The Roadmap to Energy Security in Egypt

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Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

I hereby declare, on oath, that I have written the present dissertation by my own and have not used other than the acknowledged resources and aids.

Mostafa Shaaban, Hamburg, den 02. August 2017

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All perfect praise and thanks be to Allah The Almighty, the Lord of the worlds. I testify that there is none worthy of worship except Allah and that Prophet Muhammad, sallallahu ‘alayhi wa sallam (Peace be upon him), is His slave and Messenger. To Allah I devote all my good deeds and success.

Then, special thanks to my parents and daughters who alleviated the stresses of life during my research. This dissertation was implemented with the guidance and the help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this study. My utmost gratitude to my advisor Prof. Jürgen Scheffran, whose sincerity and encouragement I will never forget and to my co-advisors Prof. Jürgen Böhner and Prof. Mohammed S. Elsobki. Throughout my research, they provided me encouragement, sound advice, and lots of good ideas. I would like to thank the committee of Doctoral scholarships awarded in accordance with the Hamburg Act to Promote Young Academics and Artists (HmbNFG) for the financial support of this study. This work was supported in part by the German Science Foundation (DFG) through the Cluster of Excellence ‘‘CliSAP” (EXC177). Special thanks to the coordinators of the School of Integrated Climate System Sciences (SICSS) for their continuous technical and financial support and the very helpful and open staff and to Jun. Prof. Janpeter Schilling, the chair of the advisory panel of SICSS. Last but not least, I would like to thank all my colleagues in the research group Climate Change and Security (CLISEC).

حَدَّثَنَا عَلِيُّ بْنُ عَبْدِ اللَّهِ حَدَّثَنَا مُحَمَّدُ بْنُ عَبْدِ الرَّحْمَنِ أَبُو الْمُنْذِرِ الطُّفَاوِيُّ عَنْ سُلَيْمَانَ الْأَعْمَشِ قَالَ حَدَّثَنِي مُجَاهِدٌ عَنْ عَبْدِ اللَّهِ بْنِ عُمَرَ رَضِيَ اللَّهُ عَنْهُمَا قَالَ أَخَذَ رَسُولُ اللَّهِ صَلَّى اللَّهُ عَلَيْهِ وَسَلَّمَ بِمَنْكِبِي فَقَالَ كُنْ فِي الدُّنْيَا كَأَنَّكَ غَرِيبٌ أَوْ عَابِرُ سَبِيلٍ وَكَانَ ابْنُ عُمَرَ يَقُولُ إِذَا أَمْسَيْتَ فَلَا تَنْتَظِرْ الصَّبَاحَ وَإِذَا أَصْبَحْتَ فَلَا تَنْتَظِرْ الْمَسَاءَ وَخُذْ مِنْ صِحَّتِكَ لِمَرَضِكَ وَمِنْ حَيَاتِكَ لِمَوْتِكَ . رواه البخاري

Abdullah the son of Umar reported: The Messenger of Allah, peace and blessings be upon him, took hold of my shoulder and said, “Be in this world as if you were a stranger or a traveler.” Mujahid added: the son of Umar said, “If you survive till the evening, do not expect to be alive in the morning, and if you survive till the morning, do not expect to be alive in the evening, and take from your health for your sickness, and take from your life for your death.”
Source: Sahih Bukhari 6053

Abstract

Energy plays an important role in our life being one of the major vital needs of human beings and affecting all aspects of the development of our life. Until recently, electricity, the most widely used form of energy, represents an attractive field of research and development by many researchers in order to compromise between the efficiency and the economy of the electricity supply technologies. However, nowadays, the climate change phenomenon and its impacts broaden the vision towards these technologies by including other social and environmental aspects and the concept of sustainable development into their evaluation. In response to the increasing demand of electricity in Egypt, actors have to compare reasonably between all potential technologies and make decisions on the suitable energy-mix that could secure a sustainable future energy in Egypt.

By exploring the literature, previous studies are concerned with the sustainability assessment of the installed power plants projects regading the surrounding community in their case studies whereas some of these studies assess the technologies in a static evaluation and with an emphasis on renewable energy technologies. No attention has been given to the role of the interaction of the decisions by multiple actors in the planning process of future energy. Moreover, previous studies of electricity planning in Egypt are pursued by assessing the technical and economic aspects only with a little attention to the social and environmental aspects. This study introduces a new approach of spatial and temporal dynamic sustainability assessment of technologies for electricity planning and the analysis of the decision making process of multiple actors in the energy sector. I investigate scenarios and strategies for future planning of energy security in Egypt, with a focus on alternative energy pathways and a sustainable electricity supply mix as part of an energy roadmap till the year 2100. The selection process is based on the assessment of the technologies according to the preferences of actors in multi-criteria evaluation that represents relevant dimensions of sustainability.

In this assessment process I use a novel approach of integrating three methodologies: the multi-criteria decision analysis (MCDA), the spatial Geographic Information System (GIS) data analysis and the agent-based modelling (ABM). Furthermore, I investigate the emissions of Greenhouse Gases from the different energy-mix scenarios. The scope of the study includes 13 assessment indicators covering the four main dimensions of the sustainable development, 13 spatial factors representing the local surrounding conditions, 11 actor-based scenarios (4 actors from the energy sector in Egypt, 4 virtual actors where each represents one dimension of sustainability, a mixed sustainable scenario and 2 game scenarios that represent the interaction between the actors) and 7 electricity supply technologies (coal, natural gas, wind, concentrated solar power, photovoltaics, biomass and nuclear).

By comparing the results of the different scenarios, I found that the actors from the energy sector show comparable future energy-mix scenarios due to the close preferences of their assessment of the technologies. However, the four virtual actors with a preference to only one dimension of the sustainability generate a big difference in future energy-mix scenarios which proves a correlation between some technologies to certain sustainability dimensions. The game scenario explains the interaction between the decisions of different actors and how these interactions could change their behavior in the assessment of the technologies in order to increase their benefits. Generally, there is an energy landscape transition towards renewable technologies in order to meet the increasing demand in a secure and sustainable manner with the possibility of including coal and nuclear in a limited extent as a diversification tool of energy resources ensuring more security. The study clarifies the complexity of

the decision making process in the planning of future energy supply which necessitates the involvement of a multi-dimensional dynamic assessment of energy systems and the involvement of the preferences of all stakeholders, who are affected by the decision process, in the evaluation of these systems from their perspectives. In this study a novel prototype model that has wide applications in different fields and with different case studies is designed. Finally, it is recommended to perform the analysis at a higher resolution and with more input data to increase the accuracy of the results. It is recommended also to include investigations about the interactions with actors from other sectors like water and food sectors and actors who are concerned with the climate change issue and to assess the cooperation-conflict responses and consequences of these kinds of interactions.

Zusammenfassung

Energie spielt eine wichtige Rolle in unserem Leben, weil sie sowohl ein lebensnotwendiges Bedürfnis der Menschen ist, als auch in alle Aspekte der Entwicklung unseres Lebens eingreift. Dabei stellt der elektrische Strom die am weitesten verbreitete Energieform dar und ist zugleich ein attraktives Gebiet von Forschung und Entwicklung, um zwischen der Effizienz und der Wirtschaftlichkeit der Stromerzeugungstechnologien einen Kompromiss zu finden. Heutzutage jedoch erweitert das Phänomen des Klimawandels mit seinen Auswirkungen den Blick auf diese Technologien. Dadurch werden weitere Sozial- und Umweltaspekte und besonders der Begriff der nachhaltigen Entwicklung in die Bewertung aufgenommen. Als Antwort auf den zunehmenden Strombedarf in Ägypten müssen die Akteure im Energiesektor zwischen allen potentiellen Technologien abwägen und Entscheidungen über eine passende Energiemischung treffen, die eine nachhaltige zukünftige Energieversorgung in Ägypten sichern kann.

Eine sorgfältige Literaturrecherche zeigt, dass bisherige Studien sich mit der nachhaltigkeitsorientierten Beurteilung der installierten Kraftwerk-Projekte hinsichtlich der anliegenden Gemeinden in ihren Fallstudien beschäftigen, wobei einige dieser Studien auf eine statische Untersuchung der Technologien und erneuerbaren Energietechnologien beschränkt sind. Keine Aufmerksamkeit ist jedoch der Rolle der Wechselwirkung der Entscheidungen von mehreren Akteuren im Planungsprozess der zukünftigen Energie gewidmet worden. Außerdem wurden bisherige Studien zur Stromversorgung Ägyptens vor allem mit Blick auf die technischen und ökonomischen Aspekte und mit geringer Berücksichtigung der sozialen und Umwelt-Aspekte durchgeführt. Diese Studie verfolgt einen neuen Ansatz der räumlich und zeitlich dynamischen nachhaltigen Beurteilung der Technologien für die Stromplanung und die Analyse des Entscheidungsprozesses von mehreren Akteuren im Energiesektor. Ich untersuche die Szenarien und die Strategien für die Zukunftsplanung der Energiesicherheit in Ägypten, mit Fokus auf alternative Energiewege und auf eine nachhaltige Mischung der Stromerzeugung als Teil eines Energie-Fahrplans bis zum Jahr 2100. Der Auswahlprozess beruht auf der Beurteilung der Technologien entsprechend der Präferenzen der Akteure in Multikriterien-Bewertungen, die relevante Dimensionen der Nachhaltigkeit berücksichtigen.

In diesem Beurteilungsprozess verwende ich einen neuen Ansatz, der drei Methoden integriert: die Multikriterien-Entscheidungsanalyse (MCDA), das räumliche Geographische Informationssystem (GIS) für die Datenanalyse und die Agentenbasierte Modellierung (ABM). Darüber hinaus untersuche ich den Ausstoß von Treibhausgasen in den verschiedenen Szenarien der Energiemischung. Die Studie umfasst 13 Bewertungs-Indikatoren, welche die vier Hauptdimensionen der nachhaltigen Entwicklung vertreten, 13 räumliche Faktoren, welche die lokalen Umgebungsbedingungen repräsentieren, 11 akteursbasierte Szenarien (4 Akteure des Energiesektors in Ägypten, 4 virtuelle Akteure, von denen jeder eine Dimension der Nachhaltigkeit vertritt, ein gemischtes Nachhaltigkeits-Szenario und 2 Spielszenarien, die die Wechselwirkung zwischen den Akteuren darstellen) und 7 Stromerzeugungstechnologien (Kohle, Erdgas, Wind, konzentrierte Sonnenkraft, Photovoltaik, Biomasse und Kernkraft).

Durch den Vergleich der Resultate der verschiedenen Szenarien komme ich zu dem Ergebnis, dass die Akteure des Energiesektors vergleichbare zukünftige Szenarien der Energiemischung aufgrund ähnlicher Präferenzen ihrer Beurteilung der Technologien zeigen. Allerdings zeigen die vier virtuellen Akteure, die jeweils nur einer Dimension der Nachhaltigkeit bevorzugen, große Unterschiede in zukünftigen Szenarien der Energie-Mischung, was auf einen Zusammenhang zwischen einigen

Technologien und bestimmten Nachhaltigkeitsdimensionen hinweist. Das Spielszenario erklärt die Wechselwirkung zwischen den Entscheidungen von verschiedenen Akteuren, und wie diese Interaktionen ihr Verhalten bei der Beurteilung der Technologien ändern können, um ihre Vorteile zu vergrößern. Generell gibt es eine Wende in der Energie-Landschaft zu erneuerbaren Technologien, um die zunehmende Nachfrage in einer sicheren und nachhaltigen Weise bereitzustellen, mit der Möglichkeit Kohle und Kernkraft in beschränktem Maße als Mittel der Diversifizierung und Sicherung der Energieversorgung einzubeziehen. Die Studie verdeutlicht die Komplexität des Entscheidungsprozesses in der Planung der zukünftigen Energiebereitstellung, die eine multidimensionale dynamische Beurteilung von Energie-Systemen und die Berücksichtigung der Präferenzen aller vom Entscheidungsprozess betroffenen Stakeholder in der Auswertung dieser Systeme erforderlich macht. Die Studie entwirft ein neues Prototyp-Modell, das breite Anwendungen in verschiedenen Feldern und mit verschiedenen Fallstudien hat. Schließlich wird empfohlen, die Analyse mit einer höheren Genauigkeit und mit mehr Eingangsdaten durchzuführen, um die Sicherheit der Resultate zu verbessern. Es wird auch empfohlen, Wechselwirkungen mit Akteuren aus anderen Sektoren wie Wasser- und Nahrungsmittelversorgung, mit Akteuren im Kontext des Klimawandels oder Reaktionen und Konsequenzen von Kooperation und Konflikten zu untersuchen.

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Abbreviations

ABM	Agent-based modeling
AHP	Analytical Hierarchy Process
CSP	Concentrated solar power
DM	Decision maker
DNI	Direct Normal Irradiance
EEA	European Environment Agency
EEHC	Egyptian Electricity Holding Company
ENSAD	Energy-Related Severe Accident Database
ETSAP	Energy Technology Systems Analysis Program
EURELECTRIC	Electricity for Europe
EUROSTAT	Statistical Office of the European Communities
EWFN	Energy, water and food nexus
Frauenhofer ISE	Frauenhofer Institute of Solar Energy Systems
GEO	Global Energy Observatory
GHGs	Greenhouse gases
GIS	Geographic Information System
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
ISO	International Organization for Standardization
LCA	Life cycle assessment
LNG	Liquefied Natural Gas
MC	Monte-Carlo
MCA	Multi-Criteria Analysis
MCDA	Multi-criteria decision analysis
MCDM	Multi-Criteria Decision Making
MDGs	Millennium Development Goals
MIT SDEP	System Dynamics in Education Project at Massachusetts Institute of Technology
NEA	Nuclear Energy Agency
NG	Natural gas
NREA	New and Renewable Energy Authority
NREL	National Renewable Energy Laboratory
O&M	Operation and maintenance
OECD	Organization for Economic Co-operation and Development
PCA	Principal Component Analysis
PSI	Paul Scherrer Institute
PV	Photovoltaics
RA	Risk assessment
SAGA	System for Automated Geoscientific Analyses
SD	Sustainable Development
SDGs	Sustainable Development Goals
SE4A	Sustainable Energy for All
SEPS	Sustainable Energy Project Support

TARES	Technical Assistance to support the reform of the Energy Sector
UNDESA	United Nations Department of Economic and Social Affairs
US EIA	United States energy information administration
VGB	Vereinigung der Großkesselbesitzer (Association of large boilers)
WSM	Weighted sum method

1. Introduction

In this chapter, I give an introduction about principal concepts upon which I developed my research idea. I discuss some historical backgrounds as well as theories on decision making and sustainable development. Thereafter, I review previous studies dealing with ideas similar to my study. After that I write briefly on the physical and demographic aspects of my case study, which is Egypt. Then I depict the current electricity supply status in Egypt and the governmental future plans. Finally, I end the chapter by elaborating the research gap that should be filled and the main objectives of the study together with a flow chart diagram of activities done for implementing the study.

1.1. Decision making

In our daily life, we face many problems, to which a lot of questions are raised into our mind seeking for a solution. In order to find the best solution, we evaluate all possible actions to be taken in order to tackle this problem. This process might be very instantaneous and takes place in our mind without we feel its detailed analysis while others might be long lasting taking days or even months till one take an action. The answer could be as simple as in the case of two possible actions like in YES/NO questions where one has the probability of 50% for the selection of the right choice but this does not reflect an easy decision question as in the case of wars. On the other hand the answer could be a selection between many alternatives where the probability of the right choice decreases as the number of the alternatives increases. However, this does not necessarily mean that it is a life threatening decision as for instance the shopping process. In some cases the action could be conditional in response to an event as in the contingency plan. In such case the decision maker will take a certain action in case another triggering action is occurred. This kind of cognitive brain activity is called the decision making process. Simply it is a single mental action in response of a raised question after evaluating the pros and cons of all possible alternatives trying to achieve the maximum benefits or values with minimum losses or costs. The decision could affect only the decision maker or a group of people or a community or even the whole world. Due to the importance of this process in some circumstances, philosophers, researchers and strategic managers show their interest in studying the detailed steps of this process and the underlying reasons of the decision taken by an actor in an individual basis as well as the interaction of multiple actors whose decisions affect each other. As a result, scientists developed theories and methodologies that have been involved in past strategic decisions and still play nowadays a crucial role in economic, social and political decisions. Here below are some examples of these theories:

1.1.1. Decision theory

Decision theory investigates the reasoning underlying the choice of a decision maker. This reasoning reflects beliefs, desires and preference attitudes of the decision maker (Steele and Stefánsson 2016). The theory dates back to the 17th century as an evolved idea known as the expected value (Paul J. H. Schoemaker 1982) and has been developed since the middle of the 20th century and contributed in variety of research fields like economy, statistics, psychology, political and social sciences and philosophy. There are two types of decision theory: normative and descriptive decision theory. The former identifies the best decision to make in an ideal and perfect manner based on a prospective study. This approach applies in decision analysis by finding support systems and tools to help people make rational decisions. The latter describes the observed behaviors based on a retrospective study assuming that the decision makers behave under certain rules. Simply a normative decision theory is a theory of how decisions “should” be made while a descriptive decision theory is a theory of how decisions “are actually” made (Hansson 2005).

1.1.2. Game theory

As has been mentioned before, the decision making process could be based on an individual action or as a result of the interaction of many agents whose decision affects each other. This latter type introduced the game theory. It is defined as the study of mathematical models of conflict and cooperation between intelligent rational decision-makers (Myerson 2004). Here, the environment affecting the decision of actors includes the decisions of other actors with different preferences. Similarly, it has a wide application in many fields like the decision theory. It has been originally introduced in 1713 in a letter written by Charles Waldegrave in which a minimax mixed strategy solution to a two-person card game has been provided (Bellhouse 2007). The idea has continued its path of development until it came into real existence with the idea of two-persons zero-sum game where one wins while the other loses by John von Neumann in 1928 (Neumann 1928). Finding a solution to the zero-sum game so that all players could have the opportunity to achieve a win-win situation in multi-player games, in 1950 John Nash introduced his well-known Nash equilibrium in which he developed a criterion for mutual consistency of players' strategies. Due to the wide application of this theory and its great importance, 11 game theorists have won Nobel Prize in economic sciences.

1.1.3. System dynamics

Another important concept that should be considered in the decision making process is system dynamics. System dynamic represents an approach for the understanding of the behavior of complex systems over time through using feedback loops, stocks, flows and time delays. It helps understanding the world around us which consists of different agents interacting with each other through feedback loops and shows the change of states of agents over time (MIT SDEP 1997). Studying this concept allows us to identify the factors that could affect the output of a process either positively or negatively and thereby to control these factors to achieve our targets. For instance, if a certain feature of a product shows no satisfaction by the customers, the manufacture should modify it or even remove this feature in order to increase the sales of his/her company.

1.2. Sustainable Development (SD)

Throughout the last three decades, there has been a great worldwide concern about SD and the identification of indicators for sustainable energy assessment by many local, regional, state/provincial, national and international organizations (see Figure 1). In 1987, the World Commission on Environment and Development identified SD as "development which meets the needs of current generations without compromising the ability of future generations to meet their own needs" (United Nations 2016, Ness et al. 2007). Going more specifically to sustainable energy development, the International Atomic Energy Agency defines SD as “provision of adequate and reliable energy services at affordable costs, in a secure and environmental manner, and in conformity with social and economic development needs” (Vera and Langlois 2007). In 1992, the Earth Summit realized the importance of identifying and developing SD indicators in addition to expressing their role in decision making. In 1997, the United Nations General

Assembly highlighted the need for more sustainable energy use patterns, and created an intergovernmental process to elaborate a common approach to the sustainable energy development agenda (Vera and Langlois 2007). In 1999, the United States National Research Council supported the idea that there are three important components of sustainable development. These are: what to be sustained, what to be developed, and how to deal with the intergenerational component (Ness et al. 2007). In 2002, the World Summit on Sustainable Development has discussed energy as a major concern. At that event, the international community reconfirmed the importance of energy access to reduce poverty by 2015 as one of the Millennium Development Goals (MDGs) although there is no direct relationship between energy and these goals. However, not considering energy in development projects will limit the achievement of the MDGs. Additionally, the summit called for the transition to sustainable patterns of energy supply and use and considered the development of sets of indicators that could be used by countries, especially developing countries, to measure the progress on sustainable energy development at the national level (Vera and Langlois 2007). In 2004, WISIONS of sustainability, an initiative by the Wuppertal Institute supported by the Swiss-based foundation ProEvolution, was launched to promote practical and sustainable energy projects in order to respond to energy needs at local level via its Sustainable Energy Project Support (SEPS) scheme.

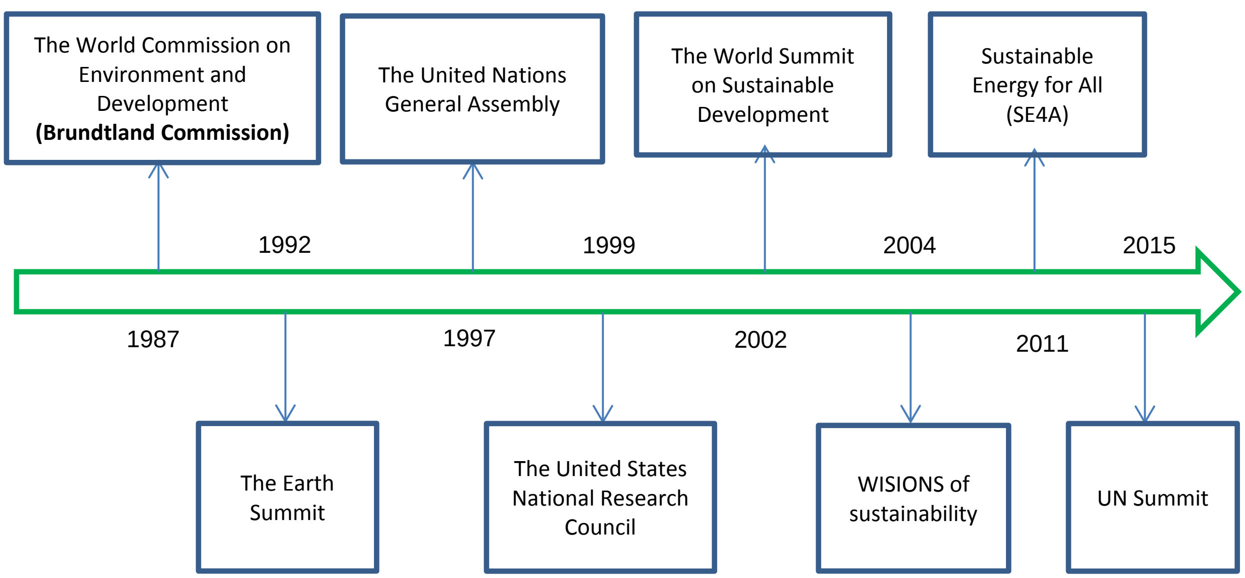


Figure 1: A historical overview about international meetings concerned with sustainable development (United Nations 2016, Ness et al. 2007, Vera and Langlois 2007, SE4All 2011, Terrapon-Pfaff et al. 2014)

In September 2011, UN Secretary-General Ban Ki-moon launched the Sustainable Energy for All (SE4A) initiative and shared his vision for how governments, business and civil society, working in partnership, can make sustainable energy for all a reality by 2030. "Energy is the golden thread that connects economic growth, increased social equity, and an environment that allows the world to thrive", said Ban Ki-moon (SE4All 2011). The initiative is concerned with renewable energy sources as a key technology offering clean electricity, heating, and lighting solutions to people who mainly depend on conventional energy sources. Nevertheless, these technologies still face a range of social, economic and structural challenges, requiring not only further technological development but also a deeper understanding of both the success factors and the barriers to accomplish a widespread dissemination (Terrapon-Pfaff et al. 2014). In September 2015, world leaders, at an historic UN Summit, have adopted 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for SD. These goals came into force on January 1, 2016 aiming at accelerating efforts worldwide to end all forms of poverty, fight inequalities and tackle climate change, while ensuring that no one is left behind. The SDGs extend the success of the Millennium Development Goals (MDGs) and aim to go further to end all forms of poverty in all countries while protecting the planet. The seventh goal of these SDGs is to ensure access to affordable, reliable, sustainable and modern energy fostering the objectives of the SE4A initiative (United Nations 2016).

There are many approaches that have been proposed to identify the main SD indicators in different applications. The United Nations Commission on Sustainable Development constructed a sustainability indicator framework for the evaluation of governmental progress towards sustainable development goals. The Wuppertal Institute proposed indicators for the dimensions of sustainable development, together with inter-linked indicators between these dimensions (Singh et al. 2009). Based on different constructions of the SD concepts, Figure 2 shows the major three dimensions of SD together with examples of the main indicators under each dimension. These indicators can be further extended to more precise and measurable sub-indicators. Not all indicators are applied globally for the assessment of the SD of a product or a system. Some of these indicators are specific for certain kinds of assessment. For example Gross National Product is an economic indicator that is used for the assessment of the economy of a country but it cannot be used for an institution or for a product. However, security and safety indicators are usually used in all kinds of the social assessment of any system, although they have a broad meaning which needs further specification by identifying sub-indicators.

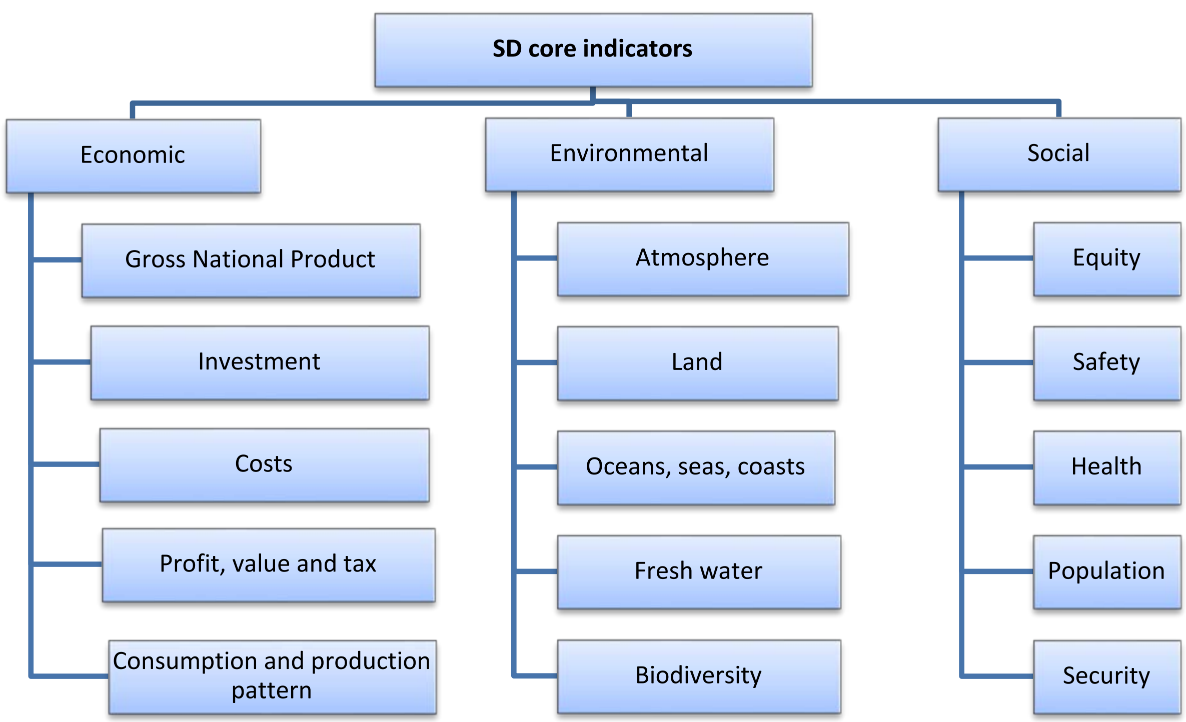


Figure 2: Sustainable development core indicators (Singh et al. 2009)

Going more specifically to one goal of the SD that is concerned with the energy sector, renewable energy sources have a large potential to contribute to SD by providing a wide variety of socio-economic benefits, including the diversification of energy supply, the enhanced regional and rural development opportunities, the creation of a domestic industry and employment opportunities (del Río and Burguillo 2009). Governments and policy-makers throughout the world introduce legislation and support mechanisms to renewable energy markets and policy frameworks in response to a number of global challenges and concerns, including climate change, increasing energy demand and energy security. Many countries now have ambitious targets for renewable energy generation and for addressing carbon emissions (Troldborg et al. 2014). According to the New and Renewable Energy Authority (NREA), a local governmental electric utility for renewable energy projects in Egypt, the Egyptian government has set a target to boost its renewable energy usage and proposed that renewable energy accounts for 20% of its power generation capacity by 2022, of which 12% would be wind, 6% hydro, and 2% solar (NREA 2015).

1.3. Literature review

Transformation of the energy sector: In order to secure the electricity supply, there is a need for more diversification of the resources and a transition towards sustainable resources. Although fossil fuels are still cheaper as compared to other resources, they have other features that should be considered as they take part in their long term cost. For instance, they constitute a major source for the emission of Greenhouse Gases (GHGs) and a driver of climate change. Moreover, they are expected to be depleted in the near future and in turn their prices will be elevated. However, there are other energy resources that could be exploited and seem to be promising but are still expensive. Several studies assessed the sustainability of electricity supply technologies based on different approaches and goals for future energy planning. Terrapon-Pfaff et al. (2014) investigated the impacts and the conditions that influence the sustainability of small-scale and community-based renewable energy projects post implementation in terms of sources (solar, wind, biomass, hydro), user needs (electricity, food preparation, lighting, productive uses), community management models, finance mechanisms and geographical locations since they are recognized as important forms of development assistance for reaching the energy poor. Stambouli et al. (2012) analyzed the existing renewable energy sector in Algeria and forecasted demand growth, additional capacity, investment requirements and Algeria's ambitious objectives of environmental protection and using renewable energy. The paper also discusses the current energy scenario and explores alternative energy sources like solar and wind to ensure energy security supply, reliability, greater efficiency in energy conversion, transmission and utilization. del Río and Burguillo (2009) studied the impact of renewable energy deployment on local sustainability in Spain by investigating the socio-economic benefits of three renewable energy technologies in three different locations.

Approaches for sustainability assessment of energy systems: Liu (2014), Singh et al. (2009) and Ness et al. (2007) explained the different methodologies for sustainability assessment by providing an overview of various sustainability indicators, a composite index, development of a general sustainability indicator for renewable energy systems, applying formulation strategies, scaling, normalization, weighing and aggregation methodology. Pohekar and Ramachandran (2004), Wang et al. (2009) and Abu Taha and Daim (2013) evaluated different Multi-Criteria Decision Making (MCDM) models for sustainable energy planning and analysis. Doukas et al. (2012) assessed rural communities' energy sustainability using the Principal Component Analysis (PCA) which is one of the MCDM models. Troldborg et al. (2014) developed and applied a Multi-Criteria Analysis (MCA) for a national-scale sustainability assessment and ranking of eleven renewable energy technologies in Scotland and to critically investigate how the uncertainties in the applied input information influence the result. Evans et al. (2009) assessed the renewable electricity generation technologies against sustainability indicators. Islam et al. (2014) examined the current energy mix, present energy crisis and its way to overcome such scenario by utilizing alternative energy sources such as biomass, solar, wind and small scale hydropower energy, in the context of Bangladesh. Góralczyk (2003), Pehnt (2006) and Varun et al. (2009a) investigated a dynamic approach towards the Life Cycle Assessment (LCA) of renewable energy technologies. Scheffran (2010) discussed principles and criteria for establishing and evaluating a sustainable bioenergy lifecycle covering all dimensions of sustainability. Demirtas (2013) studied the selection of best renewable energy technology for sustainable energy planning using the Analytical Hierarchy Process (AHP) methodology, which is one of the MDCM methods. There are many other studies that are concerned with the sustainability evaluation of energy systems for the future energy planning and decision-making process.

1.4.Physical geography and demography of Egypt

Egypt lies between latitudes 22°N and 32°N, and longitudes 25°E and 35°E. It has the world's 30th largest surface area of 1,001,450 km^2. The northern and eastern boarders lie on the Mediterranean and the Red sea, respectively. This gives Egypt a powerful strategic secure and economic location in the Middle East region. The large regions of the Sahara desert, which constitute most of Egypt's territory, are sparsely inhabited.

The climate of Egypt is characterized by arid, sunny climate with most of its land surface being desert. . Most of Egypt's rain falls in the winter months. Egypt is the driest and the sunniest country in the world. A significant rainfall occurs as a result of winter cyclonic disturbances along the northern coastal strip moving eastwards along the Mediterranean Sea. At Alexandria on the coast, total annual rainfall averages are only 196mm, whereas at Cairo, average annual rainfall has reduced to 25mm and southwards it reduces still further to only 5mm at Hurghada on the Red Sea coast and less than 2mm at Aswan in the Nile valley. In central and southern Egypt several years may pass without any significant rain. Annual mean temperature increases from around 20°C on the Mediterranean Sea coastline to around 24°C on the Red Sea coastline. It ranges between 25°C at Cairo and 26°C further south at Aswan with a seasonal variation of about ±7°C. Typical daytime maxima in mid-summer range from 30°C at Alexandria southwards to 41°C at Aswan; while the corresponding north-south range in mid-winter daytime maxima is 18-23°C. This makes even winter daytimes in the south pleasantly warm and sunny, although with cool nights, especially in the north. Climate hazards include dust storms, heat waves, localized floods and, very rarely, unaccustomed snowfall in the north. A particularly unpleasant, occasionally dangerous, phenomenon in spring and early summer is a dry and dusty 'Khamsin' wind that, from time to time, carries very hot air northwards into northern Egypt ahead of weak cyclonic disturbances in the Mediterranean (Met Office 2011).

Additionally, Egypt is characterized by the Nile River which runs from Tanzania in south of Africa then through the Nile basin countries until it ends up in the north of Egypt. This in turn has a replenishing effect on the soil along the Nile and the attraction to cultivation. For these reasons population concentrates along the Nile Valley and Delta which means that about 5% of the total area is occupied by about 95% of the population (Central Intelligence Agency 2017). Studies done by climate experts warn of a potential rise in sea levels as a consequence of global warming. This will have negative multiplier effects on the country's economy, agriculture and industry in addition to migration consequences from the densely populated coastal strip (Link et al. 2013).

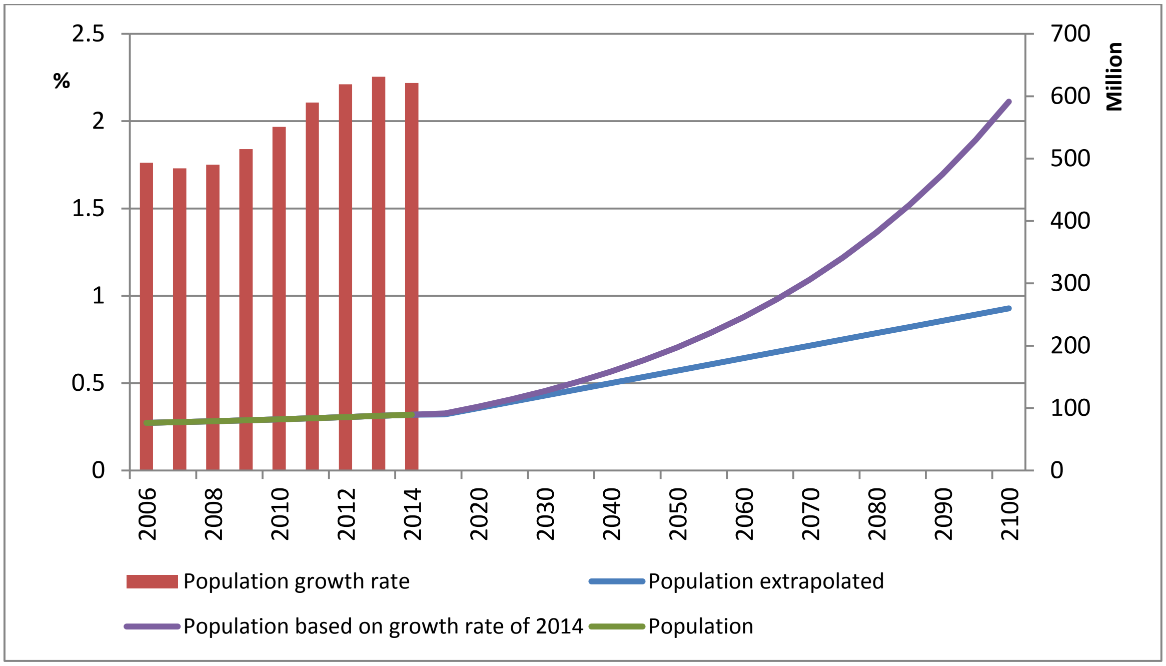


Figure 3: Population and growth rate, historical, present and projected data (The World Bank 2014a)

With over 94 million inhabitants in February 2017, Egypt is the most populous country in North Africa and the Arab World, the third-most populous in Africa (after Nigeria and Ethiopia). About half of Egypt's residents live in urban areas, with most spread across the densely populated centers of greater Cairo, Alexandria and other major cities in the Nile Delta (Worldometers 2017). According to the World Bank data, I estimated the population till 2100 through two methods (see Figure 3). The first method has been performed by analyzing the trend of historical data and predicting future population. This method reveals an estimate of 260 million people in 2100. The other method is based on the equation[1] shown below using the growth rate at 2014 of 2.22% (The World Bank 2014a) which reveals an estimate of about 600 million people in 2100 which indicates an increased demand of energy, water and food that must be considered and rationally preplanned. However, the country takes several measures to reduce this growth rate through birth control programs and spreading awareness but at the same time the quality of health system in Egypt is in improvement leading to a higher probability of a longer life span of the citizens. Additionally, the migration of some people from and to Egypt, which varies from time to time, plays an important role in the prediction of future population. Thus, there are many factors controlling the growth rate of the population which increase the uncertainty of the results.

$$y_l = x_m \times (1 + i)^n \text{ where,}$$

y_l = future population at year l, x_m = population at year m, i = Growth rate, $n = l - m$

[1] This equation used in the calculation of the future value of an asset or a deposit in micro-economics.

