 Conclusion

Energy that is the capacity for doing work can be obtained by converting other energy forms. Most of the world's convertible energy is obtained by fossil fuels that are burned and transformed to the new usable energy forms (International Energy Agency (EIA), 2016a). Fossil fuels (coil, petroleum, natural gas, etc.) are conventional energy source that is non-renewable, finite and becoming expensive in time. They also cause significant health, economic and environmental damages through air, water and land pollution and global warming. Global awareness about the dangers of fossil fuels has increased the tendency to the renewable energy usage. Renewable energies that are generated from renewable energy sources such as solar, wind, hydro, biomass, geothermal, wave and tidal actions is a very important alternative energy against the fossil fuels. In this study, we focused on the solar energy and defined the factors around the generation of solar energy as global treaties, incentives, regulations, energy cost, energy demand, energy supply, energy price, technical applicability of solar energy and availability of alternative renewable energies. The new solar energy generation system reflects the complex and uncertain real-life properties and its imprecise relationships among its factors cannot be expressed by crisp values. Therefore, system is represented by FCM and linguistic statements are used to define the imprecise causal relationships among factors. Linguistic values are transformed into crisp values by using Center of Gravity defuzzification method and FCM is simulated under the eight cases that are differentiated by applying the different initial state vectors. Steady states of the factors observed at the convergence are evaluated by experts in order to support the investors and governments for making decision about the new solar energy generation in the long term.

Future research will focus to extend the model factors that affect the generation of the solar energy. We will expect to find out the latent factors that have direct or indirect effects on the new solar energy generation by literature and field works. Also we aim to improve the new tools and methods related with the FCMs that will help us to evaluate experts' opinions expressed by their natural language as words or sentences linguistically. By these ways we aim to guide investors and governments' decisions by rightly reflecting crisp results that will help to make the right investments at the right conditions.

4. ANALYSIS OF SOLAR ENERGY GENERATION CAPACITY USING HESITANT FUZZY COGNITIVE MAPS*

Growing population and industrialization has been increasing the energy demand throughout the world (U.S. Energy Information Administration (EIA), 2016). Fossil fuels - coal, oil and natural gases- are used as a primary energy source for meeting the majority of the world energy needs. There is a consensus among scholars that conventional energy sources, fossil fuels, have catastrophic damage on the environment by increasing CO_2 emission. This emission causes an increase in the surface temperature and stimulating effects such as greenhouse effect, global warming, climate changes and disruption of the food chain (Hassanien, Li, & Lin, 2016; United State Environmental Protection Agency (USEPA), 2016; Wong et al., 2016). Also, fluctuations in the fossil fuel prices that are controlled by a few exporter countries cause an economic inequality among the countries that it leads to the social inequalities among the nations.

Against the environmental and economic damages of the fossil fuels, renewable energy has strongly emerged as an alternative energy source over the last two decades. Renewable energy (e.g. solar, wind, wave, tidal, and geothermal) is the fastest growing energy sources with average 2.6% yearly increase rate (U.S. Energy Information Administration (EIA), 2016). Solar energy has an important place in the renewable energy sources since it is abundant and expansive (Sahu, 2015). Solar can be transformed to energy from simple to high technological methods such as a solar furnace, Photovoltaic (PV), solar pond and Concentrated Solar Power (CSP) (Najafi, Ghobadian, Mamat, Yusaf, & Azmi, 2015). The extensive usage of the solar energy generation system has been increased its demand and usage to reach goals for reducing the greenhouse gas emissions and energy costs (Hosenuzzaman et al., 2015). Technological improvements and government subsidies that eliminate its high initial

* This chapter is based on the paper Çoban, Veysel, and Sezi Çevik Onar. "Analysis of Solar Energy Generation Capacity Using Hesitant Fuzzy Cognitive Maps." *Internatıonal Journal of Computatıonal Intellıgence Systems* 10, no. 1 (2017): 1149-1167.

capital costs and support the generation of the solar energy have been developing the interest of the solar systems intensively (Motte, Notton, Cristofari, & Canaletti, 2013). Although many countries (Germany, Italy, India, China, Mexico and so on) focus on solar energy generation by incentives and technological supports, solar power production capacity has not reached its deserved potentials (Yadav & Chandel, 2015) yet.

Literature reviews show that the solar energy usage relies on some fundamental factors such as governmental incentives, physical issues, and energy demand and energy provision (Dawn, Tiwari, Goswami, & Mishra, 2016). Solar energy usage can be increased by defining effective factors, and the causal connections between them. The investors and governors can be conducted toward solar power investments (C. Liu, Li, & Zha, 2016). These factors around the new solar energy generation are dynamic and complex, and the relationships among factors are ambiguous. The aim of the study is to assess the hesitant and causal relationship among the concepts around the capacity of new generated solar energy by using Hesitant Fuzzy Cognitive Maps (HFCMs). HFCMs that are the extension of Fuzzy Cognitive Maps (FCMs) are useful tools for designing model and projecting solar systems in the ambiguous and complex environment. In this paper, a new solar energy generation HFCMs is developed. The factors and causal relationships among them are defined by literature research study and experts' views (Çoban & Onar, 2017b; Onar, Oztaysi, Otay, & Kahraman, 2015).

4.1 Solar Energy Generation

Energy is a fundamental requirement of human life for the economic and social development of countries by implementing industrialization, transportation, healthcare, education, agriculture, and so on (Sindhu, Nehra, & Luthra, 2016). The energy can be provided by using either a conventional (non-renewable) or renewable energy sources.

Non-renewable (conventional) energy sources use fossil fuels such as coal, oil, natural gas, and petroleum that are carbon based substances. When the fossil fuels are burnt to obtain energy, many environmental damages occur such as air pollution, greenhouse effect, global warming, and depletion of ozone layer, climate change, and acid rain (Burnett, Barbour, & Harrison, 2014; Gherboudj & Ghedira, 2016). They are also non-renewable that means they cannot be renewed when used up, and run out one day since their resources are finite. Uncertainties and fluctuations in the global price of the fossil fuels based on the balance between provision and demand cause the economic and social problems on the economies of fossil fuels importing countries (Kar, Sharma, & Roy, 2016; Sindhu et al., 2016). These drawbacks make humankind keep looking for alternative energy sources to produce heat and electricity. However, fossil fuels continue to maintain their existence as an essential part of the energy sources. Despite these disadvantages, they have some advantages such as obtaining a significant amount of energy in a short time, abundant and easy accessibility, high efficiency, stable power generation, easy storage and transportation, and easy construction of their power plants (Dawn et al., 2016; Gherboudj & Ghedira, 2016; Hassanien et al., 2016; Okoye, Taylan, & Baker, 2016).

Renewable energy sources (e.g. the sun, the wind, bioenergy, geothermal, wave, tidal, and hydropower) are sustainable and relevant alternative energy sources against the fossil fuel. They are renewable that means they will never run out in the future. Energy production using renewable energy sources reduces the greenhouse effect since the released air pollution during the production process is low. It also provides cost advantages by means of less maintenance, transmission and production cost (Dawn et al., 2016; Hassanien et al., 2016). Besides these advantages, there are some disadvantages such as less efficiency based on technological weakness, unstable and unpredictable energy production due to the weather condition, and the requirement of substantial capital cost because their technologies are new and immature, and weakness of scale economy in their sectors.

Improvements in the solar energy technology supported by government incentives and regulations increase the usage of solar energy and enable obtaining economies of scale (Coskun, Oktay, & Dincer, 2011; Kahraman et al., 2009; Myers, 2005). From the beginning of the 21st century, countries' support for renewables includes policy targets, feed-in policies, tendering / public competition bidding, heat obligation and biofuels mandates. For example, Turkey's investment support policy changed in 2012, and new incentives and regulations were developed to support renewable energies (Boekhoudt & Behrendt, 2013). These developments remove the primary disadvantages of the solar energy for investors and consumers such as initial investment cost, long-term investment gain, and low energy cost and make it attractive as a major alternative energy source against the fossil-based energy sources for meeting the increasing energy need. These policies and regulations increased the global solar generating capacity from 1.3 GW in 2000 to 3.7 GW in 2004, 23 GW in 2009 and 229 GW in 2015 (PowerWeb, 2016).

Table 4.1 : New solar energy generation factors.

Factors	Definitions
Energy Need (ED)	The demand for energy that is used as an input to carry out human needs such as production, heating, transportation (International Energy Agency (EIA), 2016a) .
Energy Fee (EF)	The unit fee of the used energy. Increase in conventional energy costs stimulates to increase an inclination towards renewable energy investments at the base of inverse relation (M. Zhang et al., 2014).
Energy Provision (EP)	Energy is generated for future requirements. The amount of provision can be measured based on the expectation of the energy receiver and/or provider (International Energy Agency (EIA), 2016a).
Non-fossil Fuel Energy Sources (NFES)	Total available energy capacity that is generated by using renewable energy resources (e.g. sun, wind, biomass) and controlled by physical (weather, geographic, location), social and politic conditions.
Capacity of New Generated Solar Energy (CNGSE)	The amount of energy that is produced by conversion of solar energy into other energy forms such as electricity, heat, fuel, and thermal electricity (International Energy Agency (EIA), 2016a).
Capital Cost of Solar Systems (CCSS)	The total investment cost that includes the expenses of generation, transmission, and distribution of solar energy that have a downward trend with learning curve (Adaramola, 2014).
Incentives for Solar Energy Generation (ISEG)	The encourage programs that stimulate producers to buy solar energy efficient devices by way of monetary or/and non-monetary policies such as economic facilities (e.g. low or zero interest loans) and supportive policies (e.g. feed-in tariff, tax relief) (C. Liu et al., 2016; M. Zhang et al., 2014).
Availability of Solar Devices (ASD)	The applicability of the solar energy technologies under the given physical conditions in order to generate, transmit and distribute solar energy (Bogetoft & Olesen, 2007).
World Protection Agreements (WPA)	The written agreements signed among parties involve the rules and regulations in order to control and direct global energy. The Kyoto Protocol and Paris Agreement aims to hinder the global warming and climate changes that basically stem from the greenhouse gases emission (e.g. carbon dioxide, methane, nitrous oxide) by fossil fuel based energies sources (e.g. coal, oil, natural gas) (Adaramola, 2014).
Technical Infrastructure Problems (TIP)	Represents the lack of technical infrastructure abilities related with solar energy generation such as transmission channels, transformers, water provision systems, and transportation facilities whose inexistences indirectly affect the improvements of the new solar energy generation.

In this study, we described the factors (Table 4.1) that affect the capacity of new generated solar energy and causal relations among them for all countries. Causal relationships are evaluated under the proposed HFCM solar energy generation capacity model. States of the factors in the model are observed at each iteration, and their levels are analyzed in the long term. In this way, the impact of the factors and their causal relationships in the model are verified. New solar energy plant investments can be enhanced by using this model.

4.2 Fuzzy Cognitive Maps

Fuzzy Cognitive Maps (FCMs) are introduced by Kosko (Kosko, 1986) as "fuzzy-graph structures for representing causal reasoning." FCMs are extended from cognitive maps combined with fuzzy logic is a way of representing causal relationships among uncertain knowledge in complex systems (Rizwan, Jamil, Kirmani, & Kothari, 2014). A FCM is a signed and directed graph whose members are called as a node (i.e. concept, factor) and symbolized as C_i. Causal relationships among them are named as an edge (i.e. arc) that represents a weight of direction between two nodes such as node i (C_i) and node j (C_j) and symbolized as w_{ij} (Figure 4.1). Weight between edges refers the power of the fuzzy causal relationships. The weights are defined by fuzzy numbers whose values express uncertain knowledge of experts. A graphical display of a dynamic system by FCMs provides a visual description of concepts, directions and dynamic interactions among them.

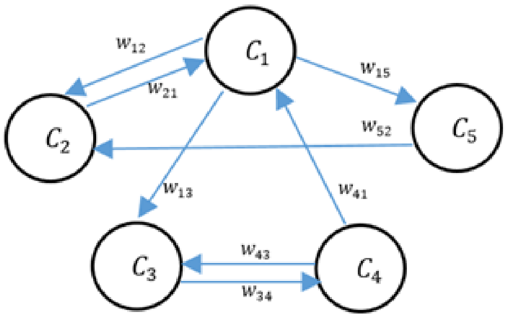


Figure 4.1 : A sample FCM model.

A sign of weight can be defined as positively that means the change occurs in the same direction or as negatively that means change takes place in the opposite direction or zero that means there is no causal relation between concepts. FCM is a fuzzy feedback loop model that means any change in any concept in the map can affect the other concepts in the system. Feedback loop process continues until all concepts reached an equilibrium state (Kosko, 1997). Concepts in FCM do not have any self-feedback loops (i.e. no causal relationship itself), for this reason, the diagonal of the weight matrix is zero. Fuzzy causal relationships between concepts and their initial state can be generated by two ways either subjective based on experts' knowledge and experiences or objective information that is obtained by an extensive literature review (Çoban, Onar, & Soyer, 2015). If there is more than one expert who generates the different FCMs according to their knowledge and experiences, their models are aggregated by the weighted values of experts in the interval [0, 1] based on experts' credibility (Kosko, 1988).

The weights of the causal relationships are defined by fuzzy numbers that are represented by triangular, trapezoidal, sigmoid, Gaussian functions or fuzzy linguistic terms such as negatively very strong, positively strong, and positively medium. Fuzzy relations should be transformed to crisp values in the [-1, 1] interval by defuzzifying methods such as the center of area, center of gravity, and weighted average methods in order to operate FCM and calculate their steady state values. The state value $\mathrm{A}_\mathrm{i}^\mathrm{t}$ represents a value of the concept C_i in a given time t, and the state values of all concepts in FCM are defined in the state vector as $\mathrm{A}^\mathrm{t} = [\mathrm{A}_1^\mathrm{t}, \mathrm{A}_2^\mathrm{t}, \dots, \mathrm{A}_\mathrm{n}^\mathrm{t}]$. A new state value of the related concept C_i in the following time $t+1$ is calculated as:

$$A_i^{t+1} = f\left(\sum_{j=1}^{n} A_j^t\, w_{ij} + A_i^t\right) \quad (4.1)$$

The new state value of the concept $\mathrm{C_i}$ at time $\mathrm{t}+1$ ($\mathrm{A}_\mathrm{i}^{\mathrm{t}+1}$) is calculated by using the threshold function ($\mathrm{f}(.)$) that transforms the sum of the previous state value ($\mathrm{A}_\mathrm{i}^\mathrm{t}$) and the total causal impact on the concept $\mathrm{C_i}$. The sigmoid and hyperbolic tangent functions are commonly used transformation (threshold) functions to compute new state values of concepts.

$$\text{Sigmoid function: } f(x) = \frac{1}{1+e^{-\lambda x}} \quad (4.2)$$

$$\text{Hyperbolic tangent function: } f(x) = \frac{e^{\lambda x} - e^{-\lambda x}}{e^{\lambda x} + e^{-\lambda x}} \quad (4.3)$$

Sigmoid and hyperbolic tangent threshold functions take values in the interval $[0,1]$ and $[-1,1]$ respectively. The optional lambda (λ) parameter in both functions is defined by the researcher as greater than 0 and used to determine the appropriate slope of the function, and x value represents inner calculation for new state vector. The new state is obtained with an iterative calculation of Equation (4.1) for each concept until the difference between consecutive two state values ($\mathrm{A}_\mathrm{i}^{\mathrm{t}+1} - \mathrm{A}_\mathrm{i}^\mathrm{t}$) is smaller than specific residua (e) value that is generally accepted as 0.001.

4.3 Hesitant Fuzzy Sets

The fuzzy set theory developed by Zadeh (Lofti Asker Zadeh, 1965) is a helpful tool to manage and model uncertainty via mathematical representation. After this pioneering work, new extended tools using fuzzy sets are proposed to handle imprecise problems and have been applied in the different scientific fields such as management science, decision theory, and artificial intelligence. New extensions of the ordinary fuzzy set (Lofti Asker Zadeh, 1965) such as type-2 fuzzy sets (Mizumoto & Tanaka, 1976), type-n fuzzy sets (Dubois, 1980), intuitionistic (inter-value) (Krassimir T Atanassov, 1986) fuzzy sets and hesitant fuzzy sets (Torra, 2010) have been proposed to overcome the real-world problems that are associated with uncertainties and vagueness. In 2010, Torra developed the Hesitant Fuzzy Sets (HFSs) to deal with situations where more than one value can be possible for the membership of a fuzzy set. HFSs are defined regarding a function that returns a set of membership values for each element in the domain (Torra, 2010).

A HFS on X that is defined as a reference set can be described by a function,h, which gives a sub-values in the [0, 1] interval (Torra, 2010). It can be mathematically described as follows:

$$h: X \to \{[0,1]\} \tag{4.4}$$

h_M represents the associated HFS with $M = \{\mu_1, \mu_2, \dots, \mu_N\}$ that is a set of N membership functions and is defined as:

$$h_M: M \to \{[0,1]\} \text{ and } h_M\ (x) = \cup_{\mu \epsilon M}\ \{\mu_x\} \tag{4.5}$$

The upper and lower bound of the hesitant fuzzy set h is given as (Torra, 2010):

$$h^-(x) = min\, h(x) \tag{4.6}$$

$$h^+(x) = max\, h(x) \tag{4.7}$$

4.4 Hesitant Fuzzy Linguistic Term Sets

Linguistic information that uses the words or sentences instead of using numeric values is a useful tool to define imprecise real life problems, and it is represented by linguistic variables that naturally reflect the perceptions of people (Lotfi Asker Zadeh, 1975). Fuzzy set theory depends on the linguistic variables that are also fuzzy variables. The fuzzy linguistic method that uses a single linguistic term is limited to handle the hesitant problems. Hesitant Fuzzy Linguistic Terms Sets (HFLTS) is proposed by Rodriguez et al. (Rodriguez et al., 2012) to overcome these type problems. The basic operations and concepts about HFLTS are described as follows (Rodriguez et al., 2012):

- H_s (HFLTS) is an ordered finite subset that is derived from consecutive terms of linguistic term set $S = \{s_0, s_{1,} \ldots, s_g\}$.

For example, while linguistic term set S is S={s_0: nothing, s_1: very low, s_2: low, s_3: medium, s_4 :high, s_5: very high, s_6: absolute}, a sample HFLTS might be H_s={s_2: low, s_3: medium, s_4: high}.

- The bounds and complement of the HFLTS, H_s, are defined as follow:

$$\text{Upper bound } \mathrm{H_{S^+}} = \max(\mathrm{s_i}) = \mathrm{s_j}, \mathrm{s_i} \in \mathrm{H_s} \text{ and } \mathrm{s_i} \leq \mathrm{s_j}\ \forall_\mathrm{i};$$

$$\text{Lower bound } H_{S^-} = min(s_i) = s_j, s_i \in H_s\ and\ s_i \geq s_j\ \forall_i;$$

The basic operations (complement, union, and intersection) of the HFLTSs (H_s, H_s^1, H_s^2) are defined as follows (Rodriguez et al., 2012):

$$H_s^c = S - H_s = \{s_i | s_i \in S\ and\ s_i\ not\ \in\ H_s\} \text{ and } (H_s^c)^c = H_s$$

$$H_s^1 \cup H_s^2 = \{s_i | s_i \in H_s^1\ or\ s_i\ \in\ H_s^2\}$$

$$H_s^1 \cap H_s^2 = \{s_i | s_i \in H_s^1\ and\ s_i\ \in\ H_s^2\}$$

New values after the basic operations also will be a HFLTS.

4.5 OWA Operators

A set of information is combined and reduced into a unique information with aggregation operators such as median, mean, arithmetic mean, weighted arithmetic mean, and ordered weighted averaging (OWA). OWA operator is one of the most used operators (Torra & Narukawa, 2009), and it can be defined as follows:

$$OWA\ (a_1, a_2, \ldots, a_n) = \sum_{i=1}^{n} w_i * b_i \tag{4.8}$$

where the ith largest element of the aggregated objects $a_1, a_2, \ldots, a_n$ is shown with b_i. Permutation of the a_i values are ordered from the largest (a_1) to the lowest (a_n) value. w_i that is a weight of the ordered ith data is an element of the aggregated weight vector W a $W = (w_1, w_2, \ldots, w_n)^T$ and defined in [0,1] interval. The sum of the all weights in W is equal one as $\sum_{i=1}^{n} w_i = 1$ (Yager, 1988). The weighting values in W can be calculated by different methods such as max, min, average that distinguish the OWA operators. In this study we used the orness method (Yager, 1988) because of its ability to represents the optimism and pessimistic degree of the OWA operator by compensative property (H. Liu & Rodríguez, 2014).

$$orness\ (W) = \frac{1}{n-1}\sum_{i=1}^{n} w_i(n-i) \tag{4.9}$$

Where $0 \leq orness \leq 1$, optimistic OWA operators are close to one as $orness \geq 0.5$ and pessimistic OWA operators are close to zero as $orness \leq 0.5$ (Yager, 1993). The OWA aggregation operator is introduced by Yager (Yager, 1988) and his pioneering study attracted the attention of researchers in many different scientific fields. The OWA aggregation operator with its ability to aggregate and design the linguistic terms has a wide using fields in the fuzzy logic and other computational intelligence studies.

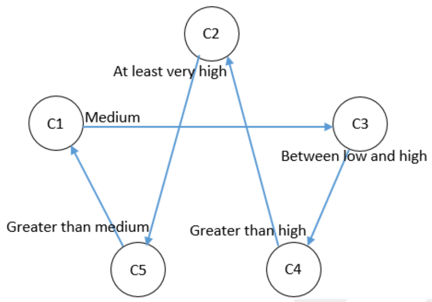
4.6 Hesitant Fuzzy Cognitive Maps

FCMs using the ordinary fuzzy sets is a useful and powerful tool to model and simulate complex and ambiguous systems that reflect the dynamic causal relationships among concepts. Hesitant fuzzy sets (HFSs) extended from the ordinary fuzzy sets by Torra (Torra, 2010) provide experts convenience to express their assessment with allowing more than one value for defining the membership value of an element (Cevik Onar, Oztaysi, & Kahraman, 2014).

Hesitant Fuzzy Cognitive Maps (HFCMs) is a comprehensive approach that allow integrating the various linguistic evaluations assigned by experts (Çoban & Onar, 2017a). Hesitant linguistic expressions define the experts' real-world cognitive assessments via their natural language as words or sentences. This type of expressions is also used to define the causal relations among the concepts and the initial state vector of the concepts in the model (Çoban & Onar, 2017a). HFCM enables representing the uncertain and imprecise conditions that cannot be evaluated or expressed by any numerical values but can be expressed with hesitant fuzzy sets. The general operation process flow of the HFCM is as following steps:

Step 1. Development of the network model

The model is generated by the joint agreement of experts who study on a professional field in academic and real sectors, and they also know the operation of the model in different situations. Experts can also draw the causal relationships among the concepts in a graph structure and model is obtained as concrete. By this way, an HFCM provides a natural representational structure for experts in the cognition that is used to represent, perceive, simplify, contextualize, and make sense of the complex systems that can be defined as the mental models or belief system (Çoban & Onar, 2017a; Surer, Onar, & Topcu, 2015).



	C_1	C_2	C_3	C_4	C_5
C_1	-	-	{medium}	-	-
C_2	-	-	-	-	{very high, perfect}
C_3	-	-	-	{low, medium, high}	-
C_4	-	{very high, perfect}	-	-	-
C_5	{high, very high, perfect}	-	-	-	-

Figure 4.2 : A simple HFCMs and HFLTS matrix of a simple HFCMs.

HFCMs graphically represent the imprecise and uncertain systems that are symbolized by the cause and effect relations among concepts in dynamic environments. In HFCMs, concepts are represented by nodes as C_i and the causal relations among the corresponding concepts are shown by the directed linguistic measures. A simple HFCM is illustrated in Figure 4.2 that includes five concepts, five directed linguistic arcs and no self-loop concep t (w_{ii}=0). The matrix representation of HFLTS for a simple HFCMs is showed in Table 4.2.

Step 2. Collecting suggestions from experts

Experts compare the causal relationships among concepts and linguistically define the degree of causal influences. Imprecise and uncertain conditions cause a hesitancy on the experts' evaluations about relational degree among concepts in the cognitive map. Therefore, experts apply the hesitant linguistic terms in order to express their thoughts more naturally (Çoban & Onar, 2017a). Hesitant linguistic expressions and linguistic terms that are represented by daily (natural) language can be formed by context-free grammar and symbolized as G_H (Bordogna & Pasi, 1993; Rodriguez et al., 2012). In Table 4.2, an example of expert's linguistic evaluations is given.

Table 4.2 : Sample expert's linguistic evaluations.

	EN	EF	EP
EN		Positive Between High and Absolute	
EF	Negative Greater Than High		Positive Between High and Very High
EP		Negative at Least Very High	
NFES			Positive at Least Medium
CNGSE			Positive Between Very Low and Medium

To obtain the usable form of the comparative linguistic expressions, transformation functions are used to convert the linguistic terms into HFLTS (Rodriguez et al., 2012). In this study, hesitant linguistic expressions that are generated by a context-free grammar (G_H) are transformed into HFLTS, H_S by transformation function E_{GH} that is developed by Rodriguez et al. (Rodriguez et al., 2012). There are different ways to transform the hesitant linguistic expressions into HFLTSs as follows:

- $E_{G_H}(s_i) = \{s_i | s_i \in S\}$
- $E_{G_H}(at\ least\ s_i) = \{s_j | s_j \in S\ and\ s_j \geq s_i\}$
- $E_{G_H}(at\ most\ s_i) = \{s_j | s_j \in S\ and\ s_j \leq s_i\}$
- $E_{G_H}(lower\ than\ s_i) = \{s_j | s_j \in S\ and\ s_j < s_i\}$
- $E_{G_H}(greater\ \ than\ s_i) = \{s_j | s_j \in S\ and\ s_j > s_i\}$
- $E_{G_H}(between\ s_i\ and\ s_j) = \{s_k | s_k \in S\ and\ s_i \leq s_k \leq s_j\}$

When S = {n: nothing, vl: very low, l: low, m: medium, h: high, vh: very high, a: absolute} is a linguistic term set, sample linguistic expressions generated by context-free grammar can be transformed as follow and sample HFLTS can be seen by Table 4.3:

Table 4.3 : HFLTS of sample expert's linguistic opinion.

	EN	EF	EP
EN		Positive {h, a}	
EF	Negative {vh, a}		Positive {h, vh}
EP		Negative {vh, a}	
NFES			Positive {m, a}
CNGSE			Positive {vl, m}

Step 3. Development of fuzzy envelope for the HFLTS

An envelope is a useful tool in order to simplify the comparison among HFLTSs (Rodriguez et al., 2012). The envelope of an HFLTS, $env(H_S)$, represents an interval whose limits are defined by its upper linguistic term (H_{S^+}) and lower linguistic term (H_{S^-}) bounds as follow:

$$env(H_S) = [H_{S^-}, H_{S^+}], \quad H_{S^-} \leq H_{S^+} \tag{4.10}$$

For example, when S= {nothing, very low, low, medium, high, very high, absolute} is a linguistic term set, the envelope of the HFLTS, H_s={s_2: medium, s_3: high, s_4 : very high} can be described as env(H_S)=[medium, very high]. By using the OWA operation, the fuzzy membership functions of the linguistic terms of the HFLTS can be aggregated, and a fuzzy membership function that represents the HFLTS is obtained in order to develop the fuzzy envelope for HFLTS (H. Liu & Rodríguez, 2014; Yager, 1988).

The trapezoidal fuzzy membership function can be accepted as a useful tool for defining and representing linguistic values (Delgado et al., 1998; Delgado, Verdegay, & Vila, 1992). Therefore, comparative linguistic statements based on HFLTS, HS should be converted to the trapezoidal fuzzy membership function $\tilde{A}$ = (a, b, c, d) whose definition domain should correspond with the linguistic terms {s_i,...,s_j}∈H_S. The trapezoidal fuzzy membership function is also used to define the fuzzy envelope of the HFLTS. For this purpose, two basic sequential stages are carried out for each linguistic expression (Figure 4.3).