The agriculture sector in Egypt depends mainly on irrigation. The agricultural land base represents only 3.5% of the total area in 2007 accounting for about 3.5 million hectares. 94% of this agricultural land lies within the Nile Basin and Delta, and the remaining 6% are rain fed or in the oases (see Figure 4). About 94% of the total cultivated area was occupied with annual crops and 6% with permanent crops in 1984. Surface water was the source for 83% of the irrigated area in 2000, while 11% of the area was irrigated with groundwater in the provinces of Matruh, Sinai and the New Valley. The remaining 6% was irrigated with mixed sources. Increasing settlement of nomads, increase in sheep numbers in marginal zones, expansion of cultivation and reduction of fallow have greatly increased pressure on available land and reduced soil fertility (El-Nahrawy 2011).

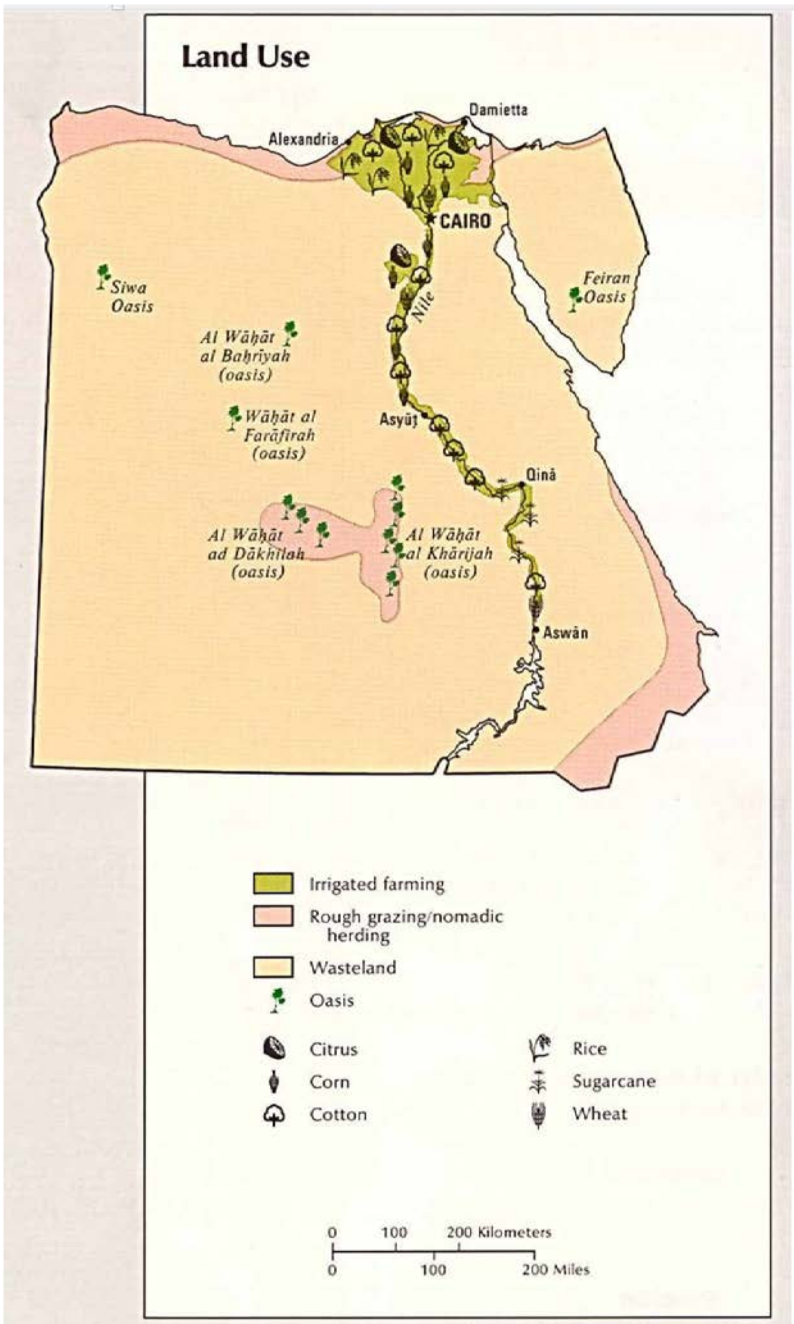


Figure 4: Map of land use in Egypt (El-Nahrawy 2011)

Livestock represents an important component of the agricultural sector, accounting for about 24.5% of the agricultural gross domestic product. In 2005 Egypt produced locally 92.5% milk, 82.2% red meat, 100% white meat, 81.9% fish, 100% eggs, 100% wool and 100% leather while the rest being imported. However, the export portion of animal production is very limited. The private sector, with the majority of animal breeders being smallholder farmers, dominates the livestock breeding market to a great extent, whereas the share of the government sector is less than 2% of the total animal numbers (El-Nahrawy 2011).

Egypt represents the largest oil and natural gas consumer in Africa, where the consumption in Egypt accounts for about 20% of petroleum and other liquids and 40% of dry natural gas consumption in Africa in 2013. Egypt's total primary energy consumption was 1.7 million barrels per day of oil equivalent in 2013. Natural gas and oil are the primary fuels used to meet Egypt's energy needs, accounting for 94% of the country's total energy consumption in 2013. Oil is mostly used in the transportation sector, while natural gas is used in the power sector, household heating systems and transportation sector in the form of compressed natural gas in vehicles (US EIA 2015).

1.5.Electricity status in Egypt

Egypt experiences frequent electricity blackouts because of rising demand, natural gas supply shortages, aging infrastructure, and inadequate generation and transmission capacity. According to the United States energy information administration (US EIA), Egypt's generating capacity was 31.45 gigawatts (GW) in May 2015 which is slightly higher than the expected peak demand in 2015 of 30 GW. About 70% of the electricity in Egypt is fueled by natural gas, 19% by petroleum and 11% by renewable energy which is mostly hydroelectricity (9%). Recently, Egypt suffers from natural gas shortages, particularly during the summer months. As a result, it imports fuel oil and diesel fuel to cover the shortfall (US EIA 2015, EEHC 2014). According to New and Renewable Energy Authority (NREA) in Egypt, there is a target to reduce energy use by 8.3%, install 4 - 5 GW nuclear, 10.5 GW renewable and retain oil and natural gas levels of production at 40% by the year 2022 (ElSobki 2015).

Figure 5 shows that Egyptian electricity consumption is expected to reach 800 TWh/y by 2100 which was about 170 TWh/y in 2015. The data is based on specific electric power consumption (kWh per capita) till the year 2012 as obtained from the World Bank (2014b). I multiplied these data by the obtained population data from the World Bank (2014a) till the year 2012 to get the total consumption. Then I extrapolated the total consumption till 2100. Finally, I divided the extrapolated total consumption by the extrapolated population to get the specific consumption. It has been observed also that the specific electricity consumption will reach 3000 kWh/capita/year in 2100 which was 1700 kWh/capita/year in 2012 which is allegedly a normal interpretation of technological development that necessitates extra power consumption. However, compared to Germany, Figure 6 shows the economic production per electricity consumption as indicated by GDP/electricity consumption per capita per year in Germany is almost 3 times that of Egypt in 2012 although electricity consumption in Germany was 7270 kWh/capita/year in 2012 which is more than 4 times that of Egypt. Consequently, this reflects the inefficient use of electricity in luxury and unimportant activities. However, it reveals the opportunity to save this wasted energy by first identifying it and putting some energy conservation plans. In response to this growing demand, Egypt put some strategies to diversify the electricity generation mix through other resources adding more security to the energy sector. Although Egypt is characterized by a very high potential of wind and solar resources, they are still undeveloped and constitute only 2% of the current energy mix.

Egypt is covered with high intensity of direct solar radiation as can be shown in Figure 7 ranging between 2000 – 3200 kWh/m^2/year from North to South. The sunshine duration ranges between 9-11 h/day from North to South, with very few cloudy days. Egypt's first solar-thermal power plant (Integrated Solar Combined Cycle), located in Kuraymat, has the capacity to generate 140 MW with only 20 MW solar share (Khalil et al. 2010).

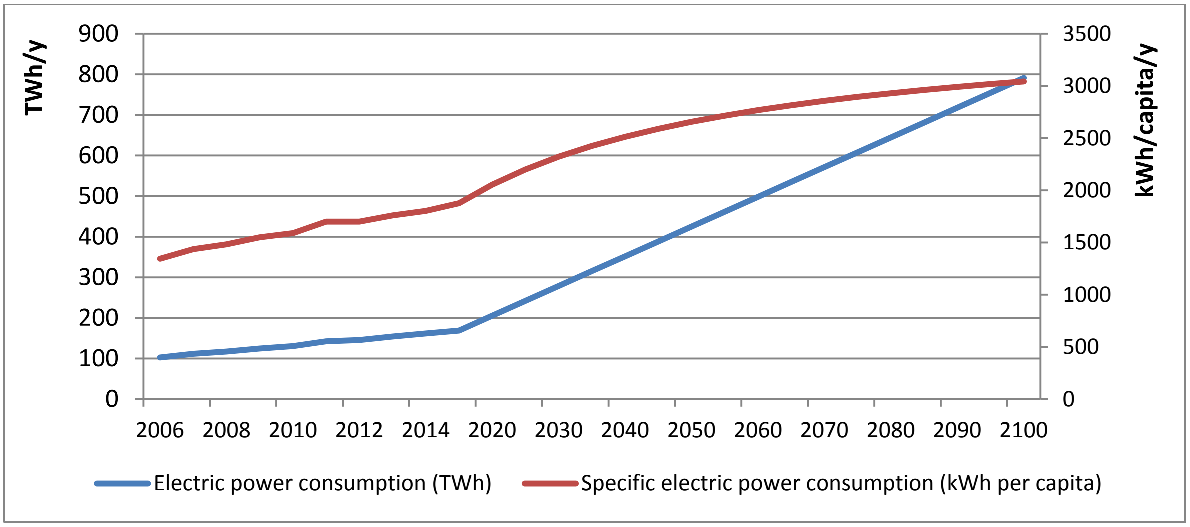


Figure 5: Electricity consumption in Egypt (past, current and future trend) (The World Bank 2014a, 2014b)

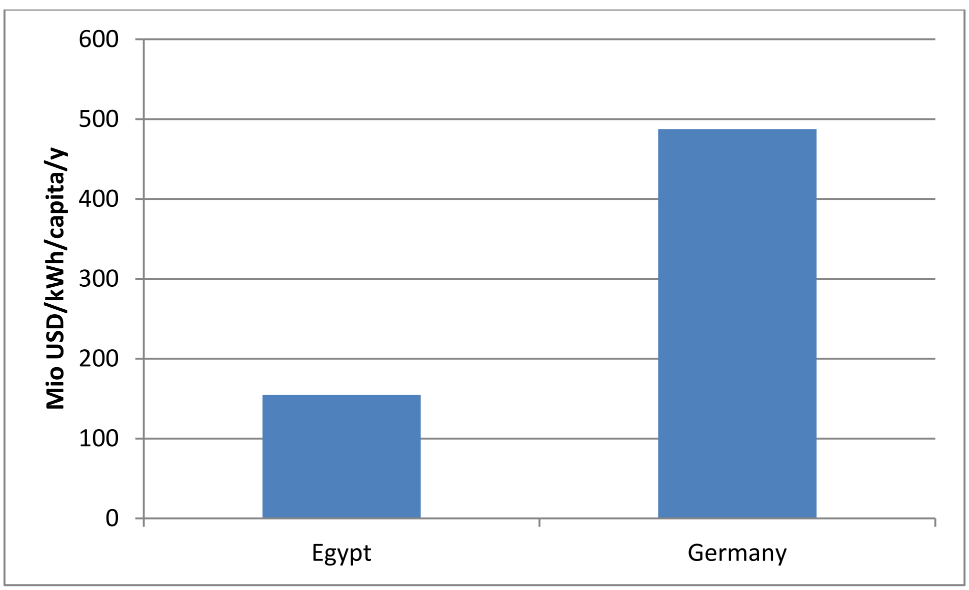


Figure 6: Economic development per electricity consumption in 2012 (The World Bank 2014b)

The average wind speed in the Suez Gulf in Egypt reaches 10.5 m/sec at 50 m height showing a high wind resource potential. Moreover, other regions especially on the Nile banks in the Eastern and Western Deserts offer a great wind resource potential as can be seen in Figure 8. The currently installed wind power plants are 545 MW in Zafarana and 5 MW in Hurghada. The plan is to expand the total wind capacity to 7200 MW by 2020 (US EIA 2015). Table 1 shows the planned allocated surface areas and capacity for solar and wind energy projects whereas Figure 9 shows the land sites across the map of Egypt.

Hydropower, as a major renewable energy resource based on the Aswan High Dam and the Aswan Reservoir Dams across the Nile River, is totally exploited in Egypt constituting 9% of the energy mix. This technology cannot be further extended, unless a new technological development is discovered.

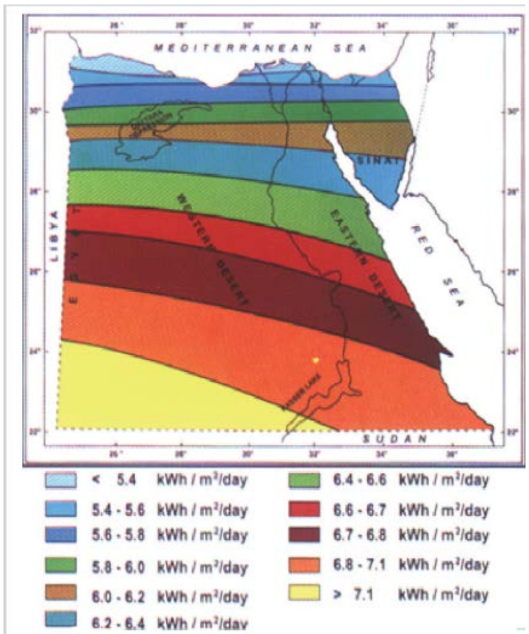


Figure 7: Solar atlas of Egypt (Khalil et al. 2010)

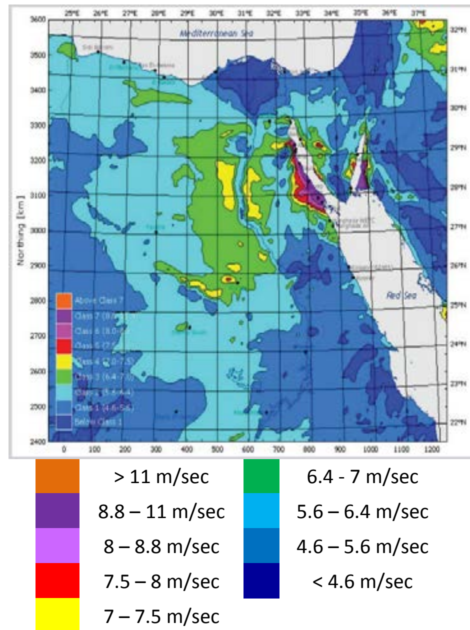


Figure 8: Wind atlas of Egypt (Khalil et al. 2010)

Table 1: Planned solar and wind projects in Egypt (ElSobki 2015)

Zone		Area (km^2)	Capacity (MW)
Suez Gulf (wind)		1220	3550
East Nile	Wind	841	5800
	Solar	1290	34900
West Nile	Wind	3636	25350
	Solar	606	17400
Benban (solar)		37	1800
Kom Ombo (solar)		7	260

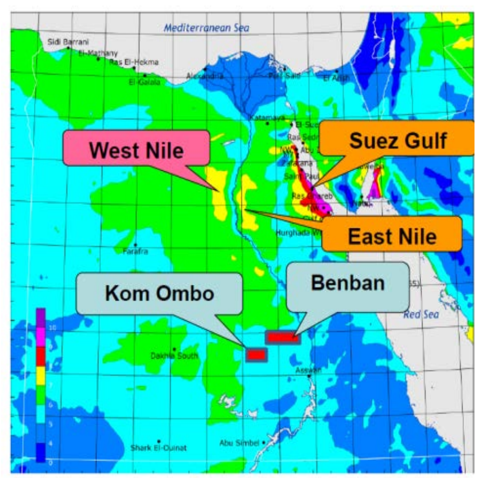


Figure 9: Planned sites for wind and solar projects in Egypt (ElSobki 2015)

Not only the government confines its plan to renewable energy resources but also it announced some agreements, despite nothing of them has been adopted yet, concerning coal and nuclear power plants. In March 2016, it has been announced in the news that a Japanese company (Marubeni) and ElSwedy company, an Egyptian electric equipment manufacturer, will conduct a feasibility study into building a coal-fired power plant in the West Mattrouh region with a capacity of 4 GW, which might cost about 3.50 billion USD (Reuters 2016a). Another announcement has been said that the Ministry of Electricity will invest 4.5 billion USD in Egypt's first coal-fired power plant, the Ayoun Moussa power station, 2,640 MW in the Suez region (ESI-Africa 2016). The third announced coal-fired power plant project is the Hamarawein Port power station. In November 2014 Orascom Construction company planned to start studies for the construction of a 2 - 3 GW coal-fired power in cooperation with the United Arab Emirates International Petroleum Investment Company and China's Dongfang Electric Corporation with an expected cost of approximately 2.5 – 3 billion USD at the Red Sea coast (SourceWatch 2016).

Nuclear power in Egypt is greatly under developed where Egypt owns a small reactor which focuses only on some research activities and does not represent a commercial power resource. However, it has been previously proposed to build a nuclear power plant at El Dabaa on the Mediterranean Sea coast in Matrouh, but the project has repeatedly been cancelled. But again, in November 2015, the idea has been ignited when the news declared that Egypt and Russia sign a deal to build a nuclear power plant that was expected to be completed by 2022 with four reactors producing 1,200 MW each (US EIA 2015 ,Reuters 2015).

From the regulatory and legislative side, in 2014 the parliament has issued two important acts related to the electricity sector. The first asks the government to gradually withdraw subsidy on electricity prices over 5 years plan. Table 2 shows the change in electricity price according to the consumption segment type and amount. The second act introduces the feed in tariff financing scheme policy for promoting renewable energy projects thus facilitating and encouraging the private sector contribution to the investment in the solar and wind energy project. The average selling price of electricity from wind energy will be 10.5 USD_{cent}/kWh and from Photovoltaics (PV) 14.34 USD_{cent}/kWh (ElSobki 2015,EEHC 2014)[2].

Table 2: Price of electricity plan throughout the period (mid 2014 - mid 2018) (EEHC 2014)

	Residential sector (Pt./kWh)			
Consumption Segment (kWh/month)	2014/15	2015/16	2016/17	2017/18*
0 – 50	7.5	9	10	13
51 – 100	14.5	17	19	22
101 – 200	16	20	26	27
201 – 350	24	29	35	55
351 – 650	34	39	44	75
651 – 1000	60	68	71	125
>1000	74	78	81	135
Consumption Segment (kWh/month)	Commercial (Pt./kWh)			
0 – 100	30	32	34	45
101 – 250	44	50	58	84
251 – 600	59	61	58	96
601 – 1000	78	81	86	135
>1000	83	86	86	140

* The values in 2017/18 are the updated values after floating of the Egyptian Pound.

[2] These values are changed after the Egyptian government has floated the Egyptian Pound in November 2016

1.6.Problem statement

There is a steep increase in electricity demand in Egypt as a result of the high population growth rate of 2.2 % (The World Bank 2014a) and the attempt of citizens to cope with the worldwide technological development by using more electrical devices for communication, and entertainment. Additionally, Egypt's electricity power supply depends mainly on natural gas as a primary energy source. However, as a result of the depletion in natural gas reserves, Egypt became an importer of natural gas instead of being an exporter. Egypt has been diverting natural gas supply away from exports to the domestic market to meet the demand. Egypt began importing Liquefied Natural Gas (LNG) in 2015 to satisfy its natural gas consumption. In May 2014, the Egyptian Natural Gas Holding Company (EGAS), the country's national gas company, signed a letter of intent with Hoegh LNG of Norway to use one of its Floating Storage and Regasification Units for five years to allow Egypt to import LNG (US EIA 2015).

In addition to the shortage of natural gas supply, Egypt suffers from non-periodic maintenance of power plants that leads to more frequent troubleshooting and improper functioning. All of these factors ended up with a frequent black-out in the electricity power supply that annoyed the citizens especially during the very hot summer. Additionally, the political instability and unclear policy and regulation hinder the intervention of the private sector in the investment in this field. Thus, there should be a short, medium and long term planning on how to resolve this issue and to secure the future supply of electricity.

Unfortunately, no previous studies of the sustainability assessment of electricity technologies in Egypt were investigated. Based on the interviews with energy experts in Egypt during February and April 2015, most of the electricity planning is pursued by assessing the technical and economic aspects only. Policy makers are concerned only with the technical and economic aspects of the electricity supply technologies in electricity planning, as evidenced by the study project "*Technical Assistance to support the reform of the Energy Sector"* (TARES). This study aims to anticipate the most economic energy-mix for Egypt till the year 2035 using the TIMES energy model generator (Egyptera 2014), developed as part of the Energy Technology Systems Analysis Program (ETSAP) implemented by the International Energy Agency (IEA). This model uses long term energy scenarios to conduct detailed analyses of energy systems (Loulou et al. 2004). It combines two complementary approaches to modelling energy: a technical engineering approach and an economic approach (Loulou et al. 2005). However, it does not take into consideration the environmental and social aspects of energy.

With growing concern about the consequences of climate change and their close relationship to energy development, in addition to the need to involve key stakeholders, including end users, in the decision making process, the concept of sustainable development (SD) has been introduced. Additionally, in this study I introduce a novel approach of a dynamic temporal and spatial MCDA for electricity planning in addition to the analysis of decision-making of multiple agents in the energy sector. This new technique could be further used as a template for electricity planning in other countries. The model could also be applied in other fields of studies.

1.7. Aim and scope of the study

The study aims at answering the research question: What is the best future energy-mix[3] scenario that could secure a sustainable electricity supply in Egypt till 2100? In order to answer this question, this study investigates conditions, scenarios and strategies for future planning of energy in Egypt, with an emphasis on alternative energy pathways and a sustainable electricity supply mix as part of an energy roadmap till the year 2100. A novel approach is developed of integrating multi-criteria decision analysis (MCDA) with agent-based modeling (ABM) and Geographic Information System (GIS) visualization to integrate the time and site factors to assess the transformation of energy landscape in Egypt. Different electricity supply technologies will be investigated and compared regarding multiple assessment criteria and multiple agents to achieve a comprehensive sustainability assessment covering technical, social, economic and environmental aspects of these technologies.

The principle of this study is based on and expands the MCDA approach that incorporates important criteria by their value and weight in the assessment process for the selection of the best alternative or for ranking of these alternatives. The study will highlight briefly also climate change regional vulnerability, projections, mitigation role of shifting to sustainable electricity mix and future assessment of the energy, water and food nexus (EWFN).

The research will be guided by the underlying hypothesis that a comprehensive sustainability assessment supports a transformation from the fossil-based energy system in Egypt towards alternative pathways developing the enormous renewable energy potentials of North Africa. Starting from an understanding of the obstacles and lock-in effects of the current energy situation, the research aims at going beyond technical and economic fixes of established structures towards expanding the range of criteria and agents that reflect sustainable development in its multiple dimensions. Scenario-based modeling and simulation will represent shifting priorities of agents that shape the evolving energy landscape in Egypt. Although policy makers show more tendencies towards the technical and economic aspects of power systems, the social and environmental aspects should be considered to sustain the supply and to ensure environmental protection and social acceptance. So, the priorities of technologies could change with time and space as new emerging aspects are considered and get more attention.

1.8.Study approach

This study builds and expands on an agent-based model that describes the interaction of values and investments regarding action pathways of multiple agents (see Scheffran and Hannon (2007); Scheffran (2008), (2013); Scheffran and BenDor (2009); Eisenack et al. (2007)). I use the open source ABM software "NetLogo" to explicitly represent spatial agents across space and time as they decide on different energy pathways, taking into consideration environmental factors that vary across the landscape and create non-uniform environments for each energy type.

Figure 10 displays a schematic diagram about the steps of the research process and the integration of the three methodologies. The study proceeds in 8 steps as follows:

Step 1: I start with data collection through meeting with stakeholders in the electric utility sector and distribution of questionnaire. The main output of this step is to get the initial preference of technologies

[3] The study is concerned only with electricity planning of the energy sector but I sometimes use the word "energy" interchangeably with "electricity".

by these actors and the importance level of the sustainability dimensions in their technology evaluation. This step will be covered in chapter 2.

Step 2: I apply one of the MCDA approaches which is the analytical hierarchy process (AHP) based on data obtained from step one. The objective of this step is to get the weights of the sustainability assessment indicators and ultimately the weights of the sustainability dimensions that will be used in a later step. The methodology will be explained in chapter 3 and the results in chapter 4.

Step 3: I focus here on a literature review of similar previous studies and collect indicators that have been previously used for the assessment of these technologies in addition to those that have been proposed by the interviewee then I pursue a selection approach of the ultimately used assessment indicators. This will be explained in chapter 2.

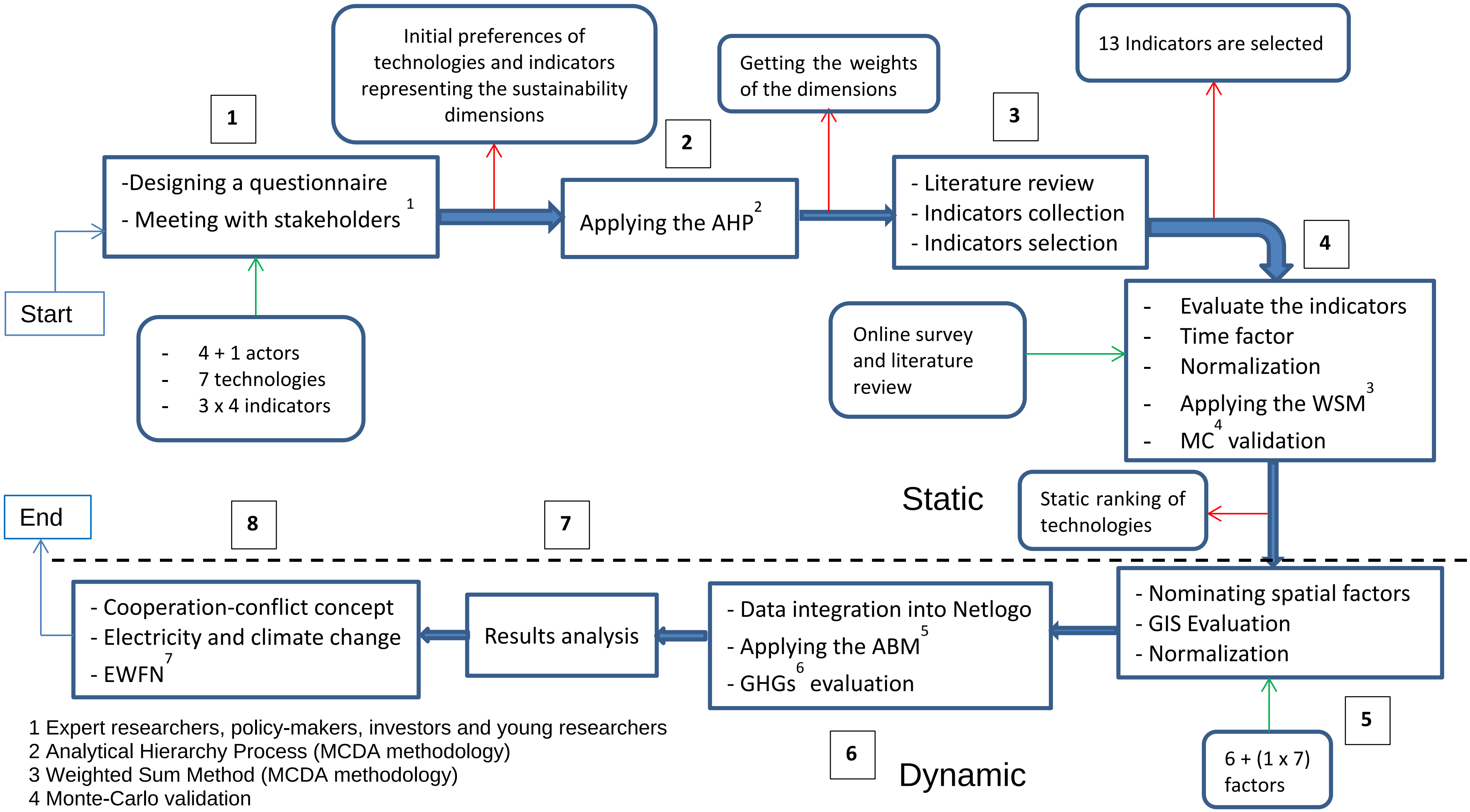
Step 4: According to the life cycle assessments (LCA) and the risk assessments (RA) of the technologies, conducting an online survey and the data present in the literature, I collect the values of the selected indicators. Additionally, I build the time function of some indicators that do not have constant values. Then, I normalize the values of these indicators and apply another MCDA methodology called the weighted sum method (WSM) for integrating the values and the weights of the indicators ending up with an integrated value for each technology by which they are ranked. In order to validate the results of ranking the technologies, I use a validation methodology called Monte-Carlo (MC) validation. This step will be discussed in chapter 2, 3 and 4.

Step 5: In order to investigate the impact of the local site condition on the decision making process, I select 13 spatial factors and obtain their values. Then I build up data maps for each of these factors so that they will be integrated in the model. Here also I use normalized values. This step will be explained in chapter 3.

Step 6: In this step, I integrate the MCDA, GIS spatial data and the ABM in the open source software, Netlogo, and build my model through this software. I add a feature in it that can analyze the GHGs emissions from the different energy-mix scenarios. This will be shown in chapter 3.

Step 7: I present and discuss the results of previous steps and compare the different employed scenarios. This will be shown in chapter 4.

Step 8: I give a final conclusion on the results and recommend future extension of the study with a brief discussion on the cooperation-conflict concept related to this study, the correlation between electricity planning and climate change, impacts projections and a hint on the energy, water and food nexus theoretical basis and the role of different energy-mix scenarios in compromising this nexus as will be shown in chapter 5.



1 Expert researchers, policy-makers, investors and young researchers
2 Analytical Hierarchy Process (MCDA methodology)
3 Weighted Sum Method (MCDA methodology)
4 Monte-Carlo validation
5 Agent-based Modelling
6 Greenhouse gases
7 Energy, water and food nexus

Figure 10: Schematic diagram of the research process

2. Sustainability Assessment Indicators

2.1. Subjective data collection

In the early stage of my work, I started with subjective data collection. I identified two main questions that are to be answered from the stakeholders in the energy sector. These are:

- o Which type of power plants do they prefer, in a ranking order, to be installed in Egypt?
- o How important are the assessment indicators relative to each other in their evaluation of power plants?

After testing different versions of the design of the questionnaire, I ended up with the one shown in Appendix A (version 1). The main objective of this questionnaire is to know the initial preference order of different electricity supply technologies and the preference order of the sustainability assessment indicators in the evaluation of these technologies by actors[4] in the energy sector. Then I use these input data in getting the weights of the indicators and subsequently the weights of the sustainability assessment dimensions using the AHP methodology. The initial preference value of the technologies by each actor will represent the initial setup value of the priorities of the technologies.

In February and April 2015, I started the field research in Egypt. I had the opportunity to meet some persons who play an important role in the energy planning process in Egypt. In June 2015, I attended a summer school and a conference in Cyprus where other young scholars participated from Middle East and North African countries, including Egypt. These scholars are doing researches relevant to energy, water and climate change topics. So, I took this opportunity to invite them to the contribution to the questionnaire as young researchers. But, due to time limitations, I changed its design to make it more easily and quickly filled as shown in Appendix A (version 2) since the previous version takes a longer time. The total number in the sample, who participated in the study, as shown in Figure 11, is 40 participants which sounds small; however, the size of the population for each category is not too big. Moreover, collecting data from employee in vital sectors in Egypt is a very sensitive issue.

The used indicators and technologies in the questionnaire are not fully consistent with my later investigation since they are initially selected randomly in order to be used in my interviews which could not be delayed, otherwise I would not be able to collect any data. In version 1 of the questionnaire, I asked about conventional fossil fuel-fired power plants in general and hydropower but not about biomass-fired power plants. Additionally, I selected randomly 3 indicators for each dimension of the sustainability assessment. In version 2, I discarded hydropower as experts have informed me that there is no more opportunity to expand hydropower in Egypt and it is totally exploited. I also broke down fossil fuel-fired power plants to coal, oil and natural gas (NG) power plants. I used 9 instead of 12 indicators but I gave the contributors the chance to suggest others and to rank them. In order to overcome this shortcoming, I manipulated the data in a way that could reduce the error to some extent. So, instead of using the weights of the individual indicators, I used the weights of the sustainability dimensions and distributed each on the sub-indicators equally. Thus, all indicators under each dimension have equal weights that are not necessarily the same as for other dimensions. I found later that the dimensional weights are more practical than the sub-indicators as it allows for further

[4] Actors and stakeholders are used here also interchangeably but they are the same

expanding the size of indicators which will be absolutely difficult to ask actors on ranking them. For the assessment technologies, in version 1, I used the same preference order of fossil fuel-fired power plants for coal and NG, whereas I discarded the preference allocation to oil-fired power plants in version 2.

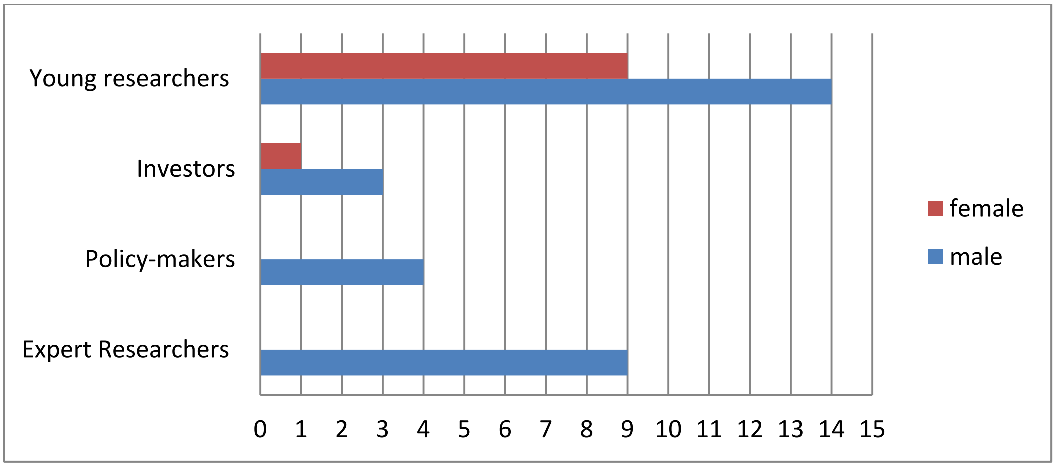


Figure 11: Data of individuals contributing to the questionnaire

I categorized the participants into four actor-type groups representing expert researchers, policy-makers, investors, and young-researchers according to their affiliations. There are inter-dependencies between these actors where expert researchers get more experience from young researchers through their studies which sometimes consider the economic and regulatory aspects while the latter get more knowledge and data from the former and the other two actors. Investors make their decisions according to feasibility studies done by young researchers that need inputs from expert researchers and policy-makers whereas policy-makers change the legislations according to feedback from expert researchers, studies done by young researchers and the policy of funding by investors. This kind of interaction plays a great role in their decision making process in selecting the technologies and on how they assess these technologies. Another virtual actor that I used in this study is the sustainable scenario where it represents equal initial preferences of all technologies and its progress while using equal weights of the sustainability dimensions. I focused in this study on seven technologies. These are coal-fired power plants, NG-fired power plants, wind power, concentrated solar power (CSP), photovoltaics (PV), biomass-fired power plants and nuclear power plants. The following two sub-sections discuss the selection process of the sustainability assessment indicators and their values.