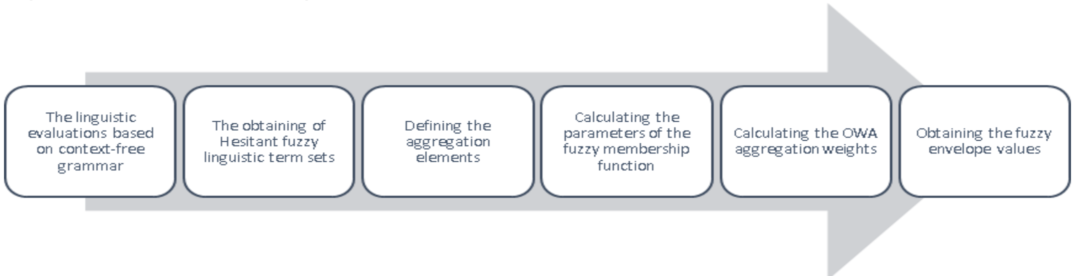


Figure 4.3 : General process to obtain the fuzzy envelope.

Stage 1. Defining the elements to aggregate

All linguistic terms, $s_k \in S$, in the HFLTS can be used to calculate the members of the trapezoidal fuzzy membership function as $A^k = T\{a_l^k, a_m^k, a_m^k, a_r^k\}, k = 0, 1, \dots, g$. The set of membership functions of the linguistic terms in the HFLTS $H_s = \{s_i, s_{i+1}, \dots, s_j\}$ is shown in the set of elements to aggregate as (H. Liu & Rodríguez, 2014): $T = \{a_L^i, a_M^i, a_L^{i+1}, a_R^i, a_M^{i+1}, a_L^{i+2}, a_R^{i+1}, \dots, a_L^j, a_R^{j-1}, a_M^j, a_R^j\}$, The set of elements to aggregate is simplified according to fuzzy partition (Ruspini, 1969) by accepting $a_R^{k-1} = a_M^k = a_L^{k+1}, k = 1, 2, \dots, g-1$ and defined as: $T = \{a_L^i, a_M^i, a_M^{i+1}, \dots, a_M^j, a_R^j\}$.

Stage 2. Obtaining the parameters of the trapezoidal fuzzy membership function

The trapezoidal fuzzy membership function $\tilde{A}$=(a, b, c, d) is defined by four parameters whose edge values are represented with the left limit (a) and right limit (d). Parameters are calculated by using the set of the elements to aggregate $T = \{a_L^i, a_M^i, a_M^{i+1}, \dots, a_M^j, a_R^j\}$ that is defined by the linguistic limits as s_i left limit and s_j the right limit where $s_i = min\, H_s$ and $s_j = max\, H_s$. Limit values can be defined as (H. Liu & Rodríguez, 2014):

$$a = min\{a_L^i, a_M^i, a_M^{i+1}, \dots, a_M^j, a_R^j\} = a_L^i \quad (4.11)$$

$$d = max\{a_L^i, a_M^i, a_M^{i+1}, \dots, a_M^j, a_R^j\} = a_R^i \quad (4.12)$$

The weighting vectors in OWA aggregation operations for b and c parameters

After determining the limit parameters a and d, the remaining elements of T ($a_M^i, a_M^{i+1}, \dots, a_M^j \in T$) are used to calculate the intermediate b and d parameters by using OWA aggregation operator. The weighting vectors that are applied in OWA aggregation operations are calculated by using Filev and Yager's method (Filev & Yager, 1998; Yager, 1988).

$$b = OWA_{W^s}(a_M^i, a_M^{i+1}, \dots, a_M^j) \quad (4.13)$$

$$c = OWA_{W^t}(a_M^i, a_M^{i+1}, \dots, a_M^j) \quad (4.14)$$

where $s, t = 1, 2$; $s \neq t$ or $s = t$. Weighting vectors W^s and W^t differentiate the interval values b and c of trapezoidal fuzzy membership function that help to design the fuzzy envelope of the HFLTS as $env_F(H_S) = T\ (a, b, c, d)$. OWA weights reflect the differentiation of the importance of the linguistic terms such that it is based on the hesitation among linguistic expressions. Although there are different ways for calculating the OWA weights, in this paper, we applied to Filev and Yager's method that are defined as follows (Filev & Yager, 1998; Yager, 1988):

The first type of OWA weights $W^1 = (w_1^1, w_2^1, \ldots, w_n^1)^T$ when the parameter α is $0 \leq \alpha \leq 1$.

$$w_1^1 = \alpha,\, w_2^1 = \alpha(1-\alpha),\, w_3^1 = \alpha(1-\alpha)^2, \ldots,$$
$$w_{n-1}^1 = \alpha(1-\alpha)^{n-2},\, w_n^1 = \alpha(1-\alpha)^{n-1} \quad (4.15)$$

The second type of OWA weights $W^2 = (w_1^2, w_2^2, \ldots, w_n^2)^T$ when the parameter α is $0 \leq \alpha \leq 1$.

$$w_1^2 = \alpha^{n-1},\, w_2^2 = (1-\alpha)\alpha^{n-2},\, w_3^2 = (1-\alpha)\alpha^{n-3}, \ldots,$$
$$w_{n-1}^2 = (1-\alpha)\alpha,\, w_n^2 = (1-\alpha) \quad (4.16)$$

Selection of the proper OWA weight types between W^1 and W^2 is based on the two reasons. One of them is that W^1 and W^2 enable researchers to calculate OWA weights within two general classes. In this calculation, the value of the parameter α must be specified and defined for each n value. Reason two can be defined with the properties of the W^1 and W^2 (H. Liu & Rodríguez, 2014). The computations of the orness measures related with W^1 and W^2 weights are defined as (Figure 4.4):

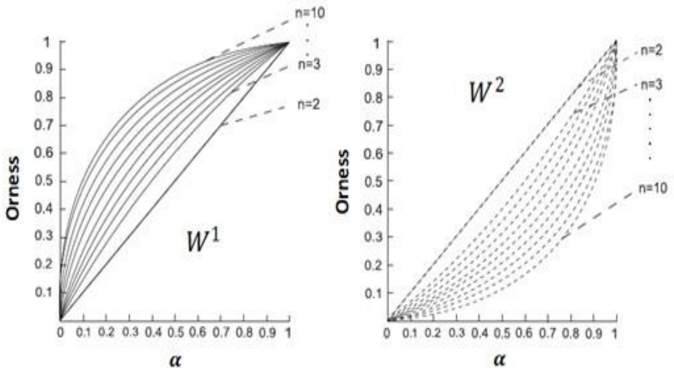


Figure 4.4 : The relationship between the $orness(W^1)$ and $orness(W^2)$ measures and parameter (adapted from Ruspini, 1969; Yager, 1988).

$$orness(W^1) = \sum_{i=1}^{n} w_i^1 \left(\frac{n-i}{n-1}\right) = \frac{n-1}{n-1}\alpha + \frac{n-2}{n-1}\alpha(1-\alpha) + \frac{n-3}{n-1}\alpha(1-\alpha)^2 + \cdots +$$
$$\frac{1}{n-1}\alpha(1-\alpha)^{n-2} + \frac{0}{n-1}(1-\alpha)^{n-1} = \frac{n}{n-1} - \frac{1-(1-\alpha)^n}{(n-1)\alpha} \quad (4.17)$$

Similar calculation steps with $orness(W^1)$ are applied and reached the $orness(W^2)$ as follow:

$$orness(W^2) = \frac{\alpha - \alpha^n}{(n-1)(1-\alpha)} \quad (4.18)$$

For $orness\ (W) > 0.5$, OWA operators are described as optimistic (OR-like) and for $orness\ (W) < 0.5$, OWA operators are described as pessimistic (AND-like). For example, if $n = 15$ and $\alpha = 0.15$ $orness(W^1) = 0.73$ that represents optimism (OR-like) and $orness(W^2) = 0.02$ that represents pessimistic (AND-like). Orness measure facilitates to assess the positive side (optimism degree) of the OWA operator. The importance of the linguistic terms of the HFLTS is measured by the orness measure whose OWA operator ($orness\ (W)$) is defined in the interval $[0, 1]$.

Calculation of fuzzy envelope

In order to clarify the fuzzy envelope, the comparative linguistic expression "at most high" described by the context-free grammar is examined in this part. Linguistic term set is defined as S={s_0=nothing, s_1=very low, s_2=low, s_3=medium, s_4=high, s_5=very high, s_6=absolute} and show in Figure 4.5**.**

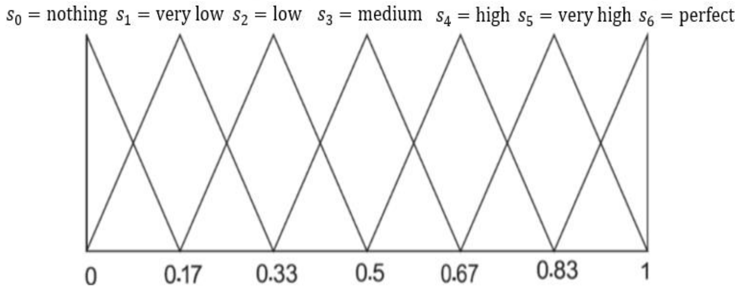


Figure 4.5 : The linguistic term set S.

Linguistic expression "at most high" is transformed into HFLTS as $E_{G_H}(at\ most\ s_4) = \{s_0, s_1, s_2, s_3, s_4\}$.

$T = \{a_L^0, a_M^0, a_L^1, a_R^0, a_M^1, a_L^2, a_R^1, a_M^2, a_L^3, a_R^2, a_M^3, a_L^4, a_R^3, a_M^4, a_R^4\}$ is defined as the set of the elements to aggregate of the HFLTS. Due to $a_L^1 = a_M^0, a_R^0, = a_M^1 = a_L^2, a_R^1, = a_M^2 = a_L^3, a_R^2 = a_M^3 = a_L^4$, and $a_R^3, = a_M^4$ it is simplified as $T = \{a_L^0, a_M^0, a_M^1, a_M^2, a_M^3, a_M^4, a_R^4\}$.

The parameters of the trapezoidal membership function that represents the fuzzy envelope $env_F(H_{s4}) = T(a_4, b_4, c_4, d_4)$ are calculated as:

$a_4 = min\{a_L^0, a_M^0, a_M^1, a_M^2, a_M^3, a_M^4, a_R^4\} = a_L^0 = 0;$

$b_4 = a_M^0 = 0;$

$d_4 = max\{a_L^0, a_M^0, a_M^1, a_M^2, a_M^3, a_M^4, a_R^4\} = a_R^4 = 0.83$

While $i = 4$ and $g = 6$, α is calculated as $\alpha = i/g = 4/6 = 0.67$ and OWA weights are obtained as:

$W^1 = (w_1^1, w_2^1, w_3^1, w_4^1, w_5^1)^T$

$W^1 = (0.67, 0.22, 0.074, 0.025, 0.012\ )^T$

where $w_1^1 = \alpha, w_2^1 = \alpha(1-\alpha), w_3^1 = \alpha(1-\alpha)^2$,

$w_4^1 = \alpha(1-\alpha)^3, w_5^1 = \alpha(1-\alpha)^4$

$c_4 = a_M^0 * 0.67 + a_M^1 * 0.22 + a_M^2 * 0.074 + a_M^3 * 0.025 + a_M^4 * 0.012$=0.59

$env_F(H_{s_4})$ is obtained in the trapezoidal membership function form as $T = (0, 0, 0.59, 0.83)$ (Table 4.4).

Table 4.4 : Trapezoidal membership functions and their defuzzified form.

	EN	EF	EN	EF
EN	(0,0,0,0)	(0,0,0,0.5)	0	0.84
EF	(-0.67,-0.97,-1,-1)	(-0.97,-1,-1,0)	-0.9	0
EP	(0,0,0,0)	(0,0,0,-0.67)	0	-0.9
NFES	(0,0,0,0)	(0,0,0,0)	0	0
CNGSE	(0,0,0,0)	(0,0,0,0)	0	0
CCSS	(0,0,0,0)	(0,0,0,0)	0	0
ISEG	(0,0,0,0)	(0,0,0,0)	0	0
FSD	(0,0,0,0)	(0,0,0,0)	0	0
WPA	(0,0,0,0)	(0,0,0,0)	0	0
TIP	(0,0,0,0)	(0,0,0,0)	0	0

Step 4. Operation of HFCM

Obtained trapezoidal membership functions through fuzzy envelope operations for each causal relationship between concepts are defuzzified to crisp values in the interval [-1, 1]. Each crisp value transformed from hesitant linguistic expression is described as directed weight w_{ij} that represents the causal relationship between related nodes C_i and C_j. This sign of the directed weight w_{ij} can be in three different form as: a direct proportion (positive relation) ($w_{ij} > 0$); an inverse proportion (negative relation) ($w_{ij} < 0$); or no relationship ($w_{ij} = 0$). All weights of the causal relationships in HFCM compose the weight matrix (W) whose diagonal elements (w_{ii}) are equal to zero.

The initial state values acquired from experts represent the initial condition of the concepts in the model. The activation level of the concept C_i in time t, A_i^t represents the new state value of the concept in the ongoing operations of the model and defined in the interval $[-1, 1]$. All concepts' state values in time t can be shown in only one form as a state vector $A^t = [A_1^t, A_2^t, \ldots, A_n^t]$ where n is the number of concepts in the model. The state vector (A^t) of a FCM is updated as $A^{t+1} = [A_1^{t+1}, A_2^{t+1}, \ldots, A_n^{t+1}]$, where A^{t+1} is the new state vector. A^{t+1} can be calculated as follows (Delgado et al., 1992), where f is a threshold (transfer - activation) function:

$$A_i^{t+1} = f\left(\sum_{j=1}^{n} w_{ij} A_j^t + A_j^t\right) \quad (4.19)$$

There are four most frequently used threshold functions: sigmoid function, sign (bivalent) function, hyperbolic tangent function and trivalent function. Because of the real life situation that includes positive and negative conditions, we apply to the hyperbolic tangent function.

$$f(x) = tanh(\lambda x) = \frac{e^{\lambda x} - e^{-\lambda x}}{e^{\lambda x} + e^{-\lambda x}}. \quad (4.20)$$

where λ is a constant that is used to shape the slope of the function. Lambda values are specified according to study type and investigation properties by researchers (Bueno & Salmeron, 2009). This process is updated until the mathematical difference between the last two vectors is equal or smaller than 0.0001 (i.e., $A^{t+1} - A^t \leq 0.0001$) that addresses convergence to a steady state. The vector achieved after consecutive iterations represented the steady states of the factors (A^l) (Glykas, 2010).

As a summary, HFCM is represented by concepts, C_i and linguistically weighted edges among concepts (w_{ij}). Experts make an assessment about the causal relations among the concepts by using the linguistic definitions that are generated by context-free grammar G_H such as at least medium, between high and very high, greater than low. These linguistic definitions are converted to HFLTS according to linguistic term set. Then the set of elements to aggregate of the HFLTS is defined and started to calculate the parameters of the trapezoidal membership function that represents the fuzzy envelope of the HFLTS. Obtained trapezoidal membership functions are defuzzified to crisp values that are accepted the weights of the causal relationships and defined as weight matrix (W) and it is operated in the HFCM until to converge to an equilibrium point (Figure 4.6).

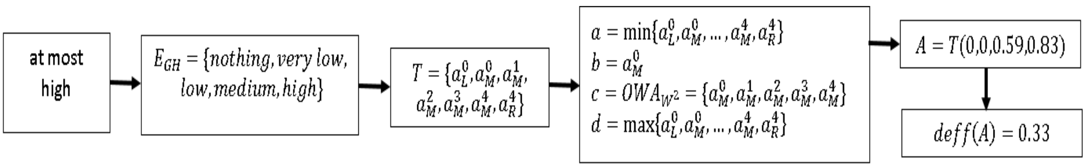


Figure 4.6 : Crisp value obtaining process from HFLTS (adapted from Çoban & Onar, 2017b).

4.7 Modelling Solar Energy Usage with Hesitant Fuzzy Cognitive Map

4.7.1 Obtaining weight matrix

In this study, the "Capacity of New Generated Solar Energy" is defined with ten different factors. The model that represents the causal relationships among factors is graphically generated by the joint agreement of experts (Figure 4.7). Dotted lines represent a negative causality, while the solid lines represent a positive causality relation between the factors in the HFCM.

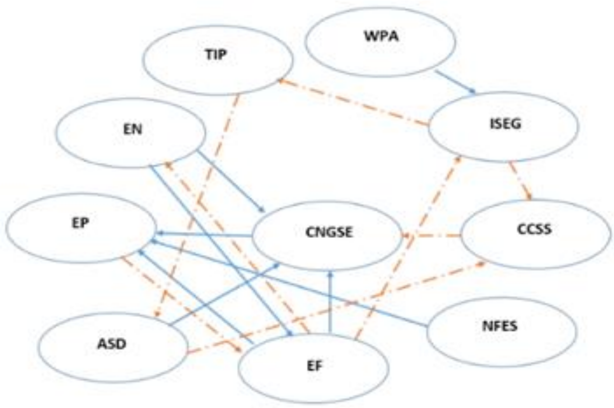


Figure 4.7 : HFCM of Capacity of New Generated Solar Energy factors and relation values based on degree.

The main concept of the study is the "Capacity of New Generated Solar Energy (CNGSE)" and affecting concepts are the other concepts around it. Three experts who are experienced and skilled in renewable and solar energy with either an academic or field experience define the weights of the relations between the concepts. These relations are defined with hesitant linguistic terms since they enable expressing experts' thoughts more naturally. The context-free grammar, S={nothing, very low, low, medium, high, very high, absolute} is used. Table 4.5 shows the linguistic term set for experts' expressions.

Causal hesitant linguistic expressions derived by using context-free grammar and reflect the experts' evaluations are converted into HFLTS (Table 4.6) by using transformation functions (Torra, 2010). Linguistic term set is defined as S={n: nothing, vl: very low, l: low, m: medium, h: high, vh: very high, a: absolute}. In the next step, comparative linguistic statements transformed into HFLTS are represented by a trapezoidal fuzzy membership function $\tilde{A}$=(a, b, c, d) (Table 4.7).

Table 4.5 : Expert's hesitant linguistic assessments about the causal relationships among factors.

	EN	EF	EP	NFES	CNGSE	CCSS	ISEG	ASD	WPA	TIP
EN		(+) between h / a			(+) between vh / a					
EF	(-) greater than vh		(+) between vh / a		(+) greater than vh		(-) between m / vh			
EP		(-) at least vh								
NFES			(+) at least m							
CNGSE			(+) between vl / m							
CCSS					(-) between vh / a					
ISEG						(-) between l / h				(-) at most vh
ASD					(+) at least h	(-) at least m				
WPA							(+) at least m			
TIP								(-) greater than h		

Trapezoidal fuzzy membership function is a useful tool for representing linguistic assessments, therefore it is used to define the fuzzy envelope of the HFLTS. In this step, OWA aggregation operators are selected among the aggregation operators in order to compute the intermediate parameters (b and c) of trapezoidal fuzzy membership function.

Table 4.6 : HFLTS of expert's hesitant linguistic expressions.

	EN	EF	EP	NFES	CNGSE	CCSS	ISEG	ASD	WPA	TIP
EN		(+) {h, vh, a}			(+) {vh, a}					
EF	(-) {a}		(+) {vh, a}		(+) {a}		(-) {m, h, vh}			
EP		(-) {vh, a}								
NFES			(+) {m, h, vh, a}							
CNGSE			(+) {vl, m}							
CCSS					(-) {vh, a}					
ISEG						(-) {l, m, h}				(-) {n, l, vl,m, h, vh}
ASD					(+) {h, vh, a}	(-) {m, h, vh, a}				
WPA							(+) {m, h, vh, a}			
TIP								(-) {vh, a}		

After that, trapezoidal membership functions matrix for each causal relationship between concepts are defuzzified to crisp values in the interval [-1, 1] for each expert and gathered under a single matrix (Table 4.8) as a weight matrix (W).

Table 4.7 : Trapezoidal membership functions of HFLTS of expert's hesitant linguistic expressions.

	EN	EF	EP	NFES	CNGSE	CCSS	ISEG	ASD	WPA	TIP
EN		(0.5,0.8,0.97,1)	(0,0,0,0)	(0,0,0,0)	(0.67,0.83,1,1)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
EF	(0.8,-1,-1,-1)		(0.67,0.83,1,1)	(0,0,0,0)	(0.83,1,1,1)	(0,0,0,0)	(-0.3,-0.64,-0.8,-1)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
EP	(0,0,0,0)	(-0.7,-0.97,-1,-1)		(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
NFES	(0,0,0,0)	(0,0,0,0)	(0.33,0.65,1,1)		(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
CNGSE	(0,0,0,0)	(0,0,0,0)	(0,0.3,0.47,0.67)	(0,0,0,0)		(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
CCSS	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(-0.7,-0.8,-1,-1)		(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
ISEG	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(-0.2,-0.47,-0.64,-0.8)		(0,0,0,0)	(0,0,0,0)	(0,0,-0.8,-1)
ASD	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0.5,0.85,1,1)	(-0.3,-0.65,-1,-1)	(0,0,0,0)		(0,0,0,0)	(0,0,0,0)
WPA	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0.35,0.67)	(0,0,0,0)		(0,0,0,0)
TIP	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(-0.7,-0.97,-1,-1)	(0,0,0,0)	

Crisp values in the weight matrix are described as a directed (positive, negative) weight or no relationships. Weight value, w_{ij} represents the causal relationship between related nodes C_i and C_j, and w_{ii} are equal to zero.

Table 4.8 : Weight matrix of HFCM.

	EN	EF	ES	NFES	CNGSE	CCSS	ISEG	ASD	WPA	TIP
EN		0.863			0.863					
EF	-0.702		0.863		0.930		-0.416			
EP		-0.912								
NFES			0.735							
CNGSE			0.450							
CCSS					-0.888					
ISEG						-0.434				-0.331
ASD					0.878	-0.804				
WPA							0.181			
TIP								-0.901		

Initial state vector of the "Capacity of New Generated Solar Energy" model can also be obtained by experts' opinion and are gathered under the initial state vector (A^0). By using weight matrix (W), initial state vector (A^0) is updated within Equation (4.19) and reached the new state vector (A^t). Iterations in the threshold function is updated until the HFCM reaches convergence at the steady state. The hyperbolic tangent function is accepted as a threshold function and its lambda value that reflects the time dependent changes of the new state values is taken as $\lambda = 0.5$. Iterations are repeated until the difference between the two consecutive state values is equal and smaller than 0.0001 (i.e., $A^{t+1} - A^t \leq 0.0001$). The last state vector is defined as the equilibrium or steady state vector of the map (A^l) (Filev & Yager, 1998).

4.7.2 Scenarios

The following part includes the simulation of different scenarios under the HFCM model. Scenarios represent the various initial states (A^0) of the "Capacity of New Generated Solar Energy" system and are operated to observe the long term changes and impacts of the concepts in the system. Scenarios are designed on the existence of some specific concepts in the system as "1", "0", and "-1", and their behaviors are observed along the consecutive iterations. Changes of the factors during the iterations are reflected on the graphs and by this way system convergences can be observed on a big picture. Factors in the last state vector in the model are named as the active, inactive, ineffective, and influential.

4.7.2.1 Presence of only one factor

In this case, predetermined factors are selected as key factors of a HFCM and other factors are accepted as a lack in the system. "Energy fee," "energy provision," "energy need," and "world protection agreements" such as Paris Agreement, and "availability of solar devices" are selected as the key existent concepts. At this step, the objective is to observe the distinct impacts of these key elements. For example, the "energy fee" is defined as an increasing factor in the system and defined as "1" in the model. Other factors are defined as an ineffective with "0" value in the initial state. As a result, initial state vector will be as $A^0 = [0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ ]$. The worst scenarios also can be described as an absence of the individual factors in the system is defined as "-1" at the initial state (Figure 4.8).

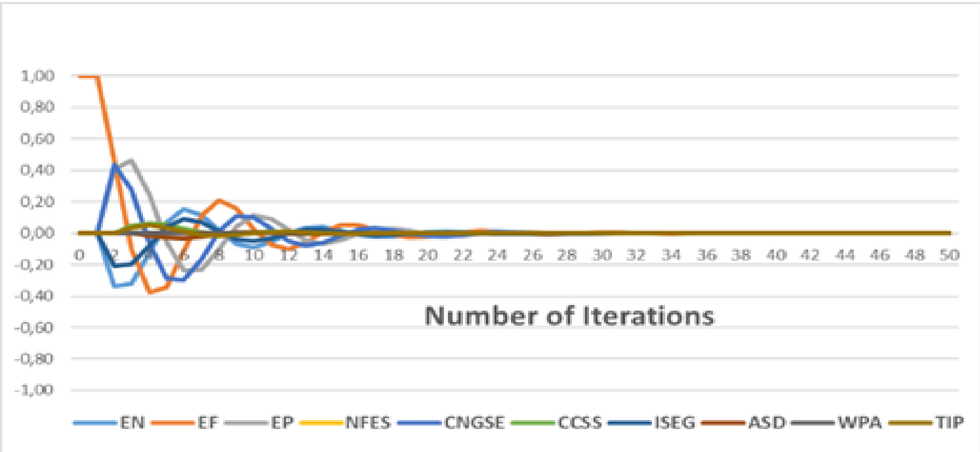


Figure 4.8 : Sample HFCM simulation processes for "Energy Fee" increase.

In this case, three different circumstances are defined, and the changes of the factors are observed at each time step for 50 iterations. The convergence states of the concepts are compared with initial state values.

Scenario 1.1: Decreasing of the energy need is designed as a worst-case scenario. This circumstance can result from the change of the energy consumption behaviors by rules, regulations, directions, energy fee, environmental sensitivity, and many other latent effects. The initial state is $A^0 = [-1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$ and obtained results are as follows (Figure 4.9).

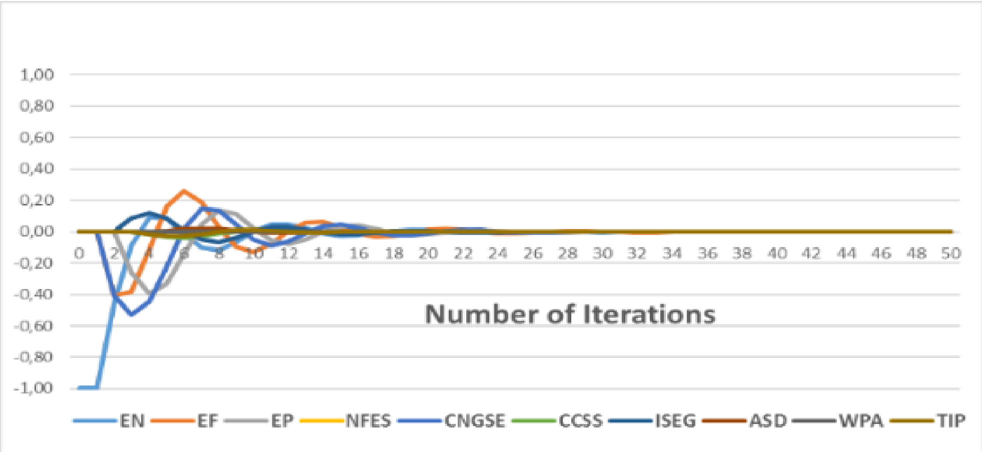


Figure 4.9 : HFCM simulation and convergence process of the Scenario 1.1.

(i) The first reaction of the map is seen in the energy fee as a decrease that causes an increase in the energy need. The new solar power generations are also reduced.

(ii) In the following reactions of the system, energy need (using) started to increase with little rates that it can stem from the rise in the solar energy incentives. The capital cost of solar energy and technical infrastructure problems decrease. At this period of simulation, the capacity of new generated solar energy continues to decline that can result from the response time of the market, long bureaucratic process or distrust to the sector.

(iii) At the third stage, an upward trend of the incentives for solar energy decreases the solar energy capital costs and increases the solar energy technical applicability. These positive reactions increase the capacity of new generated solar energy. At the same period, while energy provision is growing, energy need decreases due to increasing energy fee in the market. When energy fees are going up, the market reacts to improve the equilibrating strategies such as the rise of the incentives for generating the solar energy that causes to decline the capital expense of solar systems and raise the capacity of new generated solar energy.

(iv) Fluctuant (increase/decrease) interactions among different factors repeated until the system converges to the steady state. After 50 iterations, all concepts in the system reach "0" at the steady state. It addresses that energy market will come to an equilibrium state in the long term by the change of its need, provision, and fee. In this stage, market and government players do not modify their main solar energy policies. There is no change observed in the non-fossil fuel energy sources and world protection agreement factors' values. They stay ineffective during 50 iterations due to their transmitter properties.

Scenario 1.2: This scenario is design based on the decrease of the energy fee as a worst-case scenario (with a producer view). This circumstance can result from the surplus provision or technological improvements such as the rise of the energy provision, decline of the energy need, cost reduction on the energy sources and energy technologies. Initial state vector of this worst-case scenario is designed as $A^0 = [0 - 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$ and its operating results in HFCM are as follows (Figure 4.10):

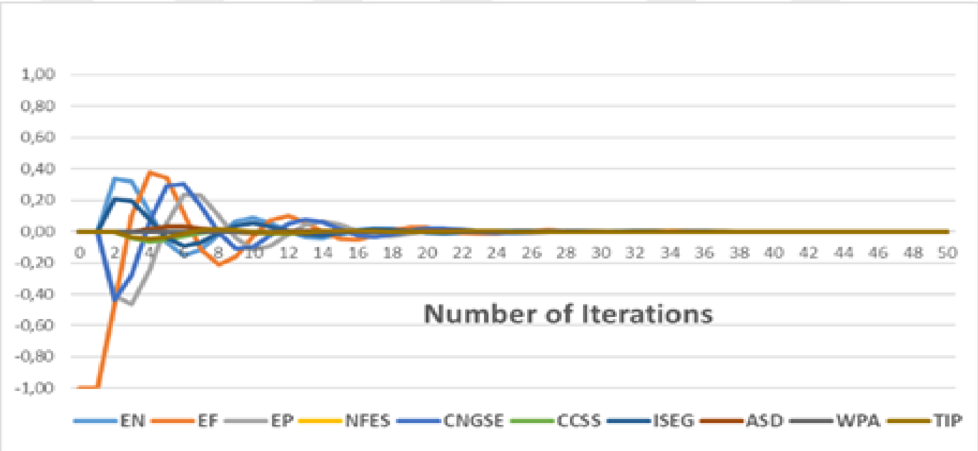


Figure 4.10 : HFCM simulation and convergence process of the Scenario 1.2.

(i) The first reaction of the model aims to close the gap between energy provision and energy need. Model tend towards to increase energy demand and decrease energy provision. This response causes a reduction in the capacity of new generated solar energy and stimulates the governments to subsidize the sector by increasing solar energy incentives.

(ii) The rise of the energy needs and decline of the energy provision stimulated to increase the energy fee. Increasing energy fee and government subsidies on solar energy decrease capital cost and infrastructure problems. This increases the technical availability of solar energy and causes a rise in the capacity of new generated solar energy. The increase in solar power generation increases energy provision and decreases the energy fee increase rate. These reactions cause the new transformation of the system at the midterm.

(iii) Increasing energy provision reduces the interest on the new energy generations that include the generation of solar energy. At the same period, governments increase supports for solar energy. It causes successive effects as increasing the capital cost of solar systems and the technical infrastructure problems and the decrease of the availability of solar devices. Decreasing the capacity of current generated solar energy reduces the rate of energy provision. At the same period, it is observed that energy need increases because of the going down of the energy fee.

(iv) In the long run, the system exhibits the balancing cycle within the free market economy that is based on the equilibrium between the energy provision and energy need. Interactions among factors in HFCM cause small changes in their rates as increasingly and decreasingly, and they converge to the equilibrium point. This balancing cycling covers all concepts except world protection agreements and non-fossil fuel energy sources. Solar energy generation system reaches to the steady state as convergence to the equilibrium point that is zero value and defines no change for each concept at the end of the 50 iterations.

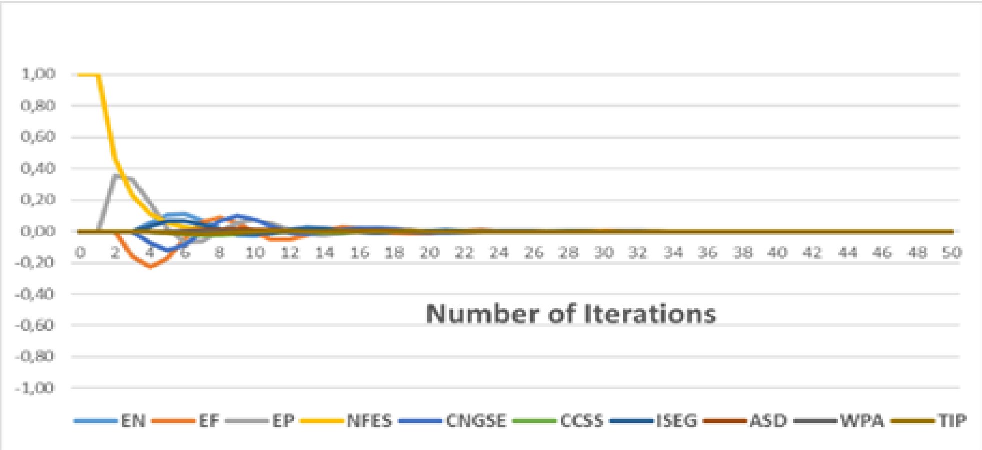


Figure 4.11 : HFCM simulation and convergence process of the Scenario 1.3.

Scenario 1.3: The scenario is established on the green energy sources in the systems. Green energy sources reflect the production of alternative renewable energies out of the solar such as biomass, thermal, wind. It is not affected by other factors in the map as a general sender (transmitter) factor and affects only energy provision. Vectorial definition of the system as an initial state is shown as $A^0 = [0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0]$ and results are as follows (Figure 4.11):

(i) After the initial reactions, energy need starts to increase because of the increasing energy provision and decreasing energy fee. At the same period, the capacity of new generated solar energy starts to go down due to surplus energy provision based on the alternative non-fossil based energy generation. Governments support solar energy generation by enhancing the incentives that decrease the capital cost of solar systems. Technical infrastructure problems decrease and the availability of the solar device with small rates increases.

(ii) When the increase rate of alternative renewable energy is converging to zero, energy provision turns to the downside due to the decrease of the capacity of new generated solar energy. At the same period, the incentives for solar energy are increasing, and energy fee is declining. Energy sector becomes unattractive for investment.

(iii) Towards to end of the period, all factors converge to the equilibrium value (zero) that addresses the steady state of the factors. It refers that there is no change in the states of the factors. For instance, there are no governmental supports by way of directive, regulation, and incentive. The capital cost of the solar systems and energy fee do not change. Energy need and energy provision are stable. There is no tendency to change the solar energy and other renewable energy capacities.

Scenario 1.4: This system is designed based on the positive scenario that includes the presence of the world environmental protection agreements in the new generated solar energy system. World protection agreements involve the compelling regulations and rules that are binding for all countries and have a sanction on the states by implementing the regulations and legislations on their energy generation politics. For example, Paris Agreement and Kyoto Protocol are international agreements that force the governments to fight against global warming to reduce greenhouse effects. Governments generate the politics that direct the energy sector to the non-fossil fuel based energies to reduce the carbon emissions. If there are any agreements to protect the environment and support the solar energy generation at the global scale, the initial state of the system can be shown as $A^0 = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1]$ and operating results of the HFCM will be as follows (Figure 4.12):

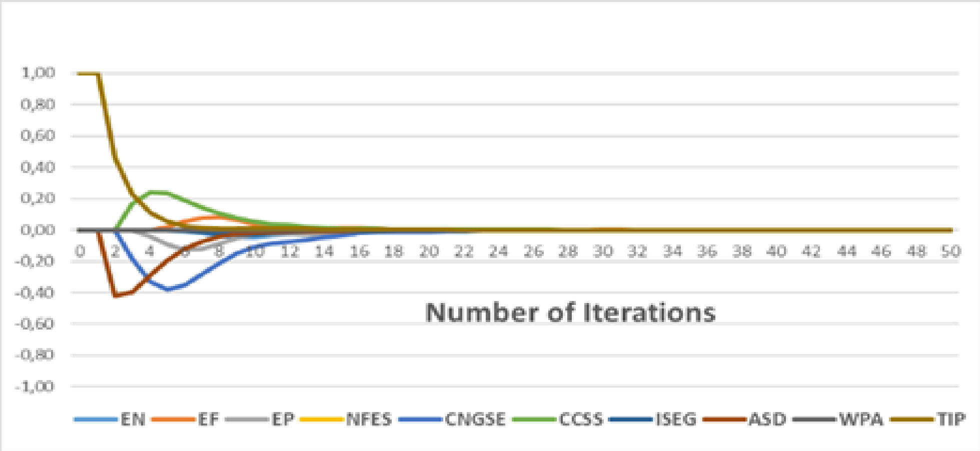


Figure 4.12 : HFCM simulation and convergence process of the Scenario 1.4.

(i) World protection agreements that aim to reduce greenhouse effect and global warming obligate the governments to improve their renewable energy capacities. The regulations related to global environmental agreements about solar energy enhance the incentives to generate solar energy. It reduces the capital cost of solar systems and technical infrastructure problems and increases the availability of solar devices factors. These factors are the basis for the new generation of the solar energy and cause to increase its capacity. At the beginning stages, while the effects of the world protection agreements are decreasing, no changes are viewed in the provision, need, and fee of the energy.

(ii) Solar energy incentives act together with world protection agreements until the end of the iterations. The capital cost of solar systems, availability of solar devices, and technical infrastructure problems reflect the parallel behaviors with solar energy incentives. There is an increase in the capacity of new generated solar energy in the short term. These improvements activate the energy market such as the rise of the provision and need of the energy, and the decrease of energy fee.

(iii) At the long term, factors converge to the equilibrium value (zero) at the stationary state that indicates the model balance and the system stay stable after that time. Extinction of the world environmental protection agreements means that governments apply all compelling targets that are executed with laws and regulations. This circumstance obviously shows that world protection agreements related to solar energy have significant influences on the capacity of new generated solar energy.

4.7.2.2 Combination of the different system cases

In this case, combinations of some concepts that are determined by experts' common view are considered as a significant contribution to the capacity of new generated solar energy systems. Selection of the factors in the combinations conform to the real world circumstances, and they reflect experts' opinion that is fed by their knowledge and experiences. There are 1012 possible combinations of the factors, but this study considers only four scenarios to observe the system behavior and capacity of new generated solar energy in HFCM model at the long term.

Scenario 2.1: Scenario evaluates the rise of the energy need and fees and existence of world protection agreements. This scenario tells that while need and fee of the energy are going up, the effects of the world protection agreements such as Paris Agreement and Kyoto Protocol are also increasing. This state also involves the contrast between awareness of environmental protection and energy trend. Initial values of this scenario are defined as $A^0 = [1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0]$ and results of the model can be given as follows (Figure 4.13):

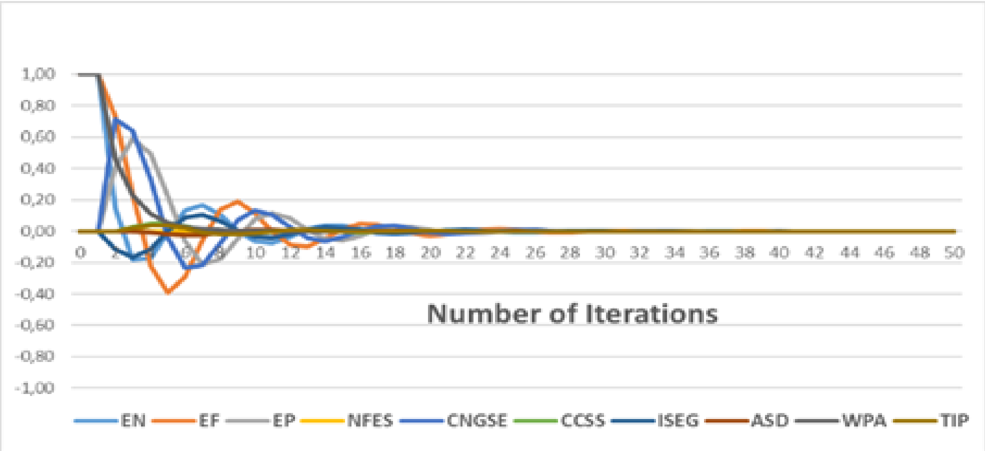


Figure 4.13 : HFCM simulation and convergence process of the Scenario 2.1.

(i) The HFCM model tends to reduce the impacts of the initial existing factors in the system. The highest decrease can be observed in demand for energy (85%), and the lowest decrease is in energy fee (27%). The decrease of the world protection agreements (54%) stays in the average rate. No changes are observed in values for the availability of solar devices, technical infrastructure problems and capital cost of solar systems, while the capacity of new generated solar energy, energy need, energy fee, and energy provision are increasing and incentives for solar energy generation is decreasing at the initial iteration. The capacity of new generated solar energy is the highest increasing factors in the model due to the high impacts of energy need, energy price and world protection agreements.

(ii) The increase in the world protection agreements at the low rate starts to show their impacts on the capital cost of solar systems and energy fee through the growth of the capacity of new generated solar energy in the medium period. Increasing energy provision with solar energy generation decreases energy fee and increases energy need. Non-fossil fuel energy sources that are transmitter factor stays stable at zero value throughout iterations.

(iii) World protection agreements protect their positive (increasing) existence until they convergence at the steady state. Besides this unchanging situation, other concepts shift their positions from increase to decrease or vice versa to react and balance the energy system in the long period. It is not observed any direct or parallel reaction among these factors and other factors in the system. For example, while incentives for solar energy generation are increasing in some iteration steps, the capital cost of solar systems increases or decreases at the same steps. Concepts reach to zero convergence values at the steady state after 50 iterations. Steady state refers that no changes will occur in the model as growth or reduction of the activation levels.

Scenario 2.2: This scenario considers both the positive (increasing) and negative (decreasing) influences on the solar energy generation capacity. In this scenario, increase the incentives, non-fossil fuel energy sources and world protection agreements whereas the reduction in the availability of solar devices is analyzed. Reference state values are defined as $A^0 = [0\ 0\ 0\ 1\ 0\ 0\ 1 - 1\ 1\ 0]$ and results are as follows (Figure 4.14):

(i) While non-fossil fuel energy sources and world protection agreement factors are keeping their trends with high rates until the convergence, the sign of the incentive for solar energy generation and availability of solar devices factors change, and they lose their influences with low rates at the same term. At the first iteration, the highest changes are viewed on the non-fossil fuel energy sources, availability of solar devices and world protection agreements factors with same rate (54%) and the lowest change is observed on the technical infrastructure problems with 16%. In this period, energy need and energy fee protect their situations as staying stable, while energy provision and capital cost of solar systems are increasing and capacity of new generated solar energy and technical infrastructure problems are decreasing with a low rate.

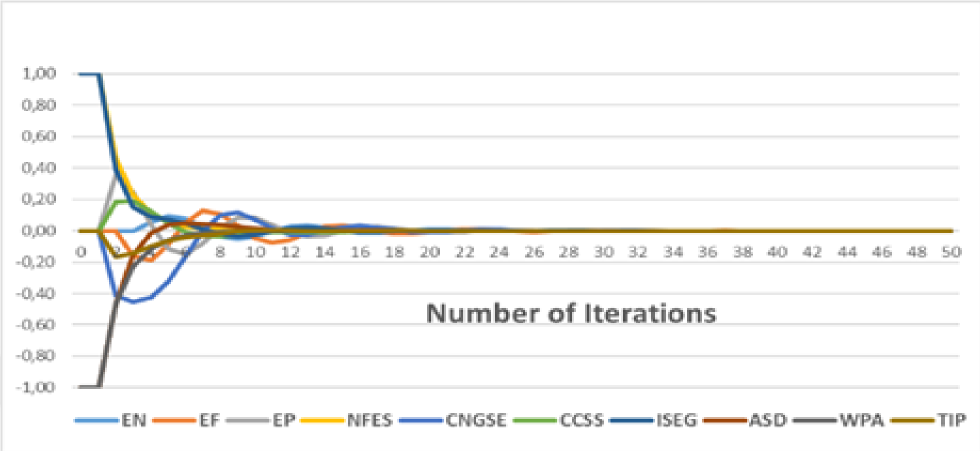


Figure 4.14 : HFCM simulation and convergence process of the Scenario 2.2.

(ii) The availability of solar devices factor changes its state from decrease to increase that means technical availability for generating the new solar energy starts to grow in the medium period. Remaining concepts protect their trends, but their effects are diminished gradually at the same time range. Increasing incentive on the solar energy shows its impacts on the capital cost of solar systems as decreasing and also causes to increase the capacity of new generated solar energy. Increasing capacity of new generated solar energy and alternative renewable energy enhance the energy provision. Increasing energy provision causes the partial decreases on the energy fee at the initial steps, but subsequent stages energy need decreases.

(iii) Non-fossil fuel energy sources and world protection agreements' influences decline at the long term. Until the steady state, the incentive for solar energy and availability of the solar device keep their high influence levels. All concepts exhibit the different properties throughout iterations such as while energy fee is increasing, energy need and energy provision are decreasing at the same time. These reactions of the system reflect its complexity and dynamism that it also indicates the real-world market. The model reaches a steady state that it refers the no-change in their behaviors.

Scenario 2.3: This scenario focuses on out-degree (transmitter – global sender) factors of solar energy generation system in the HFCM model which are non-fossil fuel energy sources and world protection agreements. State vector at the beginning is defined to enhance the capacity of new generated solar energy in the long term. Therefore, the model is theoretically designed as of increase of world protection agreements and the decrease of the non-fossil fuel energy sources in the system. Values at the basic state are defined as $A^0 = [0\ 0\ 0 - 1\ 0\ 0\ 0\ 0\ 1\ 0]$ and results of the HFCM operations as follows (Figure 4.15):

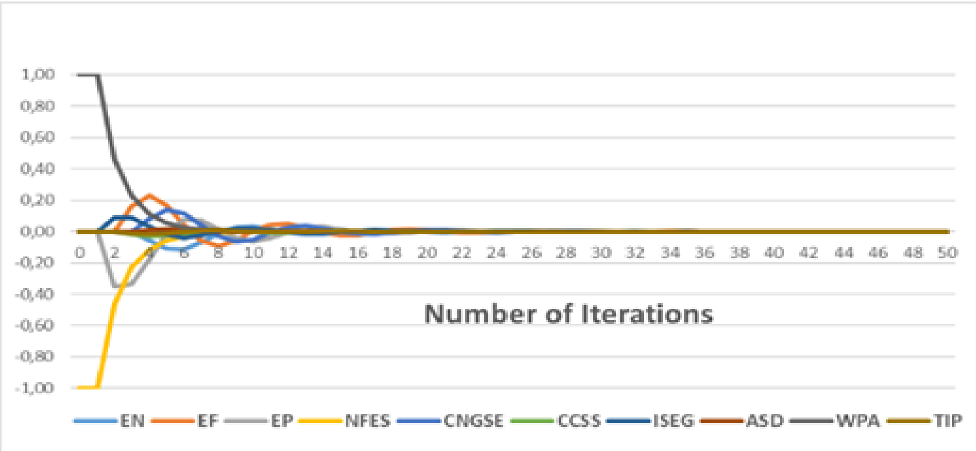


Figure 4.15 : HFCM simulation and convergence process of the Scenario 2.3.

(i) At the first iteration, current concepts at the beginning state protect their positions and their signs do not change but are reduced their influence within similar rates (54%). Energy need, energy fee, the capacity of new generated solar energy, the capital cost of solar systems, availability of solar devices, and technical infrastructure problems factors stay stable during the same period. Initial reactions are observed on the energy provision and incentive for solar energy within fractional rates as increase and decrease respectively. They can be accepted as trigger factors of the scenario that they can directly activate the majority of the factors. Following iterations show that this can be seen as an acceptable result when capital cost of solar systems and technological infrastructure problems are decreasing, and availability of solar devices and capacity of new generated solar energy are increasing at the same period.

(ii) Non-fossil fuel energy sources and world protection agreements continue to protect their signal effects within reducing rates in the long term. Other factors in the model change their position compared to their initial state. The basic reason for this cycle along iterations is the free market economy whose reactions equilibrate the market around the energy provision and energy need. Energy fee has significant influences on the other factors in the long term, and other factors lose their influences shortly.

(iii) In the long term, first non-fossil fuel energy sources and world protection agreement reach to steady state. The last factor that reaches to steady state is the capacity of new generated solar energy. State values of the concepts fluctuate around the steady state value to equilibrate the model, and in the last stage of the iterations, they reach to the converged "zero" values that represent the stable condition of the model.

Scenario 2.4: This scenario is designed for a positive availability of all concepts positively in the systems and their states at the beginning of the model are described as $A^0 = [1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 1]$. This initial state also involves some meaningly converse factors such as the relationship between energy need and energy fee at the same time. At the end of the iterations, the solar energy generation based system reaches to steady value as zero which means the stable equilibrium circumstances of the factors in the long term. Outcomes obtained from the iterations as follows (Figure 4.16):

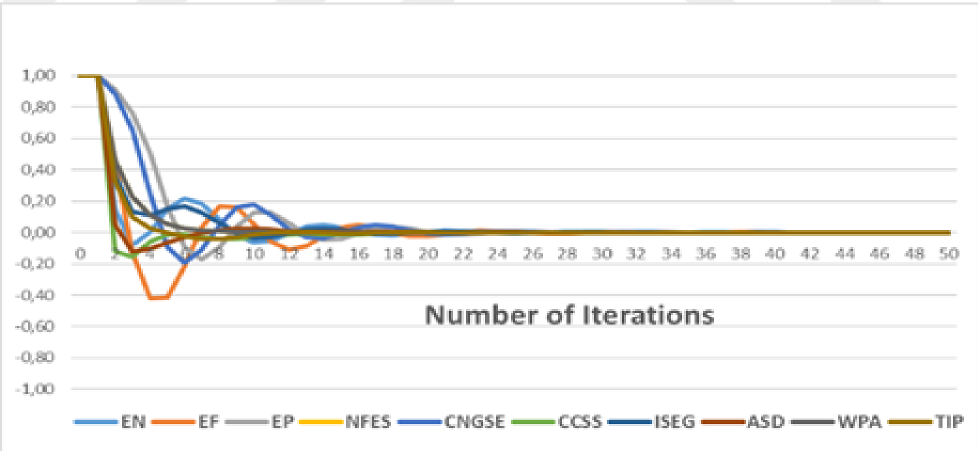


Figure 4.16 : HFCM simulation and convergence process of the availability of all concepts.

(i) At the first iteration, except the capital cost of solar systems factor, rates of all other concepts show a decline but stay in positive range. The capital cost of solar systems' increase (positive) rate turns down to decrease (negative) state due to its inverse relationships with an incentive for solar energy generation and world protection agreements. These interactions cause to increase the capacity of new generated solar energy and energy provision and decrease the energy fee factors in the short term. Increasing incentive on the solar energy enhance its generation and reduces the interest on the alternative renewable energy generation in the long term. After green energy sources reached the zero state value that means there is only installed renewable energy operations, changes in the rate of the capacity of new generated solar energy result from energy provision and energy need changes. Rapid declines are observed on the world protection agreements and green energy sources, and they converge to the stable rates that it stems from their general sender properties.

(ii) Following iterations (times) system converge to balance the energy fee within economic and legal regulations. In this step, incentive for solar energy generation, energy needs, and energy provision play a fundamental role within their increasing and decreasing loops in the model. For example, the decline of the capacity of new generated solar energy also causes to reduce the energy provision that increases the fee and decreases the needs of the energy. At this step, the model tends to transform the system to the equilibrium period.

(iii) All factors in the model converge to steady value "zero" after iterations. The steady circumstance of the system at the steady value displays the equilibrium of the new solar energy generation system. It means that they do not change their position in the long term. Energy fee and capacity of new generated solar energy converge to steady state before energy provision, energy need, and incentive for solar energy incentive.

Only four sample scenarios have been evaluated in the system where 1024 different start-up scenarios can take place. Scenarios are based on the factors that are suggested by the experts because they have a strong influence on the solar energy generation system and they are thought to reflect the behavior of the system more clearly. According to different factor characteristics in the scenario, other factors in the system react differently, and the system reaches the equilibrium state in various ways. In general, solar energy generation based on need-provision balance appears to be significantly influenced by changes in local and global incentives and supporting policies. Global protection agreements have a profound and indirect influence on solar energy generation because they support other non-fossil fuel energy sources.

4.8 Conclusion

In this study, we focused on two main titles that are “Solar Energy” and “Hesitant Fuzzy Cognitive Maps.” Solar energy is an important energy source among the renewable energies by provided abundant, infinite and environmentally friendly advantages as an origin of the all other energy sources. Although solar energy has significant advantages on environmental, economic and health, it also has some disadvantages such as high capital cost, technical infrastructure problems, and weak technical applicability. This situation creates uncertain and hesitant conditions for investors and governments about their decisions on the solar energy investment. At this stage, we applied a HFCM approach with using HFLTS and FCM. HFCM is a useful tool that allows integrating the various linguistic evaluations assigned by experts. By this way, investors or governments can evaluate their conditions in the local or global energy sector and express their opinion linguistically. These linguistic expressions can be operated in the HFCM model and transformed into the crisp values that will be more comprehensible and usable for their decisions.

We performed an application with different scenarios that represent the various cases in the new solar energy generation model to reveal our academic outcomes. Applications verified the theoretical expectations and logical consistency among the factors in the model. The HFCM operations of the system represented the free market economy that balances the solar energy market on its key factors such as energy need, energy provision, and energy fee. These results solved the real life problems also represent the validity of HFCM operations and the consistency of the solar energy generation model.

Although HFCM delivers a comprehensive tool for modeling complex systems, they have several limitations. The interpretation and the results mostly rely on the expert knowledge. Therefore, the selection of experts has a crucial importance in developing HFCMs. We should be cautious when drawing conclusions from HFCM. In order to increase the validity of the proposed HFCMs, the study must be in line with the relevant academic studies.

Future research will focus on the extension of the solar energy generation model with latent and current factors that can be improved by literature and field researchers. By this way, we aim to reveal the specific factors of the solar energy generation and define the useful model by investors and governments. Furthermore, future research will focus on improvement of the FCM that will be a useful tool for expressing experts' thoughts more naturally with their natural language as words or sentences.

5. STRATEGIC ANALYSIS OF SOLAR ENERGY PRICING PROCESS WITH HESITANT FUZZY COGNITIVE MAP [4]

Energy which allows people to live a more productive life is basically provided with six power sources and they can be transformed from one form into another as mechanical, chemical, thermal, radiant, nuclear, and electric. The primary energy sources commonly used in the world (85.52% of total energy consumption) are fossil based (coal, gasoline, natural gas) (BP, 2017). The increase in fossil fuel consumption leads to the increased atmospheric release of greenhouse gases, especially CO_2. Global warming and climate changes caused by greenhouse gases are an essential part of the economic, social and environmental problems. Therefore, the use of fossil-based fuels in energy-intensive conditions is the most precise indication of the human impact on climate change (Stern, 2015). Greenhouse effect, global warming, and climate change have led governments to turn to renewable energy sources (sun, wind, hydroelectric, biomass) as an alternative to fossil energy sources. The National Science Academies of the G8 countries reported that a joint action against climate change should be undertaken and urged governments to reduce CO_2 emissions by 50% below 1990 levels by 2050 (The National Academies of Sciences, 2009).