2.2. Indicators in the literature

Exploring previous studies, I found numerous energy indicators that have been used for the SD assessment. The International Atomic Energy Agency (IAEA), the United Nations Department of Economic and Social Affairs (UNDESA), the International Energy Agency (IEA), the European Environment Agency (EEA), and the Statistical Office of the European Communities (EUROSTAT) have developed together 30 indicators covering social, economic and environmental dimensions for the purpose of evaluating energy sustainability (Tsai 2010). The United Nations Commission on Sustainable Development (UNCSD) derived 58 indicators from a working list of 134 indicators for applications worldwide (Singh et al. 2009). Neves and Leal (2010) proposed a framework of 18 local energy sustainability indicators to be used both as an assessment and as an action-planning tool. Table 28 in Appendix B shows a list of 72 indicators covering four dimensions (21 economic indicators, 17 environmental indicators, 26 social indicators and 8 technical indicators) that I collected from a sample of 30 studies to be used as a pool of indicators from which I select the most suitable ones for my case study. The procedure and the results of the selection of the sustainability indicators have been published in an international journal (Shaaban and Scheffran 2017).

2.3.Selection of indicators

Too many indicators are not helpful for the sustainable energy decision-making. The indicators should cover all aspects of sustainability but at the same time do not show repeatability and overlap (Liu 2014) such as the inclusion of fuel cost in operation and maintenance cost, and job creations and social benefits of the energy project (Wang et al. 2009). Selection requires a compromise between simplification and complication (Singh et al. 2009). Generally, Table 3 shows a set of selection criteria that should be obeyed to select the major indicators used in energy decision making. They guide the decision makers to select criteria.

Table 3: Selection criteria of indicators

Selection criteria	Description	References
Data availability	The possibility to collect data about the indicator	(Singh et al. 2009)
Consistency with objective	The ability to describe the sustainability of energy technological systems, and provide early warning information	(Singh et al. 2009, Liu 2014, Wang et al. 2009, Mainali and Silveira 2015)
Independency	Indicators should not have an inclusion relationship at the same level and should reflect the performance of alternatives from different aspects.	(Wang et al. 2009)
Measurability	The indicators should be measurable in quantitative and qualitative terms corresponding to specific sustainability goals.	(Wang et al. 2009, Mainali and Silveira 2015, Liu 2014)
Simplicity	Ease of understanding by decision makers and ease of practical applications	(Singh et al. 2009, Rovere et al. 2010)
Sensitivity	Capacity for allowing trend analysis	(Singh et al. 2009, Rovere et al. 2010)
Reliability	Unbiased and apt to capture both positive and negative issues	(Singh et al. 2009, Liu 2014, Rovere et al. 2010)

Other methods of selection have been proposed by Singh et al. (2009) and Wang et al. (2009) but they have some drawbacks that make them difficult to apply in our case. For instance, in factor analysis and correlation coefficient methods which elaborate criteria of strong correlation, it is not necessary to have strongly correlated indicators since they should behave independently. Least mean square and minmax deviation methods which are based on discarding criteria that show very close values among alternatives seem to be convincing but these values could change with other factors in the future. For example, if they have the same or very close cost of electricity, this could change in the future due to resource depletion or economic crisis that affects some but not all alternatives. Other methods are based on subjective expert opinions as in the Delphi method which relies on the answers of the experts to a questionnaire for criteria selection with providing the reasons for their selection in two or more rounds. After each round the answers are disseminated among them and the process is repeated to get more interactive understanding of the selected criteria. However, it is not feasible in most cases to get experts for such purpose, and it is still based on subjective opinions and could raise some conflicts between participants.

In this study, I try to make the selection process simple but at the same time plausible and reliable. Figure 12 shows a schematic diagram of our selection approach which proceeds in 5 steps. In the first step, basically I collect some indicators from the literature and interview some experts who present the major indicators that pop up in their minds while assessing these technologies. The collected indicators should cover the four dimensions of sustainability assessment. As a result of this step, 72 indicators have been collected from a sample of 30 studies and some of them match with those provided by experts. The second step is to assess the frequency of these indicators in this sample of studies to find out the widely and most commonly used ones as they represent the trend of researchers while assessing the sustainability of technologies. So, I select those that have a frequency of more than 20% of the studies. This selected threshold will be explained later. Then, in the third step, I screen the selected indicators against the selection criteria in Table 3. The fourth step is to evaluate the applicability of the selected indicators to our case study with experts. Finally, I sort the indicators again according to their assessment dimension.

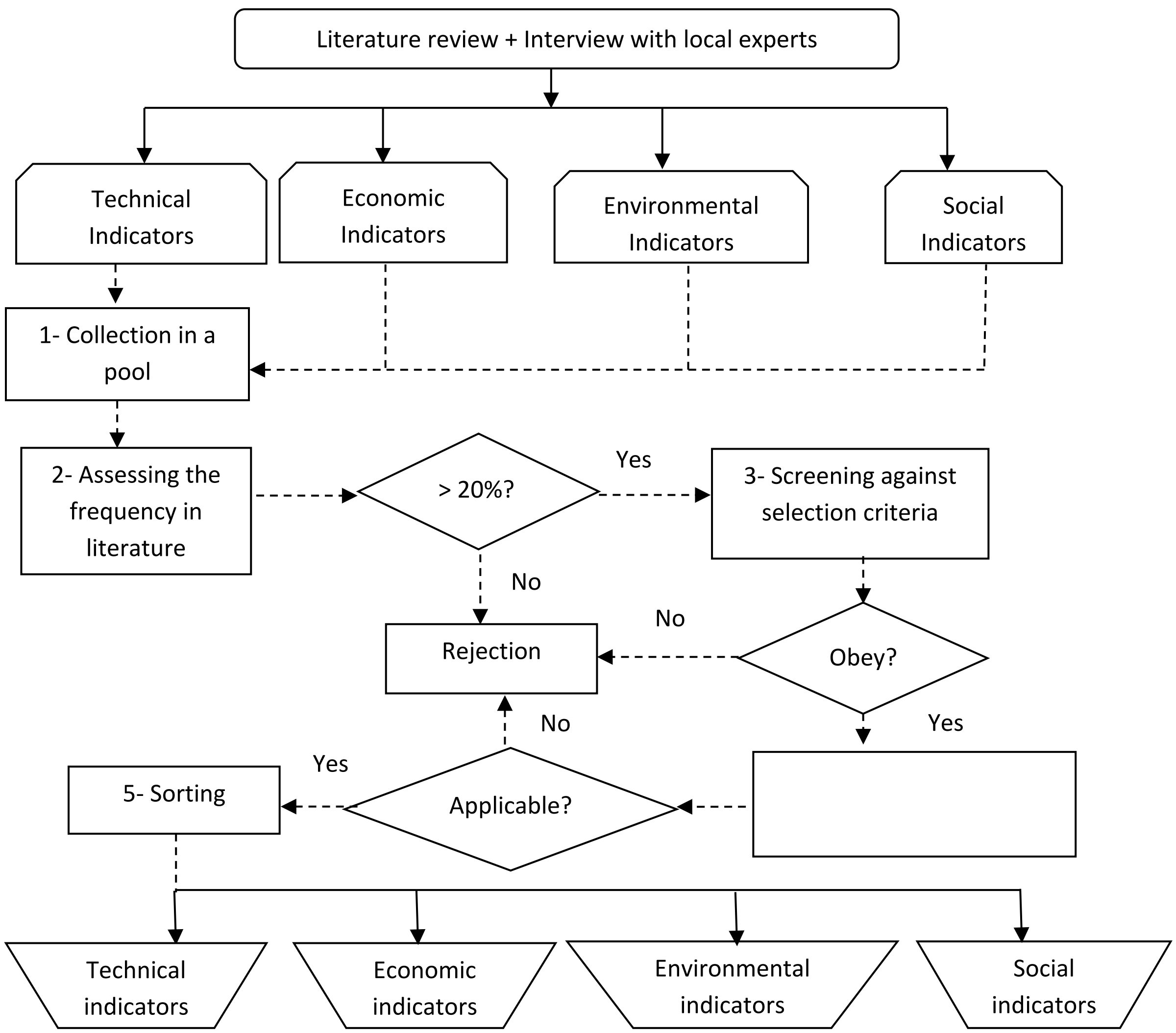


Figure 12: A schematic diagram of the empirical research approach

I observe that 26 indicators have been used once in the sample of literature which indicates their case specificity and their restricted general application. It has been found that more than 75% (55 out of 72 indicators) of the collected indicators have a frequency of less than or equal to 20% in this sample of 30 studies. This reflects the large diversification of indicators that could be used for the sustainability assessment of energy systems. If I choose the indicators of frequency higher than 10% (i.e. used in more than 3 studies), then I will get 32 indicators which are still too much to be used. However, if I select the indicators of frequency higher than 30% (i.e. used in more than 10 studies), it will end up with 7 indicators and they will not include any of the social dimensions (see Figure 13 and 14). For this reason, I selected those indicators that have a frequency of more than 20% of the 30 studies (i.e. used in more than 6 studies) which accounts for 17 indicators as shown in Table 4.

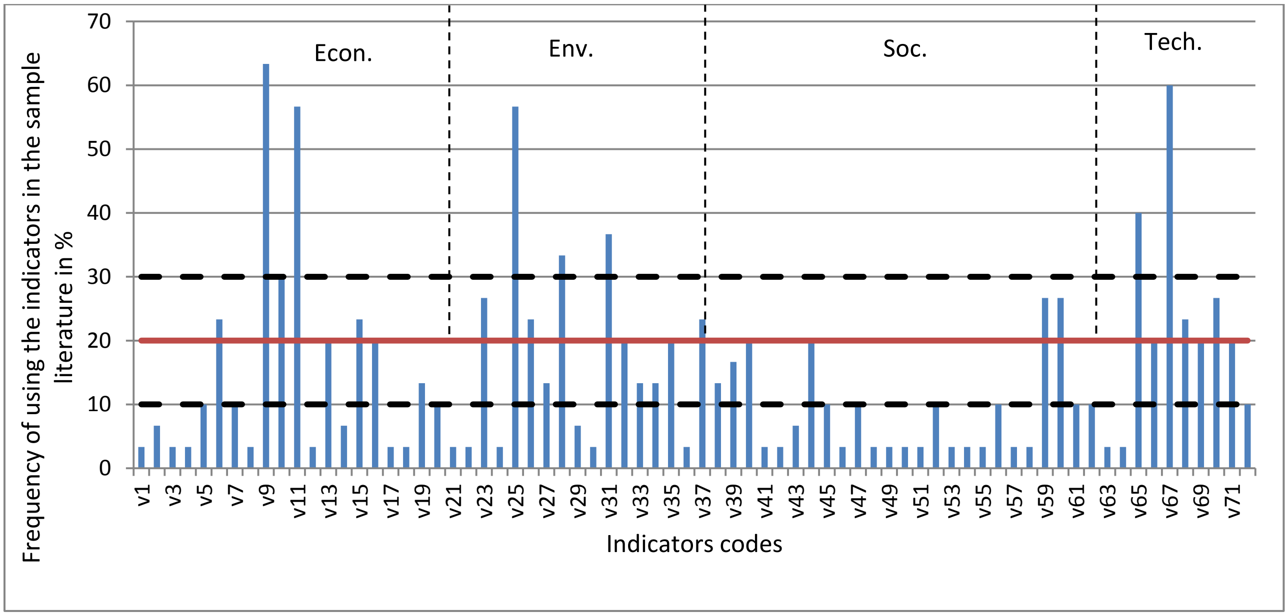


Figure 13: Frequency of collected indicators in the sample literature

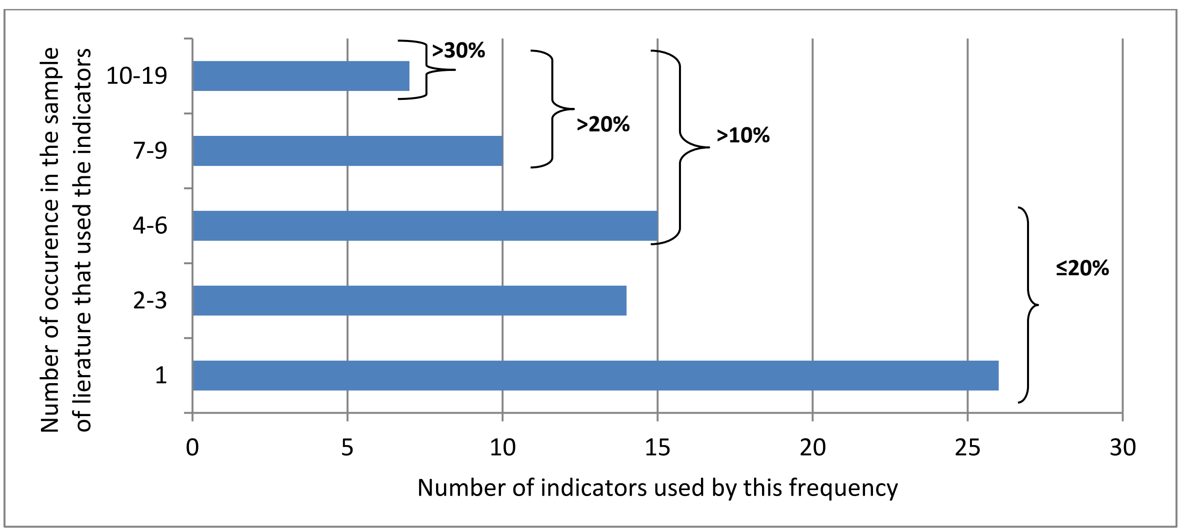


Figure 14: Number of indicators per occurrence in sample of literature

Table 4: Selected indicators from step 2

	Economic		Environmental		Social		Technical
V6	Direct employment generated	V23	Amenity	V59	Safety	V65	Area requirements
V9	Investment cost	V25	CO_2 emission	V60	Social acceptability	V67	Efficiency of energy generation
V10	Job creation	V26	Contaminant discharges in liquid effluents from energy systems			V68	Resource Potential
V11	Cost of Electricity	V28	Greenhouse gas emissions			V70	Reliability of energy supply
V15	Operation and maintenance cost	V31	NO_x emission				
		V37	SO_2 emission				

Despite the international concern about the importance of including social and environmental aspects in energy decision making, the economic and technical aspects still constitute the higher priority. Figure 13 shows that the most frequently used indicator in these studies was "investment cost" (v9) that has been used in 19 studies with a frequency of 63% followed by "efficiency of energy generation" (v67) with a frequency of 60%. However, the maximum frequency in the social dimension is 27% and only for 2 indicators although this dimension has the largest number of variables that have been used. In the environmental dimension, analysts gave more attention to indicators that have an impact on climate change like CO_2, NO_x and SO_2 emissions which imply a sound motivation among policy makers to tackle this growing phenomenon.

Passing through steps 3 and 4, I rejected 5 of the indicators selected in step 2. In the economic dimension, I found redundancy of using both direct employment and job generation. According to the perspective of experts, the impact of power generation projects on direct employment is not that much as compared with other projects in other areas where those who are employed in the operation or maintenance of the power plants are very few. However, if I take the job generation indicator including both direct and indirect jobs, then I will get tangible impacts that could affect the decision making process. The indirect jobs will include the manufacturing, construction, installation, logistics and import steps in the implementation of the project. As a result, I rejected the direct employment indicator. However, experts would accept using direct jobs only in the assessment of the technologies in case there was a high uncertainty about the data of indirect jobs.

In the environmental dimension, I rejected three indicators. Again, local experts' opinion regarding the amenity indicator which is concerned with aesthetical aspects of power plants like visual, noise and odor nuisances disregard the importance of this indicator. They justified their opinion that most of the power plants are installed in non-residential areas. Additionally, there is a little concern towards this aspect in most of the densely populated areas. This can be manifested by house facades that are mostly left unpainted, noisy workshops in densely populated areas and improper garbage disposal along the streets in many rural and urban areas. Moreover, the social acceptability could reflect this indicator. There is no available data about contaminant discharges in liquid effluents from energy systems for all technologies besides its difficulty of understanding. I discarded also the greenhouse gas emissions indicator as this can be represented more specifically through CO_2 and NO_x emissions. However, GHGs emissions will be used as an indicator for the assessment of climate change potential impacts from the energy-mix scenarios.

Finally, in the technical dimension I discarded the area requirement indicator since there is a vast unexploited desert area where the concentration of population is along the Nile River and its delta. On the contrary, this kind of projects could assist in the development of new residential areas and reduce the population pressure in the overcrowded ones. Table 5 summarizes the results of screening the selected indicators in step 2 against the selection criteria. However, I added the water consumption indicator (v72) although it has a low frequency (only in 10% of the studies) because of its importance and the deficiency in the water supply crisis that Egypt could face from two directions: one is due to the building of the Grand Renaissance Dam in Ethiopia; the second is as a consequence of climate change on precipitation. Table 6 shows the final set of indicators that have been selected and sorted through the four dimensions of the sustainability development assessment of electricity supply technologies together with the measuring unit per each indicator and the objective of each of these indicators in achieving sustainability.

Table 5: Results of screening indicators against selection criteria

Selection criteria	v6	v9	v10	v11	v15	v23	v25	v26	v28	v31	v37	v59	v60	v65	v67	v68	v70
Data availability	✓	✓	✓	✓	✓	✓	✓	x	✓	✓	✓	✓	✓	✓	✓	✓	✓
Consistency with objective	x	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Independency	x	✓	✓	✓	✓	x	✓	✓	x	✓	✓	✓	✓	✓	✓	✓	✓
Measurability	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Simplicity	✓	✓	✓	✓	✓	✓	✓	x	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sensitivity	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Reliability	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Applicability in the case study	✓	✓	✓	✓	✓	x	✓	✓	✓	✓	✓	✓	✓	x	✓	✓	✓

Table 6: The final set of indicators

Category	Indicator	Measuring Unit	Sustainability target
Economic	Investment cost	USD/kW	Minimize
	Job creation	Jobs/MW	Maximize
	Cost of electricity	USD/kWh	Minimize
	Operation and maintenance cost	USD/kW	Minimize
Environmental	CO_2 emission	g/KWh	Minimize
	NO_x emission	g/KWh	Minimize
	SO_2 emission	g/KWh	Minimize
Social	Safety risks	Fatalities/GW_eyr	Minimize
	Social acceptability	Ordinal scale	Maximize
Technical	Efficiency of energy generation	%	Maximize
	Resource Potential	TWh/year	Maximize
	Reliability of energy supply	%	Maximize
	Water consumption	kg/kWh	Minimize

2.4.Life Cycle Assessment and Risk Assessment

Life cycle assessment (LCA) aims at assessing certain aspects associated with development of a product throughout its life from cradle to grave and its potential impact. The life cycle starts from raw material acquisition, processing, manufacturing, use and ends up with final product disposal (Varun et al. 2009a). LCA guidelines have been set forth by the International Organization for Standardization (ISO) (2006) in the ISO 14040 standard (Haapala and Prempreeda 2014). Most of the aspects that are evaluated in LCA are closely related to environment and impact on ecosystems. Thus, investigating LCA of a product can improve the efficacy of environmental regulation where it can identify with great certainty the source of, for example, environmental pollution or resource use of upstream and downstream processes (Weisser 2007). Upstream processes focus on firms producing or importing raw materials, for example in energy systems, emissions associated with exploration, extraction and transport of coal, natural gas, and refined petroleum products. In contrast, downstream processes typically refer to aspects associated with the use of the raw material. These represent the direct sources of emissions in energy systems including, for instance, motor vehicles, farms, power plants, and other stationary sources. LCA is a guiding source for the values of two indicators that I use in this study: CO_2 and GHG emissions.

In the case of GHG emissions from electricity generation, all significant emissions related to the final product need to be accounted. For electricity this is usually expressed in grams of carbon dioxide equivalent per unit of electricity (i.e. gCO_2/kWh_e). For fossil fuel technology, GHG emissions from upstream processes are much lower as compared to emissions from renewable energy technologies and nuclear power. Most of emissions are obtained during downstream processes for fossil fuels, whereas upstream processes are the main source of emissions for other renewable and nuclear power technologies. For biomass downstream process, it represents a neutral resource since it absorbs the emitted carbon through photosynthesis (Weisser 2007).

Comparing the life cycle GHG and CO_2 emissions from different energy systems reveals that renewable systems emit much lower GHG and CO_2 than fossil fuels based technologies as shown in Table 7. Ranking of the technologies according to the lowest value emission of GHG reveals that nuclear has the lowest source of emission followed by wind, hydro, CSP, PV, biomass, natural gas, oil and coal as the highest emission source. However, there are many aspects that should be considered while conducting the LCA which could affect the ranking of technologies for this indicator.

Table 7: Average GHG and CO_2 emissions from different energy systems

Tech.	Coal	Natural gas	Wind	CSP	PV	Biomass	Nuclear	Hydro	Oil	References
GHG (gCO_2 eq/kWh_e)	1060	566	16	27	53	58	13	17.5	850	1
CO_2 (gCO_2 /kWh_e)	927	476	46	105	111	70	23	--	--	2
References	1. Weisser 2007, NREL 2013a 2. Varun et al. 2009a, Wang and Mu 2014, Begić and Afgan 2007, Rovere et al. 2010, Afgan et al. 2007, Afgan and Carvalho 2002, Onat and Bayar 2010, EURELECTRIC and VGB 2003									

In addition to the need for a comprehensive LCA of power plants, risk assessment (RA) represents a vital prerequisite for the achievement of a secure and sustainable vision. Safety of energy systems plays an important role in the sustainable development. Accident risks come in the front line as one of the most important perspectives in the evaluation of the safety of energy systems. Accidents in the energy sector can adversely affect people's health and property, the overall economy, and damage ecosystems and their functions. For these reasons, safety and protection measures of energy systems and their related infrastructure play a crucial role in sustaining the economy and social stability which as a consequence attract the interest and the demand of better understanding and investigating the underlying reasons and conditions of historical severe accidents as they guide us to improve the risk management and the decision making processes for technology selection.

In this study, I depend mainly on the data that have been collected by the Paul Scherrer Institute (PSI) in Switzerland for the evaluation of safety risks associated with energy systems. This institute started a long-term research activity in this area in the 1990s to develop the Energy-Related Severe Accident Database (ENSAD) and continuously update it. They focused on severe accidents because they are most controversial in public perception and energy politics, even when the total sum of the many small accidents with minor consequences is substantial. According to Burgherr and Hirschberg (2005), ENSAD studied 6404 energy-related accidents that occurred in the period 1969-2000 of which 3117 (48.7%) are severe, and 2078 have 5 or more fatalities. Although in this study I concern more about the power generation step in the energy chain, the consideration of the full energy chains is essential for a comprehensive evaluation because an accident can happen in any chain stage from exploration, extraction, processing and storage, long distance transport, regional and local distribution, power and/or heat generation, waste treatment, and disposal. Additionally, the sustainability concept should not be confined to the country under study, but rather should consider the neighboring and resource supplier countries (Paul Scherrer Institut 2016).

Severe accidents have been identified according to PSI ENSAD whenever one of the following criteria is satisfied:

- at least five fatalities or
- at least ten injured or
- at least 200 evacuees or
- extensive ban on consumption of food or
- releases of hydrocarbons exceeding 10000 tons or
- enforced clean-up of land and water over an area of at least 25 km^2 or
- economic loss of at least five million USD.

The risk associated with energy systems could be evaluated in four different means. The first is to measure the number of accidents and the number of fatalities over a period of time for one of the technology over a certain geographic area. The second is to normalize the number of fatalities per accident. This is more indicative than the individual values. The third method of measurements is similar to the previous one where the data are aggregated and normalized on the basis of the unit of electricity production for the different energy sources. For nuclear and hydropower the normalization is straightforward since in both cases the generated product is electrical energy. In the case of coal, oil, and natural gas, the thermal energy was converted to an equivalent electrical output using a generic factor of 0.35. The use of Gigawatt-electric-year (GWeyr) was chosen because large individual plants have capacities in the neighborhood of 1 GW of electrical output (GWe). This makes GWeyr a natural unit to use in discussions of total electricity production. The last method that can be used and is often better is the frequency-consequence (F/N) curves. It is a two dimensional assessment where it shows the frequency of an accident that has a consequence of X fatalities or damage. They provide information about the observed or predicted chain-specific maximum extents of damages (Burgherr and Hirschberg 2005).

The risk assessment of coal-fired power plants reveals that the majority of accidents and fatalities occur during the extraction process followed by exploration but transportation step is negligible (Hirschberg et al. 2003). China is the world's top producer of coal, hydropower, and wind (US EIA 2013,OECD/IEA 2015,The Global Wind Energy Council 2015). Major severe accidents in coal and hydropower energy chain have been recorded in China. Previous risk assessment of natural gas has revealed that during the period 1969-2000 a total of 129 severe (≥ 5 fatalities) accidents with 1971 fatalities were recorded worldwide (Burgherr and Hirschberg 2005). Regarding the risk out of hydropower, it is worth mentioning the world's most catastrophic dam failures. In August 1975, two earthfill dams in the province of Henan in China, Banqiao and Shimantan, have collapsed as a result of a typhoon that has created a maximum 24-hour rainfall of 1,005 mm and a three-day rainfall of 1,605 mm causing huge floods. More than one million hectares of land was damaged, countless of villages and small towns were submerged and millions of people lost their homes. Approximately 26,000 people were killed by the immediate flood waves from the failed dams, while further 145,000 died of epidemics and famine during the ensuing weeks (Hirschberg et al. 2003). In April 26, 1986, the largest nuclear power disaster occurred. At the Chernobyl Nuclear Power Plant in Ukraine, a test on reactor number four went out of control, resulting in a power excursion. The ensuing steam explosion, fire and radioisotope releases killed approximately 31 immediately. Future total death toll predictions state that there may be a total of between 4,000 to 33,000 latent deaths in the years to decades ahead due to radiation induced cancers (Burgherr et al. 2011). Data about accidents of renewables other than hydro are still under investigation but in general it will not be comparable to those mentioned above. Table 8 shows a comparison between energy systems in terms of the number of accidents, the number of fatalities and the aggregated, normalized fatalities that occurred in non-OECD countries during the period 1970-2008. The safety ranking of nuclear power plants is still under debate because the immediate number of fatalities as compared to coal power plants is very low. Additionally, it has a rare frequency of occurrence where the second nuclear accident, Fukushima in 2011 in Japan, was a consequence of natural disaster and it left no immediate fatalities (Hasegawa et al. 2016,Hasegawa et al. 2015). Indeed, the emitted radiation could result in latent fatalities due to its carcinogenic effect; however, there are other factors that contribute to disease induction. Moreover, in the other energy systems we should consider accident impacts on the long run in order to have a fair comparison.

Table 8: Risk assessment data of energy systems in non-OECD countries (Burgherr et al. 2011)

	Accidents	Fatalities	Fatalities/ GWeyr	Ranking
Coal: w/o China	1600	31,580	1.08	6
China	----------------No Data-----------------------		9.06	
Natural Gas	77	1,549	0.202	5
Wind (in OECD)	6	6	0.00829	3
CSP	-----------------------------No Data----------------------------------			1
PV	------------------No Data----------------		0.000245	2
Biomass	3	21	0.0149	4
Nuclear: *immediate*	1	31	0.0302	7
latent		4,000-33,000	8.76 – 32.1	

2.5. The values of the indicators

Since most of the power plants that are currently installed are not fully based on one primary resource as in the case of steam type and biomass-fired power plants in addition to the different techniques deployed for each type, the values of the indicators vary under each technology type to some extent. For that reason, I use an average value of those I collected from previous studies which have applied a detailed analysis of the technologies.

2.5.1. Technical Indicators

This dimension highlights the engineering technicality of energy systems. It is the most basic one of the four pillars for applying the sustainability assessment since it does not make sense to install an energy system that is not technically feasible as it will affect directly the economic dimension of the system. Thus, decision makers usually put this dimension as a first topic in their agenda in order to be sure that they could provide a product at the end. Here, I selected four main indicators that are necessary in the sustainability assessment of the energy systems especially for my case study.

2.5.1.1. Efficiency of energy generation

Efficiency indicates how much output (secondary) energy is gained from the input (primary) energy and in my study how much electricity is gained from the input of other forms of energy which could be mechanical as in hydropower and wind energy systems, thermal as in fossil fuels, biomass[5], geothermal, nuclear and solar concentrator systems or light energy as in photovoltaics. Researchers work on improving the efficiency of energy systems to meet the growing demand without installing new plants. Energy efficiency could be applied to the supply-side as well as to the demand-side of the electricity systems. Most of the electric appliances are subject to energy efficiency tests before distribution in the market. The manufacturers tend to reduce the electricity consumption of these devices and at the same time give the same functionality as for example the Light Emitting Diode (LED) light bulbs. Here, I am concerned with only the supply-side efficiency. It is the most used technical indicator to evaluate energy systems (Wang et al. 2009). According to several previous studies [see EURELECTRIC and VGB (2003), Evans et al. (2009), Onat and Bayar (2010), Afgan and Carvalho (2002), Afgan et al. (2007), Rovere et al. (2010), Begić and Afgan (2007), VGB (2011)], Figure 15 shows the value range and average value of the efficiencies of electricity generation of the technologies under assessment. It can be observed that natural gas-fired power plants occupy the top efficient technology with an average value of 47%, whereas PV has the lowest efficiency of around 13% with a possible maximum of 22%. However, the German Frauenhofer Institute of Solar Energy Systems and the French Soitec Institute have developed certain type of PV panels that are very expensive to be used commercially but have reached an efficiency of 46% (Frauenhofer ISE 2016).

[5] Here I do not consider the efficiency of the energy conversion step from the light of the sun to the stored carbohydrates in the bioenergy crops through photosynthesis, but rather I assume the direct consumption of the existing biomass as a fuel to be combusted in the power plants.

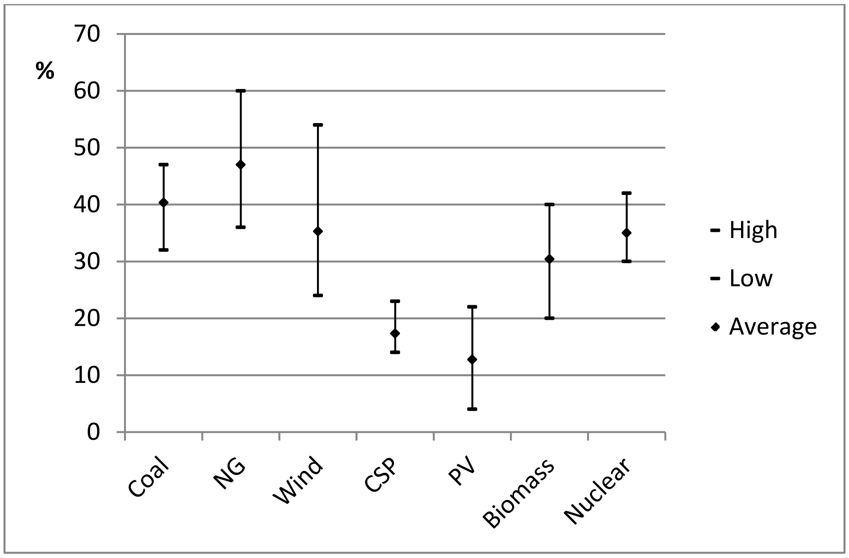


Figure 15: Efficiency of electricity generation of technologies under assessment
(EURELECTRIC and VGB 2003, Evans et al. 2009, Onat and Bayar 2010, Afgan and Carvalho 2002, Afgan et al. 2007, Rovere et al. 2010, Begić and Afgan 2007, VGB 2011)

2.5.1.2. Resource Potential

Resource potential indicates theoretically how much electricity could be provided annually from the technical energy system and across a certain area, region or country taking into account the interruptions and the characteristics of the electrical systems (Rovere et al. 2010, Mainali and Silveira 2015). The resource potential is measured in energy units per time (e.g. TWh/y). 63% of the world's petroleum reserves and 41% of the world's natural gas reserves are in the Middle East (Onat and Bayar 2010). According to the U.S. Energy Information Administration (EIA) as of January 1, 2015, Egypt held 4.4 billion barrels of proven oil reserves, and 77 trillion cubic feet of proven natural gas reserves (US EIA 2015), but it has no significant reserves for coal. Egypt has significant solar and wind potential where it has high intensity direct solar radiation of 2000–3200 kWh/m^2/year from north to south. The area west of the Gulf of Suez from south of Soukhna to Hurghada, especially the Gulf of Elzait, has an excellent wind regime, exceeding 10 m/s (at a height of 25 m) (Khalil et al. 2010). Therefore, this indicator represents a crucial measure of the spatial technical sustainability of the system where the value varies according to the availability of the resource especially for renewable energy. It justifies also the transportation costs for fossil fuels and import costs for the unavailable resources. This indicator has been used in this study as a technological dependent variable as well as a spatial dependent variable. So, I will mention it again in the spatial data analysis but from another point of view.

According to a study conducted by DLR (German Aerospace Center), Egypt has a potential of 7650 TWh/y, 73656 TWh/y, 36 TWh/y, 15.3 TWh/y for wind, CSP, PV, and biomass, respectively (Trieb 2005). In order to estimate the resource potential for coal, natural gas and nuclear in terms of TWh/y, I used the reserve capacity of each. Based on an assumption that no more reserves will be discovered, the current reserves will be used for the period of study (2015 – 2100) and they are allocated only for electricity production, I calculated the potential annual electricity production from these reserves. According to US EIA, Egypt has a reserve capacity of 18 million short tons of coal (US EIA 2014) and 77 trillion cubic feet of NG (US EIA 2017a). The average heat rate of coal and natural gas steam power plants is 10,080 Btu/kWh and 10,408 Btu/kWh, respectively. The heat content of coal and natural gas is

19,420,000 Btu/short ton and 1,029,000 Btu/Mcf[6], respectively. The amount of fuel required to produce 1 kWh equals to the heat rate divided by the heat content of the fuel (US EIA 2017b). Therefore, the estimated annual electricity production from the reserve capacity is 0.41 TWh/y and 90588.24 TWh/y for coal and natural gas, respectively. The reserve capacity of uranium in Egypt has been recently announced to be 1900 tonnes of type [<260 USD/kgU] (OECD/NEA 2016). 1 kg of uranium could generate 24 GWh (European Nuclear Society 2017). Thus, the potential of nuclear power in Egypt is about 536.47 TWh/y. The previous data are summarized in Table 9 and 10.

Table 9: Energy conversion data for coal, natural gas and nuclear (US EIA 2014, US EIA 2017a, OECD/NEA 2016, European Nuclear Society 2017)

	Reserves	**Heat Rate (Btu/kWh)**	**Heat Content**	**Amount to produce 1 kWh**	**Reserves in TWh**
Coal	18 (million short tons)	10,080	19,420,000 (Btu/Short ton)	0.00052 (Short tons)	34.6
NG	77 (trillion cubic feet)	10,408	1,029,000 (Btu/Mcf)	0.01 (Mcf)	7,700,000
Nuclear	1900 (tonnes)			0.042 mg	45,600

Table 10: Resource potential of technology under assessment

Resource potential	**Coal***	**NG***	**Wind**	**CSP**	**PV**	**Biomass**	**Nuclear***
TWh/y	0.41	90588.24	7650	73656	36	15.3	536.47

* For 85 years.

2.5.1.3. Reliability of energy supply

This indicator can be defined as the security of continuous power supply of the system in terms of performance, resistance to failure, and the ability to function as designed without interruption. Actually, many factors could contribute to the reliability of the system. It could be related to the availability of resources which is more prominent with renewable energy systems for which the resources are intermittent and not controllable, necessitating the presence of a backup or storage system. Other factors include political tensions, potential terrorist attacks, the quality of equipment, maintenance (Wang et al. 2009), the qualification of employees and how they handle trouble shootings. It could be evaluated in a broad sense qualitatively with an ordinal scale or quantitatively through the technology capacity factor which is the ratio of the actual power output to the theoretical maximum power output from the technology over a period of time and/or the availability factor which is the fraction of time that the technology is able to generate energy over a certain period, divided by the total amount of the time in that period (Troldborg et al. 2014). In practice, these two factors are easily estimated and reflect any kind of interruptions of the system that could arise by evaluating the historical data. Based on data obtained from a platform website linked to the National Renewable Energy Laboratory (NREL) that gathers published data from 2007 till 2015 concerning energy technologies, Figure 16 shows the differences in the capacity factors of energy systems that reflects the reliability indicator (Open Energy Information 2015). It is quite plausible that fuel-based power plants are more reliable than weather-based power plants as in the case of solar and wind power plants, since the latter types vary significantly

[6] Mcf = 1000 cubic feet, MMcf = 10^6 cubic feet

with changing weather and climate conditions. However, technology developments were able to overcome this issue by offering energy storage mechanisms (i.e. thermal storage systems, batteries) that could compensate the fluctuation of the supply. Thus, the excess energy is stored in order to be used when the supply is reduced.