In the long run, production of electricity from coal, oil and natural gas is expected to be replaced by entirely renewable energy sources (Figure 5.1). However, the significant disadvantages of renewable energy production against traditional energy sources are that they are more expensive and less reliable (Conkling, 2011). The difficulties in using renewable resources are also as follows: political uncertainty, the tendency of countries to move away from FITs and green certificates, changes in subsidies and the need to integrate renewable-based systems with existing power plants.

[4] This chapter is based on the book chapter Çoban, Veysel, and Sezi Çevik Onar. "Strategic Analysis of Solar Energy Pricing Process with Hesitant Fuzzy Cognitive Map." In *Energy Management—Collective and Computational Intelligence with Theory and Applications*, pp. 195-227. Springer, Cham, 2018.

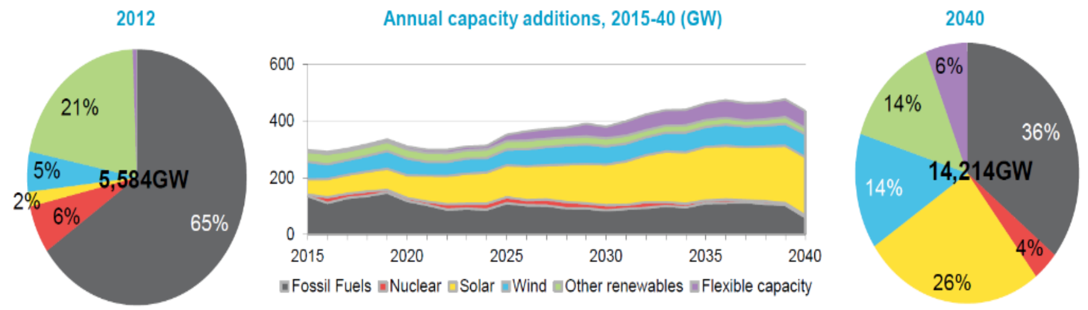


Figure 5.1 : Annual capacity additions and expectations until 2040 (Bloomberg New Energy Finance, 2015).

In order to promote the use of solar energy, which is the most important renewable energy source, it must be able to compete with other renewable and traditional energy types. Regulatory policies, fiscal incentives, and public financing bases shape the countries' support for developing solar energy capacity. For example, Turkey uses feed-in tariff/premium payment, biofuels obligation/mandate, capital subsidy, grant, or rebate, and public investment, loans, or grants methods as promotion policy (Crawley, 2016).

Price, which is the most important competitive factor in energy and all other markets, is an important measure for the adoption and diffusion of solar energy technologies. Therefore, the fundamental factors that are effective in solar energy pricing are defined and the relationship between them is modelled in this study. The national and international factors that influence solar energy pricing in the energy market include uncertainty and hesitancy. Hence, the HFCM model is utilized for developing the causal relationships of solar energy pricing. The causal relationships among the active factors in the solar energy HFCM pricing model are defined, and their effects on the solar energy pricing are reflected in the equilibrium state.

5.1 Solar Energy Pricing

Governments should access sustainable, quality and cheap energy sources to support and sustain their economic and social development. Increasing population leads to further increase in demand, hence, new energy generation methods are developed to meet this increasing demand. However, the use of fossil-based energy sources to meet rising energy demand creates environmental and economic problems (Thomas, Ashok, & Jose, 2011). Therefore, the countries have turned to renewable energy sources, especially solar with the support of national and international decisions and agreements. India, for example, has set a goal of increasing solar energy capacity from 5.2 GW in 2016 to 100 GW by 2022 (World Energy Council (WEC), 2016). Similarly, Turkey has set a target to increase the solar energy capacity of 2 GW at the end of 2017 to 5 GW in 2023 (PV-Magazine, 2017).

The price of energy is the most critical determining factor for the acceptance of renewable energies by the society and investors. Correct pricing is advantageous for energy providers to optimize capacity planning and for consumers to minimize energy costs. Energy pricing and forecasting of energy needs allow appropriate energy capacity planning, financing technologies and investments in energy diversity, and enabling investors and governments to develop stable policies (Mir-Artigues & Del Río, 2016). In particular, the economic depression and poverty caused by the rise in energy prices in the 1970s and 1980s led to the development of new policies and models based on energy availability and cost (Timilsina, Kurdgelashvili, & Narbel, 2012). Knowing the factors that affect energy prices and understanding their impact on the energy market is the starting point for solar energy pricing. The energy price (EP) is determined by the installed capacity, not by the actual energy production (Zatzman, 2012). The total energy price is calculated taking into account factors that cause economic effects and components based on performance. Factors defined in the price calculation include uncertainty, which may vary locally and temporally.

Factors affecting solar energy pricing

In this section, factors affecting solar energy pricing are defined, and causal relationships among factors are explained in the model. Causal relationships are evaluated and how the factors affect each other in the long run are observed under the HFCM model. Thus, factors that determine solar energy prices and the causal relationships between the factors shown and the decision making processes of the government and investors in the long term accurately directed.

The main factor driving a country to use renewable energy from fossil energy consumption is the conscious governments know that fossil fuels are behind their country's environmental, economic and social problems (Environmental Effects, EE and Eco-social Effects, ESE). The anticipation of the deterioration of agricultural production and living conditions caused by the change of climate change and vegetation cover is at the basis of environmental concerns. Governments develop national and international directive laws and regulations (Global treaties, GT such as Kyoto Protocol) to manage the use and widespread of renewable energies in the community. Laws and regulations differ among countries according to their renewable energy potentials (Çoban & Onar, 2017b). National regulations are severely affected by international agreements and supportive policies.

The trend towards renewable energies revealed the technical and technological infrastructure problems (IP). Having different characteristics of the environmental conditions of the energy plants reveals the infrastructure requirements of the plants and affects the initial costs and solar pricing. Therefore, the use of renewable energy has a significant price disadvantage against the use of fossil based energy. In contrast, governments' policies to support renewable energies provide price competition against fossil fuels.

The supportive laws and legislations (SLLs), which aim to generate electricity from solar energy source, specify the procedures and principles for the realization of electricity generation in the country. Incentives (Figure 5.2), which are applied in many countries around the world, are aimed at eliminating energy dependency by supporting renewable energy sources. Supporting, encouraging and inhibiting the solar energy investments can be covered by the cost of energy companies that do not produce renewable energy (Energy and Natural Resources Ministry (ENRM), 2017a). This situation, which causes fluctuations in the general energy prices, causes solar energy prices to fluctuate in an indefinite range.

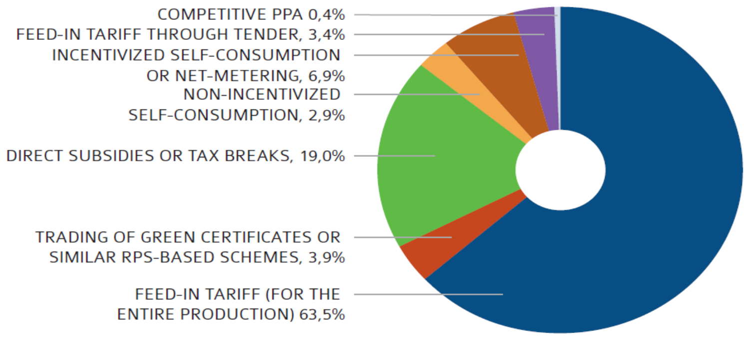


Figure 5.2 : Historical market incentives and enablers (International Energy Agency (EIA), 2016b).

The most common support scheme for the development of solar energy systems is feed-in tariff (FIT). FIT for entire production (FITEP) guarantees that the electricity generated from a solar energy system and transmitted to the grid is purchased at a predefined price for a specified period (Crawley, 2016). For example, the purchase of electricity generated by facilities that produce electricity using solar energy sources is committed by the state at a fixed price (0.133 $/kWh) for ten years in Turkey (Energy and Natural Resources Ministry (ENRM), 2017a). The support provided by the FIT policy is financed by tax revenues or by taxation on companies generating energy without renewable energy. The accurate determination of support price and duration values in FIT plans has a critical precaution for solar energy and general energy pricing. High-priced and long-term support leads to a decline in energy prices and a deterioration of the market balance (Spain 2008, Czech Republic 2010, Italy 2011) (Mir-Artigues & Del Río, 2016). In addition, if domestic producers supply mechanical and/or electromechanical components used in grid-connected solar energy generation facilities, these facilities benefit from price supports. For example, if the solar energy plant established in Turkey supplies its equipment and materials from domestic manufacturers, it wins an additional domestic contribution to FIT for five years (Energy and Natural Resources Ministry (ENRM), 2017a). If the PV modules in the installation of the PV solar energy plant are produced in Turkey, 1.3 US cents/kWh domestic production contribution is given for five years.

FIT with tender (FITT) is an alternative method of providing FIT support to reduce the cost of PV electricity. Competition with the tender procedure enables to draw the solar energy price to the lowest possible level and to reduce margins. This support method reflects how low the bids can be under competitive bidding conditions. Low bids can only be realized if the market has low capital costs, low component costs, and a low risk (International Energy Agency (EIA), 2016b).

The direct capital subsidy (DS) is the most straightforward way for governments to promote solar energy installations. The system investment cost is made attractive with this single-process subsidy method (Centre for Environment and Energy Development (CEDE), 2014). Direct capital subsidies are the financial support through taxation (tax breaks, TB) for upfront investments in solar energy systems according to their off-grid and on-grid connections (Crawley, 2016).

The Renewable Portfolio Standard (RPS) is a market mechanism based on a plan to gradually increase electricity generated from renewable energy sources (wind, biomass, geothermal and solar). Competition between renewable energies is achieved through this market-based approach. Thus, the use of renewable energy sources is continuously promoted and the cleanest energy is achieved at the lowest price (Union of Concerned Scientists, 2015). RPS and related approaches determine a share of electricity that must be generated from a particular renewable energy source. This incentive plan allows renewable electricity producers to charge a market-based fee for the electricity they give to the grid (Crawley, 2016).

Self-consumption is the independent supply of individual energy needs from the small scale solar energy systems established on the residential roof. Although self-consumption systems have high costs compared to utility-scale systems, their price advantages provided by individual investors (non-incentivized self-consumption, SCNI), in the long run, can make their use even more widespread. Sustainable building regulations have increased the interest in using solar tools (photovoltaic, solar water heater and passive solar energy) as a source of heating and electricity. The use of solar energy technologies in construction can be supported by environmental regulations and legislation to reduce the energy footprint of buildings (incentivized self-consumption, SCI). Net metering (NM) is a system that helps to arrange energy billing by following the consumed electricity by the structures and the generated electricity by the solar energy system. Electricity generated by the net-metered solar power system of the residence meets the residential energy demand primarily, and the increasing electricity is supplied to the grid. If the residential solar power system generates more electricity than needed during the billing period, net metering customers receive bill credits. The investment of solar energy is depreciated in a shorter period, and solar energy prices are affected positively with this system (International Energy Agency (EIA), 2016b).

Power Purchasing Agreements (PPAs) are a standard business model for meeting near-energy demands with electricity generated from grid-connected medium-sized solar power systems inbuilt. The system owner sells the generated electricity through a direct connection to the nearby consumers. Thus, consumers' demand for mains electricity is reduced, and a lower selling price for electricity generated from solar energy arises. The system based on profitability is affected by the electricity cost of the grid that is shaped by the electricity supply-demand (Crawley, 2016; International Energy Agency (EIA), 2016b).

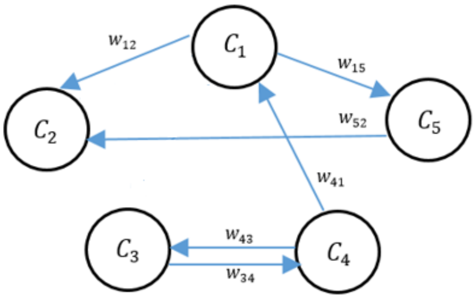
Technical and political support increases the installation of solar energy facilities and solar energy generation capacity. The increase in the generation capacity of solar energy contributes to the stabilization of total energy demand and energy supply (ES) and determines the price of solar energy in the energy market. Improvements in the solar energy technology (SETI) increase solar energy production potential by reducing the costs of solar energy installation and by developing the infrastructure requirements for installation. Economic components (EC) for solar energy pricing can be shaped with capital cost, return on equity, interest on loan, depreciation, operation and maintenance expense, insurance, taxes, service charges, and cost escalation factor (Thomas et al., 2011). In addition to these critical economic factors, installed capacity, capacity utilization and penalty factors have an important influence on pricing.

The ever-increasing world population brings with it the increase in production and consumption. The total amount demanded of energy, which is the basic element of production and consumption, is called energy demand. In order to meet the rising energy demand, it is necessary to use the sun and other energy resources together to generate energy supply. Energy prices (as a combination of renewable and non-renewable energy prices, REP/NREP) are an important factor in achieving a balance between energy demand and supply. The installation of new solar power plants and the increase in the total installed solar capacity contribute to energy supply and indirectly affect energy prices.

The support and encouragement for the dissemination of solar energy reduce the availability of existing and widespread fossil-based energy production systems and equipment. In this case, the perceived damage of fossil-based investments, existing industrial system, and production technologies lead to the emergence of anti-solar energy policies. However, the ease of transportation and storage of fossil-based energies causes serious cost disadvantages to solar-based energy systems.

5.2 Fuzzy Cognitive Maps

FCMs, which are an extension of cognitive maps with fuzzy logic, enable recognizing causal relationships among components in complex systems. Fuzzy Cognitive Maps (FCM), fuzzy graphical structures representing causal reasoning, are defined by Kosko (Kosko, 1986). An FCM is represented with signed and directed graphs showing concepts and causal relationships among concepts. In graphical notation, concepts are represented by nodes and denoted as C_i, and causal relations among nodes are represented by weighted edges and denoted as w_{ij}. The weight value of the edges expresses the fuzzy strength of causal relations and is represented by fuzzy numbers. Graphical representation of complex systems with FCM allows visual representation of concepts and directional relationships among them.



	C_1	C_2	C_3	C_4	C_5
C_1	0	w_{12}	0	0	w_{15}
C_2	0	0	0	0	0
C_3	0	0	0	w_{34}	0
C_4	w_{41}	0	w_{43}	0	0
C_5	0	w_{52}	0	0	0

Figure 5.3 : A sample FCM and relation matrix.

Figure 5.3 represents a simple FCM model with five members (C_i) and six weighted edges (w_{ij}) between these members. Weights expressed regarding the causal relationship between concepts are expressed as the values between [-1, 1]. The positive and negative sign of relationship weight expresses the direction of the relationship between concepts. The absence of a causal relationship between concepts indicates that the weight value is zero. The change in any concept in the FCM model, which has the fuzzy feedback loop feature, causes to change the current state of the other concepts in the system. If all the factors in the model reach an equilibrium state, the feedback loop process is terminated (Kosko, 1997). Since the factors in the FCM are not self-feedback (i.e., no self-causal relationship), the diagonal value of the weighted relationship matrix is zero. Subjective information based on expert knowledge and experience or objective information obtained through methods such as literature review is used to identify the concepts and fuzzy causal relationships between concepts in the FCM (Çoban & Onar, 2017b).

Some structural criteria reflect the model factors and general model characteristics. Transmitter refers to the factor affecting other factors but not being affected by other factors. Receiver refers to the factor affected by other factors but not affecting other factors. Ordinary refers to the factor affecting other factors and influenced by other factors. Centrality represents the sum of the influence values of the factor (Papageorgiou, 2013). The total value of the relationships that are directed to a factor is defined as "in-degree." The sum of relations from one factor to the other is called "out-degree."

The weight values of causal relations in the FCM can be determined using triangular, trapezoidal, sigmoid, Gaussian functions or fuzzy linguistic terms. The FCM model operates using fuzzy arithmetic operators, and defuzzification methods (weight centers, center area, and weighted average method) are used to transform the fuzzy values reached in the steady state to crisp values in the range [-1, 1]. A_i^t denotes the state value of the concept C_i in time t, and the general state values for all concepts in FCM can be shown in the form $A^t = [A_1^t, A_2^t, \ldots, A_n^t]$. The next state value of concept i (C_i) reaches after each iteration is defined as:

$$A_i^{t+1} = f\left(\sum_{j=1}^{n} A_j^t\, w_{ij} + A_i^t\right) \quad (5.1)$$

where $f(.)$ is the threshold function that is used to transform the sum of the previous state value (A_i^t) and the total causal effects. The most commonly used transformation (threshold) functions are hyperbolic tangent and sigmoid functions that get values in the range $[0,1]$ and $[-1,1]$ respectively.

$$\text{Sigmoid function: } f(t) = \frac{1}{1+e^{-\lambda t}} \quad (5.2)$$

$$\text{Hyperbolic tangent function: } f(t) = \tanh(\lambda t) = \frac{e^{\lambda t}-e^{-\lambda t}}{e^{\lambda t}+e^{-\lambda t}} \quad (5.3)$$

The optional lambda parameter (λ> 0) in the functions is used to determine the appropriate slope of the function. The value x represents the internal calculation performed on the new state vector. If the difference between the two state values ($A_i^{t+1} - A_i^t$) for each concept is 0.001 or less, the iterations are terminated, and the final state is called as a steady state (Papageorgiou, 2013).

5.3 Preliminaries

5.3.1 Hesitant fuzzy sets

Fuzzy set theory was developed by Zadeh (Lotfi Asker Zadeh, 1996) to model and calculate uncertainty and vagueness using mathematical methods. The fuzzy set theory, which is oriented towards solving complex everyday life problems, has been applied to a wide range of scientific fields such as decision theory, energy management, and artificial intelligence methods (Michael, 2010; Papageorgiou, 2013). New extensions of fuzzy sets are developed to produce more accurate approaches and solutions to the complex and ambiguous problems encountered in everyday life

(Krassimir T Atanassov, 1986; Mizumoto & Tanaka, 1976; Torra, 2010). The Hesitant Fuzzy Sets (HFSs), developed by Torra in 2010 (Torra, 2010), are aimed at dealing with the situations where more than one value of a membership of the fuzzy clusters may be possible. In HFS, a function is defined that returns a set of member values for each element in the domain (Torra, 2010).

HFS, defined on the reference set (X), is expressed as a function (h) that returns a subset in the range $[0, 1]$. The mathematical representation of the expression is as follows:

$$\mathrm{h}: \mathrm{X} \rightarrow \{[0,1]\} \tag{5.4}$$

The association of HFSs for a set of N membership functions is represented as $\mathrm{M} = \{\mu_1, \mu_2, \dots, \mu_\mathrm{N}\}$ and shown as:

$$\mathrm{h_M}: \mathrm{M} \rightarrow \{[0,1]\} \text{ and } \mathrm{h_M}(\mathrm{x}) = \cup_{\mu \epsilon \mathrm{M}} \{\mu_\mathrm{x}\} \tag{5.5}$$

The upper and lower bound of the hesitant fuzzy set h is given as (Torra, 2010):

$$\mathrm{h}^-(\mathrm{x}) = \min \mathrm{h}(\mathrm{x}) \text{ and } \mathrm{h}^+(\mathrm{x}) = \max \mathrm{h}(\mathrm{x}) \tag{5.6}$$

Some basic operations (complement, union, and intersection) of the HFSs can be defined as follows (Torra, 2010):

$$h^c = \cup_{\gamma \in h(x)} \{1 - \gamma\} \tag{5.7}$$

$$(h_1 \cup h_2)(x) = \{\, h \in (h_1(x) \cup h_2(x)) |\, h \geq max\{h_1^-, h_2^-\} \tag{5.8}$$

$$(h_1 \cap h_2)(x) = \{\, h \in (h_1(x) \cup h_2(x)) |\, h \leq min\{h_1^+, h_2^+\} \tag{5.9}$$

where h represents the hesitant fuzzy set.

5.3.2 Hesitant fuzzy linguistic term sets

Linguistic knowledge using words or phrases is applied to solve daily life problems which cannot be expressed by numerical values. The linguistic expressions used to identify and solve problems are a tool that best reflects people's perceptions and knowledge (Lotfi Asker Zadeh, 1975). The fuzzy set theory is dependent on linguistic variables which are fuzzy variables. The fuzzy linguistic approach, which uses a single language term, is insufficient to express and evaluate language variants involving hesitation. HFLTSs have been proposed as a solution to these common problems by Rodriguez et al. (Rodriguez et al., 2012).

An ordered finite subset of consecutive linguistic terms of linguistic term set $S = \{s_0, s_1, ..., s_g\}$ is represented with H_s (HFLTS). For example, a sample HFLTS can be defined as $H_s = \{s_2, s_3, s_4\}$ where linguistic term set S is determined as S ={s_0: nothing, s_1: very low, s_2: low, s_3: medium, s_4: high, s_5: very high, s_6: perfect. The upper/lower bounds (H_{S^+}, H_{S^-}), complement (H_s^c) and basic operations of the HFLTSs (H_s, H_s^1, H_s^2) are shown as:

$$H_{S^+} = \max(s_i) = s_j, s_i \in H_s \text{ and } s_i \leq s_j \ \forall_i \text{ , and}$$

$$H_{S^-} = \min(s_i) = s_j, s_i \in H_s \text{ and } s_i \geq s_j \ \forall_i \tag{5.10}$$

$$H_s^c = S - H_s = \{s_i | s_i \in S \text{ and } s_i \text{ not } \in H_s\} \text{ and } (H_s^c)^c = H_s \tag{5.11}$$

$$H_s^1 \cup H_s^2 = \{s_i | s_i \in H_s^1 \text{ or } s_i \in H_s^2\} \text{ and}$$

$$H_s^1 \cap H_s^2 = \{s_i | s_i \in H_s^1 \text{ and } s_i \in H_s^2\} \tag{5.12}$$

Generated new values for these operations also will be an HFLTS.

5.3.3 OWA operators

Collecting a set of information to obtain a new information is called aggregation and the operators used for this purpose are called the aggregation operator (mean, arithmetic mean, weighted arithmetic mean) (Modeling Decisions for Artificial Intelligence (MDAI), 2014). The ordered weighted averaging (OWA) aggregation operator is applied to aggregate the HFLTSs and obtain a universal HFLTS.

$$OWA\ (x_1, x_2, ..., x_k) = \sum_{i=1}^{k} l_i w_i \tag{5.13}$$

where l_i is the i. largest member of the aggregated elements $x_1, x_2, ..., x_k$. w_i is a weight of the ordered i. data in $[0, 1]$ interval and is defined the weighting vector W, $W = (w_1, w_2, ..., w_k)^T$. The sum of the weights defined in W equals one as $\sum_{i=1}^{k} w_i = 1$ (Yager, 1988). The methods (maximum, minimum, average) applied to determine the weighting values enable differentiation of OWA operators. The OWA collection operator, introduced by Yager, had the opportunity to practice in different branches of science (Yager, 1988). The ability of the OWA operator to collect and model linguistic expressions allows it to be used extensively in computational intelligence and fuzzy logic-based calculations as an aggregation operator.

The orness method can represent the degree of optimism and pessimism of the OWA operator (H. Liu & Rodríguez, 2014). Because of this feature, orness method which is widely used in researches is also used in this study. The mathematical representation of the orness method is as follows.

$$orness\ (W) = \frac{1}{k-1} \sum_{i=1}^{k} w_i (k-i) \quad (5.14)$$

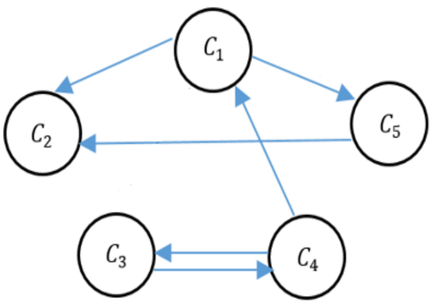
where $0 \leq$ orness (W) ≤ 1. $orness \geq 0.5$ condition points to optimistic OWA operators and $orness < 0.5$ state points to pessimistic OWA operators (Yager, 1993).

5.4 Hesitant Fuzzy Cognitive Maps

FCM is a dynamic modelling tool that reflects the concepts and causal relationships between concepts in complex and uncertain systems. Hesitant fuzzy sets (HFS) provide ease of assessment by allowing more than one value to identify membership in a situation (Kahraman et al., 2016). HFCM is a fuzzy method that models the causal relationships of linguistic evaluations defined by HFLTS. Hesitant linguistic expressions that are natural translations of experts' cognitive assessments with words or phrases are used to define concepts and their initial states. The process flow of HFCM is as follows:

Stage 1. Development of relationship model

Factors and the relationships between the factors of the HFCM model are determined by the common opinions of experts' knowledge and experiences. In the model, the system members are represented by nodes (C_i), and the causal relationships between the members are indicated by directed linguistic edges. A simple HFCM in Figure 5.4 is represented with five concepts (C_1, C_2, C_3, C_4, C_5) and six directed linguistic edges. Since the HFCM does not contain any self-loop concept, their values in the weight matrix are defined as zero ($w_{ii} = 0$).



	C_1	C_2	C_3	C_4	C_5
C_1	0	at least high	0	0	at most high
C_2	0	0	0	0	0
C_3	0	0	0	low	0
C_4	greater than high	0	at least medium	0	0
C_5	0	btw very low/ medium	0	0	0

Figure 5.4 : A simple HFCMs and HFLTS matrix.

Step 2. Collection of Experts' Information using HFLTS

Uncertain and dynamic system conditions cause experts to ambiguously identify the concepts and relationships between concepts in the cognitive map. Hence, experts use hesitant linguistic terms to convey ideas more naturally. Natural hesitant linguistic expressions of experts are defined by using context-free grammar, G_H that is generated with 4-tuple (V_N, V_T, I, P) (Bordogna & Pasi, 1993; Rodriguez et al., 2012).

Hesitant linguistic expressions are defined by using a linguistic term set where S ={s_0: nothing, s_1: very low, s_2: low, s_3: medium, s_4: high, s_5: very high, s_6: absolute} and context-free grammar. The sample hesitant linguistic statements are as follows: at most high, smaller than low, and between medium and high. Hesitant linguistic expressions provide flexibility to define and evaluate the hesitant concept and causal relationships among them.

The linguistic expressions obtained by expert evaluations must be converted to HFLTS for use in HFCM model calculations (Rodriguez et al., 2012). The transformation function, E_{G_H} developed by Rodriguez et al. (Rodriguez et al., 2012) is used in the conversion process. The methods applied according to the linguistic term set, S in the conversion process are as follows.

$$E_{G_H}(s_i) = \{s_i | s_i \in S\}$$

$$E_{G_H}(at\ least\ s_i) = \{s_j | s_j \in S\ and\ s_j \geq s_i\},$$

$$E_{G_H}(at\ most\ s_i) = \{s_j | s_j \in S\ and\ s_j \leq s_i\}$$

$$E_{G_H}(lower\ than\ s_i) = \{s_j | s_j \in S\ and\ s_j < s_i\}$$

$$E_{G_H}(greater\ \ than\ s_i) = \{s_j | s_j \in S\ and\ s_j > s_i\}$$

$$E_{G_H}(between\ s_i\ and\ s_j) = \{s_k | s_k \in S\ and\ s_i \leq s_k \leq s_j\}$$

For example, *{medium,high,very high}* is a sample HFLTS that is transformed form of the "*between medium and very high*" linguistic expression; E_{GH}*(between low and high)={low,medium,high}*.