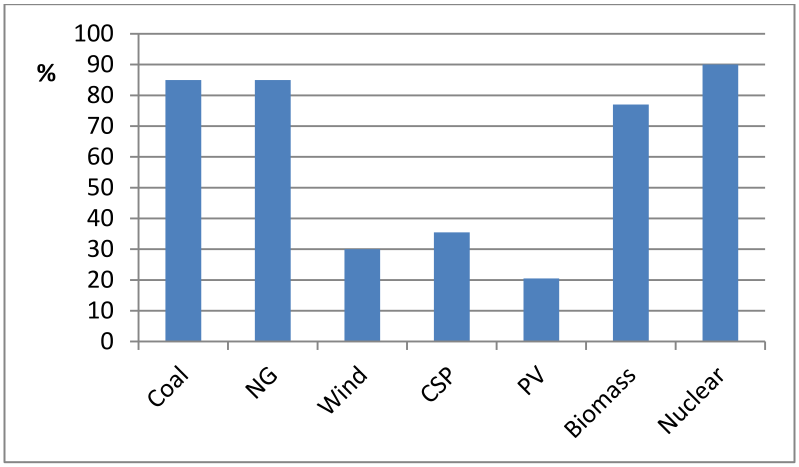


Figure 16: Capacity factor of different energy systems (Open Energy Information 2015)

2.5.1.4. Water consumption

Water losses can occur during various stages of the life cycle of the power plant, in particular during manufacturing and installation as well as during operation of the system which in the following will be our main focus. Generally, thermal power plants which are fired by fossil fuels or biomass or those heated through solar radiation or nuclear reaction have more water losses especially those using water cooling condensation systems. Alternative solutions are the use of air cooling, pressure management and the use of desalinated sea water or treated sewage water. Solar concentrators and PV panels consume water in the cleaning process but it is negligible. Wind systems have the lowest water consumption followed by photovoltaics as compared to other systems (Evans et al. 2009). Biomass has the highest water consumption if we considered the water used in the irrigation of the trees and bioenergy crops. This indicator shows a great importance to our case study since Egypt is expected to face a shortage of water as a consequence of climate change impacts and because of the Great Renaissance Dam that is nowadays under construction in Ethiopia and could affect water supply to Egypt from the Nile River with potential multiplier effects on agriculture and drinking water. Thus, decision makers should consider the trade-offs between the interacting water, energy and agriculture and compromise between them.

Figure 17 displays the consumed water across different power supply technologies. Coal, NG and nuclear power plants consume water in the range of 15 – 78 kg/kWh, whereas PV consumes water at a rate of 1 – 10 kg/kWh and wind power plants do not exceed 1 kg/kWh (Evans et al. 2009, Onat and Bayar 2010). Biomass power plants have a significant variance in water consumption due to the different types of biomass technologies used where it ranges from 18.5 – 250 kg/kWh (Rovere et al. 2010). It has been estimated that solar thermal power plants consumes water at a rate of 900 gallons/MWh which is equivalent to 3.4 kg/kWh (1 gal = 3.79 kg water) (Diehl 2013) which is quite smaller than that consumed by other thermal power plants. Another study estimated water consumption by power plants in terms of m^3/GJ (Spang et al. 2014). Table 11 shows the converted values of water consumption to kg/kWh. The study shows comparable values of water consumption of thermal power plants, while the average values of the other studies show a wide variation between CSP value and other thermal power plants. However, I depend on the average values of the other studies in my evaluation of this indicator.

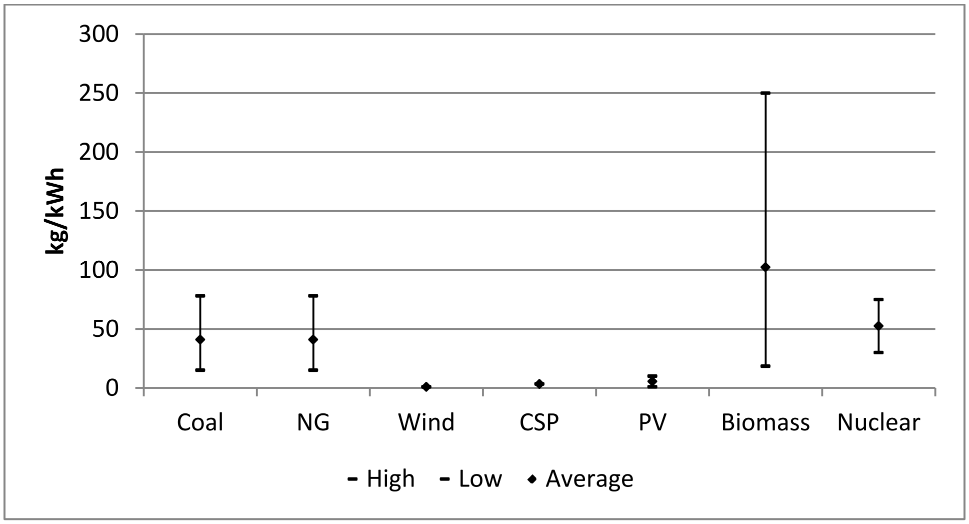


Figure 17: Water consumption by different energy systems
(Evans et al. 2009, Onat and Bayar 2010, Rovere et al. 2010, Diehl 2013)

Table 11: Water consumption by different energy systems (Spang et al. 2014)

Water consumption	Coal	NG	Wind	CSP	PV	Biomass	Nuclear
m^3/GJ	0.722	0.768	0.001	0.852	0.006	0.581	0.757
kg/kWh*	2.58	2.74	0.00	3.04	0.02	2.08	2.70

* To convert m^3/GJ to kg/kWh, I divided the value by 0.28 (1 GJ = 0.28 MWh)

2.5.2. Economic Indicators

Energy services are very critical to secure economic growth. The economy depends in all of its sectors on the availability of energy. Electricity, in particular, plays an important role in the economic development. Thus, investment in energy systems with poor economic benefits will drastically affect the whole economy of the country. This requires rational economic assessment of the different technologies to obtain a good decision about potential investment. This section explains the major economic indicators that could be used for an overall assessment of the technologies in order to secure a sustainable supply.

2.5.2.1. Investment cost (also named as capital cost)

Investment cost includes all costs related to the construction and installation of power plants, purchased equipment, engineering and consultation services and any costs that may arise before the operation of the power plants. It includes neither fuel costs, nor maintenance costs. It is the most widely used indicator by investors in the decision making for technology selection after assessing the technical feasibility. Nuclear and coal-fired units are characterized by high investment costs and low operating costs while gas-fired generation is characterized by lower capital costs and higher operating costs (Wang et al. 2009). Photovoltaics and solar thermal power still suffer very high investment costs that restrain their propagation although they consume free energy resources.

Figure 18 shows a comparative analysis of the investment costs of different power technologies. It can be observed that there is a wide range of values for most of the technologies because for each technology type there are different designs which vary to a great extent in their features, materials of constructions and ultimately their costs. Here I obtained the values from studies that are based on a collective analysis of many studies dealing with this indicator. I compiled the values of these studies and used the average value in my model although I found a significant variance between their values. This applies also for other indicators that will be discussed later. The investment costs ranges between 1300 – 2400 USD/kW for coal power plants, 450 – 1060 USD/kW for NG power plants, 1460 – 1730 USD/kW for wind power plants, 4260 – 5850 USD/kW for CSP plants, 2080 – 5000 USD/kW for PV, 2240 – 3330 USD/kW for biomass power plants and 2950 – 7980 USD/kW for nuclear power plants (OECD/IEA 2014, VGB 2011, Schröder et al. 2013, Open Energy Information 2015).

Still CSP represents the most expensive technology however it shows a comparable average value as that of nuclear. NG shows the cheapest power plants which justifies their preferences by most of the investors. Interestingly the average investment costs of wind power plants are cheaper than that of coal by about 300 USD/kW which is a significant value. It is important to mention that these values are changeable with time due to technological development and the continuous search for cutting down the costs and improving the efficiency in parallel. According to the same previously mentioned resources, Figure 19 shows the future predicted values of the investment costs for the technologies under assessment. Based on these values I constructed a regression linear equation that I use in my model instead of using a constant value. It can be seen that the ranking of the technologies could change dramatically in the future according to these predictions.

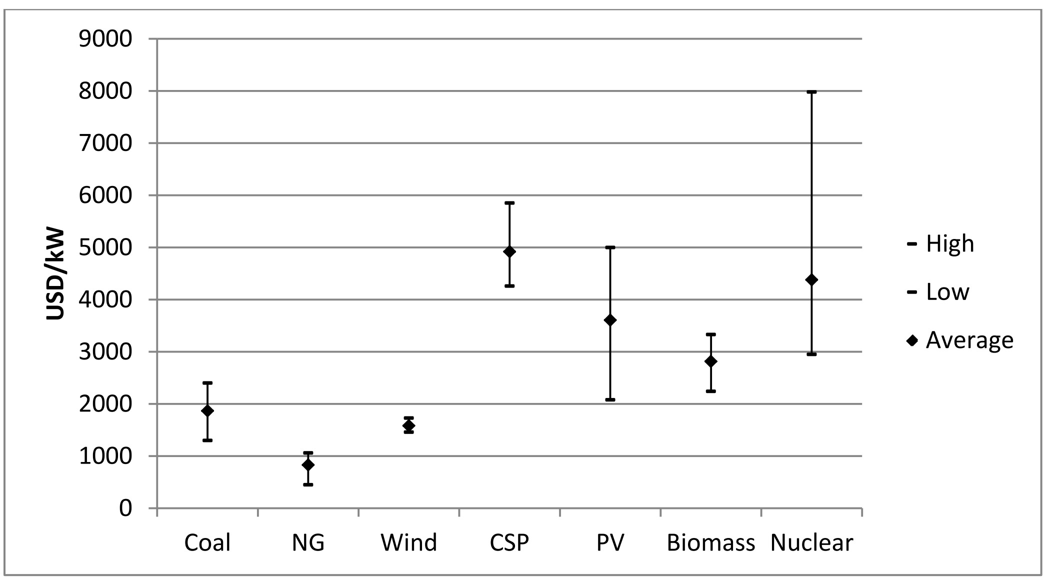


Figure 18: The investment costs of the assessed technologies
(OECD/IEA 2014, VGB 2011, Schröder et al. 2013, Open Energy Information 2015)

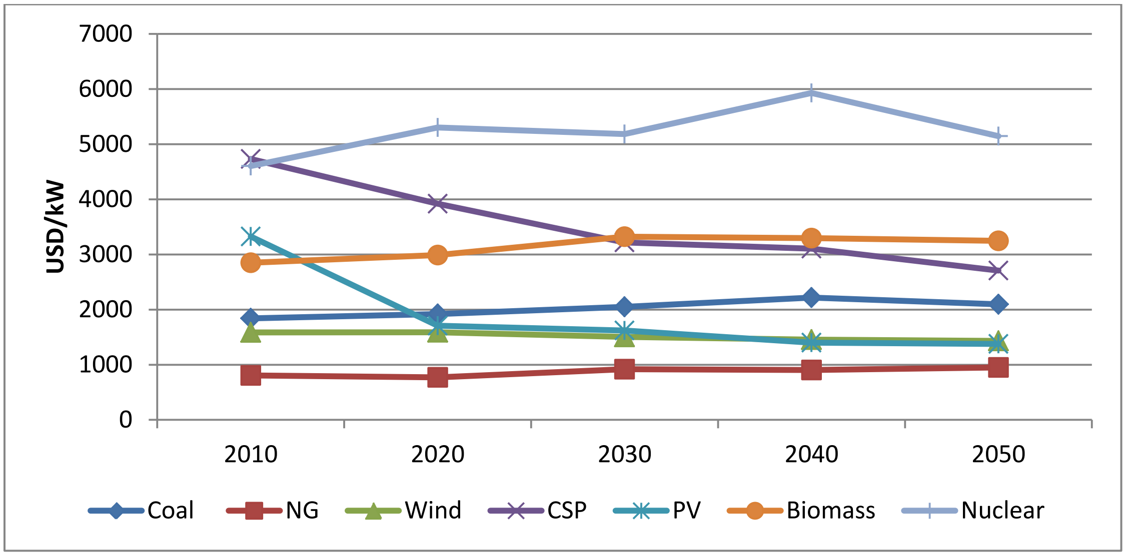


Figure 19: Future prediction of the investment costs of the technologies under assessment (OECD/IEA 2014, VGB 2011, Schröder et al. 2013, Open Energy Information 2015)

2.5.2.2. Operation and maintenance (O&M) cost

Related cost factors include employees' salaries, fuel costs, engineering and consultation services, and the funds spent on the maintenance of the system including purchasing spare parts in order to prolong energy system life and avoid failures that may lead to interruption of the system. Basically, it is much cheaper to regularly maintain the system than to repair any damage after occurrence and it ensures more security of the system supply (Wang et al. 2009). In my case study, these costs are very important since it is often mentioned in the media and during my interviews that one of the major causes of the frequent blackouts is that some parts of the plants became out of service due to the age of these parts as well as improper regular maintenance (US EIA 2015). There are two types of O&M costs: fixed and variable ones. The former reflects primarily plant operating labor, maintenance work, taxes, insurance and network use of system charges. The latter depends on periodic maintenance procedures, disposal of residuals and auxiliary materials and fuel costs (Schröder et al. 2013). I use here only the fixed O&M costs since I found no data about variable O&M costs for renewable power plants.

Figure 20 shows that the annual O&M costs ranges between 28 – 80 USD/kW for coal power plants, 14 – 28 USD/kW for NG power plants, 11 – 48 USD/kW for wind power plants, 33 – 205 USD/kW for CSP plants, 27 – 34 USD/kW for PV, 67 – 133 USD/kW for biomass power plants and 69 – 140 USD/kW for nuclear power plants (OECD/IEA 2014, VGB 2011, Schröder et al. 2013, Open Energy Information 2015). The average values of CSP, biomass and nuclear power plants are comparable. This can be seen also for coal, wind and PV, whereas NG shows the lowest average O&M costs. Figure 21 depicts the dynamic change of O&M costs across the technologies under assessment, where it is predicted that the value will decrease by about 50% for CSP in 2050. Additionally, the value for PV is expected to be the lowest by 2050. Consequently, this gives a positive future chance for solar technologies to invade the market.

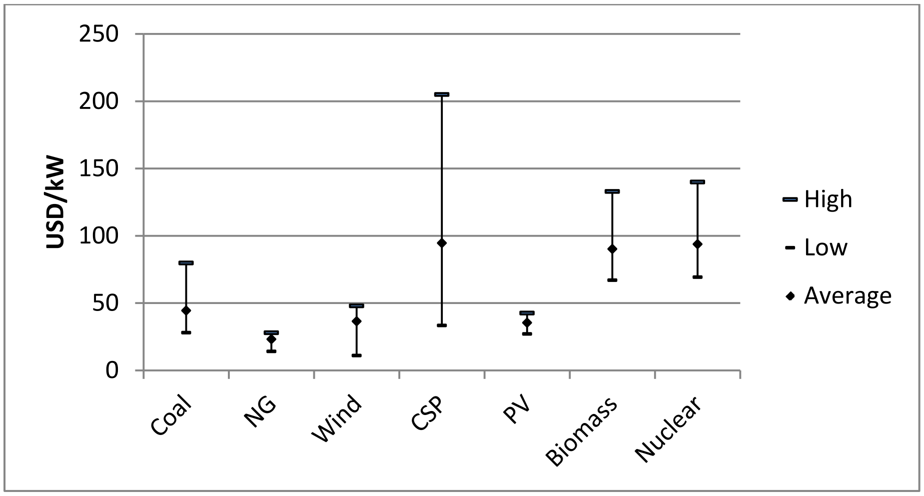


Figure 20: The operation and maintenance costs of the assessed technologies (OECD/IEA 2014, VGB 2011, Schröder et al. 2013, Open Energy Information 2015)

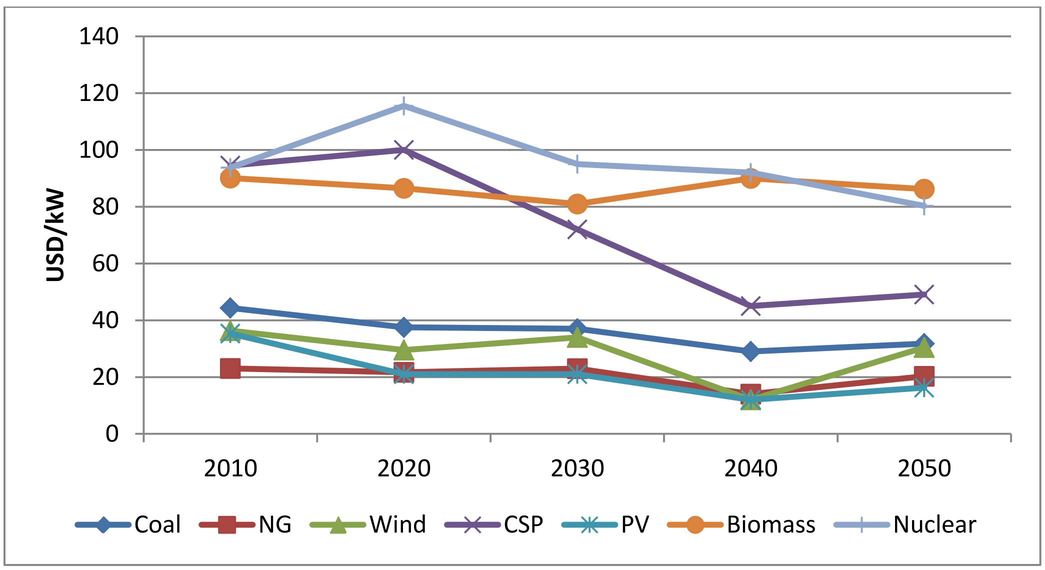


Figure 21: Future prediction of the operation and maintenance costs of the technologies under assessment (OECD/IEA 2014, VGB 2011, Schröder et al. 2013, Open Energy Information 2015)

2.5.2.3. Cost of electricity

The price of electricity offered by the power generation system includes all the costs over the systems' lifetime: initial investment, operation and maintenance, fuel cost, and cost of capital (NREL 2013b). It is also influenced by the typical characteristics of the technology, such as efficiency, annual production, service life, and the nature of the energy source utilized. It is the price at which energy is generated from a specific source to breakeven (Troldborg et al. 2014). In our case study, private investors sell the electricity to the government according to what stated in the feed in tariff law which applies only for wind and solar energy projects. Then, the government sells the electricity according to the national tariff to the consumers directly since it owns the transmission and distribution systems. For other types of power plants, it is primarily owned by the government. Actually, the price for the consumer differs according to the purpose and consumption rate segment of the end user. In 2014, the Egyptian government issued a law of gradual withdrawal of subsidies on electricity prices within the 5 years plan. This will encourage the introduction of renewable energy projects which still have higher costs of electricity production as a result of their high investment cost as compared to subsidized electricity costs from natural gas-fired power plants. I am not concerned here with the end user price but the one that corresponds to electricity generation.

In Figure 22, the average cost of electricity generation for coal, NG and nuclear are comparable at a value of around 0.05 USD/kWh, for wind and biomass, it is almost doubled, whereas for CSP and PV, it is particularly very high of 4 and 6 times the average values of coal, respectively (Evans et al. 2009, Onat and Bayar 2010, Afgan and Carvalho 2002, Afgan et al. 2007, Begić and Afgan 2007, Dombi et al. 2014, VGB 2011, Open Energy Information 2015). Surprisingly, I found in one of the literature, Onat and Bayar (2010), a wide value range for PV which again reflects the different designs and technological features. Considering the dynamics of electricity generation costs, previous studies predict no significant changes for coal, NG, biomass and nuclear, however, it is highly probable to change significantly for CSP and PV and to a low extent with wind power plants as can be seen in Figure 23.

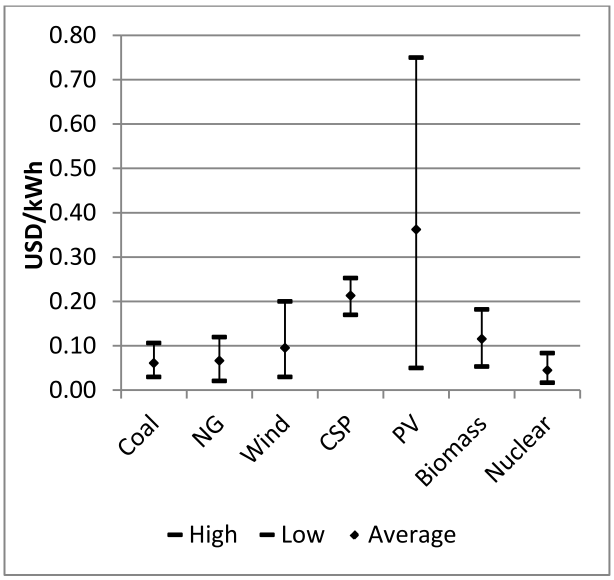


Figure 22: Electricity generation costs of the assessed technologies

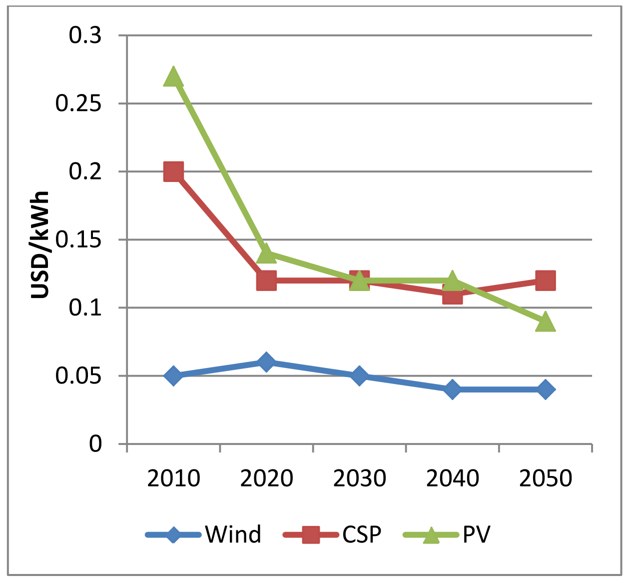


Figure 23: Future prediction of the cost of electricity of the technologies under assessment

(Evans et al. 2009, Onat and Bayar 2010, Afgan and Carvalho 2002, Afgan et al. 2007, Begić and Afgan 2007, Dombi et al. 2014, VGB 2011, Open Energy Information 2015)

2.5.2.4. Job creation

Job creation represents both the economic and social dimensions of sustainable development. As jobs are created by the energy system, they improve the quality of life of local society (Liu 2014) and reduce unemployment. Throughout the life cycle of the power plants, many people are employed either in direct jobs like in manufacturing, installation, operation and maintenance or in indirect jobs like the suppliers of equipment, construction and installation materials (Wang et al. 2009). It refers to the ''supplier effect'' of upstream and downstream suppliers (Wei et al. 2010). Moreover, induced jobs are created when wealth generated by the energy system is spent elsewhere in the economy, hereby stimulating demand in industries that may be entirely unrelated (Troldborg et al. 2014). It refers also to multiplier effects, for instance, due to the development of industry as a consumer of electricity. An important issue related to this indicator is the local and foreign impact since some of the jobs will be done by other countries that have the know-how of the technology and in this case it will constrain the installation, operation and maintenance of the energy system to local job creation. This is more prominent in some major components of power plants like the turbines of generators, wind blades, solar collectors, and photovoltaic panels. A study was done by the World Bank assessing the potential of local manufacturing of concentrated solar power plants in Egypt. The study revealed that Egypt's key strengths on production factors are: low cost of labor and of energy for industrial consumers; availability of glass, steel, and stainless steel; and a strong manufacturing capability (Servert and Cerrajero 2015). Figure 24 shows the potential jobs that could be created for each type of power systems in the construction, installation, manufacturing, O&M and fuel processing sectors (Wei et al. 2010, Rutovitz and Harris 2012). Interestingly, PV shows the highest job creation potential with an average value of 13 jobs/MW whereas coal, NG and nuclear are below 2 jobs/MW. The values stated here represent only direct jobs, while the values of indirect jobs are not included since their data are not reliable.

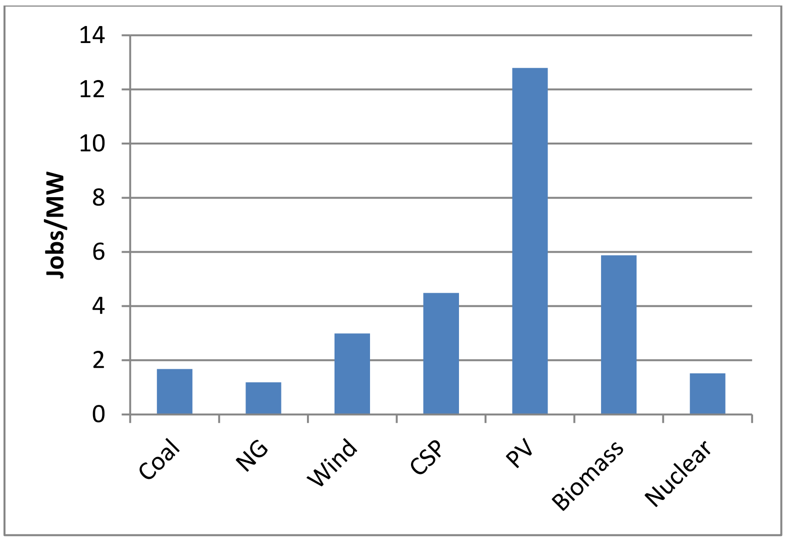


Figure 24: Job creation potential across different technologies (Wei et al. 2010, Rutovitz and Harris 2012)

2.5.3. Environmental Indicators

Greenhouse Gas (GHG) emissions associated with the provision of energy services represents a major driver for climate change. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) concluded that “Most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations” (IPCC 2007). By 2020, in Africa, between 75 and 250 million people are projected to be exposed to increased water stress due to climate change. In some countries, yields from rain-fed agriculture could be reduced by up to 50%. In many African countries, agricultural production, including access to food, is projected to be severely compromised (IPCC 2007, Meyer et al. 2014). Investigating the environmental behavior of energy systems could reduce the progression of these impacts. The GHGs and CO_2 emissions have been previously mentioned while discussing the LCA of power systems; however I will use the values of GHGs emissions (see Table 7 or Figure 25) in the comparison of the impact of different energy mix scenarios on global climate change (Weisser 2007, NREL 2013a).

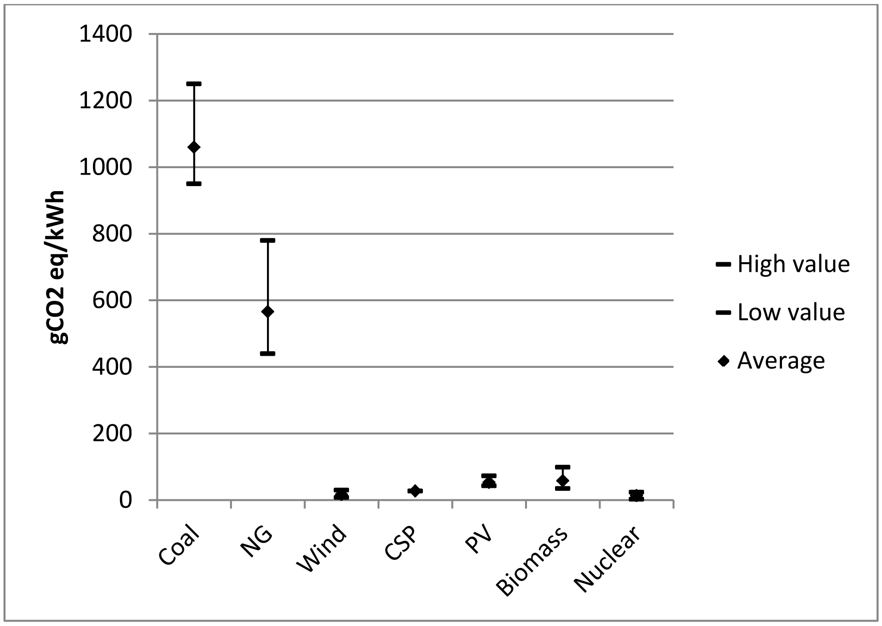


Figure 25: GHGs emissions from energy systems (Weisser 2007, NREL 2013a)

In this study, I concentrate on three gaseous emissions from energy systems that expose the environment to hazardous impacts as the indicators of the environmental dimension. These indicators have a more global effect on the environment. However, there are other indicators that are not mentioned here but still have strong impact on the environment which is more specific for each technology. For instance, the impact of wind farms on bird migration, hydropower impacts on aquatic systems, biomass impact on the ecosystem and agricultural production, and solar concentrators also could harm birds flying through the focal point of concentration. So, we recommend to include these factors in a second step of the decision making process after ranking the technologies to provide deep assessment of the selected technology.

2.5.3.1. CO_2 emission

CO_2 emissions are mainly released from the combustion of fossil fuels that are chemically composed of hydrocarbons. As the percentage of carbon in the fossil fuels increases, the emission of CO_2 increases (see Figure 26). Coal is the highest emitting source followed by petroleum and finally natural gas (methane). Renewable and nuclear systems have the potential for nearly zero CO_2 emissions, as well as hydrogen if provided by non-fossil energy sources. However, the emissions from these energy systems mostly come during the construction phase, in transportation or from the backup fuel combustion. CO_2 is physically characterized by being colorless, odorless and tasteless. It represents a major greenhouse gas contributing to 9-26% in global warming and climate change (Liu 2014). Recently, many international organizations are concerned about climate change and develop mechanisms to reduce CO_2 emissions, giving this indicator a high importance in assessing sustainability. Different methods have been proposed to capture CO_2 emissions either through climate engineering, adaptation or mitigation measures with different degree of success (Wang et al. 2009).

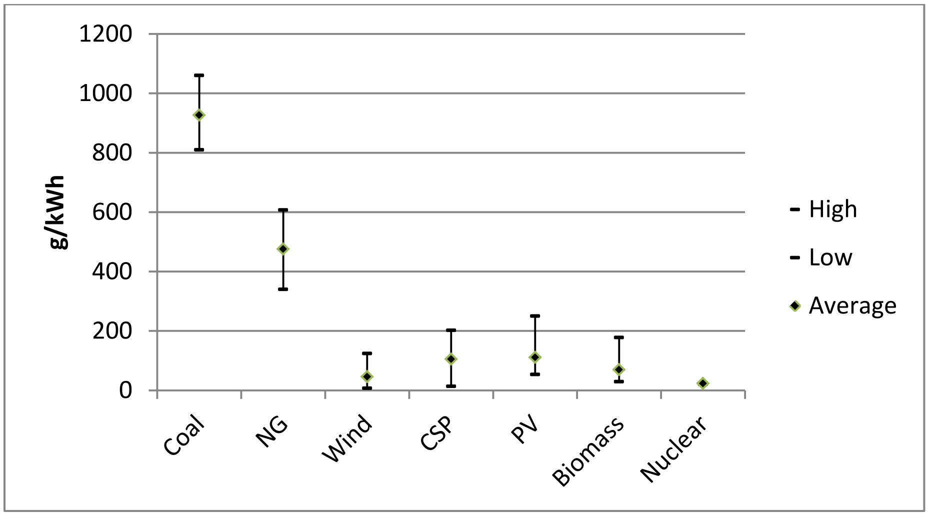


Figure 26: CO_2 emissions from the technologies under assessment
(Varun et al. 2009a, Wang and Mu 2014, Begić and Afgan 2007, Rovere et al. 2010, Afgan et al. 2007, Afgan and Carvalho 2002, Onat and Bayar 2010, EURELECTRIC and VGB 2003)

2.5.3.2. NO_x emission

Nitrogen monoxide and nitrogen dioxide (NO and NO_2) are emitted from the combustion of biomass and fossil fuels at high temperature. They not only constitute greenhouse gases that contribute to global warming and climate change, but also cause local air pollution and acid deposition, may do harm to the health of people, affect agricultural products and cause biological mutation as they form toxic products in reaction with ammonia, moisture, volatile organic compounds, common organic chemicals, and even ozone (Wang et al. 2009, Liu 2014). According to a literature review, Figure 27 gives an evidence of the contribution of biomass and fossil combustion to a great extent in the emission of NO_x gases, where it could reach almost 4 g/kWh for coal and NG and more than 1.5 g/kWh for biomass. However, the other technologies show an emission of lower than 0.5 g/kWh.

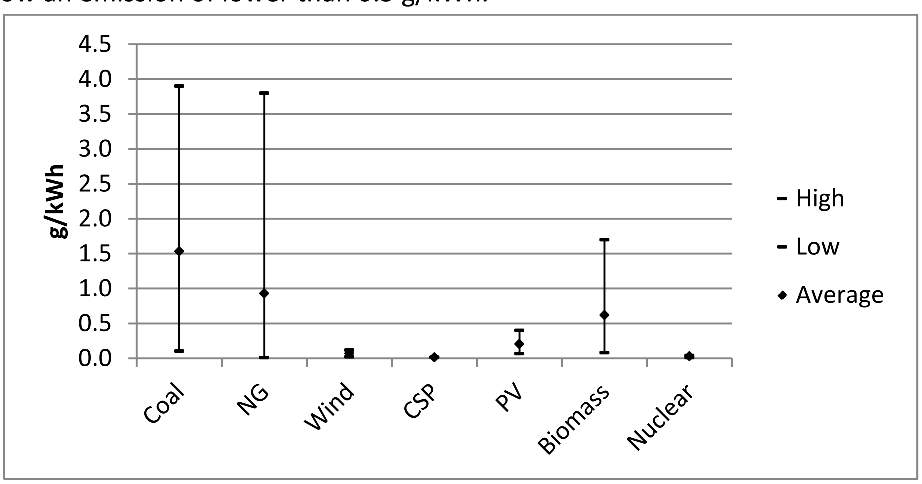


Figure 27: NO_x emissions from the technologies under assessment
(EURELECTRIC and VGB 2003, Afgan et al. 2007, Wang and Mu 2014, Begić and Afgan 2007, Turconi et al. 2013, National Research Council (U.S.) et al. 2010, Hatch 2014)

2.5.3.3. SO_2 emission

Sulphur dioxide is a third important harmful gas emitted as a result of fossil fuels combustion and during the smelt of aluminum, copper, zinc, lead and iron that are used for the construction of renewable energy components. It is a physically colorless gas or liquid with a strong offensive choking odor. Additionally, it forms sulphuric acid rain (H_2SO_4) which has very harmful effects especially on the respiratory system of humans and on damaging agricultural products. Again, it contributes to a great extent to climate change and environmental damage. Some efforts have been done to reduce this kind of emissions through chemical processes of desulfurization (Wang et al. 2009, Liu 2014). Figure 28 shows a high potential of SO_2 emissions from coal and biomass due to the high Sulphur content. However, NG emits low SO_2 as compared to wind and PV, although it is a fossil fuel that is combusted to generate electricity. This justifies the contribution of the manufacturing components to the emission of SO_2 but on the other hand it is more controllable than the emission in the operation process.

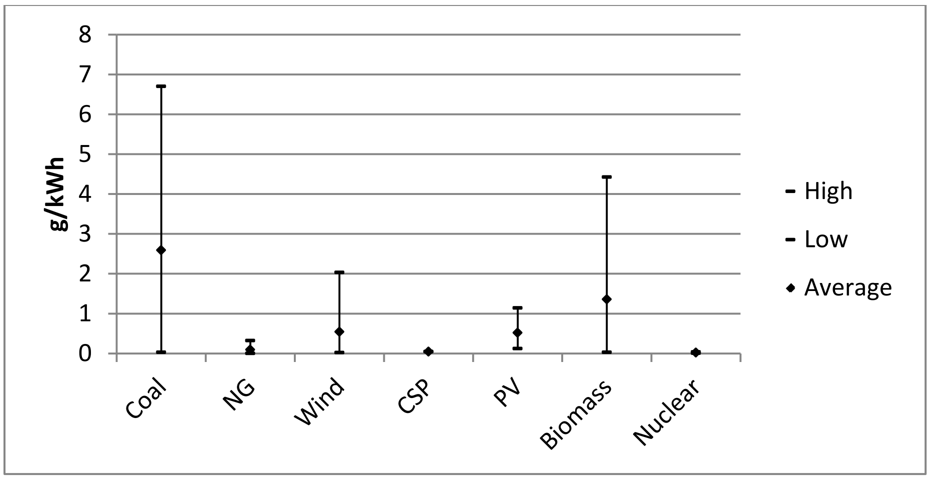


Figure 28: SO_2 emissions from the technologies under assessment
(EURELECTRIC and VGB 2003, Afgan et al. 2007, Wang and Mu 2014, Begić and Afgan 2007, Turconi et al. 2013, National Research Council (U.S.) et al. 2010, Hatch 2014)

2.5.4. Social Indicators

There is a mutual risk-benefit relationship between energy and society where energy could affect the society and vice versa. This dimension reflects the opinions, perceptions, decision making and realization regarding different energy systems by the local population. Generally, the public sector is concerned with securing access to energy at affordable costs while ensuring equity and fairness especially with low income people. Evaluation of social indicators aims at the satisfaction of the members of society by considering their opinions in the decision making process and by protecting them from any risks they may perceive in order to achieve a successful SD. The negative consequences of power plants like risks on human health, air pollution, global warming and working losses as a result of diseases and sudden accidents alter the perception of societies on energy production technologies. Essentially, fatalities and deformations as a result of mutagenic or teratogenic chemicals or radioactive emissions affect the employment and the residence in areas of concern. For instance, during normal operation nuclear power stations are assumed to have a rather low direct negative social effect. However, because of the potential of major disaster and negative perceptions created by the Chernobyl and Fukushima accidents, it is the most controversial and least accepted electric energy production technology in some countries (Onat and Bayar 2010, Vera and Langlois 2007). Here, we consider two main aspects of the social dimension that are characterized by prominent stabilization effects on SD.