Step 3. Fuzzy envelope of HFLTS

The enveloping method is used to compare the HFLTS converted from the linguistic expressions of the experts and to start the calculation processes in the HFCM model.

Envelopment of an HFLTS, $env(H_S)$ is indicated by upper (H_{S^+}) and lower (H_{S^-}) bounds as follows:

$$\mathrm{env}(\mathrm{H_S}) = [\mathrm{H_{S^-}}, \mathrm{H_{S^+}}], \quad \mathrm{H_{S^-}} \leq \mathrm{H_{S^+}} \tag{5.6}$$

For example, the HFLTS, $H_s = \{\, low, medium, \mathrm{h}igh\}$ of "$between\ low\ and\ high$" linguistic evaluation can be enveloped under S={nothing, very low, low, medium, high, very high, absolute}linguistic terms set as $env(H_S) = [low,\ high]$.

The OWA operator is contacted to obtain the fuzzy membership function of HFLTS and bring these membership functions together (H. Liu & Rodríguez, 2014). To reflect the linguistic uncertainties expressed by HFLTS, it is appropriate to use the trapezoidal membership function, $\tilde{A}$=(a, b, c, d) in the OWA operator procedure (Delgado et al., 1998). The process stages for calculating the coefficients expressing the trapezoidal membership function are as follows (H. Liu & Rodríguez, 2014):

Stage 1. Defining the aggregation elements

Linguistic terms are applied to calculate the parameters of the trapezoidal fuzzy membership function, $\tilde{A}$=(a, b, c, d) , as $A^k = T\{a_l^k, a_m^k, a_m^k, a_r^k\}, k = 0, 1, \dots, g$. The set of aggregation elements of the linguistic terms in the HFLTS $H_s = \{s_i, s_{i+1}, \dots, s_j\}$ are shown as; $T = \{a_L^i, a_M^i,\ a_L^{i+1}, a_R^i, a_M^{i+1},\ a_L^{i+2}, a_R^{i+1}, \dots, a_L^j,\ a_R^{j-1},\ a_M^j, a_R^j\}$,

The set of aggregation elements can be simplified with fuzzy partition under $a_R^{k-1} = a_M^k = a_L^{k+1}, k = 1, 2, \dots, g-1$ acceptance and defined as (Ruspini, 1969) $T = \{a_L^i, a_M^i, a_M^{i+1}, \dots, a_M^j, a_R^j\}$.

Stage 2. Calculation of the TFMF's parameters

Parameters of the TFMF, $\tilde{A}$=(a, b, c, d) that defines the fuzzy envelope, $env_F(H_S)$ of the HFLTS, H_S are determined using the set of aggregation elements, $T = \{a_L^i, a_M^i, a_M^{i+1}, \dots, a_M^j, a_R^j\}$. Limit values, a and d, are defined by the linguistic limits as $s_i = min\, H_s$ and $s_j = max\, H_s$.

$$a = min\{a_L^i, a_M^i, a_M^{i+1}, \dots, a_M^j, a_R^j\} = a_L^i,$$

$$d = max\{a_L^i, a_M^i, a_M^{i+1}, \dots, a_M^j, a_R^j\} = a_R^i \tag{5.16}$$

The intermediate parameters, b and d, of the TFMF are calculated using OWA aggregation operator.

$$b = OWA_{W^s}(a_M^i, a_M^{i+1}, \dots, a_M^j) \text{ and } c = OWA_{W^t}(a_M^i, a_M^{i+1}, \dots, a_M^j) \quad (5.17)$$

where $s, t = 1, 2;\ s \neq t$ or $s = t$. Filev and Yager's methods is used calculate the weighting vectors, W^s and W^t, in the OWA aggregation operations (Filev & Yager, 1998).

The first type of OWA weights $W^1 = (w_1^1, w_2^1, \dots, w_n^1)^T$, $0 \leq \alpha \leq 1$.

$$w_1^1 = \alpha, w_2^1 = \alpha(1-\alpha), w_3^1 = \alpha(1-\alpha)^2, \dots,$$

$$w_{n-1}^1 = \alpha(1-\alpha)^{n-2}, w_n^1 = \alpha(1-\alpha)^{n-1} \quad (5.18)$$

The second type of OWA weights $W^2 = (w_1^2, w_2^2, \dots, w_n^2)^T$, $0 \leq \alpha \leq 1$.

$$w_1^2 = \alpha^{n-1}, w_2^2 = (1-\alpha)\alpha^{n-2}, w_3^2 = (1-\alpha)\alpha^{n-3}, \dots,$$

$$w_{n-1}^2 = (1-\alpha)\alpha, w_n^2 = (1-\alpha) \quad (5.19)$$

The orness measures, $orness(W^1)$ and $orness(W^2)$, are calculated with the weighting vectors as follow:

$$orness(W^1) = \sum_{i=1}^{n} w_i^1 \left(\frac{n-i}{n-1}\right) = \frac{n-1}{n-1}\alpha + \frac{n-2}{n-1}\alpha(1-\alpha) + \frac{n-3}{n-1}\alpha(1-\alpha)^2 + \cdots + \frac{1}{n-1}\alpha(1-\alpha)^{n-2} + \frac{0}{n-1}(1-\alpha)^{n-1} = \frac{n}{n-1} - \frac{1-(1-\alpha)^n}{(n-1)\alpha} \quad (5.20)$$

$$orness(W^2) = \frac{\alpha - \alpha^n}{(n-1)(1-\alpha)} \quad (5.21)$$

The orness value whose OWA operator is described in the $[0, 1]$ interval is used to measure the importance of the HFLTS.

Stage 3. Sample fuzzy envelope

In this section, the transformation of a sample linguistic expression into a TFMF form is illustrated to clarify the fuzzy envelope. The linguistic term set, S={s_0= nothing, s_1= very low, s_2= low, s_3= medium, s_4= high, s_5= very high, s_6= absolute} is used in the sample application and its graphical representations is as follows (Figure 5.5):

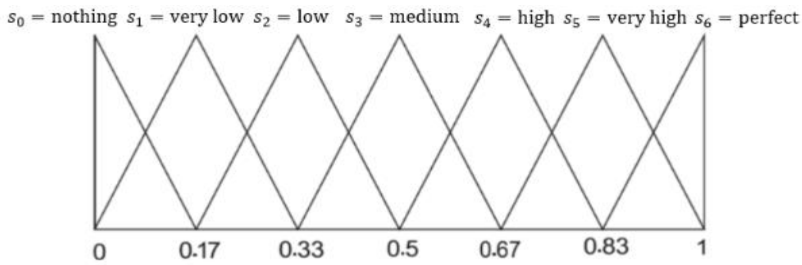


Figure 5.5 : Graphical representation of a sample linguistic term set S.

The following process steps are as follows:

a. The comparative linguistic evaluation is defined by the context-free grammar form: $between\ low\ and\ high$

b. Linguistic evaluation is converted into HFLTS as $E_{G_H}(between\ low\ and\ high) = \{s_2, s_3, s_4\}$.

c. The set of aggregation elements of the HFLTS is defined: $T = \{a_L^2, a_R^1, a_M^2, a_L^3, a_R^2, a_M^3, a_L^4, a_R^3, a_M^4, a_R^4\}$.

where $a_R^1 = a_M^2 = a_L^3$, $a_R^2 = a_M^3 = a_L^4$, and $a_R^3 = a_M^4$, so set T can be simplified as $T = \{a_L^2, a_M^2, a_M^3, a_M^4, a_R^4\}$.

d. The parameters of the TFMF, $env_F(H_{s_4}) = T(a_4, b_4, c_4, d_4)$, are calculated as:

$$a_4 = min\{a_L^2, a_M^2, a_M^3, a_M^4, a_R^4\} = a_L^2 = 0.17$$
$$d_4 = max\{a_L^2, a_M^2, a_M^3, a_M^4, a_R^4\} = a_R^4 = 0.83$$

$$b_4 = OWA_{W^2}(a_M^2, a_M^3)$$
$$c_4 = OWA_{W^1}(a_M^3, a_M^4)$$

while $i = 2$ and $g = 6$, α is calculated as $\alpha = (g - (j - i))/(g - 1) = 0.8$ and OWA weights are defined as:

$W^2 = (w_1^1, w_2^1)^T$=(0.8, 0.2 $)^T$ and $W^1 = (w_1^1, w_2^1)^T$=(0.2, 0.8 $)^T$

$b_4 = a_M^2 * 0.2 + a_M^3 * 0.8 = 0.466$ and $c_4 = a_M^2 * 0.2 + a_M^3 * 0.8 = 0.636$

e. TFMF of the fuzzy envelope of H_{s_4}, $env_F(H_{s_4})$ is defined: T= (0.17, 0.466, 0.636, 0.83).

Step 4. Operation of HFCM

Linguistic evaluations of experts define the causal relationship between concepts in the HFCM model. The linguistic expressions are transformed into the crisp values in [-1, 1] interval using defuzzification methods. Thus, the causal relationships between the concepts in the dynamic HFCM can be calculated, and the stable states of the concepts to be reached in the long term can be determined. The crisp values obtained by the defuzzification method express the causal relationship strength between the concepts (C_i, C_j.) and are called directed weight (w_{ij}). The sign of the directed weight represents the directly related or inverse relationship among concepts. The weights of all causal relationships in HFCM are defined in the weight matrix (W) whose diagonal elements, w_{ii} are equal to zero because of absence of self-loop in model.

Experts' linguistic expressions can define the initial state of the concepts. New state value of the concept C_i at the time t time iteration is represented as A_i^t in the interval $[-1, 1]$. $A^t = [A_1^t, A_2^t, \ldots, A_n^t]$ representation is also shows general state values for all concepts. The new state vector of a concept, C_i in the next iteration is measured as follows:

$$A_i^{t+1} = f\left(\sum_{j=1}^{n} w_{ij} A_j^t + A_j^t\right) \tag{5.7}$$

Threshold function operation is an essential step in the new state calculation process. The hyperbolic tangent function is chosen for this study among the most commonly used threshold functions (sign, trivalent, sigmoid, and hyperbolic tangent function). The hyperbolic tangent function is chosen because the [-1,1] values obtained after the threshold calculation are compatible with real-life problems.

$$f(x) = tanh(\lambda x) = \frac{e^{\lambda x} - e^{-\lambda x}}{e^{\lambda x} + e^{-\lambda x}} \tag{5.8}$$

The value of the lambda $(\lambda > 0)$ constant, which shapes the slope of the hyperbolic tangent function, is predefined by researchers according to their research characteristics (Bueno & Salmeron, 2009). The calculation of the causal relationship in the HFCM model is terminated when the difference between the two consecutive iteration values of all concept relationship values is less than 0.0001 (i.e., $A^{t+1} - A^t \leq 0.0001$), and the last state reached is defined as the "steady state".

5.5 Application: Solar Energy Price Modelling with Hesitant Fuzzy Cognitive Map

The increasing importance of energy in life affects and is influenced by economic, social and environmental factors. The pricing of solar energy that is a developing member of the energy sector is shaped under similar factorial circumstances. The definition of causal relations among the main factors that determine solar energy prices is defined by the opinions and evaluations of experts under uncertainty and unpredictability conditions. Experts of this study is both the academic and energy-business community. Experts selected from the academic community are preferred because of their studies on economic analysis and decision making of renewable energies. The experts selected from the energy sector consist of analysts and specialists who make installation assessments of large-scale renewable and solar energy systems. Since the renewable energy pricing mechanisms are similar each other, the experts in renewable sector are consulted in assessing the factors that determine the solar energy price. Under these conditions, the HFCM model is used to describe the causal relationships among factors and the initial states of the factors around the solar energy price. The initial states of the factors are randomly developed, and different scenarios are defined. The scenarios are operated on the HFCM model, and the solar energy price and other factors' reactions are observed during the model.

5.5.1 Determining of weight matrix and initial state vector

Firstly, the causal relationship between the factors and the powers of the causal relations among them must be defined for the operating the HFCM model. The "solar energy price" -based model is defined by twenty different models and the direction and sign of the causal relationship between the factors is determined by the collective opinion of experts (Figure 5.6). The orange causality represents the inverse proportion (that is, the value of a factor increases while the value of the other factor that is related decreases) and the blue causality represents the direct proportion (that is, the value of a factor increases while the value of the other factor that is related increases).

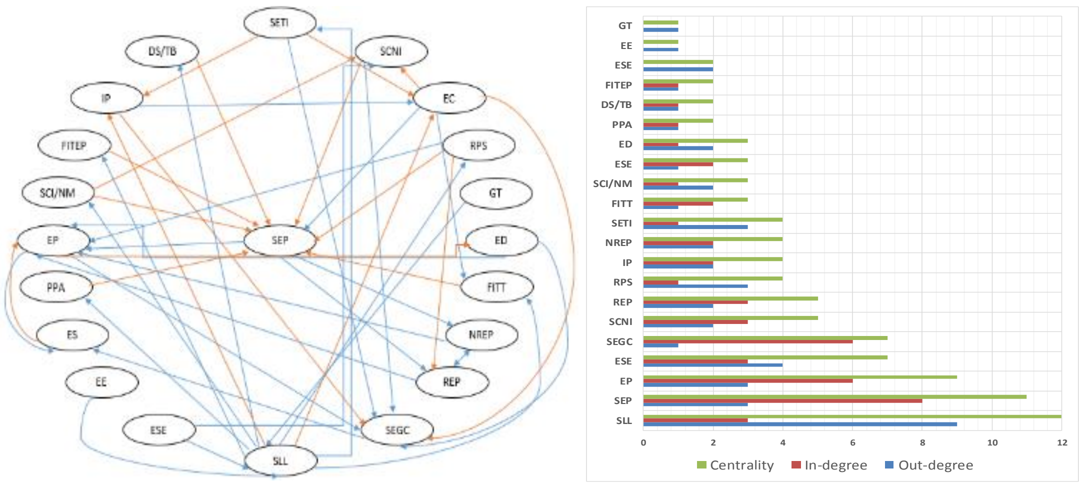


Figure 5.6 : Solar energy price centered HFCM and the values of the model structure metrics.

The HFCM consists of twenty-four factors, three of which are transmitters (GT, EE, ESE), eighteen of which are ordinary, and no receiver factor (Figure 5.6). The highest in-degree factor is the SEP (Solar Energy Price) that is also the center of the model structure, and the highest out-degree factor is SLL (Supportive Law and Legislations).

The highest centrality factor is SLL with twelve value and followed by SEP and EP (Energy Price).

The causal relationship between the factors of the model that is shaped around the solar energy price factor is determined by the academic and sectoral specialists in the field of solar energy and solar economics. Experts make evaluations based on hesitant linguistic terms to express causal relationships among factors more realistically and explicitly. Linguistic term set S ={s_0: nothing, s_1: very low, s_2: low, s_3: medium, s_4: high, s_5: very high, s_6: absolute} is used to generate linguistic assessments based on the context free grammar. The relationship matrix, which is defined linguistically by the common view of experts, is shown in Table 5.1.

Expressions of linguistic evaluation are shown in abbreviation on Table 5.1. The "+" sign indicates a positive relationship, and the "-" sign indicates a negative relationship. Explanations of other abbreviations are as follows; btw: between, atl: at least, gth: greater than, lth: lower than, atm: at most, n: neighter, vl: very low, low:l, m: medium, h: high, vh: very high, and a:absolute. Linguistic expressions that describe the causal relationship between the factors are transformed into HFLTS using conversion functions (Table 5.2).

HFLTSs transformed from linguistic evaluations are converted into a trapezoidal fuzzy membership function $\tilde{A} = (a, b, c, d)$ (Table 5.3). The intermediate b and c parameters of the trapezoidal fuzzy membership function are calculated using the OWA aggregation operator at this stage.

The linguistic expressions converted to numerical values by the trapezoidal fuzzy membership function are transformed into crisp values using the weighted average method to obtain computation values. The causal relations between the factors in the HFCM model are expressed by a single numerical value in the range [-1,1] by defuzzification of the trapezoidal representations (Table 5.4). This obtained table is defined as the weight matrix of HFCM and expresses the causal relationship between the factors.

Since the initial states of the factors cannot be expressed with definite values within the dynamic energy system, the initial states of the factors are linguistically defined by the experts. The combination of different initial states of the factors reveals different solar energy price centered scenarios. The process steps followed in obtaining the weight matrix are also followed when the initial state table is obtained. Defuzzified trapezoidal fuzzy membership functions give crisp valued at the initial state scenarios. Applications are made on two scenarios (Case1, Case2) selected from ten cases developed by experts.

Equation 5.26 based on the initial states of the factors (A^0) and the weight matrix of HFCM (W) is run to obtain the next state vectorA^1. The equation that calculates the next state vector A^{t+1} from the previous state vector A^t is repeated until the state vector reaches the steady state, A^l. It is a common practice to terminate the iteration if the difference is less than 0.001 for each factor in the two consecutive state vectors ($A^{t+1} - A^t \leq 0.001$). In the application section, the hyperbolic tangent function (Equation 5.27), which derives values in the range [-1,1], is used as a threshold function and the value of lambda is assumed to be 0.7 ($\lambda = 0.7$).

5.5.2 Case studies base on solar energy price

The two initial state vectors selected from the scenarios identified by the experts' joint evaluations are evaluated in this section. The values in the initial state are defined in the range [-1,1], and the value of the corresponding factor reflects the current state of the solar energy price in the HFCM model. The positive (negative) value means that the factor has increased (decreased), while the zero value means that the factor has not changed. The changes in the initial state values of the factors over time and the convergence values of the factors are graphically displayed throughout the iterations. The number of iterations and the steady-state values of the factors change for each scenario. The order of the factors in the initial state vector is: Renewable Portfolio Standard (RPS), Power Purchasing Agreements (PPA), FIT with Tender (FITT), Self-consumption (non-incentivized) (SCNI), Direct Subsidies or Tax Breaks (DS/TB), Economic Components (EC), FIT for Entire Production (FITEP), Infrastructure Problems (IP), Self-consumption or Net-metering (incentivized) (SCI/NM), Energy Price (EP), Renewable Energy Price (REP), Non-renewable Energy Price (NREP), Supportive Law and Legislations (SLL), Environmental Effects (EE), Eco-social Effects (ESE), Solar Energy Price (SEP), Energy supply (ES), Energy Demand (ED), Solar Energy Generation Capacity (SEGC), Global Treaties (GT), Solar Energy Technological Improvement (SETI).

Table 5.1 : Experts' shared views on the causal relationships among the factors.

	RPS	PPA	FITT	SCNI	DS/TB	ESE	FITEP	IP	SCI/NM	EP	REP
RPS										+atm_l	-atm_m
PPA											
FITT											
SCNI											
DS/TB											
ESE			+btw_lvh	-atm_m							
FITEP											
IP						+atm_h					
SCI/NM				-btw_vlm							
EP											
REP										+gth_m	
NREP										+gth_l	+lth_h
SLL	+atl_m	+gth_m	+lth_h		+atm_m	-btw_lh	+lth_h	-btw_vlm	+lth_h		
EE											
ESE				+lth_m							
SEP										+gth_m	+btw_lm
ESE										-atl_h	
ED										-btw_ma	
SEGC											
GT											
SETI						-atm_h		-gth_m			

Table 5.1 (continued) : Experts' shared views on the causal relationships among the factors.

	NREP	SLL	EE	ESE	SEP	ESE	ED	SEGC	GT	SETI
RPS					-atm_m					
PPA					-btw_vlm					
FITT					-ism					
SCNI					-gth_vl			+lth_h		
DS/TB					-btw_vlh					
ESE					+gth_m			-ish		
FITEP					-atl_m					
IP								-atm_m		
SCI/NM					-lth_l					
EP						+lth_h	-gth_h	+btw_vlm		
REP	+gth_l									
NREP										
SLL										+lth_m
EE		+atl_h								
ESE		+gth_vh								
SEP	+atm_m									
ESE										
ED								+gth_vl		
SEGC						+btw_lm				
GT		+atm_h								
SETI								+lth_l		

Table 5.2 : HFLTS transformation of experts' linguistic evaluations.

	RPS	PPA	FITT	SCNI	DS/TB	ESE	FITEP	IP	SCI/NM	EP	REP
RPS										(+){n,vl,l}	(-){n,vl,l,m}
PPA											
FITT											
SCNI											
DS/TB											
ESE			(+){l,m,h,vh}	(-){n,vl,l,m}							
FITEP											
IP						(+){n,vl,l,m,h}					
SCI/NM				(-){vl,l,m}							
EP											
REP										(+){h,vh,a}	
NREP										(+){m,h,vh,a}	(+){n,vl,l,m}
SLL	(+){m,h,vh,a}	(+){h,vh,a}	(+){n,vl,l,m}		(+){n,vl,l,m}	(-){l,m,h}	(+){n,vl,l,m}	(-){vl,l,m}	(+){h,vh,a}		
EE											
ESE				(+){n,vl,l}							
SEP										(+){h,vh,a}	(+){l,m}
ESE										(-){h,vh,a}	
ED										(-){m,h,vh,a}	
SEGC											
GT											
SETI						(-){n,vl,l,m,h}		(-){h,vh}			

Table 5.2 (continued) : HFLTS transformation of experts' linguistic evaluations.

	NREP	SLL	EE	ESE	SEP	ESE	ED	SEGC	GT	SETI
RPS					(-){n,vl,l,m}					
PPA					(-){vl,l,m}					
FITT					(-){m}					
SCNI					(-){l,m,h,vh,a}			(+){n,vl,l,m}		
DS/TB					(-){h,vh,a}					
ESE					(+){h,vh,a}			(-){h}		
FITEP					(-){m,h,vh,a}					
IP								(-){n,vl,l,m}		
SCI/NM					(-){n,vl}					
EP						(-){n,vl,l,m}	(-){vh,a}	(+){vl,l,m}		
REP	(+){m,h,vh,a}									
NREP										
SLL										(+){n,vl,l}
EE		(+){h,vh,a}								
ESE		(+){vh,a}								
SEP	(+){n,vl,l,m}									
ESE										
ED								(+){l,m,h,vh,a}		
SEGC						(+){l,m}				
GT		(+){n,vl,l,m,h}								
SETI								(+){n,vl}		

Table 5.3 : Trapezoidal representation of HFLTS.

	RPS	PPA	FITT	SCNI	DS/TB	ESE	FITEP	IP	SCI/NM	EP	REP
RPS	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0.2,0.5)	(0,0,-0.4,-0.7)
PPA	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
FITT	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
SCNI	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
DS/TB	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
ESE	(0,0,0,0)	(0,0,0,0)	(0.17,0.43,0.77,1)	(0,0,-0.35,-0.67)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
FITEP	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
IP	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0.6,0.8)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
SCI/NM	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,-0.3,-0.5,-0.7)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
EP	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
REP	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0.5,0.9,1,1)	(0,0,0,0)
NREP	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0.3,0.7,1,1)	(0,0,0.4,0.7)
SLL	(0.3,0.7,1,1)	(0.5,0.9,1,1)	(0,0,0.4,0.67)	(0,0,0,0)	(0,0,0.4,0.7)	(-0.2,-0.5,-0.6,-0.8)	(0,0,0.4,0.7)	(0,-0.3,-0.5,-0.7)	(0,0,0.4,0.7)	(0,0,0,0)	(0,0,0,0)
EE	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
ESE	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0.2,0.5)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
SEP	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0.5,0.9,1,1)	(0.2,0.3,0.5,0.7)
ESE	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(-0.5,-0.9,-1,-1)	(0,0,0,0)
ED	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(-0.3,-0.6,-0.9,-1)	(0,0,0,0)
SEGC	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
GT	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
SETI	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,-0.6,-0.8)	(0,0,0,0)	(-0.5,-0.9,-1,-1)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)

Table 5.3 (continued) : Trapezoidal representation of HFLTS.

	NREP	SLL	EE	ESE	SEP	ESE	ED	SEGC	GT	SETI
RPS	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,-0.4,-0.7)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
PPA	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,-0.3,-0.5,-0.7)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
FITT	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(-0.3,-0.5,-0.5,-0.7)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
SCNI	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(-0.2,-0.4,-1,-1)	(0,0,0,0)	(0,0,0,0)	(0,0,0.4,0.67)	(0,0,0,0)	(0,0,0,0)
DS/TB	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,-0.3,-0.6,-0.8)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
ESE	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0.5,0.9,1,1)	(0,0,0,0)	(0,0,0,0)	(-0.5,-0.7,-0.7,-0.8)	(0,0,0,0)	(0,0,0,0)
FITEP	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(-0.3,-0.7,-1,-1)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
IP	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,-0.4,-0.7)	(0,0,0,0)	(0,0,0,0)
SCI/NM	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,-0.03,-0.3)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
EP	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0.4,0.7)	(-0.7,-0.9,-1,-1)	(0,0.3,0.5,0.7)	(0,0,0,0)	(0,0,0,0)
REP	(0.3,0.7,1,1)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
NREP	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
SLL	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0.2,0.5)
EE	(0,0,0,0)	(0.5,0.9,1,1)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
ESE	(0,0,0,0)	(0.8,1,1,1)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
SEP	(0,0,0.4,0.7)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
ESE	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
ED	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0.2,0.4,1,1)	(0,0,0,0)	(0,0,0,0)
SEGC	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0.17,0.33,0.5,0.67)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
GT	(0,0,0,0)	(0,0,0.6,0.8)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)
SETI	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	(0,0,0.03,0.3)	(0,0,0,0)	(0,0,0,0)

Table 5.4 : Weight matrix of solar energy price HFCM model.

	RPS	**PPA**	**FITT**	**SCNI**	**DS/TB**	**ESE**	**FITEP**	**IP**	**SCI/NM**	**EP**	**REP**
RPS	0	0	0	0	0	0	0	0	0	0.133	-0.23
PPA	0	0	0	0	0	0	0	0	0	0	0
FITT	0	0	0	0	0	0	0	0	0	0	0
SCNI	0	0	0	0	0	0	0	0	0	0	0
DS/TB	0	0	0	0	0	0	0	0	0	0	0
ESE	0	0	0.59	-0.23	0	0	0	0	0	0	0
FITEP	0	0	0	0	0	0	0	0	0	0	0
IP	0	0	0	0	0	0.334	0	0	0	0	0
SCI/NM	0	0	0	-0.366	0	0	0	0	0	0	0
EP	0	0	0	0	0	0	0	0	0	0	0
REP	0	0	0	0	0	0	0	0	0	0.867	0
NREP	0	0	0	0	0	0	0	0	0	0.77	0.23
SLL	0.770	0.867	0.23	0	0.23	-0.534	0.23	-0.366	0.23	0	0
EE	0	0	0	0	0	0	0	0	0	0	0
ESE	0	0	0	0.133	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0	0	0	0.867	0.417
ESE	0	0	0	0	0	0	0	0	0	-0.867	0
ED	0	0	0	0	0	0	0	0	0	-0.733	0
SEGC	0	0	0	0	0	0	0	0	0	0	0
GT	0	0	0	0	0	0	0	0	0	0	0
SETI	0	0	0	0	0	-0.334	0	-0.867	0	0	0

Table 5.4 (continued) : Weight matrix of solar energy price HFCM model.