2.5.4.1. Safety risks

Safety risks can be assessed in terms of accident fatalities per energy unit produced in different fuel chains (IAEA 2007, IAEA 2005, Vera and Langlois 2007). It represents a vital issue to society, and people's life including safety measures for employees on site that must be guaranteed. Safety combines both the social and technical dimensions of sustainability (Wang et al. 2009). In some cases, power plant accidents are catastrophic affecting residents near the power plants. This perspective on severe accidents may lead to different system rankings, depending on the individual risk aversion (Hirschberg et al. 2003). Apparently, safety measures add more costs to the system for preventive measures but at the same time they save much of the costs resulting from accidents due to corrective measures. It is a very crucial indicator to assess the sustainability of technologies although some countries are not concerned so much about it. The assessment of this indicator has been previously discussed in sub chapter 2.4 and the values can be seen in Table 8 or Figure 29 with an emphasis on the greatest risk potential of nuclear power plants with an average value of 13.6 fatalities/ GWeyr while considering immediate and latent fatalities (Burgherr et al. 2011). This explains the tendency of many developed countries to decommission their own nuclear power plants and the transition into safe and clean technologies.

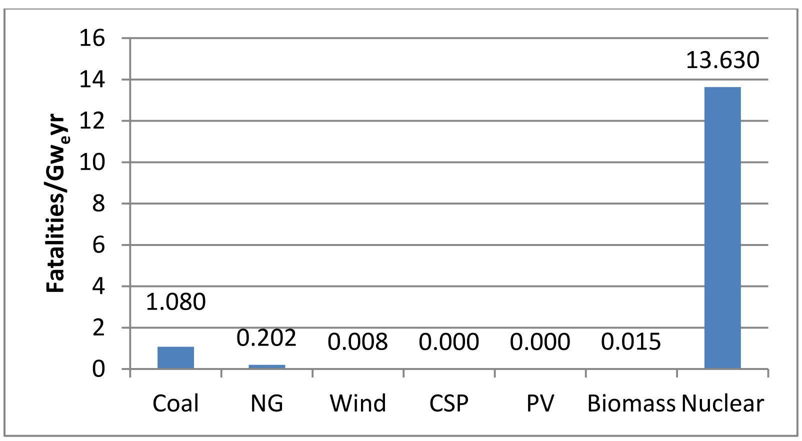


Figure 29: Safety risk assessment across different technologies (Burgherr et al. 2011)

2.5.4.2. Social acceptability

It ensures the contribution of the opinions and interests of all stakeholders in the decision making process and gives the feeling of respect and consideration to the public sector which is affected by the project. It represents a feedback on the perceived impact of the energy system on the landscape from an aesthetical point of view in terms of noise, visual and odor aspects. It is a very important social indicator since the rejection and opposition of the project by a group of people may lead to conflicts, delay the implementation, and in worst cases entirely damage the project. Therefore, stakeholder analysis is essential to study the interests, incentives and strategies of actors and their interactions (del Río and Burguillo 2009). A concept known as NIMBYism (Not In My Backyard) expresses high resistance against the energy system when it is implemented near the living area; however, there is also an 'inverse NIMBYism' where people living close to the energy production are in favor of it due to the accompanied values of job generation and improved income suggesting that an oversimplification of complex processes and competing factors are behind local opposition. The social acceptance of a technology is heavily dependent on benefits, costs and risks as well as personal tastes and preferences (Burton and Hubacek 2007). This indicator could be assessed qualitatively through surveys and public hearings with the local community (Wang et al. 2009). It has been found that local opposition arises as a result of some issues, like for example people's belief about the impacts of the proposed project, the proximity of the project to the population, uncertainty regarding the outcomes and promises and lack of awareness. Additionally, some studies have shown that public responses to energy projects change over time, with the likelihood of more positive responses after implementation (Troldborg et al. 2014). Thus, social acceptability is a necessary prerequisite for a successful sustainable development.

In order to assess this indicator, I conduct a bi-lingual online anonymous survey which can be found under the following link: https://www.surveymonkey.com/r/6KMG2G3 and in Appendix C. After introducing the main idea and the objective of the survey, it proceeds to 5 questions that have been designed in a way that insures the validity of the responses. The first question asks about the awareness and the knowledge extent of the technologies under assessment which reflects the weights of their responses to the subsequent questions. The other four questions end up with the same target, the extent of acceptance of the technology, but have been formulated in four different dimensions. Thus, the second question deals with a general support of the installation of the technology in Egypt; the third question is concerned with how fast the technology should be installed; the fourth question focuses on the individual concern about the installation of the power plant near to the residence location; the last question asks for ranking the technologies according to preferences. From the survey, I get an average weighted value for each technology and each question as shown in Table 12.

Finally, I integrated the five questions by multiplying Q1 by the summation of Q2 - Q5 (i.e. Social acceptability ranking = Q1 x (Q2 + Q3 + Q4 + Q5)). The results are shown in Figure 30 where wind comes in the first top accepted technology, however biomass is the least accepted because of lack of awareness as can be seen in Table 12. A more detailed explanation of the calculation of the values stated in Table 12 is presented in Appendix C.

Table 12: Collective responses on social acceptability from the online survey

	Coal	NG	Wind	CSP	PV	Biomass	Nuclear
Q1. Knowledge	1.67	1.93	2	1.53	1.33	0.3	1.23
Q2. Technology support	1.27	2.83	3.47	3.57	3.6	2.57	1.73
Q3. Year of installation	2.11	3.32	3.82	3.75	3.79	3.357	2.46
Q4. Near to living area	0.5	1.18	2.82	2.82	3.04	2.21	0.32
Q5. Technology ranking	1.76	4.68	6.08	6.08	6.68	4.44	2.48
Social acceptability ranking	9.42	23.18	32.38	24.82	22.76	3.77	8.60

Unfortunately, the survey had a low response (only 30 responses) where some organizations which I asked to assist me in distributing the survey apologized for the assistance like the German Science Centre (DWZ) in Cairo; others asked me for an application as a scholar at the University. Additionally, I tried to distribute it through a professor at the faculty of Engineering, Cairo University who had an excellent connection with almost all the Universities in Egypt through his educational training project "Pathways". He welcomed the idea and posted my survey on his Facebook account and the project account which is followed by about 3000 individuals, however I got only 3 responses out of it. What made the collection process more difficult is that the ministry of interior affairs has announced a public warning on responding to surveys as it poses risks to the internal security of the country (Reuters 2016b). Evidences on the challenges in distributing the survey are depicted in Appendix C . However, due to the importance of this indicator in my analysis, I used the 30 responses that I collected.

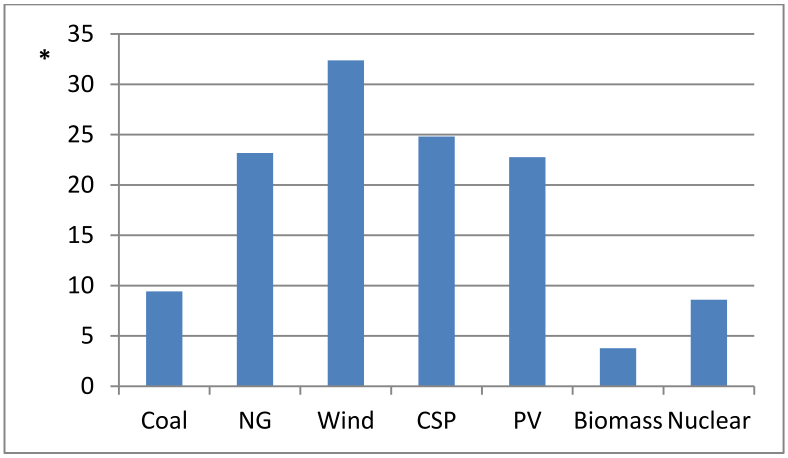


Figure 30: Social acceptability potential of the technologies under assessment
(Unitless values as it is based on ordinal scale weighted average values)*

After introducing a brief description about the indicators that are to be used in the sustainable ranking of the technologies, Table 13 gathers the values of all these indicators across the energy systems. These values together with the weights of the indicators represent a basic component in my model, by which I can apply an integrated MCDA in order to rank the technologies from their sustainability perspectives. However, they are not sharing the same unit and proportionality with sustainability. Consequently, this necessitates the application of a uni-directional normalization methodology in order to overcome this obstacle. The normalization technique is explained in the following sub-chapter.

2.6.Normalization of values

Some of the selected indicators represent on the one hand costs that investors always seek to avoid or to minimize as in the case of investment cost. On the other hand, the other indicators represent values that are in favor by investors, for example plant efficiency. In other words, some indicators are directly proportional to sustainability while others are inversely proportional to sustainability. Moreover, the integration of values of multi-criteria requires a standardization of the measurement scale. Some studies prefer to use the monetary sensible evaluation of the criteria which influence greatly the decision making process as most of the decisions are built on the economic evaluation. Here I apply the feature scaling standardization method. The formulas are shown below:

1) $\frac{(v - v_{min})}{(v_{max} - v_{min})}$ 2) $\frac{(v_{max} - v)}{(v_{max} - v_{min})}$

The first formula is used when the indicator represents a positive value (i.e. the higher the value, the more sustainable), whereas the second formula is used when the indicator represents a negative value or cost (i.e. the lower the value, the more sustainable), so that ultimately I get a value between 0 and 1 for each indicator across the assessed technologies with an equal interpretation (i.e. 1 means the best). In order to avoid zero values of the indicator, I reduced the minimum value in the first formula by 10%, and added the same 10% to the maximum value in the second formula. A comparison of the normalized multi-criteria evaluation of the technologies under assessment is shown in Figure 31.

Table 13: A collective tabulation of the average values of the indicators selected for the sustainability assessment of different power technologies

Technology Indicator	Unit	Coal	NG	Wind	CSP	PV	Biomass	Nuclear
Investment cost	USD/kW	1867	831	1582	4918	3605	2816	4380
O&M cost	USD/kW	44.3	23	36.4	94.5	35.3	90.1	93.7
Cost of electricity	USD/kWh	0.061	0.067	0.095	0.213	0.362	0.115	0.045
Jobs	Jobs/MW	1.6750	1.1850	2.9920	4.4833	12.7917	5.8750	1.5150
CO_2 emission	g/kWh	926.8	475.9	45.7	105.2	110.9	69.5	23
NO_x emission	g/kWh	1.53	0.93	0.07	0.02	0.21	0.62	0.03
SO_2 emission	g/kWh	2.59	0.09	0.54	0.04	0.52	1.36	0.02
Safety risks	Fatalities/GW_eyr	1.08	0.202	0.0083	0	0.0002	0.015	13.63
Social acceptability	ordinal scale	9.42	23.18	32.38	24.82	22.76	3.77	8.6
Plant efficiency	%	40.3	47	35.3	17.3	12.8	30.4	35
Reliability (Capacity factor)	%	85	85	30	35.5	20.5	77	90
Resource potential	TWh/y	0.4072	90588.24	7650	73656	36	15.3	536.47
Water consumption	Kg/kWh	41	41	1	3.4	5.5	102.42	52.5
GHGs	gCO2 eq/kWhe	1059.7	565. 7	16.3	27	53.3	58	13.4

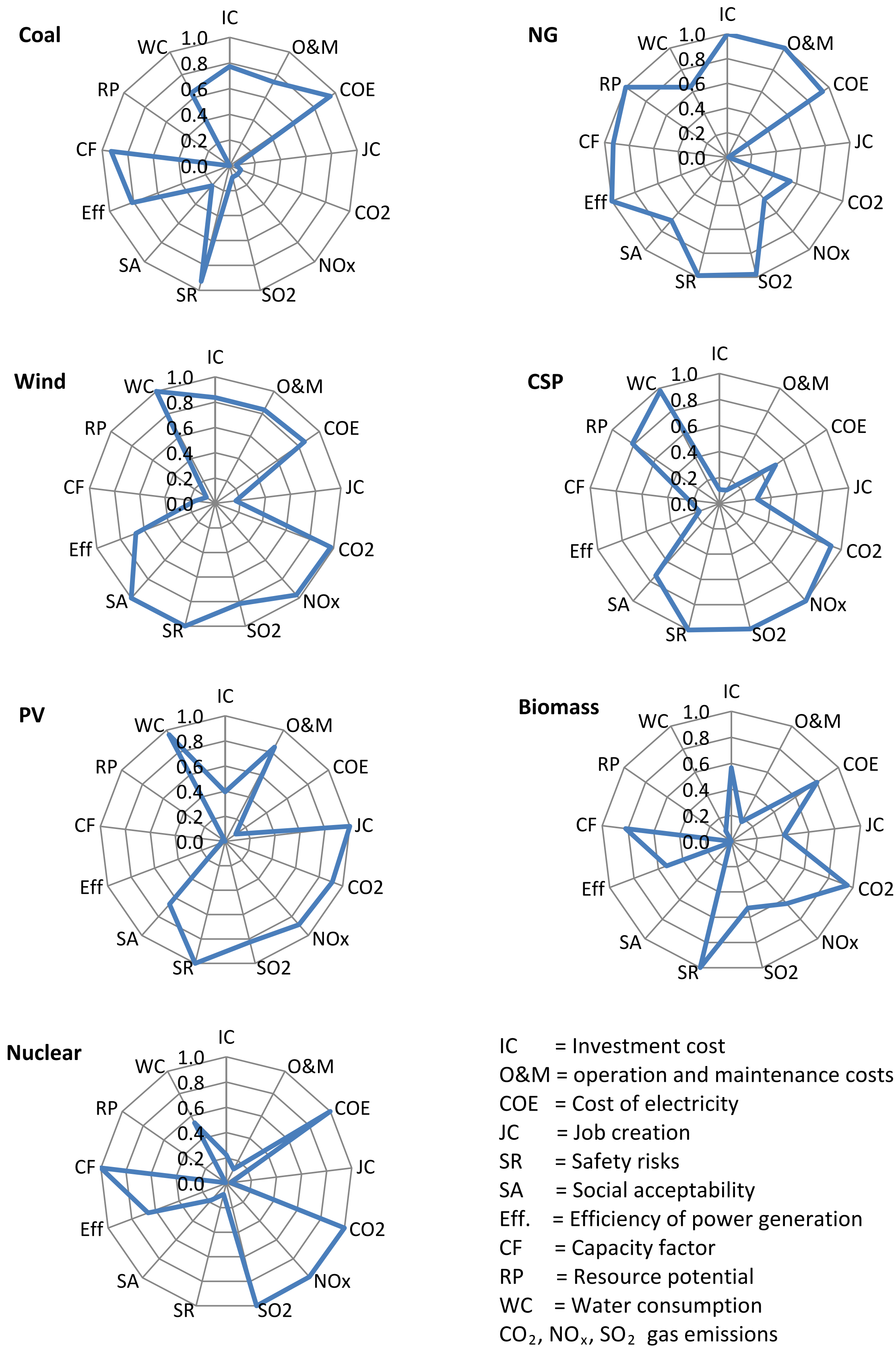


Figure 31: Normalized multi-criteria evaluation of energy system

2.7.Electricity supply technologies selected

In this part, I give a short explanation of the principles of operation, the different fuel types used and the designs of power plants under assessments. Generally, electricity is a form of energy that applies the rules of energy conversion theory; it cannot be created nor destroyed. There are three main energy forms from which electricity is converted: kinetic, chemical and light energy. The first energy conversion type is based on the rotation of a coil of wire in a magnetic field inducing the flow of electron through this wire which is the basic idea of the generators. In order to create this kind of kinetics, several ideas have been applied. The most widely used is the utilization of thermal energy derived from the combustion of fossil fuels (coal, oil, natural gas), biomass, heat stored in the earth crust (geothermal), nuclear fission or fusion, or solar thermal energy to heat water resulting in a very high temperature and high pressure steam which in turn hits turbines stemming out of a shaft that ends with a generator. This is the principle of a simple Rankine-cycle power plant using steam turbines.

In some other power plant types, mainly those using natural gas as a fuel, gas rather than steam hits the turbines as a result of the internal combustion of the fuel with air. This type is known as a gas turbine which is less efficient than a steam turbine. A lot of modifications have been applied in order to improve the efficiency of these types of power plants. The combined cycle power plant comprises the most famous one which combines the principles of both steam and gas turbine. The heat content of the primary energy resource plays an important role in the efficiency of these power plants which justifies the differences in the efficiencies of different types of thermal power plants.

The kinetic energy could be derived through other forms of energy like in the case of hydropower, tidal, wave and wind energy. Converting chemical energy to electricity is mainly used in a very small scale electricity production which is batteries. The last type of energy conversion is from light. When semiconductors are exposed to the photon component of light, this exposure induces electron excitation in these semiconductors ending up with current flow, which is the principle of photovoltaics (Weston 1992).

2.7.1. Coal-fired power plants

Figure 32 illustrates a schematic diagram of a coal-fired power plant that uses a steam turbine. However, there are different types of coals used as a combustion fuel for power generation according to carbon and moisture content as can be seen in Figure 33. Coal power plants are classified according to the criticality of the boilers into three types: subcritical, supercritical and ultra-supercritical. In the subcritical type, the boiler operating pressures are below 221 bar and has an efficiency of 30-40%. Supercritical point is a state in which water exist in the liquid and gaseous phase as a homogenous fluid at a pressure level of around 240 bar and temperature level of about 570-590 °C producing an efficiency of around 45%, however the capital costs are higher than that of subcritical. The ultra-supercritical boilers employ at even a higher pressure and temperature reaching 350 bar and 700 °C giving more efficiency rate of 50% and more. Thinking of an alternative to this third type of boilers leads to the development of an Integrated Gasification Combined Cycle (IGCC). It is based on the conversion of liquid or solid fossil fuels into a synthesis gas mixture, known as syngas, composed of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2) and small amounts of hydrogen sulphide (H_2S) through a thermo-chemical reaction with oxygen and steam. As mentioned before the combined cycle is built up from gas and steam turbine. So the purified syngas is fired in the gas turbine producing electricity while the exhausted gas produces superheated steam that drives the steam turbine generating additional electricity. A major disadvantage of this type is being very expensive which constrains its commercial viability. Other types of coal power plants utilize lignite which has lower energy content or the coal-biomass co-firing which necessitates some modification in the combustion chamber design due to the differences in the characteristics between coal and biomass like having lower carbon content, lower energy content, lower density, different ash, higher moisture content and a higher fraction of volatile matter. Additionally, biomass ash is more prone to forming deposits within the combustor, called "slagging" and "fouling" due to reactive salt compounds (K_2O) (Schröder et al. 2013).

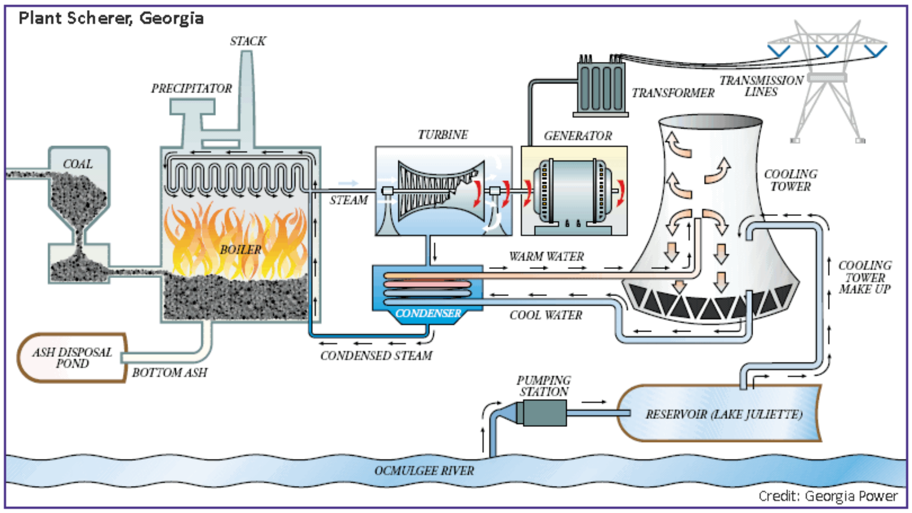


Figure 32: A schematic diagram of a coal-fired power plant (Georgia Power's Plant Scherer 1982)

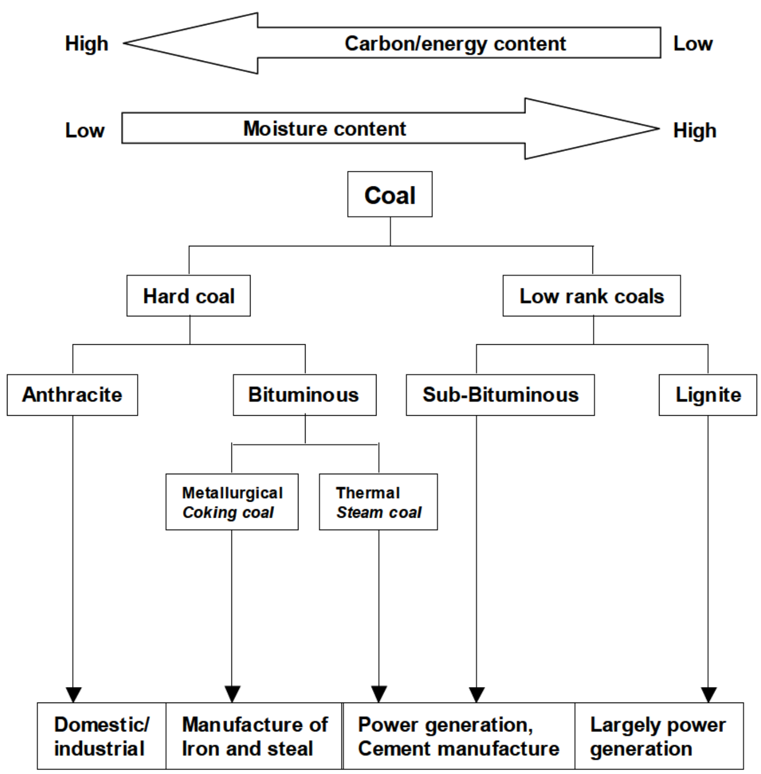


Figure 33: Classification and uses of coal (Hirschberg et al. 2003)

2.7.2. Natural gas-fired power plants

Natural gas, also known as methane (CH_4), is a colorless fossil gas lighter than air. After extraction, it passes through several steps of purification before it can be transported by pipeline. NG is used to fire either a gas turbine power plant which has a low efficiency and is illustrated in the left part of the diagram below, a steam turbine power plant with higher efficiency and is represented by the right part of the diagram below or a combined cycle which is characterized by higher efficiencies reaching 60% and is represented by the whole diagram shown in Figure 34. It is worth mentioning that gas turbine and combined cycle power plants could be fired by natural gas and/or light fuel oil, whereas steam turbine power plants could be fired by natural gas and/or light fuel oil and/or heavy fuel oil. In Egypt, 43% of the electricity is generated by steam turbines, 35% by combined cycles and 11% by gas turbines where mostly natural gas and oil are used together (EEHC 2014).

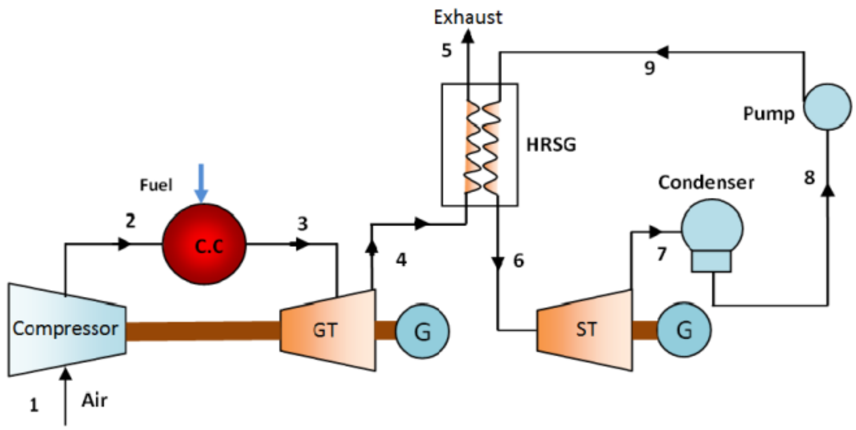


Figure 34: A schematic diagram of a combined cycle gas turbine (K. Ibrahim and Rahman 2012)
(C.C=combustion chamber, GT=gas turbine, ST=steam turbine, G=generator, HRSG=heat recovery steam generator)

2.7.3. Wind power plants

As a result of the environmental polluting effect from fossil fuel-fired power plants with its major contribution to climate change and global warming, in addition to its dependency on not only limited but also depleting resources, researchers were trying to explore other cleaner and more secure alternatives for generating electricity. Wind energy is an excellent finding to be employed in electricity generation, where wind flows continuously, does not require a combustion step in the generation process and has no cost. However, since being weather-controlled, it is characterized by a fluctuation in power production. Previously wind has been used in sailing and grain grinding windmills. Based on the same principles of fluid dynamics, wind instead of steam induces the rotation of the generator. The kinetic energy of the wind is converted first into rotational kinetic energy in the turbine which in turn is converted to electric energy. The power generated depends on the wind speed and the swept area of the turbine according to this formula:

$P = \frac{1}{2}\rho A V^3$, where, ρ is air density, A is the swept area and V is wind speed.

It can be noticed that the captured power increases 8 times if the wind speed is doubled. The main components of a wind turbine are shown in Figure 35. Wind farm is a term given to an allocated area where wind turbines are installed. It could range from a single turbine to thousands. Large wind farms are designed to include a large number of wind turbines distributed homogenously over a flat open land. The capacity of one turbine ranges from 0.5 MW to 4.5 MW being the largest until today (Chaouki Ghenai 2012). Wind turbines are mostly installed on a land which is known as onshore wind farm; however some are installed in bodies of water where it is usually characterized by an excellent wind regime. These are known as offshore wind farm. In this study I am concerned only with onshore wind farms.

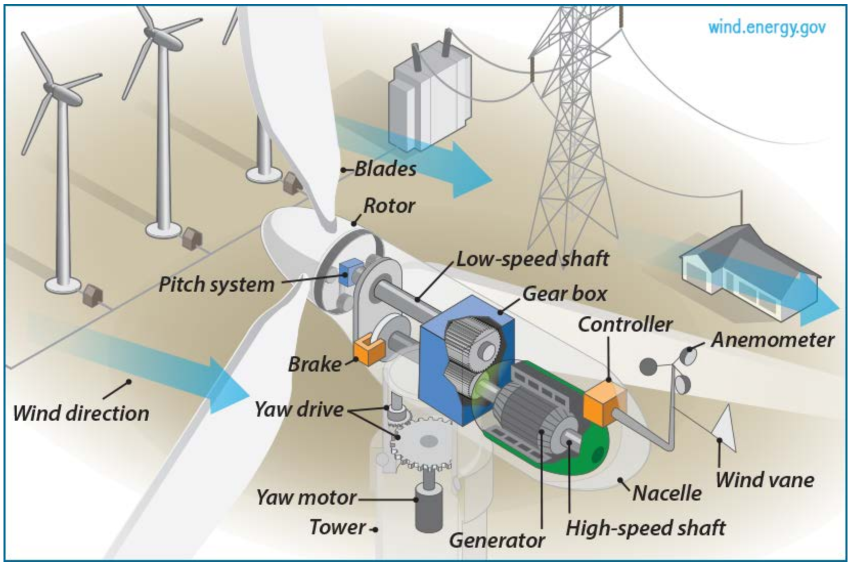


Figure 35: The main parts of a wind turbine
(U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy)

2.7.4. Concentrated solar power plants

A second application of a clean and unlimited resource dependent power generation technology is the concentrated solar thermal power. Solar thermal power depends on concentrating the direct solar radiation using mirrors on a receiver. As a result, the very high temperature thermal energy in the concentrated solar radiation is transferred to a heat transfer fluid that circulates in a heat exchange system with a water loop producing steam. It is a clean alternative for fossil fuel based thermal power plants where no combustion here is applied. However, being time and location dependent it has some drawbacks, where the sun shines only during the day and inconsistently over the space.

Four CSP designs have been developed and installed in many countries. The first is the parabolic trough system which is designed with mirrors being bent in a shape of trough so that it focuses the received sun rays onto a collector tube through which flows the heat transfer fluid (usually oil) to be heated to a very high temperature that triggers steam production from the water loop. The second design which is called Fresnel is quite similar to the first, but instead of using parabolic shaped mirrors, it uses flat segmented mirrors. Both can be complemented with the use of fossil fuels at the steam turbine to overcome fluctuations. The solar tower or heliostats is the third design where the sun radiations are focused on a central receiver, instead of a tube, located over a tower using a sun tracking mirrors. These previous three designs are mostly working with one-dimensional tracking system. A fourth design which has the possibility of two-dimension tracking is the parabolic dish system. It consists of a parabolic-shaped dish that reflects sun rays onto a central receiver mounted on the dish itself (Schröder et al. 2013). Figure 36 shows a typical example for each of these designs. The scope of this study covers the four designs possibility.

Figure 36: Designs of CSP technology: upper-left is parabolic trough, upper-right is solar tower, lower-left is Fresnel and lower-right is the parabolic dish (Trieb 2005)

2.7.5. Photovoltaics

A third clean power generation technology that has succeeded to spread in the energy market rapidly is the solar cells or photovoltaics (PV). This technology also depends on solar energy but here it operates through the elementary particles or photons of the solar radiation not through the thermal energy in the electromagnetic waves. So, it has advantages over the previous technology where it works using direct and/or indirect (diffused) radiation. The mechanism of power generation, as shown in Figure 37, is simply based on the semiconducting properties of certain elements like silicone where the atoms of solid silicone are distributed in a crystalline lattice. When the photon strikes the atoms of silicon it causes excitation of an electron creating an electron and a hole (i.e. a hole is an electron-free silicon atom). This electron is attracted towards the n-type silicon whereas the holes are attracted towards the p-type silicon creating a potential difference by which an electric current flows. The n and p types of silicone are silicone with impurities that create negative and positive charges respectively. Photovoltaic technology is expected to be a leading technology to solve the issues concerning the energy and the global environment due to several advantages of the PV system (IEA 2014).

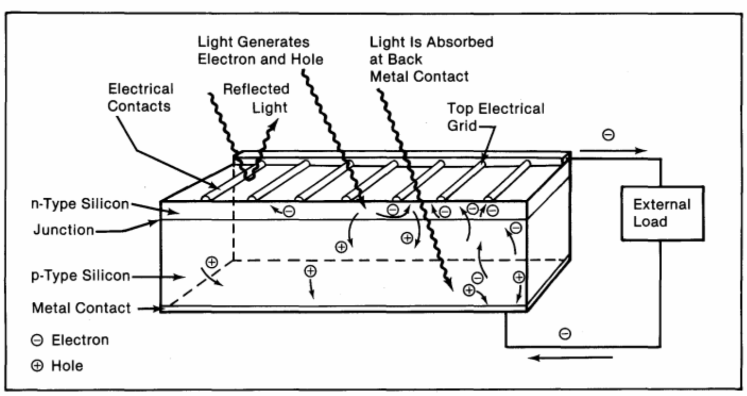


Figure 37: Principle of electricity generation from PV cells (Hersch and Zweibel 1982)

According to the semiconductor type used in the construction of PV panels, three categories have been identified. The first type is the crystalline silicone which is subdivided into single and poly crystalline. This type is characterized by an efficiency range of 16-20% and can be produced with low energy input except for the monocrystalline type which is more energy-intensive that reflects on its costs. The second category is called thin film type which could be made of CdTe (cadmium-telluride), amorphous silicon, microcrystalline silicon or copper indium gallium selenide/sulfide (CIGS). They perform with an efficiency ranging between 7-20%. The third category is based on new technologies like quantum dot solar cells, casting wafers instead of sawing, concentrator modules, Sliver cells, organics and others. Concentrator solar cells have successfully reached efficiency over 40% but are still at the research and development stage not on the mass market. Figure 38 demonstrates the historical and predicted efficiency development of different types of PVs throughout the years 1975 till 2020 (Schröder et al. 2013)

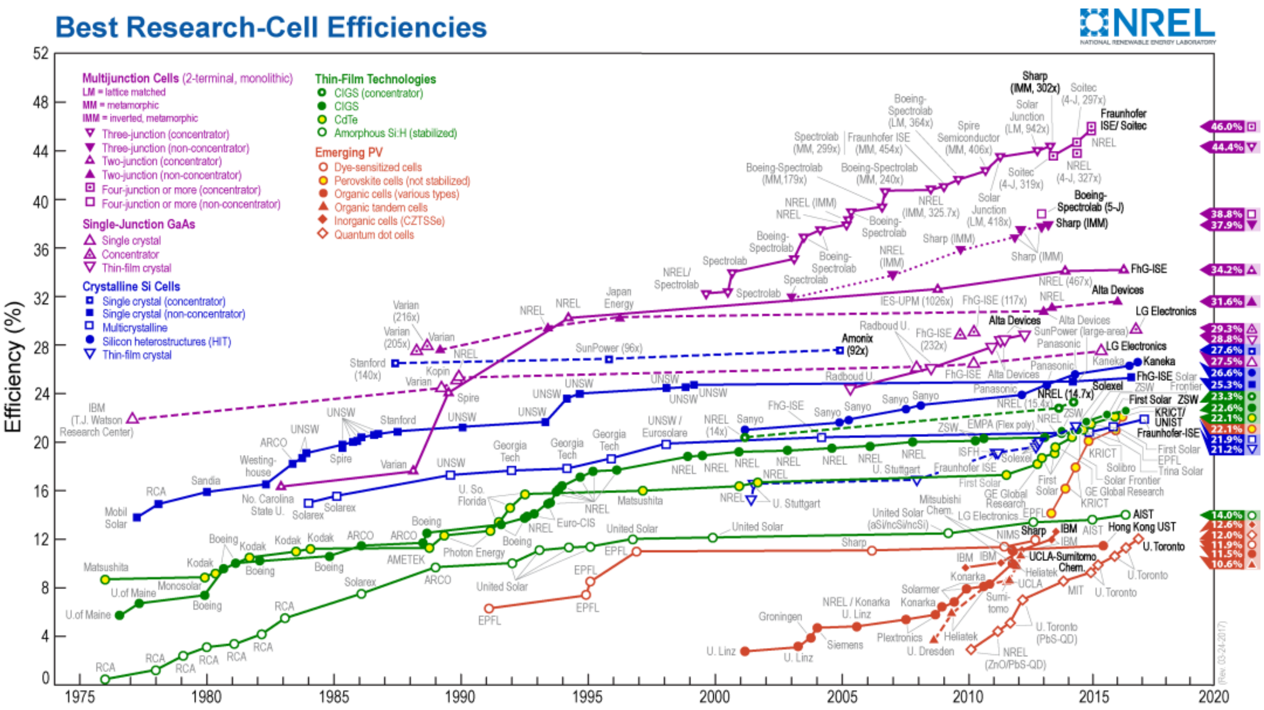


Figure 38: Reported timeline of PV efficiency (NREL 2015)

2.7.6. Biomass-fired power plants

An old fashion, primitive, renewable source of energy and emits zero carbon is biomass. Biomass represents all organic materials coming from mainly a plant or an animal origin. It has been named a zero carbon resource although it emits CO_2 when burned since the building up of this biomass is based on the absorption of CO_2 in the atmosphere forming carbohydrates after the chemical interaction with water vapor and sun light in a process known as photosynthesis. However this is exclusive for biomass from plants where the animal biomass is composed mainly of animal fats that are formed through a different biochemical process. The stored light energy in the form of chemical energy inside the biomass is released as heat when it burns. The sunlight-to-biomass photosynthetic efficiency actually sounds very low showing values between 0.5 – 3% (Hall 1976). Considering the cultivation of bioenergy crops to be used as a biomass resource reveals a poor overall efficiency of biomass power plants as compared to other renewable technologies.

Examples of biomass include woods, agricultural crops and their wastes, municipal solid waste (MSW) garbage, animal manure and human sewage. Most of these forms could be burned directly or pre-treated and converted into syngas, in a similar gasification process that has been mentioned under coal power plants (see Figure 39) which is more advantageous as it could be used to fire gas, steam turbines or combined cycle. They could be converted also to methane-rich biogas which is produced through decomposition in landfills or digesters through anaerobic bacteria, to biofuels such as ethanol and biodiesel which are used mainly as a transportation fuel and produced from fermented crops and vegetable or animal oils, respectively (US EIA 2016).

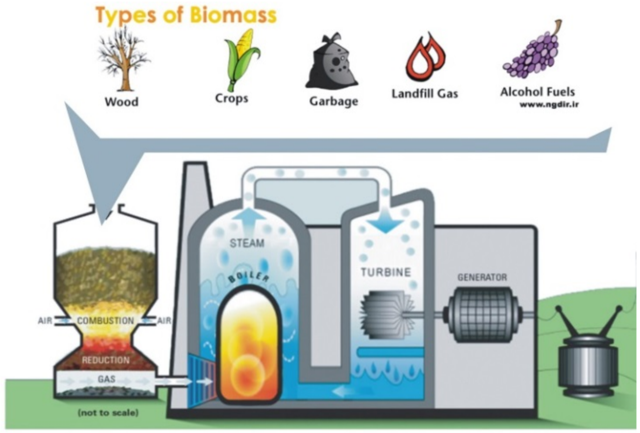


Figure 39: Biomass gasification and syngas utilization in steam cycle (Ileana 2015)

2.7.7. Nuclear power plants

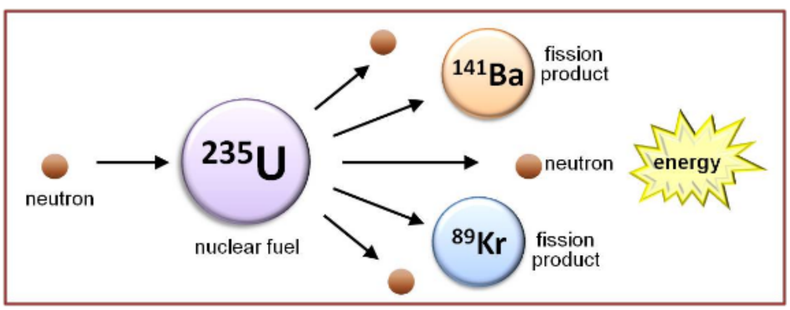


Figure 40: Energy production from nuclear fission (McMaster University 1996)

A non-renewable clean thermal power plant is the nuclear power plant. Although it has been widely accepted as a promising power generation technology alternative to fossil fuels, nowadays many countries start to decommission their nuclear power plants after the catastrophic consequences resulted from Chernobyl and Fukushima accidents as mentioned before under risk assessment section. It depends on uranium as a fuel producing huge energy through a nuclear fission process as shown in Figure 40. The nuclear fission takes place at the reactor core producing energy in the form of heat that induces steam generation through heat exchanger which is used afterwards in a normal steam turbine cycle. 1 kg of uranium can produce 3 million times electricity produced by 1 kg of coal (European Nuclear Society 2017). It is true that CO_2 emissions from nuclear power plants are very low when compared with fossil fuel-fired ones; however, it has a radioactive property that subjects humans, animals and even plants to serious risks.

Nuclear reactors are classified according to the neutron moderator and cooling medium. Mostly are cooled and moderated by light water which is subcategorized into boiling water reactors (BWR) and pressurized water reactors (PWR). Moreover, they are categorized into four generations of which the first is outdated, while the second generation is widely distributed in Europe, Russia and Canada. The third and fourth generations are evolutionary developmental designs on the second generation in order to enhance safety and minimize radioactive waste production. However, the very high costs of the fourth generation reactors hinder its commercial deployment. (Schröder et al. 2013).

3. Assessment Methodology

3.1.Multi-criteria decision analysis (MCDA)

MCDA represents a decision-making approach for the evaluation of the sustainability of a system in an integrated form. It addresses complex problems while considering the evolving biophysical and socio-economic systems. It has been widely applied in different fields like social, economic, agricultural, industrial, ecological and biological systems. Moreover, it plays an important role in energy systems planning especially after the concern on environmental protection has increased. In fact, MCDA is a theoretical interpretation of the spontaneous decision making process. The theory is based on comparing different alternatives, as in my case the power generation technologies, through identifying a set of evaluation criteria that are applicable to all of these alternatives. The values of these criteria are then normalized, and their weights are determined according to the relative importance of the criteria. The main objective of MCDA is to integrate the weights and the normalized values of the criteria so that each alternative is associated with an integrated value that reflects its ranking as expressed by the following matrix (Wang et al. 2009):

$$
\begin{array}{ll}
 & \begin{array}{lcccc} \textit{Criteria} & a_1 & a_2 & \dots & a_n \\ \textit{Weights} & w_1 & w_2 & \dots & w_n \end{array} \\
\textit{Alternatives} & \\
\begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} & \begin{pmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{pmatrix}_{m \times n}
\end{array}
$$

where x_{ij} is the performance of j^{th} criteria of i^{th} alternative, w_j is the weight of criteria j, n is the number of criteria and m is the number of alternatives.

Different MCDA methods have been developed and exist in the literature. Abu Taha and Daim (2013) have conducted a literature review study on the frequency of the application of different MCDA approaches per each renewable energy research category. Wang et al. (2009) has presented a fruitful study that describes the concept of each of these methodologies in addition to elaborating the selection approaches of the evaluating criteria, categorizing and explaining the weighing, the normalization and MCDA approaches.

In this study, I applied two MCDA approaches: the analytical hierarchy process (AHP) and the weighted sum method (WSM). The former is used for weighing the indicators based on the questionnaire that has been mentioned in the subjective data collection section, while the latter is used for generating an integrated sustainability index for each technology. The main concept of these two MCDA methods is described below.

The analytical hierarchy process (AHP): This method was proposed primarily by Saaty (1980) and is based on the decomposition of a complex problem into a hierarchy with an objective at the top of the hierarchy, indicators and sub-indicators at levels and sub-levels of the hierarchy, and decision alternatives at the bottom of the hierarchy as shown in Figure 41. Here, I evaluate the weights of the indicators in a pair-wise comparison using the scoring scale presented in Table 14, based on their importance regarding energy technology selection according to the perspectives of the participants in the questionnaire I designed.

Thus for example when comparing C1 with C2, if C1 is more important than C2, therefore C1 will acquire one of the integer values presented in Table 14 except the value 1 which means an equal importance, whereas C2 will acquire the reciprocal of the value of C1 and vice versa. Since this method is based on an individual judgement, the probability of inconsistency and illogic judgement is high, where in some instances the participant could give more importance to C1 over C2, and more importance to C3 over C1 then decide that C2 is more important than C3 which is illogic. For this reason, the method includes a measurement of a consistency ratio to assess the degree of consistency of the pair-wise comparison.

A detailed explanation of the AHP is presented in Appendix D. The same process could be extended for evaluating the different technologies through a pair-wise comparison against each of the indicators; however, the comparison of the technologies per each indicator does not make sense since this approach is a subjective one that is dependent on stakeholders opinions whereas the values of each indicator across the technologies is obtained from an objective evaluation that is irrelevant of the perspectives of the stakeholders except for few indicators like the social acceptability in my case. Additionally, this will add more questions in the survey which will complicate the data collection process. Therefore, I constrain this method only for weighing the indicators and I used the WSM, described below, for generating the integrated sustainability index.

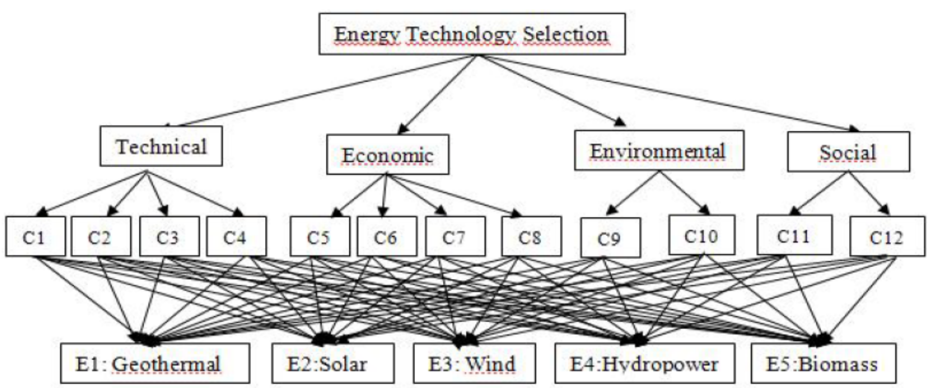


Figure 41: Illustrative scheme of the MCDA network (Demirtas 2013)

Table 14: Scoring scale of AHP and its interpretation (Wang et al. 2009)

Scale	Degree of preference	Scale	Degree of preference
1	Equal importance	7	Very strong
3	Weak	9	Extreme importance
5	Strong	2, 4, 6, 8	Intermediate values

The weighted sum method (WSM) is the most commonly used approach in sustainable energy systems (Wang et al. 2009) and satisfies the following expression:

$$A_i = \sum_{j=1}^{n} a_{ij} w_j, \text{ for } i = 1,2,3,\ldots.m$$

where A_i is the WSM score of alternative i, n is the number of decision indicators, m is the number of alternatives, a_{ij} is the normalized value of the j^{th} indicator in terms of the i^{th} alternative and w_j is the weight of the j^{th} indicator that has been obtained from the AHP. The total value of each alternative is equal to the sum of products, which is ultimately used to rank, screen or choose an alternative with the maximum score.

From this step we can get a static ranking of the technologies per actor where the ranking is general for the whole country and does not assume any changes in the values of the indicator with time or in response to other factors. In order to overcome the shortage of number of participants in this analysis, I applied the Monte-Carlo validation approach to assess the uncertainty of technology ranking per actor. In this approach the probability of technology ranking by individual members of the sample is compared with a simulated probability of technology ranking over a specified number of simulated observations that generate a random value between 0 and 1. The number of the simulated observations could be from hundreds to thousands of values based on the accuracy of the simulation needed. The more simulated observation is, the higher the accuracy will be. Here, I run the simulation over 1000 random values. A detailed explanation of the Monte-Carlo validation approach is explained in Appendix E. The Monte-Carlo methodology could be applied also to assess the uncertainty of ranking of the technologies due to the wide range of values of the indicators. Thus, the ranking could change dramatically if the high or the low values, instead of the average values, of the indicators are used.

3.2.GIS-based spatial data analysis

In this section I evaluate the influence of some important factors that represent the local conditions on the selection of an energy pathway. These factors are more site specific than being dependent on the technology type except for a few of them. They play an important role in the ranking of sites for the installation of technologies.

To prepare the spatial framework of Egypt, in addition to the resource potential, which is evaluated for each of the seven technologies separately, I selected six spatial factors: population density, primary roads availability, water availability, grid availability, political stability and the negative impact potential on crops. I build these data maps as layers of vector data, as will be explained shortly, on the political boundary layer of the base map of Egypt obtained from the Russian GIS-lab website (GIS-Lab 2014) using ArcGIS. Then I convert it to raster data layers at a resolution of 0.01745 degree (cell size = 0.02) using the open source SAGA GIS. For some spatial factors I divide the map into zones that have similar features related to the analyzed factor and give a score for each zone based on an ordinal scale between 0 and 10. For other factors I divide the map according to the reference map that displays a certain value of this factor.

According to my own evaluation, I apply the AHP in getting the weights of these factors for each technology and I use the same normalization formula that has been used with the assessment indicators to get a normalized value of the scores that have been given to the divided zones. Also I apply the WSM to get an integrated value for each location so that they could be ranked. Here below I give a detailed explanation for each spatial factor. It is important to mention that for almost all types of the technologies, the required area for installation is not a major problem in Egypt where one tenth of the total surface area of Egypt is enough for the installation of 25 GW from CSP type power plants which mostly requires a vast land space. Additionally a very limited area along the Nile Valley and the delta is exploited. So a high accuracy of the spatial data is not necessary at this step of investigation.

3.2.1. Resource potential

The resource potential factor has been discussed before as one of the technical indicators for the sustainability assessment which plays an important role in the decision making process especially with renewable energy projects where the resource used is uncontrollable and site dependent. Hence in some locations it is technically feasible to install a power plant where in others insignificant electricity production will be generated. For fossil fuels and nuclear power plants it is possible to transfer the fuel from the sites of mines or ores to the power plants even it could be imported from other countries, however this transportation will add more costs and risks. The ranking of zones is based on data available in the literature and it will be considered as a weight for the normalized values that I used in the technical indicator assessment. Here below I will investigate how I designed this factor for the technologies under assessment.

3.2.1.1. Coal

Based on the information I mentioned in the technical resource potential of coal in section 2.5.1.2, I assume that no imports of coal will take place and this potential is homogenous over the whole country with a spatial normalized value of 0.1 multiplied by the normalized value that is obtained from the technical resource potential indicator assessment (0.4×10^{-6}) although the only coal mine in Egypt, El Maghara mine, is found to be in Egypt's Sinai Peninsula (Amer et al. 2002).

3.2.1.2. Natural gas

I build up the spatial data of NG resource potential through dividing the map into 6 zones. The first zone with the highest ranking represent sites where already NG power plants exist according to data obtained from the Global Energy Observatory website (GEO 2016) as shown in Figure 42. I assume that these locations have the best infrastructure for another NG power plant to be installed or through direct upgrading of the old ones. The detailed information about the site and size of these power plants are shown in Table 30 in Appendix F. The second ranking zone represents areas covered by the NG pipeline and the very near areas as it will need no new NG pipeline connection to fuel the new power plant. This has been built based on a reference map shown in Figure 43. As the distance from the nearest pipeline increases, the zone ranking decreases. According to this rule, I build up the vector data map shown in Figure 44. The scoring is based on an ordinal scale from 0 to 10. Thereafter, I converted the vector data into a raster one after normalizing the scores which I used in my model (see Figure 45).

Figure 42: NG power plants in Egypt (GEO 2016)

Figure 43: NG pipeline grid across Egypt (EGAS 2013)

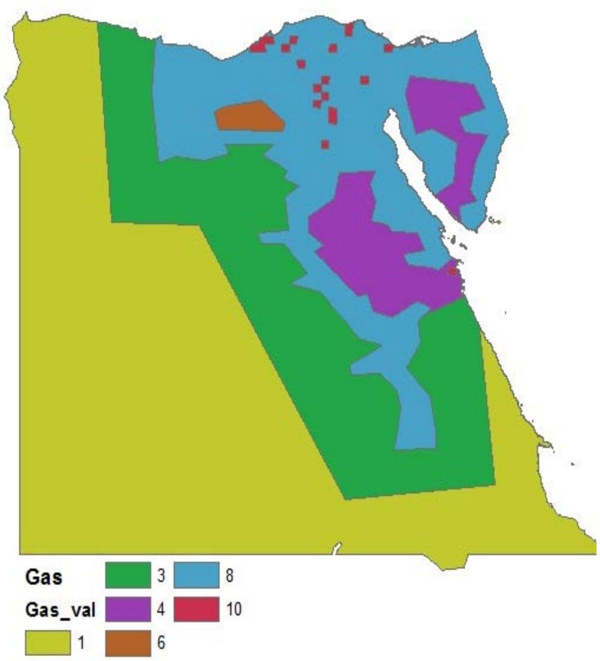


Figure 44: Vector data zone ranking of NG

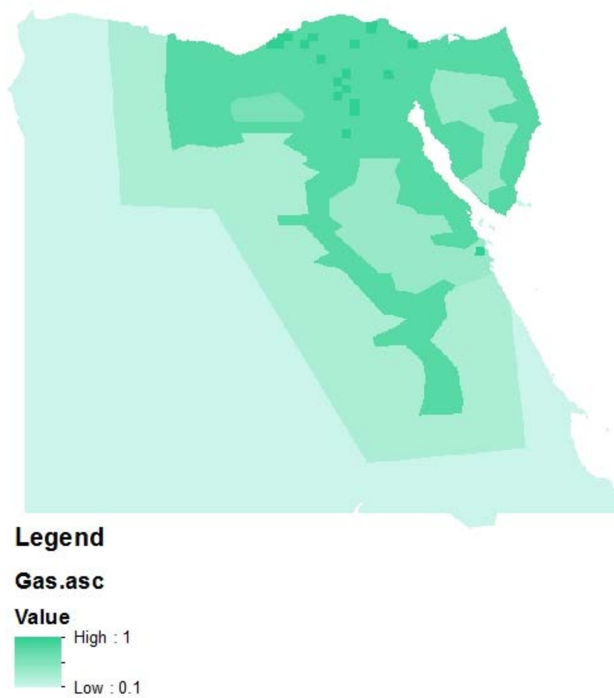


Figure 45: Raster data zone ranking of NG

3.2.1.3. Wind

The wind spatial data resource potential has been constructed by geo-referencing the wind atlas of Egypt shown in Figure 46 to the base map of Egypt in GIS. Then I drew polygons similar to the reference map and they got the same score which corresponds to the average wind speed in m/sec in each zone as shown in Figure 47. After normalization I converted it to a raster data as shown in Figure 48. As it can be observed from the wind atlas, the coastal area along the Red Sea which is known by the Gulf of Suez is characterized by a good wind regime. Moreover, the wind at the yellow and green areas on both sides of the Nile River flows at a moderately useful speed which although not very high but could be compensated by exploiting a vast space of the land.

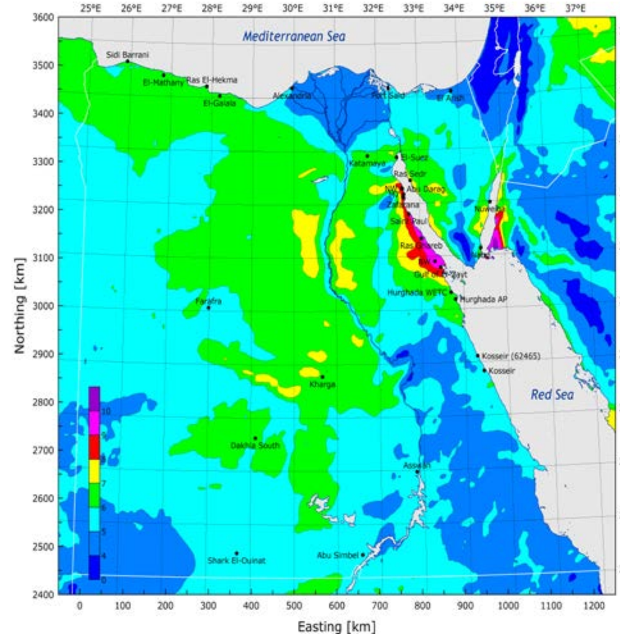


Figure 46: Wind atlas of Egypt (Gylling Mortensen et al. 2006)

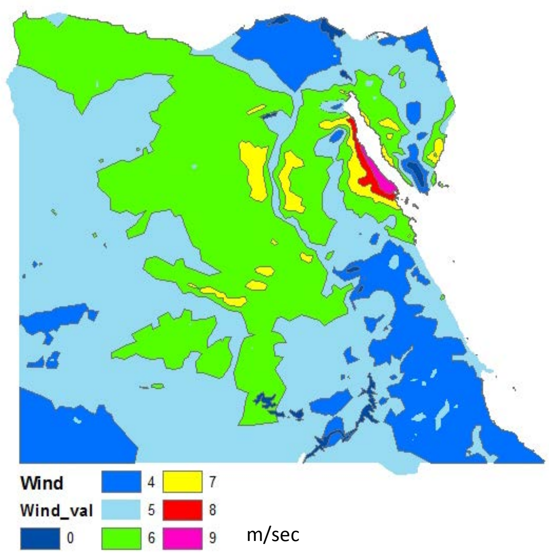


Figure 47: Vector data zone ranking of wind

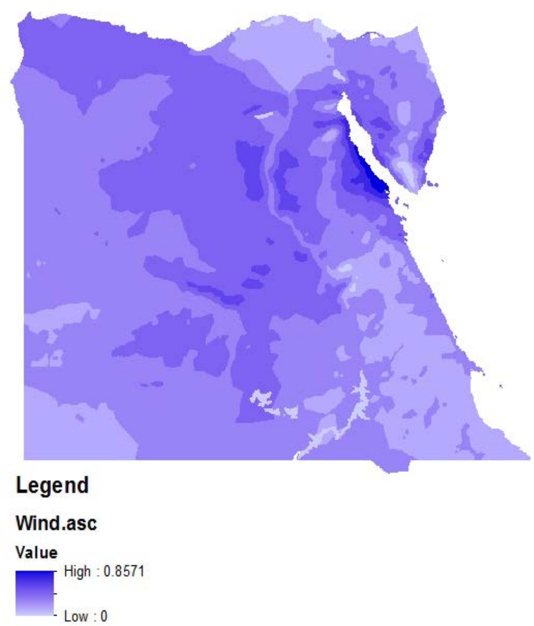


Figure 48: Raster data zone ranking of wind

3.2.1.4. CSP

The same principle that is used with wind has been applied to CSP where I used the solar atlas of Egypt for the direct normal irradiance (DNI) (see Figure 49) as the reference map on which I build the vector data map (see Figure 50) but I take the average value of the ranges shown in each zone in the solar atlas map. Then again I converted it after normalization into a raster data map as shown in Figure 51). The DNI increases from north to south. Thus, it is recommended to give more attention to the south of Egypt while thinking about CSP technology. However, other factors should be absolutely considered.

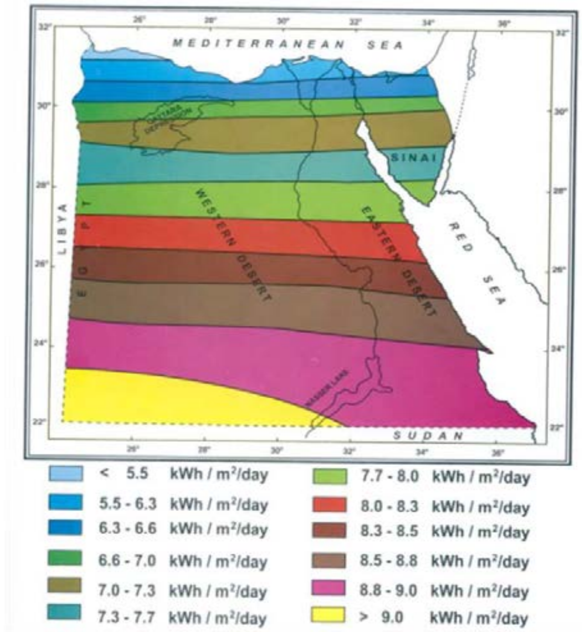


Figure 49: Solar atlas of Egypt DNI (NREA 2015)

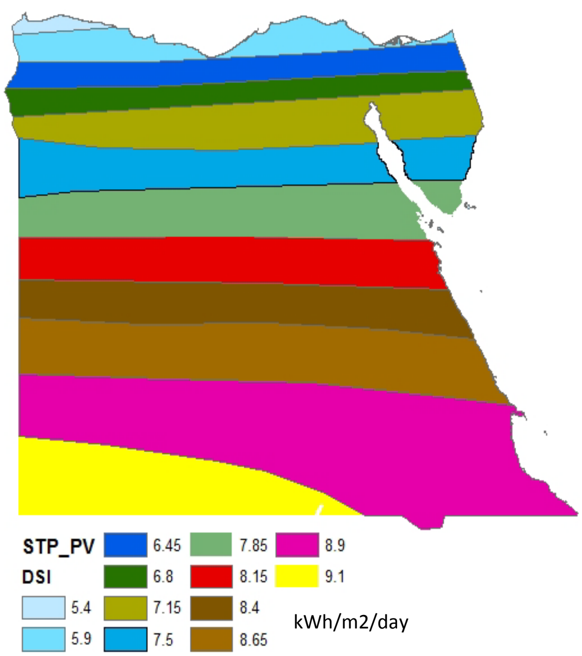


Figure 50: Vector data zone ranking of CSP

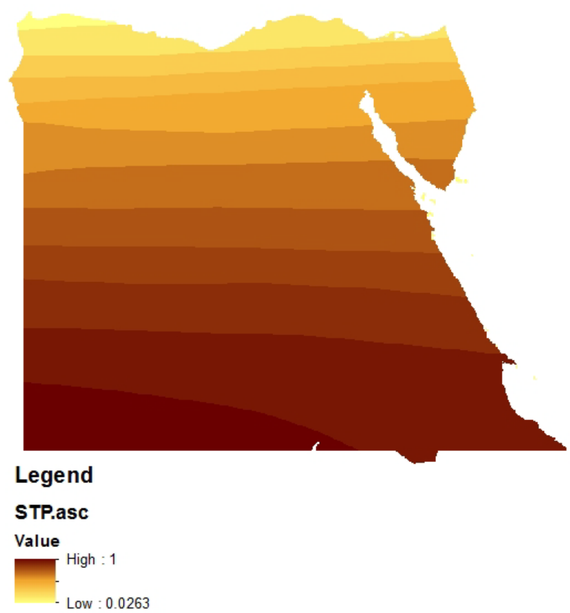


Figure 51: Raster data zone ranking of CSP

3.2.1.5. PV

Actually the resource potential of PV has been constructed in an inverse relationship to that of CSP (see Figure 52), this is because CSP depends mainly on the direct solar radiation which carries the heat energy that is required for steam generation. However, PV does not require the heat carried by the solar radiation; but it depends on the light energy which is accompanied by both the direct and also the diffuse solar radiation. Moreover, the performance of PV decreases as the temperature increases where both the electrical efficiency and the power output of a PV module depend linearly on the operating temperature (Dubey et al. 2013), therefore it is not advisable to install PV panels in a very hot zone like the south of Egypt. Although some researches and developments have been performed on the design of PVs in order to overcome this issue, I am concerned here with the commercial types of PVs that still suffer from this issue.

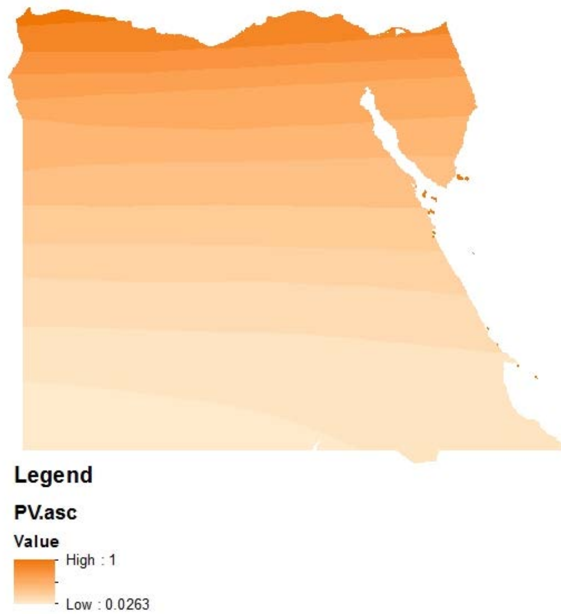


Figure 52: Raster data zone ranking of PV

3.2.1.6. Biomass

Biomass resources are limited to areas where livestock, plant farms exist in addition to the human inhabited area. Forests represent also a good resource for biomass but this is not available in Egypt, since most of the land is desert. I construct the biomass resource potential map according to the National Geographic base map (see Figure 53) which has been taken through satellites and is available on ArcGIS. It can be seen from this map that the green area is concentrated along the Nile Valley and delta which is a favored residence area for the Egyptian. Hence, the map is divided only into two zones: the first where an excellent biomass resource could be found has been scored 10; while the other zone has been scored 2 as there might be some resources which are available in some oasis in the western desert of Egypt. Figure 54 and Figure 55 show the vector and the raster maps of biomass resource potential.

Figure 53: Base map of Egypt from National Geographic (ESRI ArcGIS)

Figure 54: Vector data zone ranking of biomass

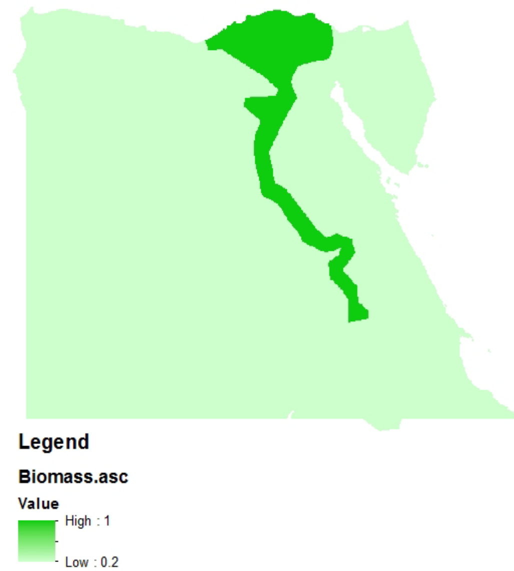


Figure 55: Raster data zone ranking of biomass

3.2.1.7. Nuclear

Figure 56 shows six identified nuclear ores in Egypt, 5 in the eastern desert and one in Sinai. These ores have been discovered since 1996 (AbdulRazek 2009), however, it has been never announced that uranium has been extracted from these ores for a commercial use like export or power production. For this reason, I deal with the nuclear resource in the same manner as I did with coal, where I assume that the normalized technical resource potential which is 0.006 is the same potential in all parts of the map multiplied by a spatial normalized score of 0.1. The latter value is based on a low score value of the resource potential as a spatial factor. Since all zones across Egypt are homogenous regarding this factor, I compare it with other countries that have a significant resource potential of nuclear or mainly uranium. Thus, if we compare Egypt with Russia, for instance, regarding this factor, Russia will be scored 10 and Egypt will be scored 1. Thus the normalized value of this score is 0.1.

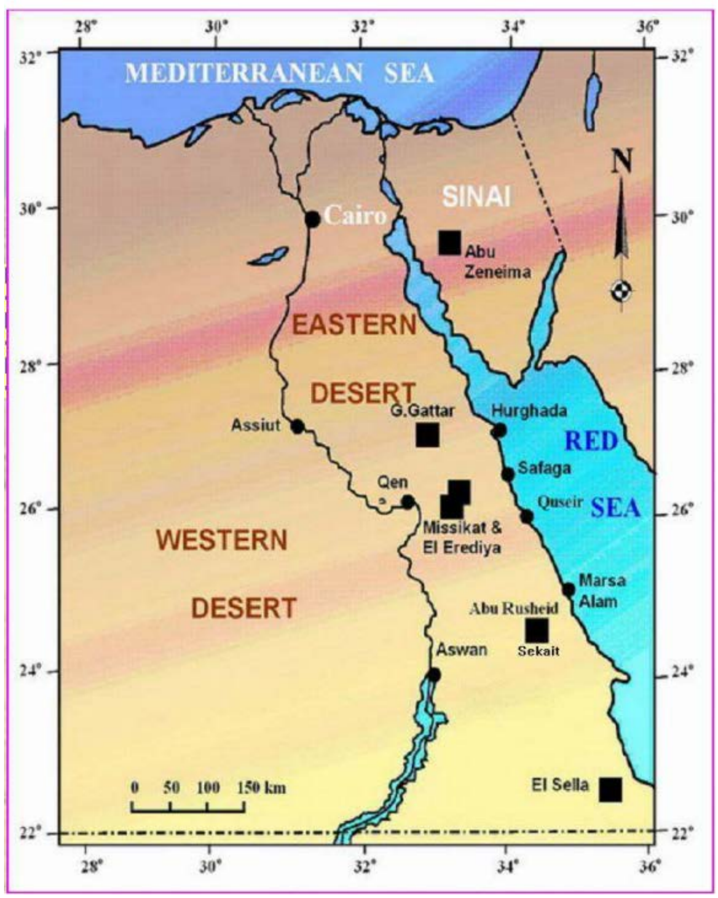


Figure 56: Discovered nuclear ores in Egypt (AbdulRazek 2009)

3.2.2. Population density

The second important spatial factor which plays an important role in the selection of a location for the installation of a power plant is the population density. Generally, it is not advisable to install a power plant in a residential area in order to reduce the negative consequences of an accident. Moreover, the surrounding area of a power plant during normal operation is usually subjected to pollution and/or danger which come from emissions, radioactive wastes, high voltage cables or inverters. Therefore, lower population density areas are ranked higher than the densely populated areas. Based on the Egyptian population in 2016 and surface area per each governorate obtained from the Central Agency for Public Mobilization and Statistics (CAPMAS), I construct the population density map shown in Figure 57, which is converted to a raster map after normalization (see Figure 58). The exact values of population, surface area and the calculated population density are shown in Table 31 in Appendix F. It can be noticed from Figure 57 that almost 80% of the land has a population density between 1 – 500 per km^2. Only one governorate has a very high population density of around 4700 per km^2 which although the population there is lower than that of Cairo but due to the smaller area it shows a high population density. Figure 58 contradicts what is shown in Figure 57 as the normalized value is in favor of a lower population density. However one should consider also the distance between the demand center and the installation site since this adds transmission costs to the power plant. Hence a compromise between the distance and the risk should be considered in a real planning.

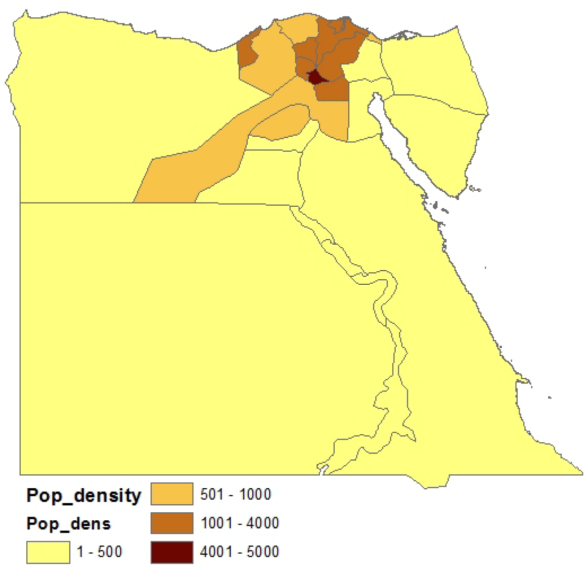


Figure 57: Population density per governorate (CAPMAS 2016)

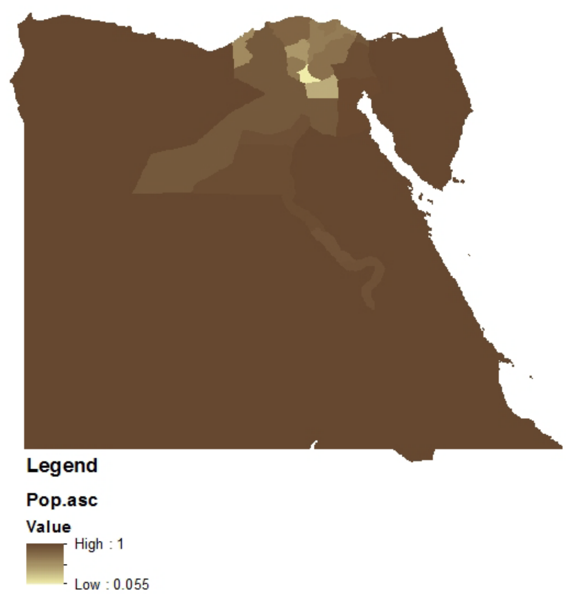


Figure 58: Raster data zone ranking of population density

3.2.3. Primary roads availability

All power plants in their initial phase require construction equipment and materials which should be transported to the site of installation. Roads are the mostly used transportation route through trucks or in some rare cases through the railway. Thus, existing paved roads will assist in the ease of installation of a new power plant. Moreover, it will save the costs of the pavement or the construction of new roads. Therefore, I consider here the role of existing primary roads in the selection of a site. According to the National Geographic base map (see Figure 53), I divide the land into 9 zones and ranked them as follows: the first zone represents the delta area which is almost covered by an excellent road network facilitating the mobilization within this zone; the second zone is along the Nile Valley which connects the upper and lower Egypt and represents an important connection route; the third zone represents the coastal area along the Mediterranean Sea which is also well paved as it connects to ,especially in summer, coastal touristic villages and cities; the fourth zone connects also to coastal touristic cities but along the Red Sea but it is not well constructed as the previous one since it has a lower rate of usage; the other five zones are of less importance and rarely used since they connect to a very low inhabited cities, accordingly I ranked them based on the road length per the area of each zone as shown in Figure 59. The normalized ranking is shown in Figure 60 where there is a direct proportionality between road availability and sustainability.