	NREP	SLL	EE	ESE	SEP	ESE	ED	SEGC	GT	SETI
RPS	0	0	0	0	-0.23	0	0	0	0	0
PPA	0	0	0	0	-0.366	0	0	0	0	0
FITT	0	0	0	0	-0.5	0	0	0	0	0
SCNI	0	0	0	0	-0.666	0	0	0.23	0	0
DS/TB	0	0	0	0	-0.423	0	0	0	0	0
ESE	0	0	0	0	0.867	0	0	-0.669	0	0
FITEP	0	0	0	0	-0.77	0	0	0	0	0
IP	0	0	0	0	0	0	0	-0.23	0	0
SCI/NM	0	0	0	0	-0.064	0	0	0	0	0
EP	0	0	0	0	0	0.23	-0.936	0.366	0	0
REP	0.77	0	0	0	0	0	0	0	0	0
NREP	0	0	0	0	0	0	0	0	0	0
SLL	0	0	0	0	0	0	0	0	0	0.133
EE	0	0.867	0	0	0	0	0	0	0	0
ESE	0	0.972	0	0	0	0	0	0	0	0
SEP	0.23	0	0	0	0	0	0	0	0	0
ESE	0	0	0	0	0	0	0	0	0	0
ED	0	0	0	0	0	0	0	0.666	0	0
SEGC	0	0	0	0	0	0.417	0	0	0	0
GT	0	0.334	0	0	0	0	0	0	0	0
SETI	0	0	0	0	0	0	0	0.064	0	0

Case1:

In this scenario, different initial states of the factors that affect the solar energy price are examined. The scenario analyzes the long-term effects of increasing and decreasing states of factors on solar energy price and other factors. Initial state vector is defined as A_1^0 =[0.332 -0.972 0.332 0.168 -0.668 0.972 0.028 -0.5 0.028 -0.168 0.832 0.972 0.972 0.668 0.168 0.028 -0.168 0.168 0.028 0.5 0.028]. According to the scenario, the EC, NREL, SLL and REP factors appear with the highest increase of 0.972 in the initial state of the system. The increase in investment costs leads to an increase in renewable and non-renewable energy costs and energy prices. Laws and regulations that increase solar energy production capacity arise in order to balance high energy production prices. The scenario also includes high environmental sensitivity and high international agreement impacts with the other high positive values. The factors that decrease in the initial state are EP, ES, IP, DS / TB, and PPA factors and the greatest reduction is seen in DS / TB and PPA factors supporting solar energy production capacity. Other remaining factors have a weak impact on the system with their low growth rates.

The simulated solar energy price-centered HFCM model simulated under the defined initial state reaches equilibrium state after 45 iterations. In the equilibrium model (Figure 5.7), the final state vector of the factors is as follows: A_1^l =[0 0 -0.003 0.001 0 -0.001 0 0 0 -0.862 -0.193 -0.337 0 0 0 0 -0.050 0.813 0.429 0 0]. The steady-state values obtained by simulating the HFCM model are interpreted as follows:

- The system shows complex fluctuations in the first twelve iterations. After twelfth iteration, the tendencies of the factors begin to appear more clearly. Factors which direct to the converged values after forty-first iteration reaches to the final state values after forty-fifth iteration.
- The factors of RPS, PPA, DS/TB, FITEP, IP, SCI/NM, SLL, EE, ESE, SEP, GT, and SETI converge to zero in the balanced system. This state means that there is no enhancing or reducing effects on these factors. The solar energy price among these factors is also a constant value; there is no tendency to increase or decrease. The state of the solar energy price causes the general system factors to remain unchanged.

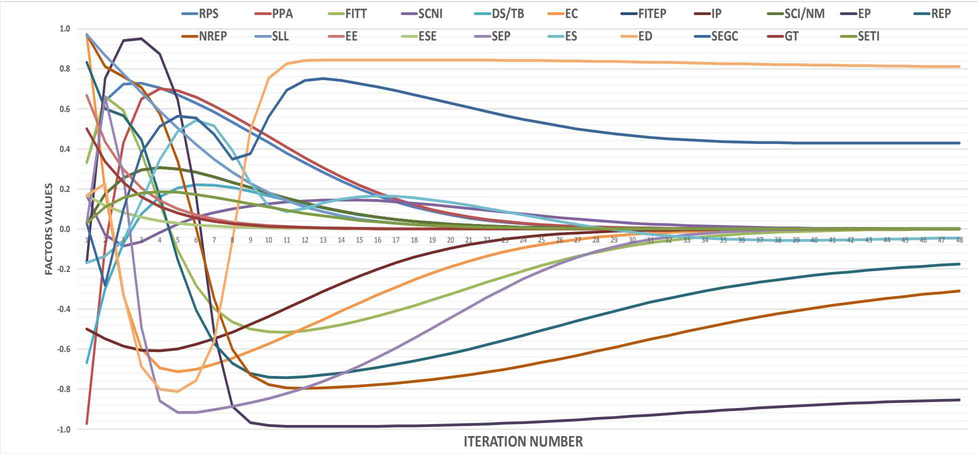


Figure 5.7 : HFCM simulation of Case1.

- In this scenario, ED, SEGC, and SCNI factors show an increasing tendency with 0.813, 0.429, and 0.001 values. The main reason for the high increase in energy demand is the decrease in renewable energy, non-renewable energy, and general energy prices. Increased energy demand is balanced by increasing solar energy production capacity. The installation of individual solar energy systems without incentive contributes to increasing solar energy capacity with a low increase.
- While the highest reductions are seen in EP, NREP, and REP factors (-0.862, -0.337, -0.193 respectively); ES, FITT, and EC factors affect the system with low reductions (-0.020, -0.003, -0.001 respectively). The inverse relationship between energy demand and energy prices is the leading cause of the decline in energy prices. The decline in energy prices is also triggered by reductions in renewable energy (excluding solar energy) and non-renewable energy prices. Reductions in support and incentives for solar energy generation may have led to a lower reduction in overall energy supply. The scale economy created by the developing solar energy systems technology leads to a reduction in installation costs, though there are no incentives for solar energy.

Case2:

This scenario is designed to examine the effects of the supports and programs for improving solar energy systems on solar energy price and general system factors. Therefore, the system consists of supportive factors with increasing GT, FITT, PPA, SLL, DS/TB and RPS (0.972, 0.972, 0.972, 0.832, 0.668, 0.500, 0.168) and decreasing EC and IP (-0.028, -0.500). Nevertheless, there are some mitigating factors to increase the solar energy capacity and reduce the solar energy price in the system such as

FITEP, ESE, SETI, SCNI, and SCI/NM (-0.168, -0.668, -0.668, -0.832, -0.832). The solar energy price, solar energy generation capacity, demand for energy, energy supply, and other supportive factors tend to increase in this scenario. Initial state vector is defined as A_2^0= [-0.972 0.5 0.028 0.332 -0.668 0.168 -0.832 0.332 -0.332 -0.028 0.972 0.168 0.832 0.832 0.168 -0.028 -0.668 -0.168 -0.332 0.5 0.332]. The HFCM simulation model reaches to the equilibrium state at the 37th iteration and obtained steady state vector is as follows: A_2^l =[0 0 0.004-0.001 0 0.001 0 0 0-0.724 0.007 0.012 0 0 0 0.001 0.047 0.766 0.451 0 0] The general behavior of the factors according to the graphical representation (Figure 5.8) and the obtained values are summarized as follows.

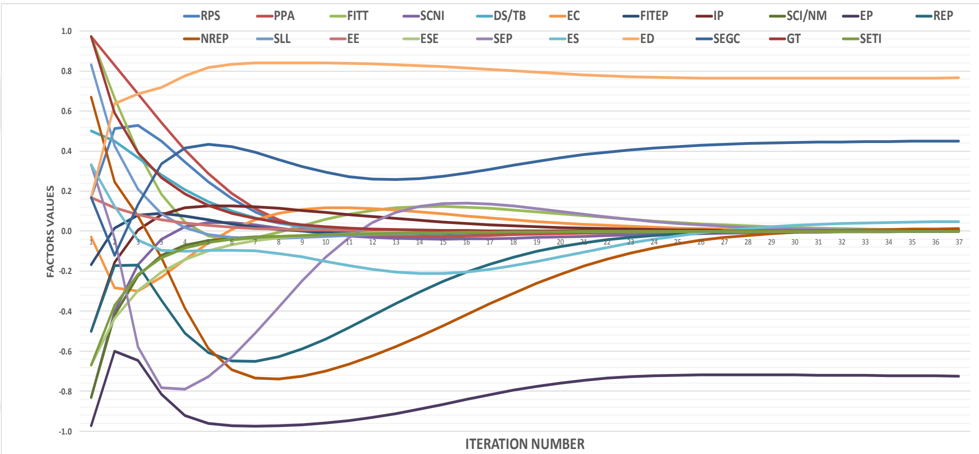


Figure 5.8 : HFCM simulation of Case2.

- The highest tendency to increase is seen in the energy demand (0.766) that is resulted from the high reduction in energy price (-0.724). The high decline in energy prices in the initial state and the increase in solar energy production support will lead to an increase in energy supply and cause energy prices to continue at low levels over the long run. The second highest increase is seen in solar energy generation capacity (0.451) which is the result of the focus of this scenario that includes the high increase in solar energy support. The increase in solar energy capacity provides a low level of energy supply (0.047) and causes the installation costs to increase (EC, 0.001). The increase in the installation costs of solar energy systems can lead to an increase in the bid prices for the FIT (0.004) and solar energy prices. The high increase in energy demand also leads to renewable (including solar energy, 0.007) and non-renewable energy prices (0.012).

- When the system reaches equilibrium, the factors of IP, GT, EE, ESE, SLL, SETI, DS / TB and FITEP go into inertia position, and the steady-state values of these factors are indicated by zero. The inertia of most of the policies that support the development of solar energy systems proves that the system can stand independently as unsupported and uncontrolled. The inertia results show that the widespread of solar energy use has removed environmental, economic and social problems, has stopped national and international concerns, and has led to the more balanced distribution of incentives.
- The establishment of individual solar energy systems (-0.001) and energy price (-0.724) factors show a decline in an equilibrium state. Solar energy capacity reaches satisfying with high support and encouragement, so support for the establishment of new systems is either eliminated or reduced. Increasing energy demand with energy price can be balanced by increasing solar energy generation capacity or raising the renewable or non-renewable energy prices.

The solar energy price HFCM model is evaluated through two different scenarios that are developed according to the initial state values of the factors. Scenario models reach equilibrium state with different iteration numbers, and model factors take different equilibrium state values according to their initial state values. The solar energy price reaches a constant equilibrium value at the end of calculations made with different initial state vectors. The inertia state of the solar energy price causes the factors supporting and disturbing the solar energy system to go into inertia state. The continuation of the equilibrium energy model by energy supply, energy demand, and energy price factors shows that solar energy price is evaluated within renewable and non-renewable energy prices. The solar energy generation capacity increase occurs depending on energy demand in market conditions without any incentive mechanism.

5.6 Conclusion

In this chapter, the causal relationships among the solar-energy price factors are identified. The economic, environmental and social conditions and the uncertainties are considered in the model. This HFCM model is used for identifying and assessing relationships among factors accurately. The causal relationships among the factors are determined by linguistic evaluation depending on the experts' knowledge, skills, and experience. Since the initial states of the factors cannot be measured, the initial state values of factors are determined by the knowledge of the experts. The linguistic expressions used in determining the causal relationships between the factors and the initial state value of the factors are transformed into the HFLTS and the trapezoidal fuzzy membership function. The weight matrix and the initial state vector are obtained by defuzzification of the TFMF and they are used to simulate the HFCM model. The simulated HFCM models result in different equilibrium state values for the factors. For example, the energy price reaches -0.862 in the first scenario and solar energy generation capacity converges 0.451 in the second scenario.

Similar results are obtained in the equilibrium states of the HFCM models that are developed at the solar energy price cantered. Although the initial state vectors are different, the solar energy price does not tend to increase or decrease at the end of the simulations. The inertia state of the solar energy price causes the factors directly affecting the solar energy system to go into an inertia state for each scenario. The energy model, which continues its existence by energy supply, energy demand, and energy price factors, accommodates solar energy price in renewable and non-renewable energy prices. Also, equilibrium situations show that the development of new solar power generation systems takes place in market conditions without any incentive mechanism.

In the future studies, the applied HFCM model-based pricing studies can be extended for other renewable energy sources since the renewable energy sector has similar pricing structure to solar energy. Thus, renewable energy price prediction models can be improved by considering the factors affecting renewable energy price and their impact levels on pricing. As a result, more accurate energy price estimation can be made with a more realistic price estimates of renewable energies, which will have significant shares in meeting future energy demand.

6. PYTHAGOREAN FUZZY ENGINEERING ECONOMIC ANALYSIS OF SOLAR POWER PLANTS*

The technological developments and the increase in the population rise the need for energy. The fossil fuels, primary sources of energy, are currently cost-effective but they are limited. Carbon-based fuels produce carbon dioxide and other greenhouse gases and the rise in the greenhouse gases weakens the ozone layer and cause harmful radiation that endangers the food chain and ecological order (Kalogirou, 2013). The ecological problems and need for new energy resources have enhanced the interest on alternative energy sources. Hydraulics, wind, solar, geothermal, and biomass are the non-fossil energy sources and defined as renewable energy sources (Energy and Natural Resources Ministry (ENRM), 2017a). There is a growing interest in renewable energy sources since they create environmental and social benefits (U.S. Energy Information Administration (USEIA), 2017b).

Sun is one of the leading energy providers for most of the renewable and conventional generated energy (except nuclear and tidal energies) (Çoban & Onar, 2017b). Additional to its secondary usage, solar energy is directly used for generating energy. The newly developed technologies enhance solar energy usage. Solar energy investments as costly, especially the initial investment costs are very high, which limits the usage of solar energy. Evaluating both the costs and benefits of solar energy can reveal the economic value of solar energy investments. Such an analysis enables selecting the most suitable locations and conditions for solar energy investments. The economic analyses and evaluations to be made are of critical importance at this stage. On the other hand, predicting both the revenue generated from solar energy and the costs initiated by the solar energy generation is hard since both the generated energy and energy prices are highly uncertain (Zatzman, 2012). Fuzzy sets are excellent tools for modeling uncertainty.

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* This chapter is based on the paper Çoban, Veysel, and Sezi Çevik Onar. "Pythagorean Fuzzy Engıneerıng Economic Analysis of Solar Power Plants." *Soft Computing* (2018) 22: 5007-5020. DOI: 10.1007/s00500-018-3234-6

Pythagorean fuzzy sets (Yager, 2013) initially developed by Atanassov in 1986 (K. Atanassov, 1989) as second type intuitionistic fuzzy sets are the extensions of intuitionistic fuzzy sets and useful for representing the uncertainty inherent in a system. Similar to the intuitionistic fuzzy sets they enable defining both the membership and non-membership values for an element, but unlike intuitionistic fuzzy sets, the square sum of the membership and non-membership degrees is maximum one. This advantage of Pythagorean fuzzy sets provides a stronger representation of uncertainty than intuitionistic fuzzy sets.

In this study, Pythagorean fuzzy sets are used for engineering analyses. To the best of our knowledge, this is the first study that uses Pythagorean fuzzy sets in engineering economic analyses. This method is applied to a solar energy investment decision. More realistic results are achieved due to a better representation of uncertainties.

6.1 Solar Energy and Economic Bases

6.1.1 Renewable energy and solar energy

The United Nations estimates that the world population, which is about 8 billion in 2017, will rise to about 10 billion in 2050 and 16 billion in 2100 (United Nations (UN), 2017) (Figure 6.1). The growing world population and the economy are expected to increase the global energy demand by about 37% by 2040. Fossil-based energy sources are used as primary energy source to meet the growing energy need. In 2040, the world energy supply is expected to be met by oil, gas, coal and low carbon energy sources (International Energy Agency (IEA), 2017) (Figure 6.1).

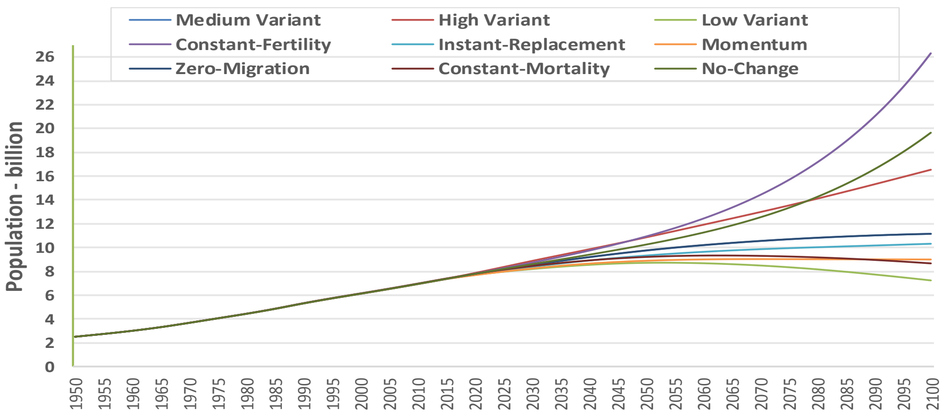

Figure 6.1 : Trend in world total population (United Nations (UN), 2017).

The use of fossil-based resources in the energy production process has serious problems: carbon dioxide emission, pollution, greenhouse effect, global warming, sulfur dioxide emission that causes acid rain. The use of fossil-based resources to meet energy demands causes economic and social problems as well as these environmental-based problems. The development of alternative energy sources against the depleting fossil energy sources is critical to meet the demand for energy for the future (BP, 2017).

Renewable energy (solar, wind, geothermal, hydropower, biomass and hydro energy) derived from existing energy flows in the natural processes emerges as the most important alternative energy source (Figure 6.2). Renewable energy technologies constitute a significant part of the efforts to meet the global energy supply from low carbon energy sources. Global subsidies of $ 120 billion were provided in 2013 to improve renewable energies (International Energy Agency (IEA), 2017). Renewable energy sources (wind, biomass, solar energy, geothermal) planned to take the place of fossil-based (energy, oil and natural gas) energy resources have disadvantages of being expensive and less reliable (Conkling, 2011).

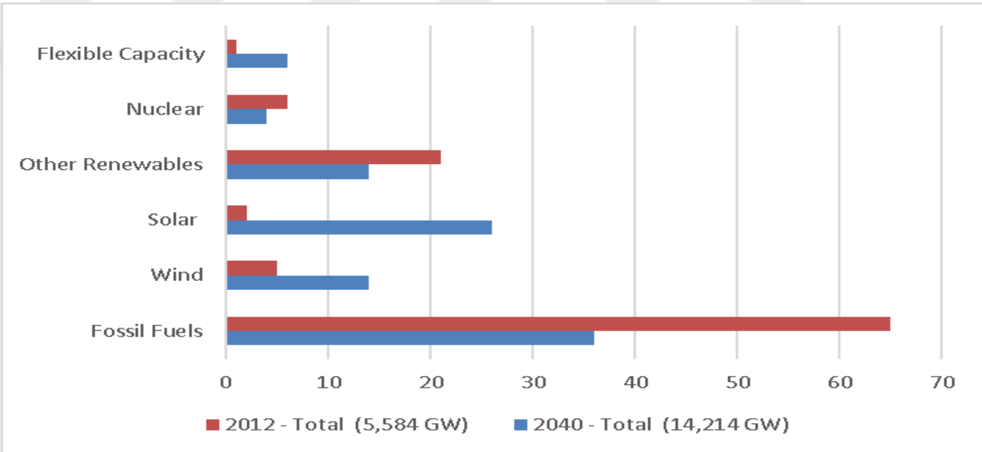

Figure 6.2 : Annual capacity additions for renewable energy (Bloomberg New Energy Finance, 2015).

The sun, which is the primary source of all fossil and non-fossil energy in the world (except nuclear, geothermal and tidal energies), is the most important renewable energy source with its environmental protection and low operational costs. The main advantages of solar energy are easy accessibility, high supply potential, inexhaustible, no release of greenhouse and other harmful gases, silence, and the source of all renewable energies (except tidal and geothermal) (Energy and Natural Resources Ministry (ENRM), 2017b). The main disadvantages of solar energy can be listed as follows: intermittency, seasonal variation of energy potential, unpredictability, geographical obstacles, lack solar energy and storage. The sun rays reaching the earth are utilized in the energy production directly or indirectly methods (Energy and Natural Resources Ministry (ENRM), 2017b; Kalogirou, 2013). Solar energy technologies that differ according to the method, material and technological characteristics can be gathered in two main categories: Photovoltaic (PV) and thermal solar technologies. Photovoltaic solar technology is a method of converting solar light directly into electricity in photovoltaic cells composed of semiconducting materials. Thermal solar technology is the direct use of thermal energy from solar energy or conversion of thermal liquid to electrical energy (Energy and Natural Resources Ministry (ENRM), 2017a).

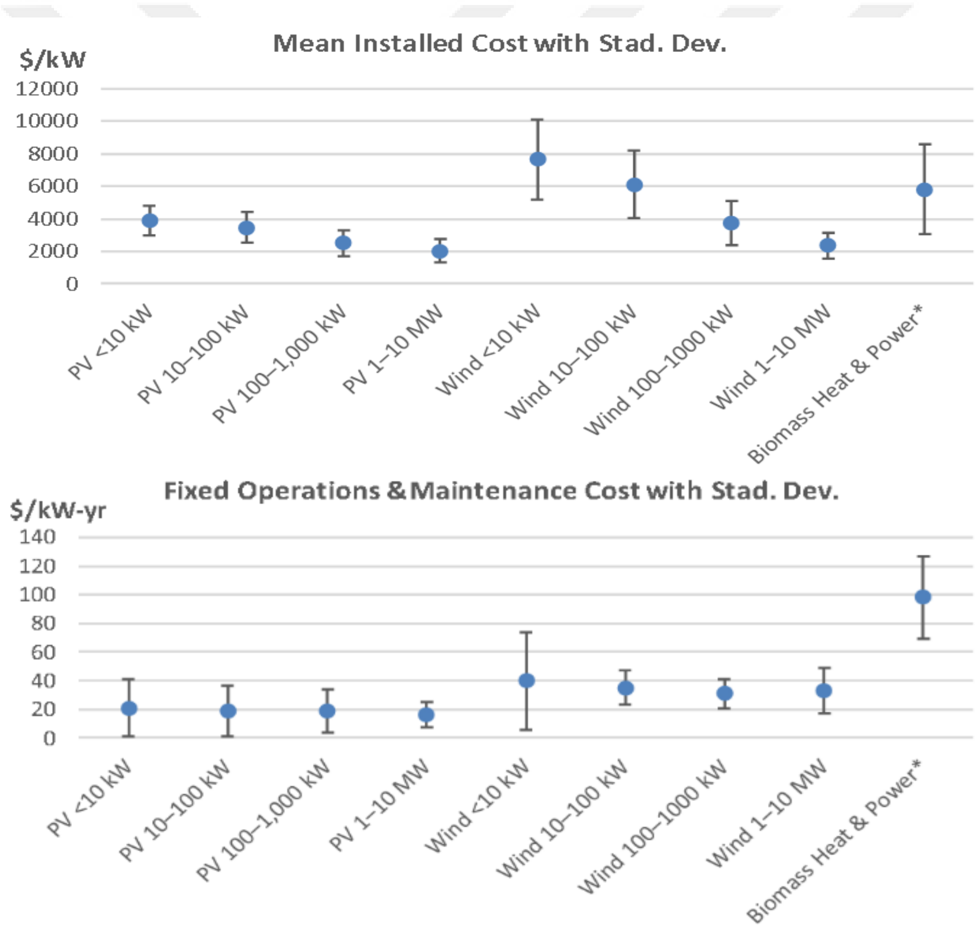

Figure 6.3 : Cost variation ranges according to PV system specifications (National Renewable Energy Laboratory (NREL), 2017).

PV technology works by converting photovoltaic energy into solar electricity (photovoltaic principle). The use of different materials (crystal silicon, cadmium telluride (CdTe) gallium arsenide (GaAs), amorphous silicon, optical concentrating cells) in the production of photovoltaic cells changes the usage and properties of the

PV system (Energy and Natural Resources Ministry (ENRM), 2017b). The change in the physical properties of the system equipment also changes the life cycle (25-40 years), installation, operation and maintenance costs of the PV solar system (National Renewable Energy Laboratory (NREL), 2017) (Figure 6.3).

In addition to material properties, solar radiation collection and energy storage are other important factors affecting the efficiency of PV systems. PV systems are the most common solar energy generation method for small and large scale (Bolinger, Seel, & LaCommare, 2017). The amount of sunlight reaching photovoltaic cells is increased with concentrated systems and concentrated photovoltaic (CPV) systems, which allows more energy production, emerges as a new technology. Achieving 46% energy efficiency in CPV systems has increased expectations for the development of more efficient solar energy technologies (World Energy Council (WEC), 2016).

Thermal solar technology is divided into low and high-temperature systems according to the reached thermal value. The technology used in low-temperature systems such as planetary solar collectors, solar vacuum collectors, solar pools, solar chimneys, water treatment systems, product drying and greenhouses, solar furnaces is more straightforward, and the solar energy obtained from the system is relatively low. High-temperature systems have high technological properties, and the system reaches very high thermal values. In these systems, high thermal values are obtained by using concentrator constructions which focus solar rays to a certain point (parabolic trough collectors, parabolic dish systems, central receiver systems, fresnel trough technology) (Energy and Natural Resources Ministry (ENRM), 2017b). The system fluid, which is heated to high temperatures by the concentrating system, allows the water to evaporate through the channels. The evaporated water activates the system turbines and provides electrical energy that is defined as concentrated solar power (CSP). PV and CSP systems are the most common methods for individual and commercial use regarding technological development and economic superiority (Figure 6.4).

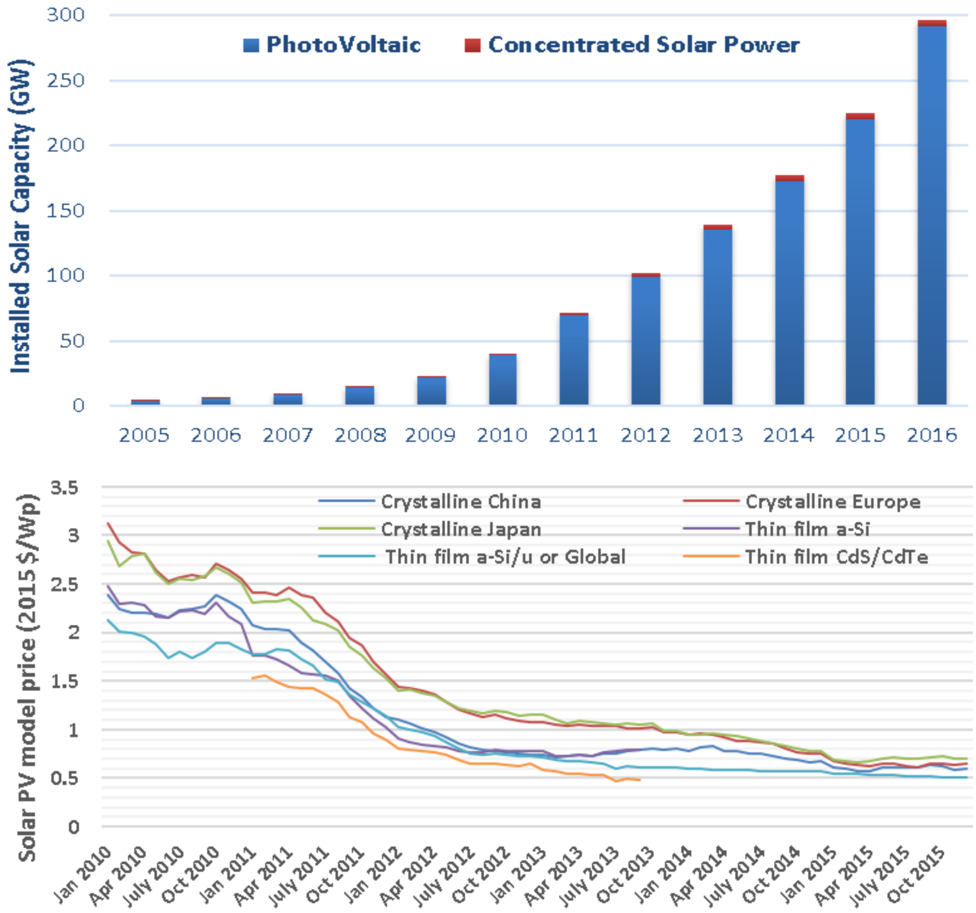

Figure 6.4 : Global installed solar capacity, 2005-2016 (kW) and trend in solar PV module prices (World Energy Council (WEC), 2016).

6.1.2 Economic requirements of solar energy systems

Solar energy systems similar to the other renewable energy investments initiate high initial costs but low operating costs. The economic analysis of solar investments is done by comparing the calculated initial investment cost that includes the purchase and installation of solar energy equipment with estimated future operating costs. The investment cost of solar energy is compared with the future equivalent fuel bill, or the gain from the sale of the energy generated (Timilsina et al., 2012). The investment made for solar energy systems is aimed to reduce the future fuel consumption.

The overall cost of solar energy systems includes equipment costs, the installation costs, hardware costs, labor costs and operating costs. It is essential to consider the interest on borrowing money, maintenance, taxes (income and property), resale of equipment, insurance, and other operating expenses in investment calculations (Crawley, 2016). Hence, life cycle saving methods, which allow the time value of money must be considered and the cost range should be examined in detail. The most important problem encountered in the economic analysis of solar energy systems is to determine the size of the most suitable solar energy system that meets the lowest cost of solar energy production and the storage of the energy obtained.

The most significant disadvantage of renewable energy technologies that are developed as an alternative to fossil fuels is a high initial investment cost. This disadvantage is tackled with national and international political and economic support (Dahl, 2015). Although economic supports encourage investors to invest in renewable energies, general economic evaluations should be done for investments to be successful in the long run. Solar energy systems similar to the other renewable energy investments initiate high initial costs but low operating costs. As a result of this characteristic, the economic analysis of solar investments is done by comparing the calculated initial investment cost that includes the purchase and installation of solar energy equipment with estimated future operating costs (Crawley, 2016). The overall cost of solar energy systems includes equipment costs, the installation costs, hardware costs, labor costs and operating costs. Also, it is essential to consider the interest on borrowing money, maintenance, taxes (income and property), resale of equipment, insurance, and other operating expenses in investment calculations. However, the most important economic problem of solar energy systems is to determine the size of the most suitable solar energy system that meets the lowest cost of solar energy production and the storage of the energy obtained.

The investment cost of solar energy is compared with the future equivalent fuel bill or the gain from the sale of the energy generated. The investment made for small-scale systems is aimed to reduce the future fuel consumption (Timilsina et al., 2012). High installation and total operating costs should be balanced against the gain from solar energy generation. Usually, solar energy economic analyses focus on finding the lowest cost method that meets the energy need and these methods considers only the solar energy production (Energy and Natural Resources Ministry (ENRM), 2017b; Timilsina et al., 2012).

Large-scale solar energy systems (on-grid or off-grid) are actively involved in meeting rising energy demands. Large-scale systems whose processing principles resemble small-scale systems have more initial and annual costs than small systems because of the size difference. Improvements in solar energy technology and financial and technical support provided by national/international institutions also encourage the installation of large-scale solar energy facilities (e.g., Tengger Desert Solar Park – 1500MW – China, Kurnool Ultra Mega Solar Park – 900 MW – India (Solar Insure, 2017)). The realization of large-scale projects requires economic analysis methods that ensure the proper planning of financial resources. The economic analysis aims to realize solar projects with the lowest risk by accurately anticipating the vague and uncertain future expectations. Economic calculations made through the project life cycle also allow comparative assessment of alternative conditions. In general, large-scale projects (e.g., PV-Si, CPV, CSP, thin-film) are preferred in solar energy generation due to their financial advantages (Electricity Markets and Policy Group, 2016; Energy and Natural Resources Ministry (ENRM), 2017b). When PV and CSP facilities are compared at the same nominal power and environmental conditions, the economic outcome of the CSP is more significant, and the occupied area is less than that of PV systems. However, the initial investment and regular maintenance costs for CSP facilities were found to be very high compared to PV systems. It is hard to define priorities since environmental and technical conditions are different in the investment decisions (Vergura & Lameira, 2011).

Life cycle cost (LCC) analysis and Levelized Cost of Energy (LCOE) values are critical parameters used in the evaluation and comparison of large-scale solar energy projects. LCC analysis is based on the assessment of all costs incurred at the beginning and during the project lifetime (Kahraman, Çevik Onar, & Öztayşi, 2015). The LCC assessment is based on the current value of total costs for each alternative solar project (Crawley, 2016). LCOE is defined as the average cost per kWh of the useful electricity generated by the solar energy system. The LCOE value calculated for the project is compared with the market price to determine the suitability and acceptance of the project (HOMER Energy, 2017; U.S. Energy Information Administration (USEIA), 2017a) (Figure 6.5). If the LCOE value is higher than the market energy price, unit margin becomes negative, and the project is rejected, otherwise the project is accepted (U.S. Energy Information Administration (USEIA), 2017a).

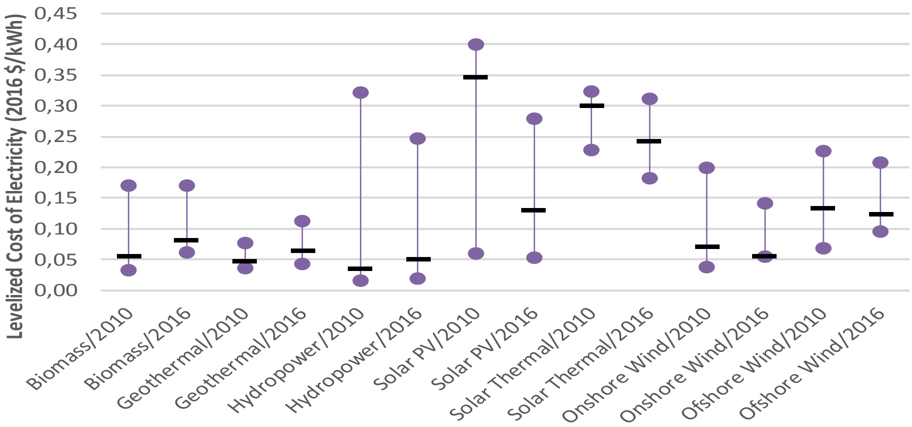

Figure 6.5 : Trends in LCOE of electricity in the period 2010-2016 (World Energy Council (WEC), 2016).

6.2 Preliminaries for Pythagorean Fuzzy Sets (PFS)

6.2.1 Intuitionistic fuzzy sets

Intuitionistic fuzzy sets (IFS) introduced by Atanassov (1983) are the generalization of the fuzzy set (FS) concept (Krassimir T Atanassov, 1986). The membership and non-membership degrees are real numbers between 0 and one as in fuzzy sets. Intuitionistic fuzzy sets (IFSs) in the X fixed crisp set are defined as an objective of the following form (Krassimir T Atanassov, 1999).

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x), v_{\tilde{A}}(x)) | x \in X\} \quad (6.1)$$

$\mu_{\tilde{A}}(x)$ is the degree of membership of x in $\tilde{A}$ and $v_{\tilde{A}}(x)$ is the degree of non-membership of x in $\tilde{A}$ in the [0,1] interval, and following condition is satisfied as;

$$0 \leq \mu_{\tilde{A}}(x) + v_{\tilde{A}}(x) \leq 1, \forall x \in X \quad (6.2)$$

$$\mu_{\tilde{A}}: X \to [0,1],\ v_{\tilde{A}}: X \to [0,1] \quad (6.3)$$

$\tilde{A}$ and $\tilde{B}$ are two IFSs on a universe X, and some basic relations and operations are defined as following;

$$\tilde{A} \cup \tilde{B} = \{\left(x, \max\left(\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)\right), min\left(v_{\tilde{A}}(x), v_{\tilde{B}}(x)\right)\right) | x \in X\} \quad (6.4)$$

$$\tilde{A} \cap \tilde{B} = \{\left(x, \min\left(\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)\right), max\left(v_{\tilde{A}}(x), v_{\tilde{B}}(x)\right)\right) | x \in X\} \quad (6.5)$$

$$\tilde{A}' = \{\left(x, v_{\tilde{A}}(x), \mu_{\tilde{A}}(x)\right) | x \in X\} \text{ (negation, complement)} \quad (6.6)$$

where Type-I fuzzy sets can be defined as;

$$\{(x, \mu_{\tilde{A}}(x), 1-\mu_{\tilde{A}}(x))|x \in X\} \quad (6.7)$$

$$\tilde{A}+\tilde{B} = \{(x, \mu_{\tilde{A}}(x)+\mu_{\tilde{B}}(x)-\mu_{\tilde{A}}(x)\mu_{\tilde{B}}(x), v_{\tilde{A}}(x)v_{\tilde{B}}(x))|x \in X\} \quad (6.8)$$

$$\tilde{A}.\tilde{B} = \{(x, \mu_{\tilde{A}}(x)\mu_{\tilde{B}}(x), v_{\tilde{A}}(x)+v_{\tilde{B}}(x)-v_{\tilde{A}}(x)v_{\tilde{B}}(x))|x \in X\} \quad (6.9)$$

Subtraction and division operations can be defined for given IFSs A and B as follows (Krassmir T Atanassov & Riecan, 2006):

$$\tilde{A}:\tilde{B} = \{(x, \mu_{\tilde{A}:\tilde{B}}(x), v_{\tilde{A}:\tilde{B}}(x))|x \in X\} \quad (6.10)$$

where

$$\mu_{\tilde{A}:\tilde{B}}(x) = \begin{cases} \frac{\mu_{\tilde{A}}(x)}{\mu_{\tilde{B}}(x)}, \text{if } \mu_{\tilde{A}}(x) \leq \mu_{\tilde{B}}(x) \text{and } v_{\tilde{A}}(x) \geq v_{\tilde{B}}(x) \\ \text{and } \mu_{\tilde{B}}(x) > 0 \text{ and } \mu_{\tilde{A}}(x)\pi_{\tilde{B}}(x) \leq \mu_{\tilde{B}}(x)\pi_{\tilde{A}}(x) \\ 0, \text{otherwise} \end{cases} \quad (6.11)$$

$$v_{\tilde{A}:\tilde{B}}(x) = \begin{cases} \frac{v_{\tilde{A}}(x)-v_{\tilde{B}}(x)}{1-v_{\tilde{B}}(x)}, if\ \mu_{\tilde{A}}(x) \leq \mu_{\tilde{B}}(x) and\ v_{\tilde{A}}(x) \geq v_{\tilde{B}}(x) \\ and\ \mu_{\tilde{B}}(x) > 0\ and\ \mu_{\tilde{A}}(x)\pi_{\tilde{B}}(x) \leq \mu_{\tilde{B}}(x)\pi_{\tilde{A}}(x) \\ 1, otherwise \end{cases} \quad (6.12)$$

$$\tilde{A}-\tilde{B} = \{(x, \mu_{\tilde{A}-\tilde{B}}(x), v_{\tilde{A}-\tilde{B}}(x))|x \in X\} \quad (6.13)$$

where

$$\mu_{\tilde{A}-\tilde{B}}(x) = \begin{cases} \frac{\mu_{\tilde{A}}(x)-\mu_{\tilde{B}}(x)}{1-\mu_{\tilde{B}}(x)}, if\ \mu_{\tilde{A}}(x) \geq \mu_{\tilde{B}}(x) and\ v_{\tilde{A}}(x) \leq v_{\tilde{B}}(x) \\ and v_{\tilde{B}}(x) > 0\ and\ v_{\tilde{A}}(x)\pi_{\tilde{B}}(x) \leq v_{\tilde{B}}(x)\pi_{\tilde{A}}(x) \\ 0, otherwise \end{cases} \quad (6.14)$$

$$v_{\tilde{A}-\tilde{B}}(x) = \begin{cases} \frac{v_{\tilde{A}}(x)}{v_{\tilde{B}}(x)}, if\ \mu_{\tilde{A}}(x) \geq \mu_{\tilde{B}}(x) and\ v_{\tilde{A}}(x) \leq v_{\tilde{B}}(x) \\ and\ v_{\tilde{B}}(x) > 0\ and\ v_{\tilde{A}}(x)\pi_{\tilde{B}}(x) \leq v_{\tilde{B}}(x)\pi_{\tilde{A}}(x) \\ 1, otherwise \end{cases} \quad (6.15)$$

$$\tilde{A}*\tilde{B} = \left\{\left(x, \frac{\mu_{\tilde{A}}(x)+\mu_{\tilde{B}}(x)}{2(\mu_{\tilde{A}}(x)\mu_{\tilde{B}}(x)+1)}, \frac{v_{\tilde{A}}(x)+v_{\tilde{B}}(x)}{2(v_{\tilde{A}}(x)v_{\tilde{B}}(x)+1)}\right)\middle|x \in X\right\} \quad (6.16)$$

$\pi_{\tilde{A}}(x)$ represents the degree of non-determinacy (i.e. uncertainty) of the element $x \in X$ to the intuitionistic fuzzy set $\tilde{A}$ and its value defined as:

$$\pi_{\tilde{A}}(x) = 1-\mu_{\tilde{A}}(x)-v_{\tilde{A}}(x) \quad (6.17)$$

The degree of non-determinacy is described zero in the ordinary fuzzy set for every $x \in X;\pi_A(x) = 0$. In this context, every ordinary fuzzy set is defined as follows;

$$\{(x, \mu_{\tilde{A}}(x), 1-\mu_{\tilde{A}}(x))|x \in X\} \quad (6.18)$$

Multiplication of an IFS with a natural number n and nth power of an IFS defined as (De, Biswas, & Roy, 2000):

$$n.\tilde{A} = \{(x, 1 - (1 - \mu_A(x))^n, (v_A(x))^n)|x \in X\} \tag{6.19}$$

$$\tilde{A}^n = \{(x, (\mu_A(x))^n, 1 - (1 - v_A(x))^n)|x \in X\} \tag{6.20}$$

6.2.2 Definitions and operations of Pythagorean fuzzy sets

Non-standard second-order fuzzy clusters such as intuitionistic fuzzy (Krassimir T Atanassov, 1986, 2012), and interval-valued fuzzy (J. Mendel & Wu, 2010; J. M. Mendel & John, 2002) are referenced for more accurate acquisition and modeling of user-defined membership grades that are critical to the use of fuzzy clusters (Yager, 2013). Pythagoras fuzzy sets developed by Yager as a new class of non-standard fuzzy sub-sets allow uncertainty in the specification of membership levels (Yager, 2013). Nevertheless, Pythagorean Fuzzy Set (PFS) statement was first expressed and graphically defined as “Second type IFS” (2-IFS) by K.T. Atanassov in 1989 (K. Atanassov, 1989).

Proposed PFS provides a condition that the sum of the squares of membership grade and non-membership is less than or equal to 1. Pythagorean membership grades allow for non-standard membership grades to be represented larger than intuitionistic membership grades (Yager, 2013). The PFS allows the user to determine uncertainties in the real world better and more accurately model these uncertainties than IFS (Peng, Yuan, & Yang, 2017).

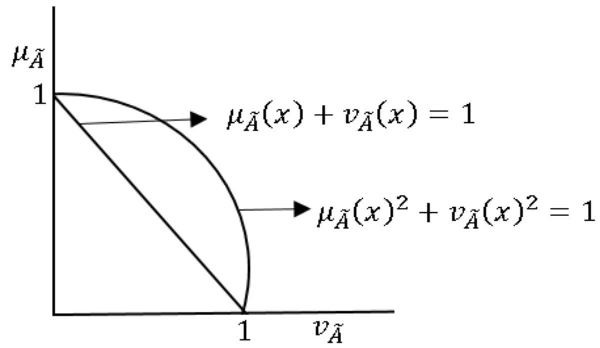

Figure 6.6 : Difference between PFS and IFS spaces (Yager, 2013).

The main reason for the difference between the PFN and IFN is that the conditional constraints are different (Figure 6.6). Each IFN is a PFN and that each PFN is not an IFN. PFS $\tilde{A}$ in X that is nonempty set is defined as following form:

$$\tilde{A} = \{(x, \mu_{\tilde{A}}(x), v_{\tilde{A}}(x))|x \in X\} \quad (6.21)$$

where membership function and non-membership function of $\tilde{A}$ are denoted as $\mu_{\tilde{A}}(x): X \to [0,1]$ $v_{\tilde{A}}(x): X \to [0,1]$ for each $x \in X$ respectively and provide the following condition.

$$0 \leq \left(\mu_{\tilde{A}}(x)\right)^2 + \left(v_{\tilde{A}}(x)\right)^2 \leq 1 \quad (6.22)$$

It is clear that for all real numbers a, b in the [0,1] interval, if $0 \leq a + b \leq 1$ then $0 \leq a^2 + b^2 \leq 1$. Therefore, it can be said that all intuitionistic fuzzy sets (IFSs) are Pythagorean fuzzy sets (PFS). The redefinition of Second type IFS by Yager as "Pythagorean fuzzy set" (Yager, 2013) allows to generate the creation of new models and operation. The degree of indeterminacy (uncertainty) of an element $x \in X$ to the PFS $\tilde{A}$ is defined as;

$$\pi_{\tilde{A}}(x) = \sqrt{1 - \mu_{\tilde{A}}(x)^2 - v_{\tilde{A}}(x)^2} \quad (6.23)$$

6.2.3 Basic operations of PFSs

$\tilde{A} = \{(x, \mu_{\tilde{A}}(x), v_{\tilde{A}}(x))|x \in X\}$ and $\tilde{B} = \{(x, \mu_{\tilde{B}}(x), v_{\tilde{B}}(x))|x \in X\}$ are Pythagorean fuzzy sets (PFSs) and $\lambda > 0$;

- Distance between $\tilde{A}$ and $\tilde{B}$, $d(\tilde{A}, \tilde{B})$ (X. Zhang & Xu, 2014):

$$d(\tilde{A}, \tilde{B}) = 1/2(|(\mu_{\tilde{A}})^2 - (\mu_{\tilde{B}})^2| + |(v_{\tilde{A}})^2 - (v_{\tilde{B}})^2| + |(\pi_{\tilde{A}})^2 - (\pi_{\tilde{B}})^2|) \quad (6.24)$$

- Score function of $\tilde{A}$, $s(\tilde{A}) \in [-1,1]$ (X. Zhang & Xu, 2014):

$$s(\tilde{A}) = (\mu_{\tilde{A}})^2 - (v_{\tilde{A}})^2 \quad (6.25)$$

- Accuracy function of $\tilde{A}$, $a(\tilde{A}) \in [-1,1]$ (X. Zhang & Xu, 2014):

$$a(\tilde{A}) = (\mu_{\tilde{A}})^2 + (v_{\tilde{A}})^2 \quad (6.26)$$

- Arithmetic operations (X. Zhang & Xu, 2014):

$$\tilde{A} \oplus \tilde{B} = \left(\sqrt{(\mu_{\tilde{A}}(x)^2 + \mu_{\tilde{B}}(x)^2 - \mu_{\tilde{A}}(x)^2\, \mu_{\tilde{B}}(x)^2}, v_{\tilde{A}}(x) v_{\tilde{B}}(x)\right) \quad (6.27)$$

$$\tilde{A} \otimes \tilde{B} = \left(\mu_{\tilde{A}}(x)\mu_{\tilde{B}}(x), \sqrt{v_{\tilde{A}}(x)^2 + v_{\tilde{B}}(x)^2 - v_{\tilde{A}}(x)^2 v_{\tilde{B}}(x)^2}\right) \quad (6.28)$$

$$\lambda\tilde{A} = \left(\sqrt{1 - (1 - \mu_{\tilde{A}}(x)^2)^\lambda}, v_{\tilde{A}}(x)^\lambda\right) \quad (6.29)$$

$$\tilde{A}^\lambda = \left(\mu_{\tilde{A}}(x)^\lambda, \sqrt{1 - (1 - v_{\tilde{A}}(x)^2)^\lambda}\right) \quad (6.30)$$

Subtraction and division operations are generated by Peng and Yang (Peng & Yang, 2015):

$$\tilde{A} \ominus \tilde{B} = \left(\sqrt{\frac{\mu_{\tilde{A}}(x)^2 - \mu_{\tilde{B}}(x)^2}{1-\mu_{\tilde{B}}(x)^2}}, \frac{v_{\tilde{A}}(x)}{v_{\tilde{B}}(x)}\right),$$

$$if\ \mu_{\tilde{A}}(x) \geq \mu_{\tilde{B}}(x), v_{\tilde{A}}(x)\ min\left\{v_{\tilde{B}}(x), \frac{v_{\tilde{B}}(x)\pi_{\tilde{A}}(x)}{\pi_{\tilde{B}}(x)}\right\} \quad (6.31)$$

$$\frac{\tilde{A}}{\tilde{B}} = \left(\frac{\mu_{\tilde{A}}(x)}{\mu_{\tilde{B}}(x)}, \sqrt{\frac{v_{\tilde{A}}(x)^2 - v_{\tilde{B}}(x)^2}{1-v_{\tilde{B}}(x)^2}}\right),$$

$$if\ \mu_{\tilde{A}}(x) \leq min\left\{\mu_{\tilde{B}}(x), \frac{\mu_{\tilde{B}}(x)\pi_{\tilde{A}}(x)}{\pi_{\tilde{B}}(x)}\right\}, v_{\tilde{A}}(x) \geq v_{\tilde{B}}(x) \quad (6.32)$$

Yager (2013) proposes aggregation Operators as follows (Yager, 2014):

- **Pythagorean fuzzy weighted geometric average (PFWGA) operator**

$\tilde{A}_i = \left(x, \mu_{\tilde{A}_i}(x), v_{\tilde{A}_i}(x)\right)$ for $i = 1,2,\ldots,n$ are a series of PFWGA and $w = (w_1, w_2, \ldots, w_n)^T$ is the weight vector of $\tilde{A}_i$ $(i = 1,2,\ldots,n)$ with $\sum_{i=1}^{n} w_i = 1$;

$$PFWGA(\tilde{A}_i) = \left(\prod_{i=1}^{n} \mu_{\tilde{A}_i}(x)^{w_i}, \prod_{i=1}^{n} v_{\tilde{A}_i}(x)^{w_i}\right) \quad (6.33)$$

- **Pythagorean fuzzy weighted power average (PFWPA) operator**

$\tilde{A}_i = \left(x, \mu_{\tilde{A}_i}(x), v_{\tilde{A}_i}(x)\right)$ for $i = 1,2,\ldots,n$ are a series of PFWPA and $w = (w_1, w_2, \ldots, w_n)^T$ is the weight vector of $\tilde{A}_i$ $(i = 1,2,\ldots,n)$ with $\sum_{i=1}^{n} w_i = 1$;

$$PFWPA(\tilde{A}_i) = \left(\left(\sum_{i=1}^{n} w_i \mu_{\tilde{A}_i}(x)^2\right)^{\frac{1}{2}}, \left(\sum_{i=1}^{n} w_i v_{\tilde{A}_i}(x)^2\right)^{\frac{1}{2}}\right) \quad (6.34)$$

- **Pythagorean fuzzy weighted power geometric average (PFWPGA) operator**

$\tilde{A}_i = \left(x, \mu_{\tilde{A}_i}(x), v_{\tilde{A}_i}(x)\right)$ for $i = 1,2,\ldots,n$ are a series of PFWPGA and $w = (w_1, w_2, \ldots, w_n)^T$ is the weight vector of $\tilde{A}_i$ $(i = 1,2,\ldots,n)$ with $\sum_{i=1}^{n} w_i = 1$;

$$PFWPGA(\tilde{A}_i) = \left(1 - \prod_{i=1}^{n}\left(1-\mu_{\tilde{A}_i}(x)^2\right)^{w_i}\right)^{\frac{1}{2}}, \left(1 - \prod_{i=1}^{n}\left(1-v_{\tilde{A}_i}(x)^2\right)^{w_i}\right)^{\frac{1}{2}} \quad (6.35)$$

- **Pythagorean fuzzy weighted average (PFWA) operator**

$\tilde{A}_i = \left(x, \mu_{\tilde{A}_i}(x), v_{\tilde{A}_i}(x)\right)$ for $i = 1,2,\dots,n$ are a series of STIFNs and $w = (w_1, w_2, \dots, w_n)^T$ is the weight vector of $\tilde{A}_i$ $(i = 1,2,\dots,n)$ with $\sum_{i=1}^{n} w_i = 1$ (Yager, 2014);

$$PFWA(\tilde{A}_i) = \left(\sum_{i=1}^{n} w_i \mu_{\tilde{A}_i}(x), \sum_{i=1}^{n} w_i v_{\tilde{A}_i}(x)\right) \quad (6.36)$$

6.2.4 Defuzzification of Pythagorean fuzzy

Comparing and sorting of the Pythagorean fuzzy numbers is an essential operation step. The Roubens sorting function (Roubens, 1990), which is suitable for intuitionistic fuzzy numbers in the sequence, is also appropriate for the ordering of Pythagorean fuzzy numbers. $\tilde{A}$ is a PFN with $\mu_{\tilde{A}}$ membership and $v_{\tilde{A}}$ non-membership, the rank is defined as follows:

$$R(\tilde{A}) = \frac{R_r(\mu_{\tilde{A}}) + R_r(v_{\tilde{A}})}{2} \quad (6.37)$$

where R_r is a Roubens's sorting function. The Nayagam and Sivaraman's defuzzification method is transformed and applied to the membership and non-membership values for ranking of PFNs (Nayagam & Sivaraman, 2011). The defuzzified value of a PFN $\tilde{A} = (\mu_{\tilde{A}}, v_{\tilde{A}})$ can be defined as:

$$P_{deff}(\tilde{A}_{\mu v}) = \frac{\mu_{\tilde{A}}^2(1-\gamma) + \gamma(1 - v_{\tilde{A}}^{\ 2})}{2} \quad (6.38)$$

where γ is a weight of member and non-membership values defined by decision maker. Defuzzification of $\tilde{A}$ PFN can be obtained by an extension of the Roubens's sorting function.

$$P_{deff}(\tilde{A}) = \frac{\sum_{i=1}^{k} c_i \left(P_{deff}(\tilde{A}_{\mu v_i})\right)^2}{\sum_{i=1}^{k} \left(P_{deff}(\tilde{A}_{\mu v_i})\right)^2} \quad (6.39)$$

6.2.5 Fuzzy engineering economics

Failure to determine the future economic situation based on the estimation of past economic values leads to uncertainty in the identification and calculation of future economic values (Sullivan, Wicks, & Luxhoj, 2009). The fuzzy set theory is utilized in the development of economy calculations involving uncertain conditions and values of the future. Thus, the primary concepts in the engineering economy (interest rates, time of money, worth factors, future value, present value, regular annuities capital recovery and sinking fund factors) can be fuzzy and should be defined in fuzzified forms (Kahraman et al., 2015). The economic calculations are made more realistic and obtained more accurate results for real-life problems. Future value, current value, and regular annual value calculations are the basic concepts of the engineering economy. The cash amount, interest rate and period parameters included in these basic economic calculation methods are defined as fuzzy (Kahraman, 2008; Kahraman et al., 2015).