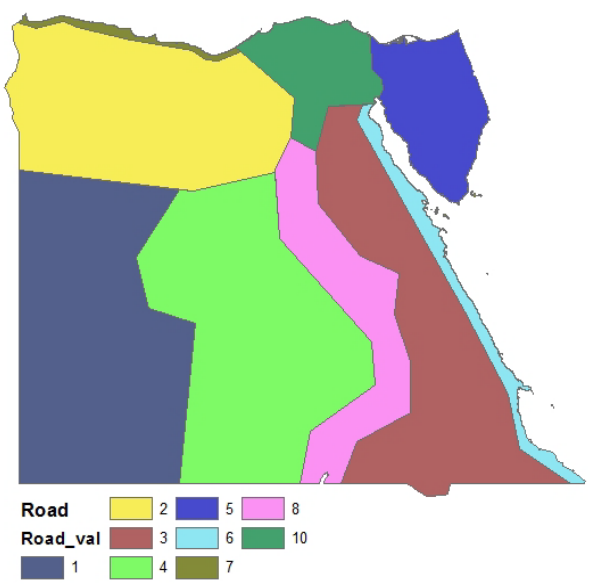


Figure 59: Vector data zone ranking of primary roads availability

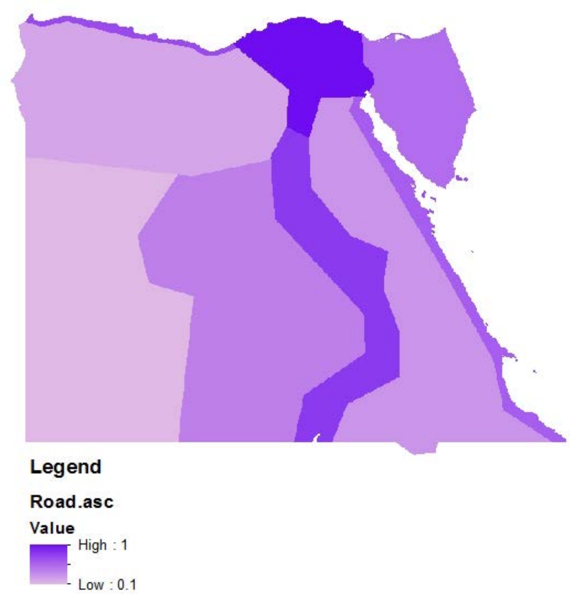


Figure 60: Raster data zone ranking of primary roads availability

3.2.4. Water availability

Another important factor especially for thermal power plants is the distance from water resource. Water is required in steam cycle power plants and for steam cooling in the condenser. Additionally, water is used for cleaning of mirrors of CSP and PV panels. Although sea water can be used for such purposes, however, due to the high content of minerals and salts in sea water, the erosion rate of the equipments and the construction components of power plants will be very high which makes it not recommended. Thus, as shown in Figure 61 and Figure 62, I divided the map into 5 zones: the first zone covers the nearby areas from the Nile River; the second zone is a lake branched from the Nile; the third zone is another lake on the north west of Egypt; the fourth zone represents all coastal areas; the rest reflects the fifth zone. Water plays an important role in the selection process as it has been mentioned before in the technical indicators for the sustainability assessment of power plants since the water responsible authority interacts with the energy responsible authority sometimes in cooperative manners and sometimes in conflict manners. The tradeoff between using water in energy, drinking or irrigation builds up the energy, water and food nexus that will be mentioned later. Thus, the costs of lost food or drinking water should be compensated or taken into consideration in our calculations while considering the values of a new energy project.

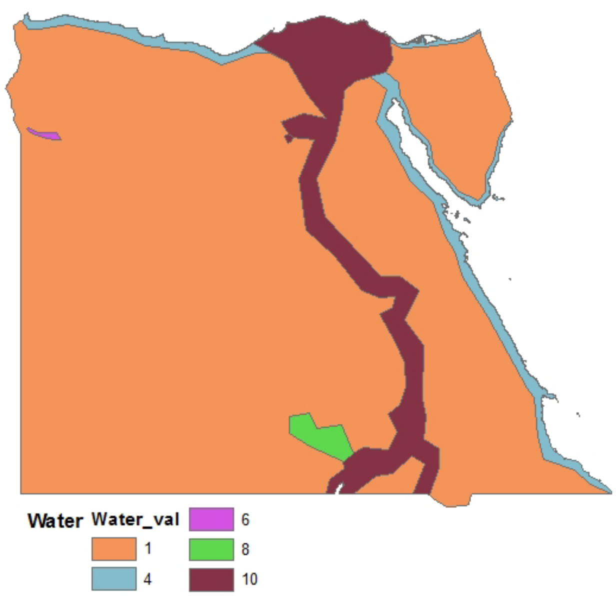


Figure 61: Vector data zone ranking of water availability

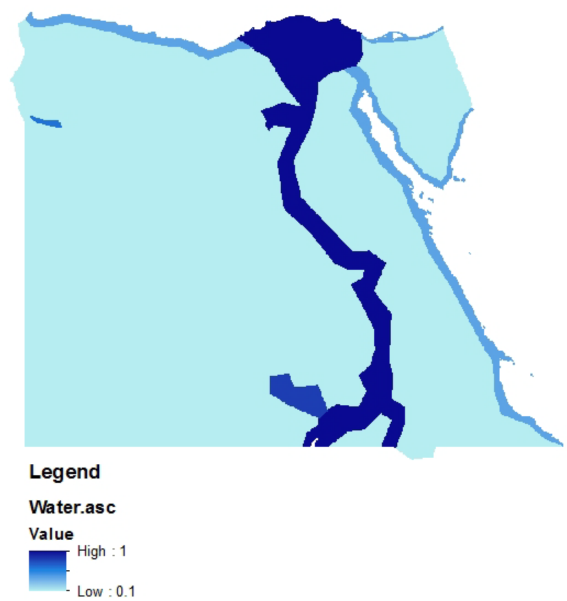


Figure 62: Raster data zone ranking of water availability

3.2.5. Grid availability

The electric utility is composed of three main operators: power generation system operators which represents the power plants (in Egypt there are 6 governmental production companies that administer all power plants; transmission system operators which transmit electricity from power generation companies to distribution companies (in Egypt there is only one transmission company owned by the government); distribution system operators which distributes electricity to households and end consumers (in Egypt there are 9 government owned distribution companies). The electricity grid in Egypt has been constructed in a centralized network basis where there is one grid that connects all power plants together. Thus, the electricity grid availability is considered also an important spatial factor in the decision making process for installing a new power plants. Based on the electricity grid network according to the Egyptian Electricity Holding company in 2004 shown in Figure 63, I divide the base map into four zones as shown in Figure 64. The highest rank zone corresponds to areas where transmission lines are already installed connecting the existing power plants and the nearby areas. The second zone reflects places where substations are installed, although they are shown in Figure 63 not connected to the grid. The third and fourth zones are grid-free lands which necessitate a new transmission line connection with short to long distance, respectively. If the location of the new power plant is at a much long distance from the grid, the investment cost will increase. These costs come from the connecting cables, towers and capacitors. The values are normalized and the vector data is converted to the raster data as has been done with other factors (see Figure 65).

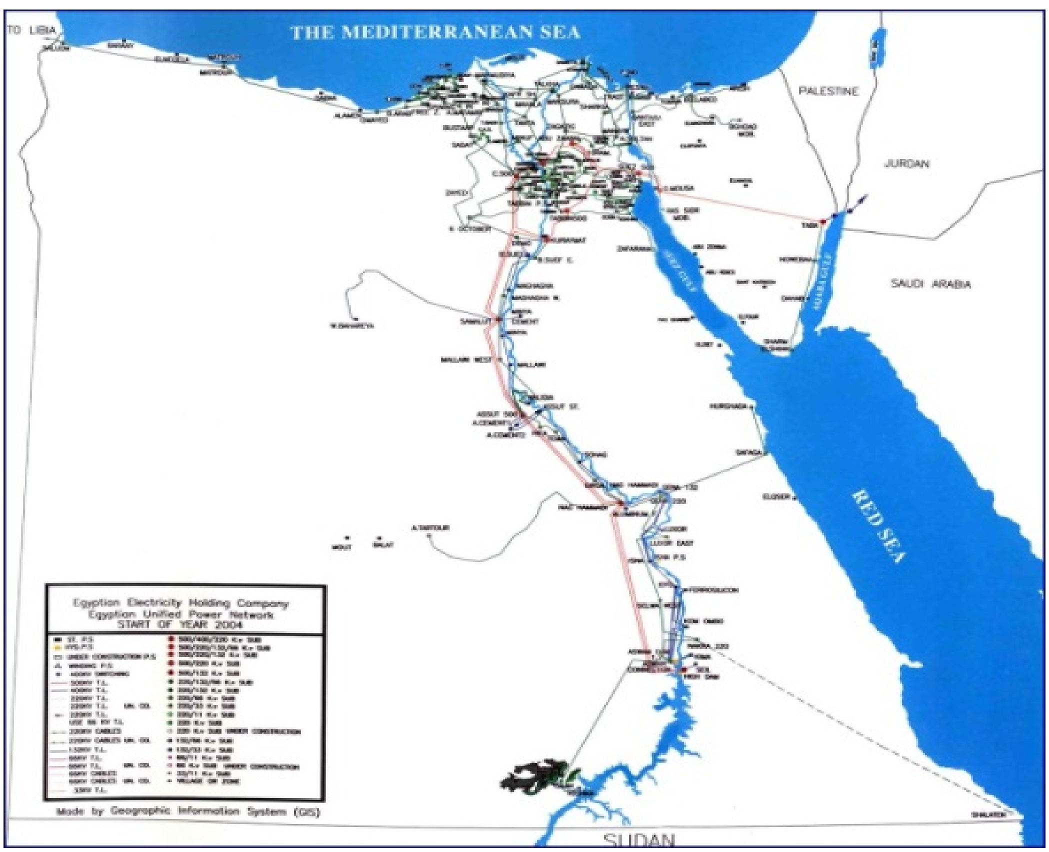


Figure 63: Grid coverage in Egypt (Global Energy Network Institute 2016)

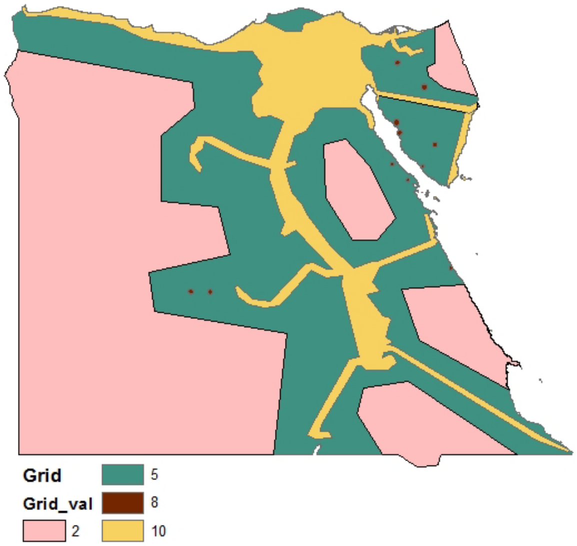


Figure 64: Vector data zone ranking of grid availability

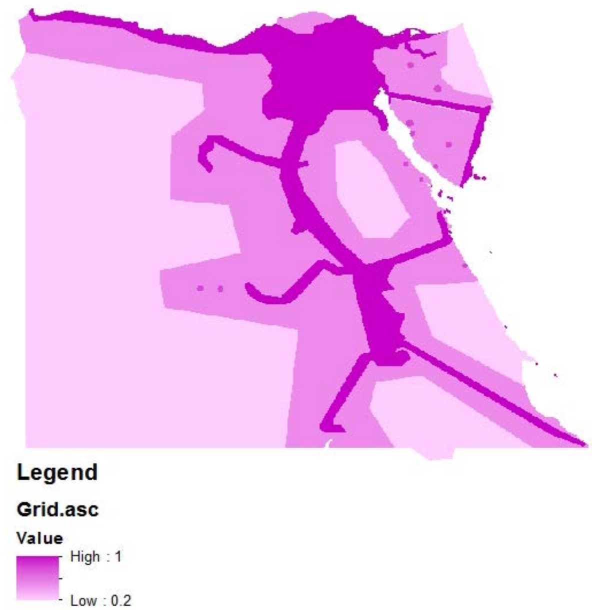


Figure 65: Raster data zone ranking of grid availability

3.2.6. Political stability

As I mentioned that the safety risk, as one of the social indicators, plays an important role in the sustainability of power plants but more in sense of technical or natural causes of accidents, here comes another very important spatial factor which could also cause accidents but most probably intended accidents through attacks from individuals, groups or even countries. It is very crucial to install power plants in areas that politically seem to be more stable or controlled. Indeed, a general political instability in a country subjects all parts of the country to the risk of attack, however, I am concerned here with the areas that are highly susceptible to attacks. Thus, what comes first to the mind of any decision maker is the border of the country, especially if the neighboring countries suffer from political instability. This is true with Libya and Sudan where since more than 4 years there have been civil wars. For this reason I assumed that it is not advisable to build a power plant near to the borders with Libya and Sudan (≈ 50 km). Another hotspot area of political instability is North Sinai where the Egyptian military army intertwines with a movement living there as announced in the media leaving everyday victims from both sides and sometimes from citizens. Additionally, at the right down side corner, there are two cities called Halayeb and Shalateen, which is a disputed area between Egypt and Sudan. Although within the country there are some internal conflicts which could subject power plants even in Cairo to some kinds of attacks, however, the risk is lower than in these three areas that I mentioned. Figure 66 and Figure 67 shows the constructed vector and raster data map concerning this factor, respectively.

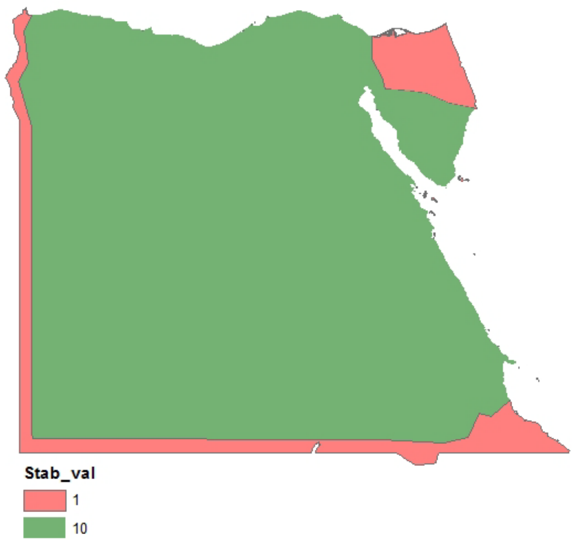


Figure 66: Vector data zone ranking of political stability

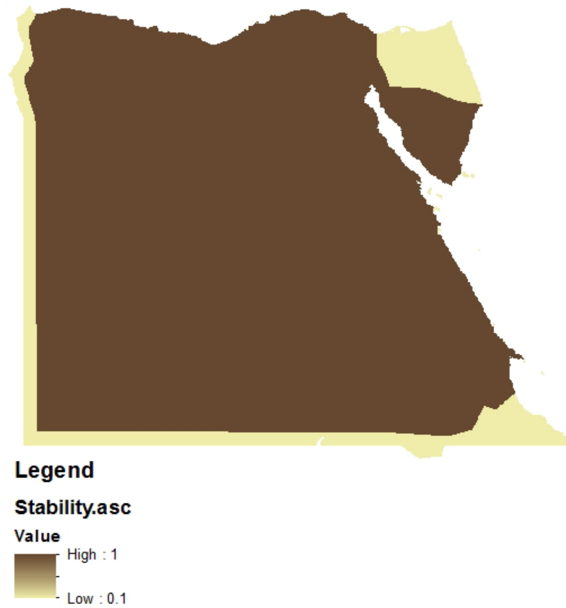


Figure 67: Raster data zone ranking of political stability

3.2.7. The negative impact potential on crops

Last but not least, the negative impact potential from the installed power plants on crops cultivated in a nearby area should be considered also. This factor is an inverse relationship to the resource potential of biomass as shown in Figure 68 since there is only a fixed location that is specified for agriculture. However, here I consider the negative impacts of power plants that could influence negatively on crop production and even on farming animals. This danger comes from gaseous emissions which could lead to acid rains, from air particulate matters or radioactive emissions which could damage the crops entirely. This factor is more technology dependent where technologies like fossil fuels power plants and nuclear power plants mostly have adverse impacts on the crops. Therefore, it is advisable for such types of technologies to be installed in areas apart from the farming zones. However for wind, CSP and PV, the impact is much lower since they have lower emissions. However, for biomass technology as a quite similar technology to fossil fuel, one should compromise between the costs of biomass transportation and the cost of damage, which I personally prefer to be installed also in distant areas from crop cultivation.

Figure 68: Raster data zone ranking of negative impact potential on crops

These spatial factors are not the only ones that should be considered in energy system planning, however, there are still numerous factors that play also important roles in this process but I just use some of them to build up my basic model. Thereafter, I can extend the model more and more by including all relevant factors and assessment indicators. Moreover, the evaluation of these factors is recommended to be more accurate and at a higher resolution. The next step is to include the agent-based model reflecting the temporal dynamics of the decision making process based on cost benefit analysis as will be discussed in the next section.

3.3.Agent-based modelling

Agent-based simulation has become increasingly popular as a modeling approach in the social sciences because it enables one to build models where individual entities and their interactions are directly represented. In comparison with variable-based approaches using structural equations, or system-based approaches using differential equations, agent-based simulation is a bottom-up modeling approach which offers the possibility of modeling individual heterogeneity, representing explicitly agents' decision rules, and situating agents in a geographical or another type of space. It allows modelers to represent in a natural way multiple scales of analysis, the emergence of structures at the macro or societal level from individual action, and various kinds of adaptation and learning, none of which is easy to do with other modeling approaches (Billari et al. 2006, Gilbert 2008).

An agent is a discrete and autonomous entity with its own goals and behaviors, autonomous, with a capability to adapt and modify its behaviors. Complex social processes and a system can be built "from the bottom up". An agent-based model consists of a set of agents, their relationships, rules of behavior and a framework for simulating agent behaviors and interactions. Unlike other modeling approaches, agent-based modeling (ABM) begins and ends with the agent's perspective (Macal and North 2006) which makes it particularly suitable to apply it to modeling agent choices and investments among energy pathways.

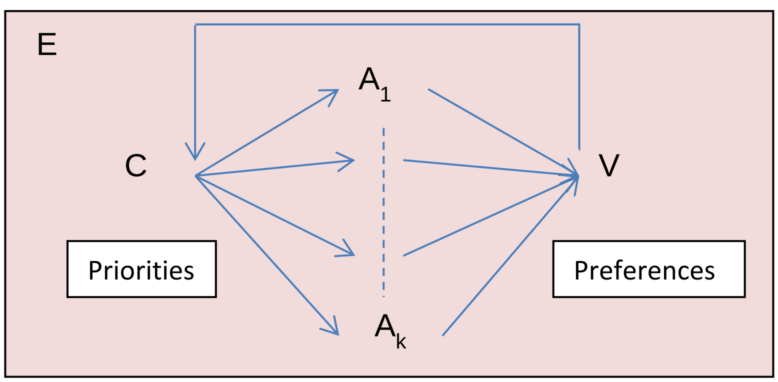


Figure 69: An illustrative diagram of the agent-based model (based on Scheffran and Hannon 2007)

In the following the ABM is built on agents who act by adjusting their priorities (p) for action pathways (A) in response to the change in the marginal values of the pathways as a function of investment costs (C) and value preferences (V) as well as environmental conditions (E) that changes in space and time as shown in Figure 69 (for a description of the VCX framework model see Scheffran and Hannon 2007). This form of simulation corresponds to the descriptive decision theory where a single agent which could be a group of individuals is distributed over a space but they have the same evaluation preference of the action pathway. They interact differently according to the local condition in each site and they are called spatial agents. This is applied in the analysis of each of the four actor types that are involved in this study. When the evaluation preference of the spatial agents is directed to achieve a certain target, this corresponds to the normative decision theory which in my case is the sustainable scenario type. A test actor could be also evaluated in order to assess the extreme preferences to one of the four dimensions of sustainability.

However, in real practice the actors interact in response to decisions taken by other actors in the respective spatial cells since these actions affect the marginal value of the action pathways. This type of interactive simulation among multiple actors reflects game theoretical and collective decision-making principles. The agents could be customers or suppliers who are directly affected by the action pathways; or they could be supporters or opposers who are indirectly affected.

In this study, I am concerned with the interaction between actors who represent energy planners selecting among energy system technologies that could supply the growing electricity demands. In the game scenario, each of these actors will rank the technologies in each spatial location and the winning actor will be the one with the maximum priority of technologies following their marginal value preferences. The other actors could thereafter modify their evaluation preferences to get the maximum priority technology in future time steps as will be explained later. Other types of interaction could be assessed like the most selected technology by the agents, voting on the selected technology or the one with the least deviation from the sustainable scenario. The selection could also influence the assessment indicators which are mostly controlled by other agent groups like for instance the investment cost of a technology could be reduced in response to increased market affinity; the insurance costs can be increased in response to the selection of technologies with high risks.

I modified and expanded this ABM by including value functions based on the MCDA assessment models as well as evaluations of the stakeholders and projected future electricity demand to compare different energy pathways used in electricity mix scenarios and sustainability of land use. The multi-criteria assessment is applied to classify typical agents characterized by weighted priorities for certain criteria sets. These types of agents are then used in agent-based models where agents follow these priorities to select energy pathways that meet these criteria. Agent decision-rules are applied to a GIS-based spatial (cellular) model landscape, taking into account spatially specific environmental and socio-economic conditions. The dynamics of changing action priorities for energy pathways describes agents that iteratively shift their action pathways towards large marginal value-cost preferences by comparing the marginal value of one pathway with the weighted average marginal value including all pathways. This is given by the following evolutionary equations of shifting priorities for action pathway *k* of actor type *q* in spatial cell (agent) *i*:

$$\frac{\Delta p_{iq}^{k}}{\Delta t} = \alpha_{iq}\, p_{iq}^{k}(v_{iq}^{k} - \sum\nolimits_{l} p_{iq}^{l} v_{iq}^{l})$$

where,

- $\frac{\Delta p_{iq}^{k}}{\Delta t}$ is the change in action priority p of actor q for energy pathway k in spatial cell i for time period Δt which is one year in my case.
- α_{iq} is the adaptation rate of actor q in spatial cell i (in this study I apply the same adaptation rate for all actors).

- v_{iq}^{k} is the marginal value of energy pathway k for actor q in spatial cell i which is a function of the value and the weight of the spatial factors and the assessment indicators.
- $\sum_l p_{iq}^{l} v_{iq}^{l}$ is the sum of weighted marginal value (average) including all energy pathways l.

$$v_{iq}^{k} = \frac{\left(\frac{(\sum_{m=1}^{o} s_{mi}^{k} \times h_m)}{\sum_{i=1}^{z}(\sum_{m=1}^{o} s_{mi}^{k} \times h_m)}\right) \times (\sum_{j=1}^{n} a(t)_{kj} \times w_{jq})}{\sum_{k=1}^{l}[\left(\frac{(\sum_{m=1}^{o} s_{mi}^{k} \times h_m)}{\sum_{i=1}^{z}(\sum_{m=1}^{o} s_{mi}^{k} \times h_m)}\right) \times (\sum_{j=1}^{n} a(t)_{kj} \times w_{jq})]}$$

- s_{mi}^{k} is the value of spatial factor m influencing spatial cell i which is for some factors specific to energy pathway k as in case of the resource potential, where z is the number of spatial agents
- h_m is the weight of the spatial factor m, where o is the number of spatial factors.
- $a(t)_{kj}$ is the value of the assessment indicator j for energy pathway k which is for some indicators a function of time.
- w_{jq} is the weight of the assessment indicator j of actor q, where n is the number of the assessment indicators.

Now after I gathered all necessary data and explained the basic methodologies used for conducting the analysis, the next step is to integrate all of them in an interface that simulate the whole process producing the results that will guide us to the right roadmap to secure energy in Egypt.

3.4.Integration of the three methodologies

I use the open source ABM software “NetLogo” to explicitly represent spatial agents across space and time as they decide on different energy pathways, taking into consideration environmental factors that vary across the landscape and create non-uniform environments for each energy type. The multi-criteria assessment based on stakeholder responses and the agent-based modeling have been basically built up in Netlogo and coupled with raster data maps constructed by ArcGIS and SAGA software.

Basically, the spatial agent-based modelling describes the interaction of decisions of spatial agents where one agent changes its decision in response to the decisions of other agents. However, here I try to apply this principle but at the same time mimic the actual occurring process in the planning of power plants. In fact, Egypt is centrally regulated where one ministry makes decision for all parts in Egypt. Thus, the administrative divisions are not allowed to be governed independently. I assume that I have virtual representatives of each of the four assessed actors distributed across the map of Egypt which has been divided into cells or patches of equal size. The number of these patches depends on the resolution of analysis. In each patch I have an independent representative of each actor type who can make a decision for the selection of one technology, which is the technology with the highest priority, to be installed on this patch or to identify the preferred energy-mix in the spatial cell. The decision making process is based on the local condition in each patch as a result of the spatial factors as well as the sustainability multi-criteria analysis of the technology. These two factors will build the marginal value of each technology by which the actor will change his/her initial priority. Thus, in each patch, each actor should rank the technologies and identify the technology with maximum priority. This will reflect the most preferred technology to be installed on this specific patch by this actor at a specific time step or year. It could be interpreted in another way, where it shows the allocated investment in the energy-mix by one actor at one patch at a specific time step. Going back to reality where I investigate a national energy-mix planning across the whole country, I took the average priorities of each technology of all spatial agents (i.e. the virtual representative) of each actor getting the overall priorities of the technologies changing with time. These priorities of investments will be allocated on the upcoming energy demand in the future.

The best location identification for each technology will be based on the ranking of patches for each technology according to the integrated spatial factors which has been conducted using the multi-criteria methodology, the weighted sum method. Since I have different actors thinking differently, I reach a competitive tendering interaction between these actors trying to apply their target planning. Their planning differs originally as a result of their different subjective preferences of the sustainability assessment indicators of the technologies. Although there are many interaction possibilities that could be investigated, I apply here only one interaction assumption representing the game scenario. I assume that the actor with the maximum priority value of the highest ranking technology will win the game. In this way each of the other losing actors will try later to modify their preferences of the assessment indicators in order to win the game in the future. The change in these preferences will be reflected in changing policies, prices and other impact factors.

I chose this rule in the game scenario because the priority of the technology is a function of the marginal value of the technology. The marginal value is a function of the spatial factors and the integrated sustainability index. The actors can control only the weights of the assessment indicators in the marginal value while the other variables are not controllable. The main objective of the MCDA is to rank the technologies where the highest ranking technology is the most sustainable. Thus, if we ignored the weights of the indicators or if we give equal weights to all indicators as in the case of the sustainable scenario, therefore the best technology will be the one that shows the highest integrated marginal value. The normalization approach is based on comparing the values of the indicators across the technologies. For some indicators the difference between the values is not too big. In such case, the technologies are close to each other in their evaluation and it will not make a big conflict when selecting between them. However, for some other indicators the difference between the values is big and this will play an important role in the selection process since our target is to select the highest value technology. If we included the weights of the indicators and one actor give a high weight to an indicator that has a very close values between the technologies, then this actor at the end will have the value of the maximum priority technology low. However, if the actor gives a high weight to an indicator that shows a big difference across the technologies, this will ultimately end up with the right sustainable selection.

Table 15 shows an illustrative example that explains my idea. I assume to have three actors who are asked to rank three technologies and three indicators are used for the evaluation of these three technologies. The actors give weights to the indicators according to their preferences. The last row in the actor column represents an objective unbiased evaluation of the technologies but with equal weights of the indicators as in the sustainable scenario. If we compare the normalized values (N.V.) of the indicators across the technologies, we will observe that the indicator A and C show comparable normalized values across the indicators but one shows high values while the other shows low values. Indicator B shows a big difference in the normalized values across the technologies where Technology I has a very high normalized value as compared to Technology II and III. In comparing the three technologies with equal weights of the indicators, we find obviously that Technology I has the highest aggregated value which makes sense to be selected over the other two technologies because of the indicator B. Actor 1 gives the highest weight to indicator C ending up with Technology II as the highest aggregated value. Actor 3 gives the highest weight to indicator A ending up with Technology III as the highest aggregated value. Actor 2 gives the highest weight to indicator B ending up with Technology I as the highest aggregated value and the selection agrees with the sustainable scenario. If we compare the highest aggregated values of the three actors, we will find that Actor 2 has the highest value, which gives this actor the highest priority to apply his/her selection. By this rule I direct the actors to change their preferences in the assessment of the technologies to the most sustainable technology. However, if we compare the highest aggregated value of actor 1 and 3 with that of the equal-weights actor, we will find that Technology I still has a higher value than Technology II and III which will make the equal-weights sustainable scenario wins the game in the absence of actor 2. Moreover, if actor 1 compares the value of the highest aggregated value technology which is Technology II with the value of Technology I, the difference is not too big that could induce a conflict. The same applies to actor 3. Thus Technology I will make no conflicts between the actors and will satisfy the sustainability objective of the evaluation of the technologies. This is the rule of the game in this model.

Table 15: An illustrative example of the game scenario (N.V.: Normalized value)

Actors	Technologies	Indicator A		Indicator B		Indicator C		Aggregated value
		Weight	N.V.	Weight	N.V.	Weight	N.V.	
Actor 1	Tech. I	0.1	0.7	0.1	0.8	0.8	0.1	0.35
	Tech II		0.7		0.2		0.2	0.39
	Tech III		0.8		0.1		0.1	0.26
Actor 2	Tech. I	0.1	0.7	0.8	0.8	0.1	0.1	0.63
	Tech II		0.7		0.2		0.2	0.22
	Tech III		0.8		0.1		0.1	0.15
Actor 3	Tech. I	0.8	0.7	0.1	0.8	0.1	0.1	0.34
	Tech II		0.7		0.2		0.2	0.31
	Tech III		0.8		0.1		0.1	0.35
Equal weights	Tech. I	0.33	0.7	0.33	0.8	0.33	0.1	0.43
	Tech II		0.7		0.2		0.2	0.30
	Tech III		0.8		0.1		0.1	0.27

As mentioned before, I included an objective unbiased sustainable scenario and a test actor. The test actor plays a role in investigating other potential actors directly in the model but without applying the AHP methods in getting the weights of the assessment indicators. Additionally, it investigates the induction role of this actor in the decision of other actors in the game scenario, where it could be applied in order to force other actors to change their assessment behaviors. The interface of the assessment model as built in Netlogo software is presented in Figure 70. Figure 71 shows a schematic diagram summarizing the previous principle of integrating the three methodologies in the assessment of the technologies.

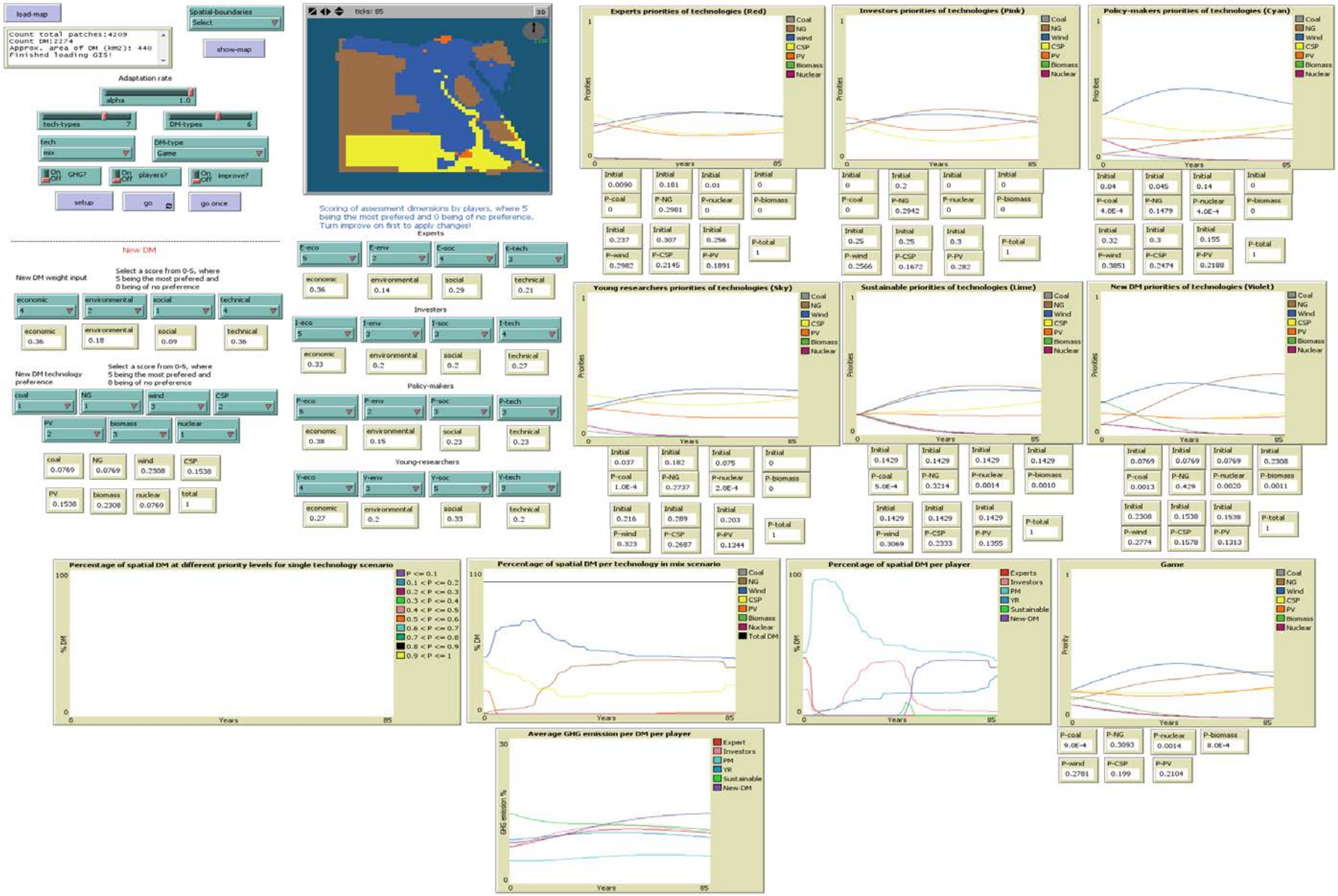


Figure 70: The agent-based model coupled with MCDA and GIS data interface in Netlogo

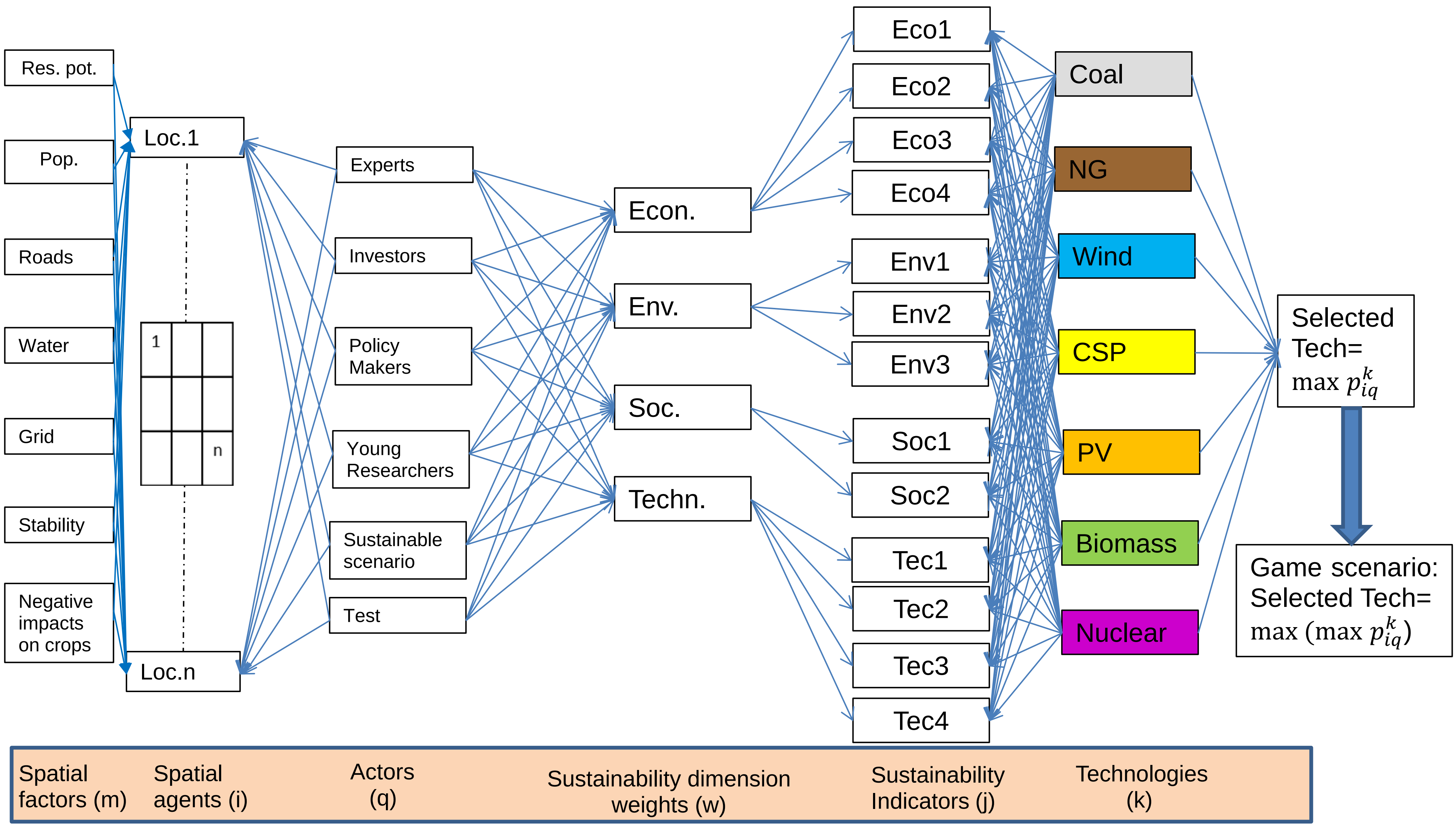


Figure 71: A schematic diagram describing the principle of the integrated assessment

Description of the model in the software:

First the model is initiated by importing the raster data of the spatial factors into the patches through pressing the Load-map button as shown in Figure 72. The view screen shown in Figure 73 is the spatial interface that shows the change of landscape while running the model. It is divided into equal sized cells called patches. Their number can be changed and specified according to the prefered resolution of analysis. In my case I have a total count of patches of 4209 (69 x 61 cells). The viable patches are those coinciding with the map carrying the spatial factors and on which I assume the presence of virtual representatives of each actor type. These viable patches are called Decision Makers (DM) or the spatial agents with a count of 2274 patches. Each patch has an average area of 440 Km^2 (see Figure 72).