The value reached at the end of the uncertain investment becomes uncertain by the uncertain investment value and interest rate. The "future value" economic method calculates the $\widetilde{FV}$ future value of the $\widetilde{PV}$ (≥ 0) amouthe nt invested today at the end of $\tilde{n}$ periods. The interest rate applied for each period is $\tilde{r}$ in [0,1] interval (Buckley, Eslami, & Feuring, 2013; Kahraman, 2008).

$$\widetilde{FV} = \widetilde{PV}(1+\tilde{r})^{\tilde{n}} \tag{6.40}$$

The $\widetilde{PV}$ of $\widetilde{FV}$ at a future time for the $\tilde{n}$ period and $\tilde{r}$ the interest rate is calculated by the "present value" economic method (Buckley et al., 2013; Kahraman, 2008).

$$\widetilde{PV} = \widetilde{FV}(1+\tilde{r})^{-\tilde{n}} \tag{6.41}$$

The amount of $\widetilde{FV}$ obtained in the future from the $\tilde{A}_{nn}$ value which is regularly deposited in the $\tilde{n}$ period is calculated by the "future value of annuities" economic method. The uncertain interest rate is defined as $\tilde{r}$ (Buckley et al., 2013; Kahraman, 2008).

$$\widetilde{FV} = \tilde{A}_{nn} q(\tilde{n}, \tilde{r}) \text{ where } q(\tilde{n}, \tilde{r}) = \frac{(1+\tilde{r})^{\tilde{n}}-1}{\tilde{r}} \tag{6.42}$$

The present $\widetilde{PV}$ obtained from the $\tilde{A}_{nn}$ value deposited regularly in the $\tilde{n}$ period is calculated by the "present value of annuities" economic method. The uncertain interest rate is defined as $\tilde{r}$ (Buckley et al., 2013; Kahraman, 2008).

$$\widetilde{PV} = \tilde{A}_{nn} \beta(\tilde{n}, \tilde{r}) \text{ where } \beta(\tilde{n}, \tilde{r}) = \frac{1-(1+\tilde{r})^{-\tilde{n}}}{\tilde{r}} \tag{6.43}$$

The net present worth model is the most common method used to evaluate economic investments. The net present worth analysis collects the equivalent amount of all cash flows at the present time and evaluates alternative investments at a common point. Because the inputs used in the analysis contain fuzzy data, the net present value calculation is defined as fuzzy. The sum of the present values of the initial investment

$\tilde{A}_0$ and the periodic cash flows ($\tilde{A}_i$) gives the net present value $\widetilde{NPV}(\tilde{A}, n)$ (Buckley et al., 2013; Kahraman, 2008).

$$\widetilde{NPV}(\tilde{A}, n) = \tilde{A}_0 + \sum_{i=1}^{n} \tilde{A}_i (1 + \tilde{r})^{-i} \quad (6.44)$$

The fuzzy cash flows defined by the fuzzy interest rate represent the capital cost of the firm. While the initial investment value ($\tilde{A}_0$) is expressed as a negative fuzzy number, other cash flows ($\tilde{A}_i$) can be expressed as either positive or negative fuzzy numbers.

If alternative projects have different lifetimes, the net present value is calculated by taking the common multiple of the lifetimes of the alternatives. In this case, if the life of one of the alternative projects is infinite, the calculation period is taken as infinite. The evaluation of alternative projects by Pythagorean fuzzy present value analysis is defined as follows (Kahraman, Onar, & Oztaysi, 2017).

$$\widetilde{PV} = \widetilde{NCF}\left(\frac{P}{A}, \tilde{\imath}\%, n\right) - FC$$

$$= \left(NCF; (\mu_{NCF}, v_{NCF})\right)\left(\frac{P}{A}, \left(i; (\mu_i, v_i)\right), n\right) - \left(FC; (\mu_{FC}, v_{FC})\right)$$

$$= \langle NCF \frac{(1+i)^n - 1}{i(1+i)^n}, \left(\min(\mu_{NCF}, \mu_i, \mu_{FC}), max(v_{NCF}, v_i, v_{FC})\right)\rangle \quad (6.45)$$

where $\widetilde{NCF}$ is net cash flow, $\tilde{\imath}$ is annual interest rate, n is life time period and FC represents the initial cost of project. Present values for each alternative project are calculated and the project with the largest $\widetilde{PW}$ value is selected. The following defuzzification method is applied for comparison of alternative projects (Kahraman et al., 2017).

$$deff\tilde{A} = \frac{\sqrt{\mu} - v^2}{2} \quad (6.46)$$

6.3 Pythagorean Fuzzy Engineering Economic Analyses for Solar Systems

The objective of economic analysis of the solar energy system is to find the lowest cost system on uncertain conditions. Therefore, the economic analysis is based on a long-term comparison of the gain of energy generated from solar radiation with the high initial investment. There are various economic calculation methods for economic evaluation of solar energy systems, which vary according to the system type and dynamic country conditions (Duffie & Beckman, 2013).

The Life Cycle Cost (LCC) method is the most appropriate method for economic evaluation of the installation and operation period of the solar energy system (Crawley, 2016; Duffie & Beckman, 2013). The LCC method, which requires long-term computations and contains future uncertainties, has been restructured by fuzzy logic to make more realistic calculations as Pythagorean Life Cycle Cost method (PLCC). The PLCC method allows a timely assessment of the investment with the technique of reducing future cash flow to present worth. The time value of the money causes the PLCC method to be selected as an economic evaluation tool for solar energy systems.

The general PLCC of the solar power generation system is the sum of the initial investment ($\widetilde{II}$) and the current values of the annual operating and maintenance costs incurred throughout the lifetime of the system (Talavera, Nofuentes, De La Casa, & Aguilera, 2013). Initial investment is financed directly by existing sources (own capital, $\widetilde{PW}_{oc}$) or financed by borrowing (external capital, $\widetilde{PW}_{EC}$) over a variable time period (t_l) at an annual loan interest rate (i_l). The initial investment financed by debt will result in an annual interest cost over the specified period.

The operating and maintenance ($\widetilde{OM}$) costs foreseen for the life cycle of the solar power system are included in the total current value by withdrawing the investment turnover. Local economic expectations, technological developments and similar factors are taken into account in setting annual operating and maintenance costs. The nominal discount rate ($\tilde{r}$) is used to calculate the life cycle cost since the present value of the investment will be determined (Crawley, 2016).

$$\widetilde{PLCC} = \widetilde{PW}_{II} + \widetilde{PW}_{OM}(t) \tag{6.47}$$

$$\widetilde{PW}_{II} = \widetilde{PW}_{OC} + \widetilde{PW}_{EC} \tag{6.48}$$

If the investment is financed from own capital, the present value of the own portion of the investment cost ($\widetilde{PW}_{OC}$) is calculated under the assumption that the annual dividend rate ($\tilde{d}_\iota$) is on the capital and the system investment will be depreciated at the end of the system life ($\tilde{t}$). The present worth of own capital use in the investment is as follows:

$$\widetilde{PW}_{OC} = \widetilde{OC}\left[\tilde{d}_\iota \frac{\tilde{q}\left(1-\tilde{q}^{\tilde{t}}\right)}{(1-\tilde{q})} + \tilde{q}^{\tilde{t}}\right] \tag{6.49}$$

where $\tilde{q} = 1/(1+\tilde{r})$. The present worth of the external capital portion of the total initial investment ($\widetilde{PW}_{EC}$) is calculated as:

$$\widetilde{PW}_{EC} = \left[\widetilde{EC} * i_l \frac{(1+i_l)^{t_l}}{(1+i_l)^{t_l}-1} \frac{\tilde{q}(1-\tilde{q}^{t_l})}{(1-\tilde{q})}\right] \quad (6.50)$$

where $\widetilde{EC}$ refers to the portion of the initial investment remaining from the own capital and is represented as $\widetilde{EC} = \widetilde{II} - \widetilde{OC}$.

The present worth of the operating and maintenance costs is calculated after calculating the present worth of the initial investment. It is assumed that the initial investment value of the solar energy system reflects the system greatness. Therefore, it is predicted that the annual operating costs and maintenance costs ($\widetilde{OM}_{ANN}$) are related to the initial investment cost. In addition, the annual O/M increase rate ($\widetilde{ri}_{OM}$) is determined for the operating and maintenance costs to be calculated for future periods, within the lifetime of the system. Thus, the present value of the operating and maintenance cost is calculated as:

$$\widetilde{PW}_{OM}(t) = \widetilde{OM}_{ANN} \frac{\left(\frac{1+\widetilde{ri}_{OM}}{1+\tilde{r}}\right)\left(1-\left(\frac{1+\widetilde{ri}_{OM}}{1+\tilde{r}}\right)^{\tilde{t}}\right)}{1-\left(\frac{1+\widetilde{ri}_{OM}}{1+\tilde{r}}\right)} \quad (51)$$

Levelized Cost of Electricity (LCOE) defines the unit cost of electricity (€$/kWh$) generated annually by the solar system over its lifetime. The cost expressed in terms of the current monetary value is levelised for each year the system plans to generate electricity. The LCOE, which is calculated based on the cost of life cycle, must account for temporal and environmental uncertainties. Therefore, the LCOE calculations are redeveloped by the Pythagorean fuzzy method and are defined as Pythagorean Levelized Cost of Electricity (PLCOE).

Since the value obtained in the PLCOE analysis does not include the cost of transporting and maintaining the grid, it can be regarded as grid parity. Grid parity occurs when the unit cost of the electricity generated from the solar power plant is equal to the purchase price of the electricity from the electricity grid (Short, Packey, & Holt, 1995). The PLCOE value is calculated by dividing the estimated total cost of the solar energy system during the life cycle (LCC) by the price of the electricity generated by the system.

$$\widetilde{PLCOE} = \frac{\widetilde{LCC}}{\sum_{i=1}^{t} \frac{\tilde{E}_{Ann}\,(1-\widetilde{dr}_{pw})^{i}}{(1+\tilde{r})^{i}}} \tag{6.52}$$

where $\tilde{E}_{Ann}$ represents the annual electricity yield ($kWh/year$) and $\widetilde{dr}_{pw}$ represents an annual decrease rate in producing power. The PLCOE value is an important parameter in the economic evaluation and comparison of the systems planned to produce electricity with solar energy (Campbell, Blunden, Smeloff, & Aschenbrenner, 2009) (Figure 6.7).

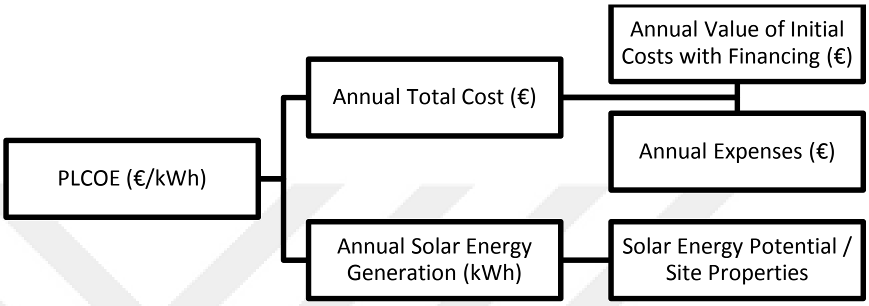

Figure 6.7 : PLCOE flow chart of sample solar energy system (adapted from U.S. Department of Energy, 2015).

The LCOE formula can be expanded by including subsidies, taxes, depreciation, interest payment, debt payment and other unanticipated costs in the LCC account of the solar power system (Darling, You, Veselka, & Velosa, 2011). PFS-based calculations are developed to eliminate the uncertainties in these parameters which are based on assumptions and predictions. The periodic cash flows in the equation are expressed in Pythagorean fuzzy form and the expanded $\widetilde{PLCOE}$ is redefined to include all cash flows.

$$\widetilde{PLCOE} = \frac{\left(\begin{array}{l} \widetilde{PW}_{ll} - \sum_{i=1}^{t} \frac{\widetilde{DEP} * \widetilde{TR}}{(1+\tilde{r})^{i}} - \sum_{i=1}^{t} \frac{\widetilde{INT} * \widetilde{TR}}{(1+\tilde{r})^{i}} + \sum_{i=1}^{t} \frac{\widetilde{LP}}{(1+\tilde{r})^{i}} \\ + \sum_{i=1}^{t} \frac{\widetilde{AO} * (1-\widetilde{TR}) - \widetilde{RV}}{(1+\tilde{r})^{i}} - \sum_{i=1}^{t} \frac{\widetilde{SS}}{(1+\tilde{r})^{i}} + \sum_{i=1}^{t} \frac{\widetilde{SC}}{(1+\tilde{r})^{i}} \end{array} \right)}{\sum_{i=1}^{t} \frac{\tilde{E}_{Ann}(1-\widetilde{dr}_{pw})^{i}}{(1+\tilde{r})^{i}}} \tag{6.53}$$

where DEP is depreciation, INT is interest payment, LP is debt payment, AO is periodic operating costs, RV is periodic residual values, SS is periodic subsidies, and SC is safety cost.

6.4 Application on the Solar Energy System

In the application section, the economic feasibility of the installation of the solar power plant from the Si-x PV modules is evaluated by PLCC and PLCOE methods under standard economic conditions. Expert opinions are taken to make the calculations more objective. Pythagorean fuzzy sets are used to evaluate parameters and experts. The parameters used for economic analysis and their possible values (valid for 2014; Crawley, 2016) are shown in Table 6.1.

The weight values of the decision makers are converted to the usable form before calculating the parameter values. The calculation steps and the decision weights obtained for the first expert are calculated as follows (Table 6.1):

$$P_{deff}\left(\tilde{E}_{11_{\mu v}}\right) = (0.5^2 * (1-0.62) + (1-0.7^2) * 0.62)/2 = 0.0754$$

$$P_{deff}\left(\tilde{E}_{12_{\mu v}}\right) = (0.8^2 * (1-0.62) + (1-0.2^2) * 0.62)/2 = 0.320$$

$$P_{deff}\left(\tilde{E}_{13_{\mu v}}\right) = (0.5^2 * (1-0.62) + (1-0.5^2) * 0.62)/2 = 0.125$$

$$P_{deff}(\tilde{E}_1) = \frac{0.1 * 0.0754^2 + 0.2 * 0.32^2 + 0.3 * 0.125^2}{0.0754^2 + 0.32^2 + 0.125^2} = 0.208$$

where γ is selected as 0.62 for this step and other weights are $P_{deff}(\tilde{E}_2) = 0.298$, $P_{deff}(\tilde{E}_3) = 0.494$. The aggregation process is performed according to the experts' opinion weights for the solar economic analysis parameters. Pythagorean fuzzy weighted power geometric average (PFWPGA) operator is used to for each parameter. Expert weights defuzzified in the previous step are considered as weight values (w_i) for PFWPGA operation and it is seen that the sum of weight values is equal to 1 ($\sum_{i=1}^{3} w_i = 0.208 + 0.298 + 0.494 = 1$). The sample aggregation for possible 1200 $kWh/kWp/year$ value of $\tilde{E}_{Ann}$ Pythagorean parameter is calculated below (Table 6.1).

$$\begin{aligned} PFWPGA\left(\tilde{E}_{Ann_{1200}}\right) &= \Big((1-(1-0.3^2)^{0.208} * (1-0.9^2)^{0.298} * (1-0.5^2)^{0.494})^{\frac{1}{2}}, (1 \\ &- (1-0.5^2)^{0.208} * (1-0.0^2)^{0.298} * (1-0.6^2)^{0.494})^{\frac{1}{2}}\Big) \\ &= (0.6938, 0.4944) \end{aligned}$$

In the next step, the defuzzification operation is performed on the possible values of the Pythagorean annual electricity yield ($\tilde{E}_{Ann}$) parameters.

The sample defuzzification operations for $\gamma = 0.8$ are calculated as follows:

$$P_{deff}\left(\tilde{E}_{Ann_{1200_{\mu v}}}\right) = (0.6938^2 * (1 - 0.8) + (1 - 0.4944^2) * 0.8)/2 = 0.3504$$

$$P_{deff}\left(\tilde{E}_{Ann_{1350_{\mu v}}}\right) = (0.3681^2 * (1 - 0.8) + (1 - 0.201^2) * 0.8)/2 = 0.3974$$

$$P_{deff}\left(\tilde{E}_{Ann_{1500_{\mu v}}}\right) = (0.3186^2 * (1 - 0.8) + (1 - 0.692^2) * 0.8)/2 = 0.2186$$

$$P_{deff}(\tilde{E}_{Ann}) = \frac{1200 * 0.3504^2 + 1350 * 0.3974^2 + 1500 * 0.2186^2}{0.3504^2 + 0.3974^2 + 0.2186^2} = 1315.465$$

The obtained defuzzified Pythagorean parameters (Table 6.1) are used in the PLCC and PLCOE economic analyzes to check the suitability of the proposed solar energy system. Investment can be financed by own capital or external capital (Equation 6.48).

The present value of the own and external part of the investment costs are calculated under the annual dividend rate ($\widetilde{d_i}$) and limited system life ($\tilde{t}$) assumptions. The present worth of own and external capital use in the investment is as follows (Equation 6.49):

$$\widetilde{PW}_{OC} = 1315.765\left[2.918\frac{0.206(1 - 0.206^{21.924})}{(1 - 0.206)} + 0.206^{21.924}\right] = 320.765\ €$$

where $\tilde{q} = \frac{1}{1+\tilde{r}} = 0.206$. The present worth of the external capital is calculated as (Equation 6.50):

$$\widetilde{PW}_{EC} = 1522.401 * 0.0413\frac{(1 + 0.0413)^{20}}{(1 + 0.0413)^{20} - 1}\frac{0.206(1 - 0.206^{20})}{(1 - 0.206)}$$
$$= 1560.205\ €$$

Present worth of the total investment is calculated as follow (Equation 6.48):

$$\widetilde{PW}_{II} = 320.765 + 1560.205 = 1880.97\ €$$

worth of the annual operating and maintenance costs ($\widetilde{OM}_{Ann}$) with an annual O/M increase rate ($\widetilde{ri}_{OM}$) are calculated as follows (Equation 6.51):

$$\widetilde{PW}_{OM}(t) = 28.916\frac{0.989\ (1 - 0.989^{21.924})}{1 - 0.989} = 565.442\ €$$

where $\tilde{p} = \frac{1+\widetilde{ri}_{OM}}{1+\tilde{r}} = 0.989$. The total current value of initial investment and annual maintenance, repair and operation costs is as follows (Equation 6.47):

$$\widetilde{PLCC} = 1880.97 + 565.442 = 2446.412\ €$$

Table 6.1 : Parameters' possible values, Pythagorean fuzzy membership values, aggregated and defuzzified result values.

Parameters	Possible Values	E1	E2	E3	Aggregated Values	Defuzzified values
		Experts' Weights				
		0.1 (0.5,0.7); 0.2 (0.8,0.2); 0.3 (0.5,0.5)	0.4 (0.47,0.6); 0.3 (0.85,0.2); 0.5 (0.5,0.7)	0.3 (0.3,0.5); 0.5 (0.85,0.3); 0.7 (0.2,0.6)		
$\tilde{E}_{Ann}$ $(kWh/kWp/year)$	1200	(0.3,0.5)	(0.9,0.0)	(0.5,0.6)	(0.6938,0.494)	
	1350	(0.5,0.4)	(0.5,0.0)	(0.0,0.1)	(0.3681,0.201)	1315.765
	1500	(0.2,0.9)	(0.4,0.5)	(0.3,0.6)	(0.3186,0.692)	
$\widetilde{dr}_{pw}$ (annual %)	0.3	(0.4,0.5)	(0.2,0.9)	(0.3,0.2)	(0.3011,0.661)	
	0.5	(0.7,0.4)	(0.3,0.4)	(0.7,0.3)	(0.6277,0.355)	0.4984
	0.6	(0.3,0.7)	(0.3,0.0)	(0.0,0.4)	(0.2159,0.449)	
$\widetilde{EC}$ (€)	1440	(0.4,0.4)	(0.5,0.2)	(0.6,0.8)	(0.5385,0.651)	
	1520	(0.7,0.4)	(0.8,0.0)	(0.9,0.4)	(0.8472,0.339)	1522.401
	1600	(0.5,0.5)	(0.7,0.5)	(0.4,0.7)	(0.5412,0.616)	
$\widetilde{OC}$ (€)	340	(0.6,0.6)	(0.9,0.1)	(0.7,0.3)	(0.7756,0.364)	
	380	(0.3,0.7)	(0.8,0.4)	(0.7,0.3)	(0.6939,0.460)	371.577
	420	(0.6,0.6)	(0.9,0.5)	(0.5,0.7)	(0.7197,0.632)	
$\widetilde{OM}_{Ann}$ (€)	27.5	(0.4,0.5)	(0.7,0.5)	(0.7,0.7)	(0.6590,0.616)	
	28.5	(0.6,0.3)	(0.9,0.2)	(0.6,0.9)	(0.7445,0.757)	28.916
	30.0	(0.5,0.5)	(0.5,0.6)	(0.7,0.2)	(0.6165,0.438)	
$\widetilde{ri}_{OM}$ $(annual\ \%)$	2.4	(0.7,0.6)	(0.1,0.0)	(0.7,0.5)	(0.6153,0.457)	
	2.8	(0.7,0.5)	(0.2,0.1)	(0.8,0.5)	(0.6939,0.430)	2.8035
	3.2	(0.7,0.6)	(0.5,0.3)	(0.1,0.3)	(0.4540,0.392)	
$\tilde{d}_i$ $(annual\ \%)$	2.5	(0.4,0.5)	(0.5,0.4)	(0.4,0.6)	(0.4335,0.531)	
	3	(0.7,0.3)	(0.3,0.0)	(0.6,0.7)	(0.5675,0.544)	2.9180
	3.5	(0.4,0.5)	(0.1,0.9)	(0.2,0.2)	(0.2402,0.661)	
$\tilde{r}$ $(annual\ \%)$	3.6	(0.7,0.2)	(0.9,0.1)	(0.9,0.3)	(0.8756,0.237)	
	3.9	(0.5,0.2)	(0.5,0.4)	(0.3,0.4)	(0.4181,0.369)	3.8531
	4.2	(0.6,0.4)	(0.7,0.7)	(0.8,0.2)	(0.7415,0.476)	
$\tilde{t}$ $(year)$	15	(0.3,0.1)	(0.2,0.9)	(0.2,0.4)	(0.2250,0.664)	
	20	(0.5,0.2)	(0.5,0.6)	(0.6,0.5)	(0.5536,0.496)	21.924
	30	(0.5,0.3)	(0.3,0.8)	(0.7,0.6)	(0.5859,0.6480)	

Levelized Cost of Electricity (LCOE) generated based on the Pythagorean fuzzy numbers is calculated with the defuzzified parameters as follows (Equation 6.52):

$$\widetilde{PLCOE} = \frac{2446.412}{17679.84} = 0.1384\ €/kWh$$

The 13.50 cent $€/kWh$ LCOE value obtained from the source evaluation of the sample application (Crawley, 2016) is reasonably consistent with the 13.84 cent $€/kWh$ values obtained from the Pythagorean basis.

The present worth of the operating and maintenance costs is calculated after calculating the present worth of the initial investment. It is assumed that the initial investment value of the solar energy system reflects the system greatness. The present

Values obtained from the LCC and LCOE methods using Pythagorean fuzzy numbers reflect economic conditions more realistically. Alternative solar energy systems with different technological features and economic conditions can be compared to the values obtained from these methods. Alternative solar energy systems evaluated on achieving the same energy capacity are ranked according to the LCC value, and the system with the lowest value is preferred.

The LCOE model is used to compare the planned solar power projects with the current market prices. If the LCOE value is higher than the market price, the unit margin of the produced energy becomes negative, and the project is seen as unprofitable (PennSatate Department of Energy and Mineral Engineering (PDEME), 2017). Therefore, it would not be sufficient to compare alternative energy systems solely by LCC while developing a grid-connected solar energy system. The solar power system with the lowest LCOE value, which is below the market price, is preferred among the alternatives.

6.5 Conclusion

Increasing population and changing consumption habits stimulate to increase energy demand. Fossil fuels, which are used as the primary energy source in meeting the increasing energy demand, cause serious harm to the environment, economy and public health. Therefore, countries have turned to alternative energy sources such renewable, nuclear, tidal and geothermal. The sun has come to the forefront with its features among the renewable energy sources that are widely accepted by the countries in the world. Investment evaluation of solar energy systems, which has a high initial cost and a low operating cost, is made according to the results of the economic analysis. The accepted and widely used methods for evaluating and comparing solar energy systems are LCC and LCOE.

LCC and LCOE values are calculated based on future operation, maintenance costs, and energy production expectations. Because the interest rates and cash flow values used in the calculations are dependent on local and global unpredictable political, economic and social variables, the cost and comparison calculations within LCC and LCOE are made incorrect and unrealistic. Also, the dependence of solar radiation values on extraterrestrial, atmospheric and terrestrial different and indefinite variabilities prevent precise calculation of the energy potential obtained from the solar energy system. Therefore, Pythagorean fuzzy numbers are included in the method to incorporate the future uncertainties and decision makers' views into the calculations. Pythagorean fuzzy sets are the enlarged states of intuitionistic fuzzy sets, which means that the sum of the squares of the membership and non-membership values of the fuzzy number is equal to or less than one. The LCC and LCOE calculation parameters defined according to the Pythagorean membership grades are exemplified by an application that includes the evaluators of the decision makers. It can be seen that the LCC and LCEO values obtained with Pythagorean based calculations are acceptable when the results are compared with the actual application results.

In the future, it is planned to develop LCC and LCEO calculations by Pythagorean fuzzy set theory by elaborating the cost and gain titles of solar energy system installation. Also, the Pythagorean fuzzy calculation method can be applied in other economic analysis applications and other renewable energy technologies to make comparative evaluations.

7. CONCLUSIONS AND RECOMMENDATIONS

Increasing population and industrialization have led to an increase in energy demand. Fossil fuels are used as the primary source of energy in meeting the rising energy demand with increasing population. The harmful gases and substances that occur during the conversion of fossil fuels to energy cause environmental and social problems. Alternative energy sources are proposed against fossil-based fuels containing environmental, social and economic problems. Renewable energy sources emerge as the most important alternative energy source with its environmental sensitivity, inexhaustible and renewable characteristics. Besides, the sun is the most important renewable energy source with its direct and indirect use characteristics as a source of all the energies on earth (except geothermal, tidal, nuclear).

In this thesis study, Turkey's solar energy potential is modelled under the environmental, social, economic and technical conditions. The study, which started with the evaluation of renewable energy systems, was completed with the economic analysis of the installation of the solar energy plant. Fuzzy logic and cognitive maps have been used as basic tools in the development of models and calculation methods. Environmental, social, economic and technical factors that are effective in the development of solar energy systems in Turkey are determined within the framework of literature and experts' opinions and causal relationships between factors linguistically identified by experts' evaluations in Turkey. The relative relations of the factors with each other are evaluated in the fuzzy based models that are operated with different initial state scenarios. Strong and weak factors are identified from the model results for the long-term process (iterations), and the conditions that investors should take into consideration are determined during the decision making process.

From these publications, economic factors in the development of solar energy systems emerge as critical and strong factors in the model. By directing our studies to solar economic evaluations, the factor affecting the price of solar energy was determined, and experts evaluated the causal relations between them and modeled with HFCM. The results indicate that the factors affecting solar energy systems have a significant effect in determining the solar energy price. The solar energy price adapts to the general energy price market in the long term. The economic analysis of the solar energy system provides concrete data in the decision-making process of the investors by determining the validity of the investment and comparing it with other energy types. The results obtained from the thesis and publications related with evaluating and modeling of Turkey's solar energy potential under different conditions provide to take into account the technical, economic, social and environmental conditions in the decision-making process of investors in solar power plant installations.

In future studies, it is planned to calculate the solar radiation values by fuzzy logic and to calculate the energy potential of the solar energy installation. Different fuzzy sets can be used to calculate the solar radiation values affected by an extraterrestrial, atmospheric and terrestrial factors in variable and uncertain conditions. The calculated solar energy potential values based on fuzzy logic can be included in the decision making process with the economic, social, environmental and technical factors obtained from this study in order to select the most appropriate alternative. A consensus decision can be obtained by using large-scale group decision-making techniques that increase participants in the decision-making process and make dynamic clustering.

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CURRICULUM VITAE

Name Surname : Veysel Çoban

Place and Date of Birth : Konya – 09/05/1983

E-Mail : veyselcoban42@hotmail.com

EDUCATION :

- **B.Sc.** : 2008, Işık University, Engineering Faculty, Industrial Engineering Department
- **M.Sc.** : 2011, Işık University, Engineering Faculty, Industrial Engineering Department

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