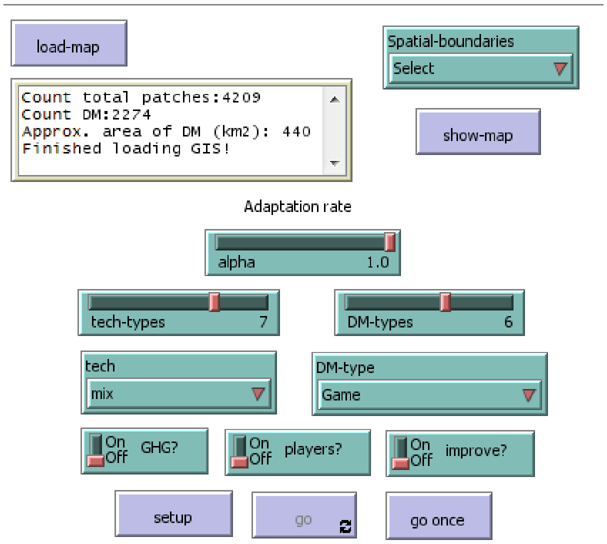


Figure 72: A zoomed view of the control buttons of the model

Figure 73: A zoomed view of the view screen showing the map of Egypt after being loaded (The patches are initially colored as the flag of Egypt for identification)

Now I can display each of the spatial factors separately on the view screen to assure the GIS loading step by selecting each of these factors from the drop-down menu button Spatial-boundaries (see Figure 74 the left one), then pressing on the show-map button. The 11 spatial factors as displayed in Netlogo are presented in Figure 75 from a to k. The spatial-boundaries button includes other variables named S-<technology>, for instance S-coal. (see Figure 74 the left one) which will not function at this step. These variables are the integrated spatial factors using the WSM for each technology in order to rank the patches and to prioritize the installation location. These variables will be activated only after pressing the setup button. The integrated spatial factors for the seven technologies under assessment as displayed in Netlogo are presented in Figure 76 from a to g. From here on I use these color codes for the visualizations on the map and plots in Netlogo: Coal = grey; NG = brown; Wind = blue; CSP = yellow; PV = orange; Biomass = green; Nuclear = magenta. The dark color indicates a higher value, for instance, in the integrated spatial factors for CSP, the dark yellow patches are of higher ranking for installation than the faded ones.

In order to set up the initial condition of the model which is programmed to start at year 2015, the setup button should be pressed but after identifying the scenario of analysis. Figure 72 shows three sliders: alpha, DM-types and tech-types. The first represents the adaptation rate of the agent-based equation which corresponds to the speed by which the actors change their decision. The slider ranges from 0.1 to 1. In all tested scenarios, I run the model at alpha = 1. The second slider reflects the number of actors which will be included in the analysis of the game scenario where I can exclude one or more actors from the game. The third slider identifies the number of technologies that will be analysed. The basic study will include 5 actors and 7 technologies.

I have two more drop-down menu buttons from which I specify the landscape analysis in the view screen, however the plots will run for all scenarios simultaneously except for one plot. The first drop-down menu is called tech (see Figure 74 the middle one) from which I can visualize the changes of the priorities of the spatial agents for each of the seven technologies or I can select the mix item which show the maximum priority technology at each patch or I can select the mix-scale item which is the same like the mix item but the color of patches is scaled according to the value of the maximum priority technology.

The second drop-down menu is called DM-types (see Figure 74 the right one) from which I select one of the actors to be visulaized on the map or the game item where all actors identified from DM-types slider will play together and be visulaized on the map. From these two drop-down menu buttons, the visualization of landscape analysis of the priorities of the actors is specified. Morevoer, I can select the New-DM item from the DM-type drop-down menu which represent a test actor, where I can perform a sensitivity analysis of the assessment of the technologies at different initial preferences of the sustainablity dimensions and the initial preferences of the technologies.

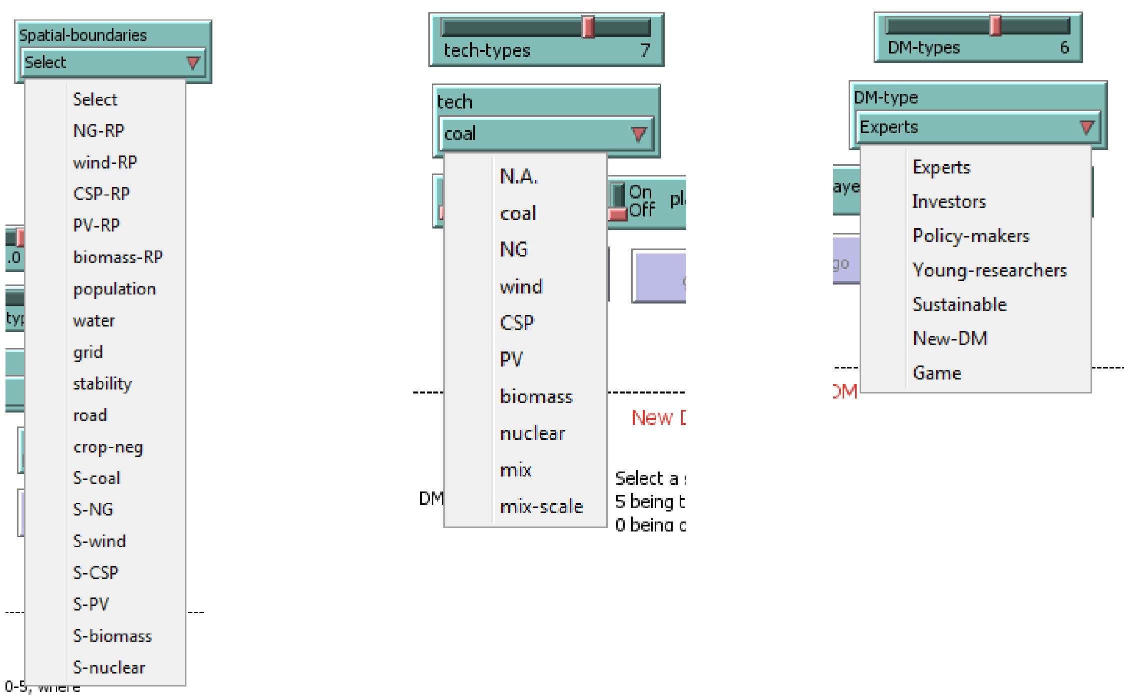


Figure 74: The expanded drop-down list buttons (from left to right: Spatial-boundaries, the technologies under assessment and the actors)

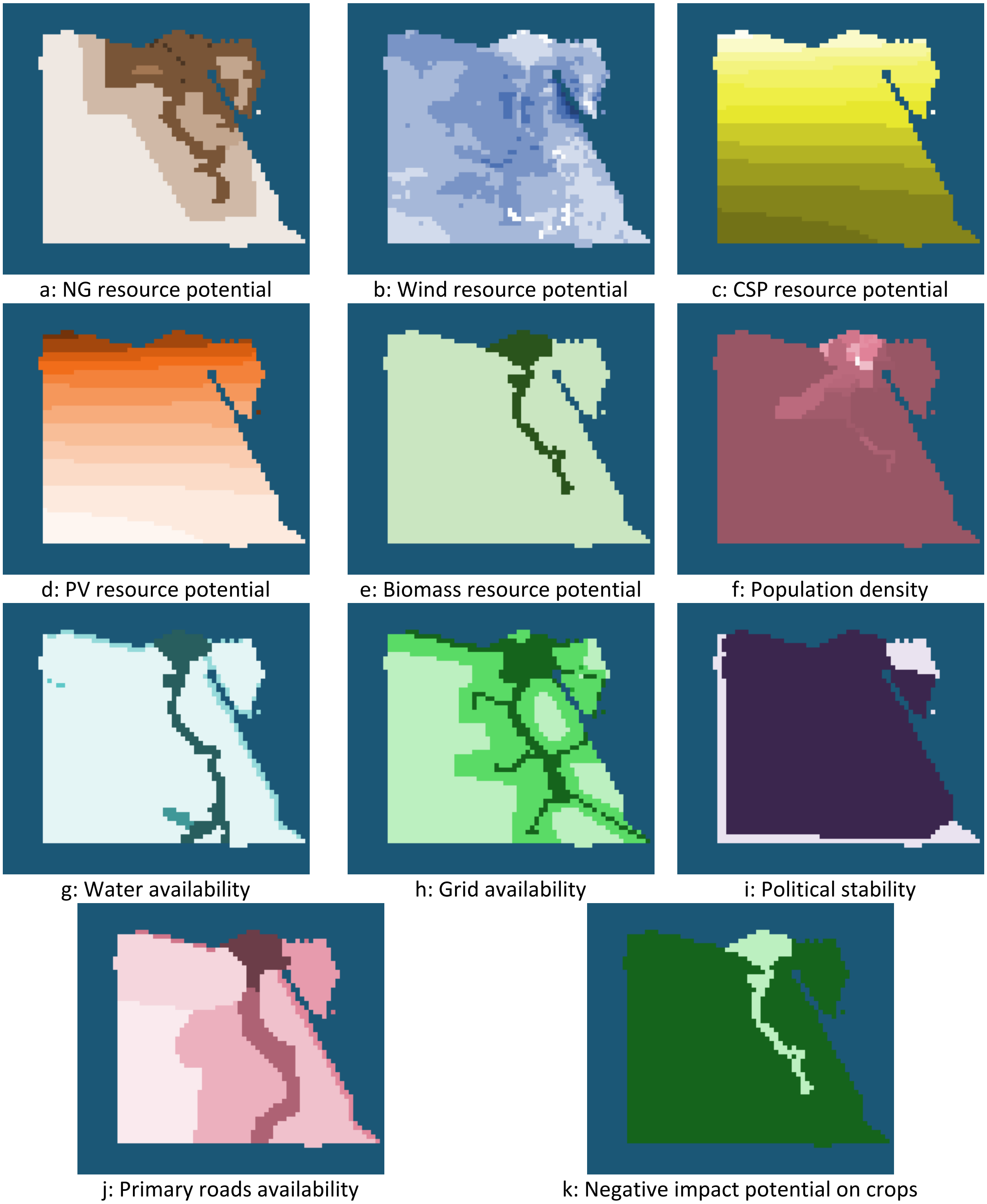
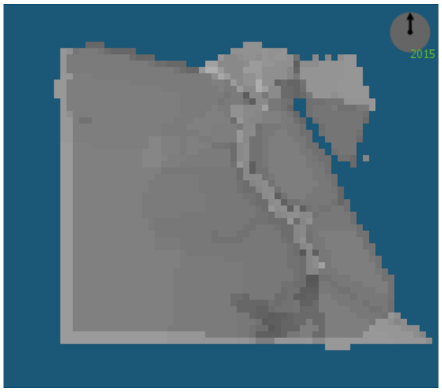
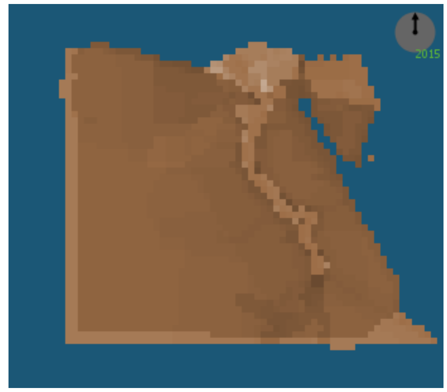


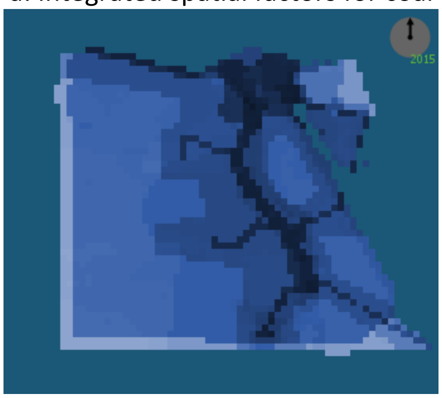
Figure 75: The individual spatial factors (a – k) as displayed on the view screen of Netlogo



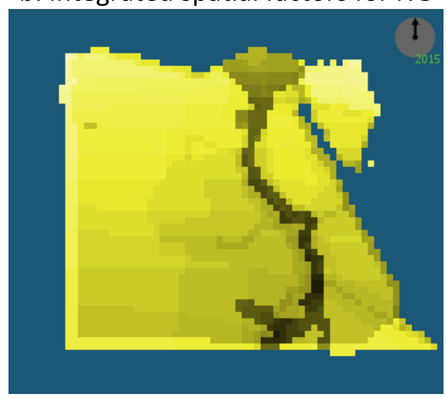
a: Integrated spatial factors for coal



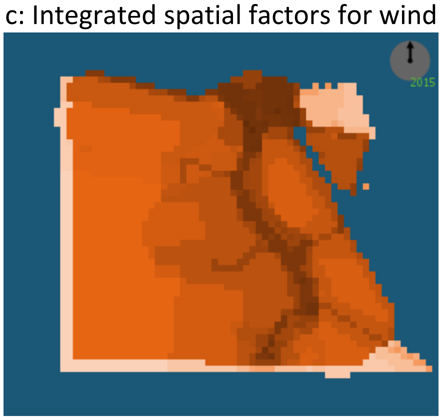
b: Integrated spatial factors for NG



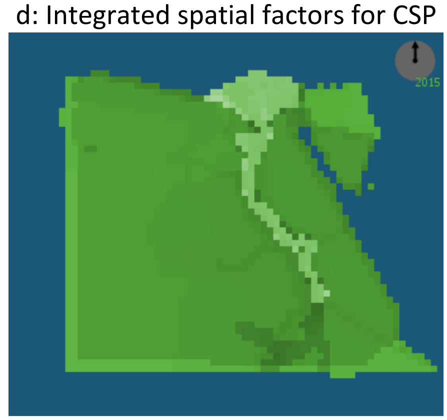
c: Integrated spatial factors for wind



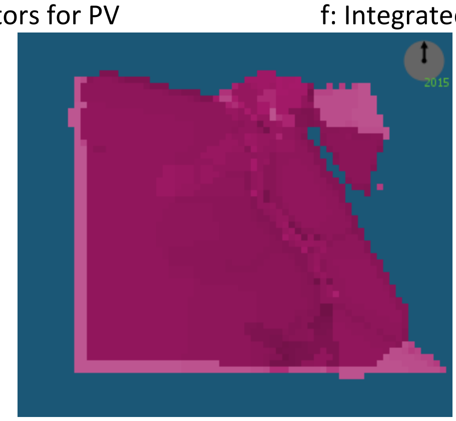
d: Integrated spatial factors for CSP



e: Integrated spatial factors for PV



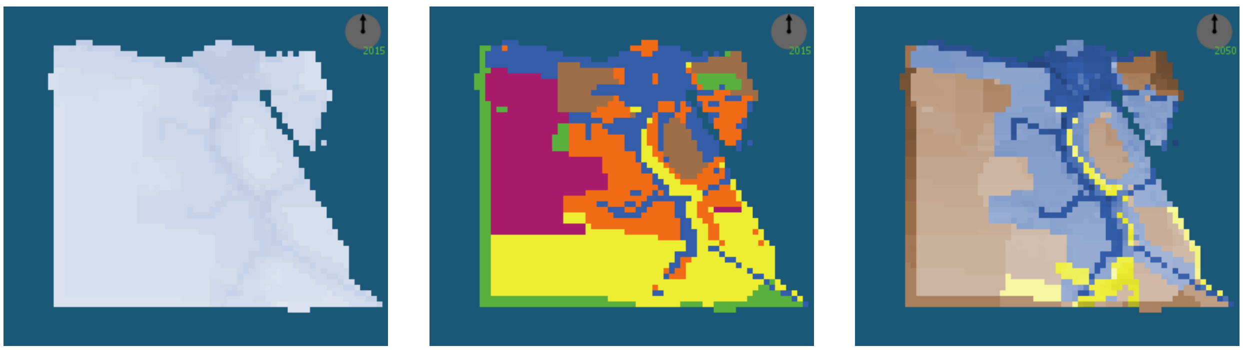
f: Integrated spatial factors for biomass



g: Integrated spatial factors for nuclear

Figure 76: The integrated spatial factors after applying the WSM for ranking the patches per technology (a – g)

Figure 77 shows the different visualizations of the landscape on the view screen when selecting one technology, mix item and mix-scale item from the tech drop-down menu. One should not be confused between the view screen of the integrated spatial factors and that of the priority of one technology type where in the former, one could identify the best location for a technology type, however in the latter, it shows the priority level for one technology across the spatial agents irrelevant to location ranking where each agent decides independently. In other words the integrated spatial factor for one technology is normalized over the whole map so that the sum of the values of the integrated spatial factor for one technology of all patches is 1. However, the sum of the values of the priorities of one technology of all patches is not 1 but the sum of the values of the priorities of all technologies in one patch is 1.



Wind item Mix item Mix-scale item

Figure 77: The different visualization possibilities on the view screen

In summary, I have four actors, one sustainable scenario, one test actor (New-DM) and the game scenario. For each of these previous actors/scenarios, I perform a landscape analysis of each technology separately across the map as in the wind item in Figure 77, or a landscape analysis of the maximum priority technology across the map either without or with scaling of the priorities as in mix item and mix-scale item in Figure 77, respectively. Therefore, 48 (8 x 6) analyses can be generated from the model without the sensitivity analysis which can be performed by the test actor and without the mix-scale analysis.

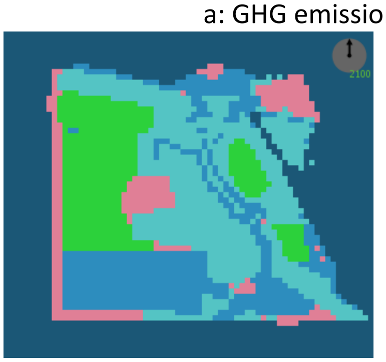
Some added features to this model can be activated through three switches: “GHG?”, “players?” and “improve?” as can be seen in Figure 72. When I turn on the “GHG?” switch button, then pressing setup or during running the model, the tech drop-down menu will select “N.A.” automatically so that the map view will display the GHG emissions of the priority-mix in each patch as a scaled turquoise color. This could be used for the analysis of GHG emissions of the spatial agents per each actor or of the sustainable or the game scenario. But again here I assume that each spatial agent will apply its priority of investment in the energy-mix scenario on the patch where it stands which is not the real case in Egypt. However, I took the average GHG emissions of all spatial agents of each actor so that one can conclude the potential negative impact on climate of the priority-mix of the technologies of each actor.

The “player?” switch button functions only in the game scenario where I use it to show the winners of the game in each patch instead of showing the winning technology. This is important for each player to know if his/her strategy in the assessment of the technologies will end up with winning the game or not and if the player wins, then for how many spatial agents or patches for each time step. The color codes for the players are as follows: Experts = red; Investors = pink; Policy-makers = cyan; Young-researchers = sky; Sustainable scenario = lime; New-DM = violet.

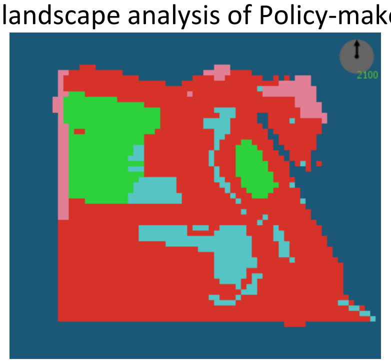
The “improve?” switch button plays a complementary role to the previous button where each of the actors could change the preferences of the sustainability assessment dimensions after turning on this button in order to apply a new strategy by which the player can improve the winning opportunities in some more patches in future time steps. This improvement as I mentioned before is directed towards getting a higher value of the maximum priority technology which is ultimately directed to a higher sustainability.

Figure 78 shows four examples of the role of these switch buttons depicted on the map view. As can be observed in figure a, the GHG emissions in some spatial agents of the policy-makers actor are greater than others. Figures b, c and d show a comparison of the game winners at year 2100. In figure b, the model runs normally with the basic initial inputs of actors’ preferences of the sustainability dimensions based only on 5 actors in the game. It can be observed that experts have a low winning coverage in the game where only few patches are colored red. In figure c, the improve button is turned on and I changed the experts preferences to the environmental and social dimensions. It can be observed that the red patches are overwhelming the map by this change. In figure d, I applied a new strategy where I run the model with 6 players which include the test actor (New-DM). I adjusted the preferences of the sustainability dimensions and the preferences of the technologies for the test actor to be the same like in the sustainable scenario. It is worth mentioning that the initial preferences of the technologies also play an important role in winning the game. Thus one actor could be the winner if a high initial preference is given to one technology. This technology will start with a high priority value but if its marginal value is low then its priority will be reduced till the more sustainable technology supersedes it. Thus, in the beginning of running model, the winning technology does not reflect the more sustainable one.

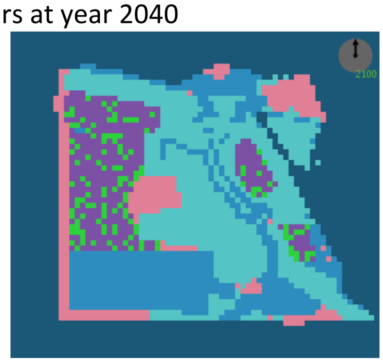
a: GHG emission landscape analysis of Policy-makers at year 2040



b: Players visualization at year 2100 under basic conditions of 5 players game



c: Players visualization at year 2100 with improvement of one player in 5 players game



d: Players visualization at year 2100 with two players having the same preferences in 6 players game

Figure 78: The role of switch buttons of the model

Figure 79 shows the control buttons of the model by which one can input the initial preferences of the sustainability dimensions and the technologies under assessment for the test actor (New-DM) on the left side. The preferences of the sustainability dimensions given by the four main actors can be modified through the buttons on the right side but only after turning on the "improve?" switch button. Generally, after pressing the setup button, the preferences of the sustainability dimensions for the four actors will be equal to the values obtained from the questionnaire. In order to change the values, first the improve button is turned on, then for each dimension for each actor a score could be given from 0 to 5. Zero score means no preference, while 5 score means the highest preference. After scoring each dimension, their weights will be directly calculated however it is not based on the AHP method but on dividing the score given to each dimension by the sum of all scores. The scoring can be changed at any time step which allows for a feedback control loop of improvement.

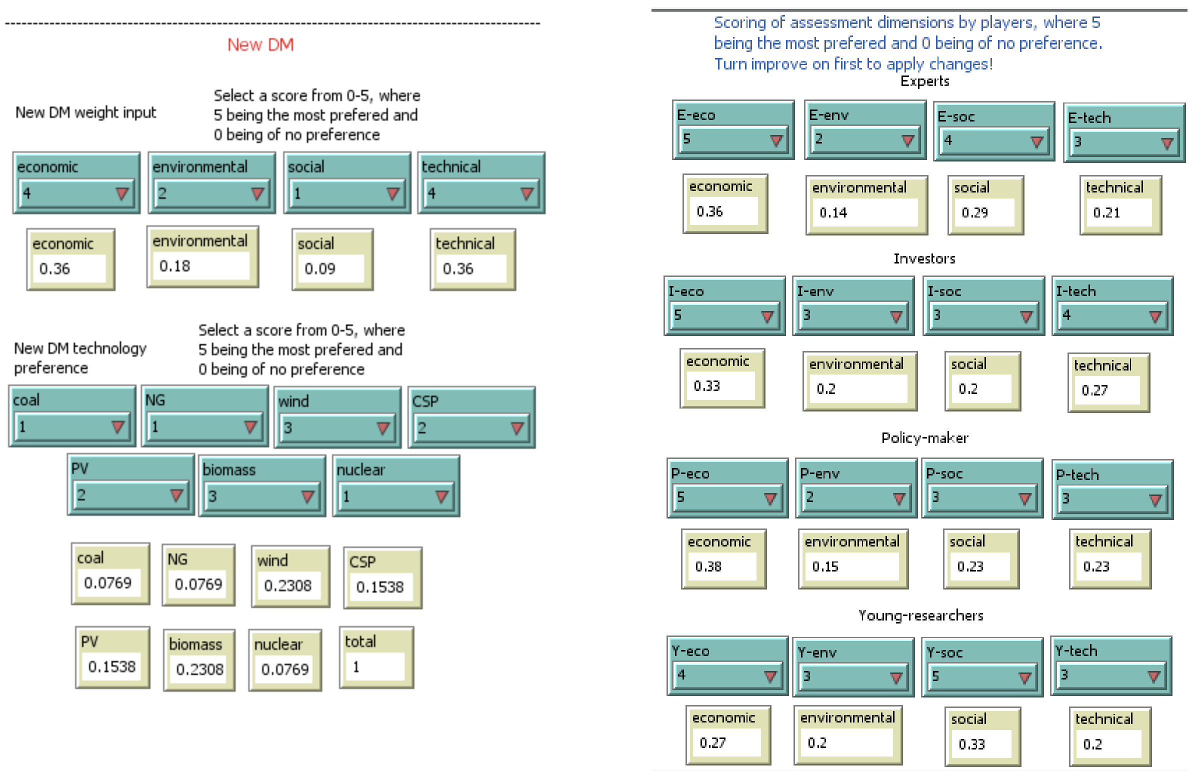


Figure 79: Specifying the initial preferences of the sustainability assessment dimensions and technologies by the New-DM (left side); changing the preferences of the sustainability dimensions by the four main actors (right side)

The view screen plays a role in the visualization of the spatial agents as they change their priorities of the technologies. However, in order to achieve my ultimate objective of the study which is to compare the energy-mix scenario by different actors for the whole country, I took the average priorities of all spatial agents of each actor for each technology and present these values on plots and on monitors.

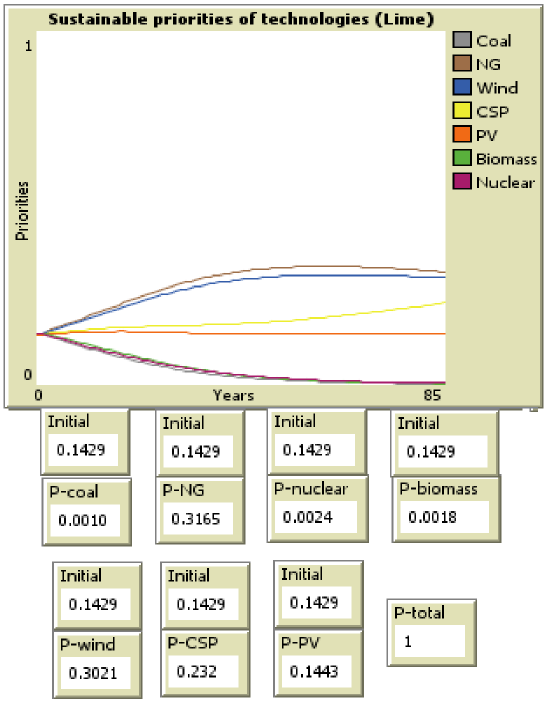
Figure 80 shows five types of plots that have been created in the model to help analyzing the results. Plot 80-a depicts the priorities of the technologies in the sustainable scenario changing with time which is done also for the other four actors, the New-DM actor and the game scenario. Below each of these plots, one can see several monitor boxes displaying the exact priority values of each technology. However, there are two values for each technology: a monitor named "Initial" which displays the initial priority value of the technology as obtained from the questionnaire and it does not change while the model is running; a second monitor below each of the initial named "P-<technology>" which displays the priority value of the technology at a certain time step taking into consideration the spatial factors and the multi-criteria assessment indicators. This latter monitor changes with time and corresponds to the plot line.

Plot 80-b compares the average GHG emission from the priority-mix scenario of each actor. It is calculated according to the following formula: $\frac{\sum_l P_q^l \times e^l}{\sum_l e^l} \times 100$, where for each actor q, the average priorities P_q^l of the technologies l is multiplied by the corresponding normalized values of the GHG emission e^l. The sum of these values is divided by the sum of the normalized values of the GHG emissions of the technologies and multiplied by 100 to get the percentage. This plot is important in comparing the negative impact on the climate between the scenarios of different actors according to the potential GHG emissions.

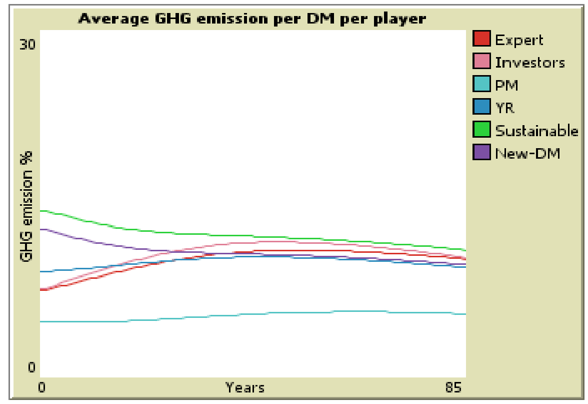
Plot 80-c is generated only in the mix or mix-scale items but with all types of actors. It shows the percentage of coverage of the spatial cells by the maximum priority technology changing with time. From this plot one can deduce the most predominant technology across the map for each actor type. For instance, in Plot 80-c at early time steps wind comes first constituting about 60% of the spatial DM, then comes CSP then PV. However, later NG spreads over PV and CSP. From this percentage, one can calculate the exact number of spatial DM that decided for which technology.

Plot 80-d and 80-e have the same principle of plot 80-c of showing the percentage of coverage of the spatial cells, however, Plot 80-d reflects only the game scenario where it shows the percentage of coverage of the winning actors not the winning technology. From this plot each actor can deduce in how many patches the actor win according to the actors predefined preferences and thereby controls the impact of changing the old preference. Plot 80-e is specific only with single technology analysis where it depicts the percentage of coverage of the spatial DM for one technology at 10 priority levels ranging from 0 – 1. From this plot one can analyze each technology priority distribution across the space for each actor type and predict the tendency of the priority for each technology.

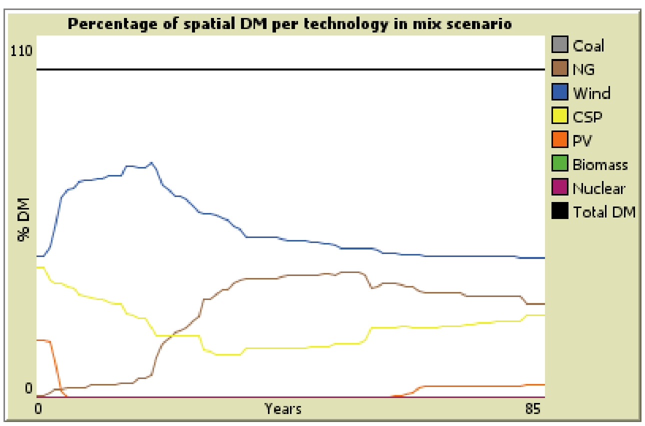
After presenting the main principle of the study, the input data and how it was collected and describing the methodologies applied to perform the analysis, the next section is concerned with elaborating the results of this study and comparing the different scenarios by different actors.



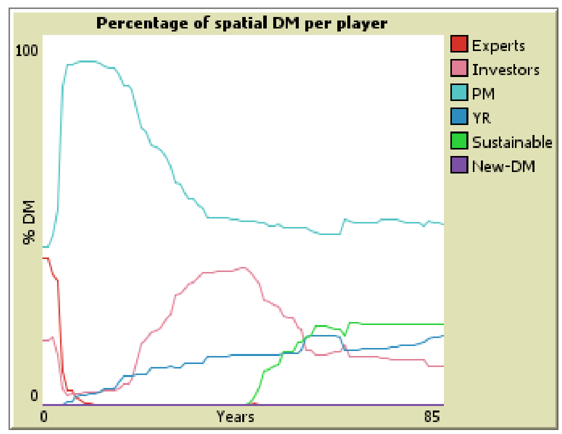
80-a: Average priorities of thetechnologies plot



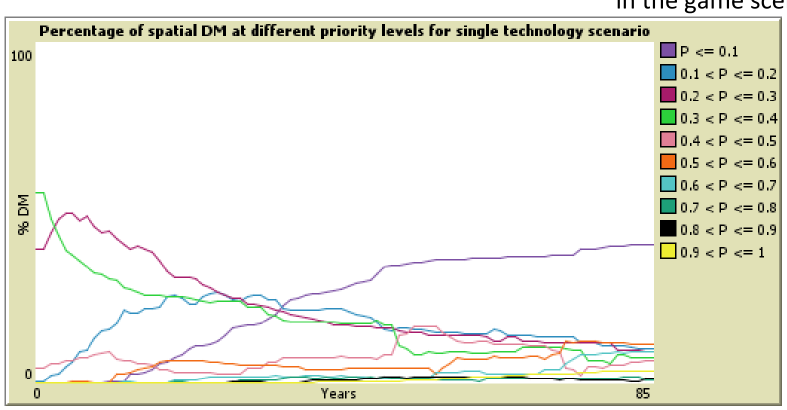
80-b: The average GHG emission comparison between actors plot



80-c: The percentage coverage of DM by the maximum priority technologies



80-d: The percentage coverage of DM by actors with maximum values of maximum priority technologies in the game scenario



80-e: The percentage coverage of DM at 10 levels of priorities for a single technology

Figure 80: The output plotting section of the model (a – e)

4. Results and Discussion

This section deals with four main topics. The first topic is concerned with the results of the questionnaire through applying the two MCDA techniques: the AHP which has been used in weighing the assessment indicators and in weighing the spatial factors; the WSM that integrated the values and the weights of the indicators to get the initial static ranking of the technologies. The integrated value from applying the MCDA does not reflect the priorities of the technologies but rather reflects a part of the marginal value where the complementary part is the integrated value of the spatial factors. Both integrated values play an important role in changing the initial preferences of the technologies and end up with the adaptive changing of the priorities of the technologies. Moreover, this part will present the results of applying the Monte-Carlo validation of the technology ranking. The second part is concerned with the results of integrating the three methodologies and applying the agent-based model in Netlogo. Actually, there are many outputs that can be generated and presented from this analysis; however I present only the most important ones. Additionally, from the priority of the technologies I generate the predicted energy-mix scenarios for all actors. The third part shows the spatial GHG emissions under different scenarios changing with time. The final sub-section compares the results of this study with the results of TARES study. The time analysis covers 85 years from 2015 till 2100, that's why I divided it into 5 periods for presenting the results. Therefore, year 2015 = initial state; year 2020 = short term planning; year 2040 = short-medium term planning; year 2060 = medium term planning; 2080 = medium-long term planning; 2100 = long term planning. The results include also a sensitivity analysis of four virtual actors where each of these actors has a preference to only one dimension of the four sustainability assessment dimensions. In other words, one actor with full preference to the economic dimension only, the second with full preference to the environmental dimension only, the third with full preference to the social dimension only and the fourth with full preference to the technical dimension only. However, they have equal initial preferences of the technologies.

4.1. Static multi-criteria decision analysis

After collecting the data from the questionnaire, I converted the answers into equivalent scores like the one used in the AHP method. Then, I applied the AHP methodology to get the weights of the individual indicators. Thereafter, I summed up the weights of the indicators of each of the sustainability dimensions in order to use it with the indicators that I used in my assessment. This is because, as I mentioned before, the indicators used in the questionnaire are not completely identical to those that I finally selected to perform the assessment. The weights of the sustainability dimensions per each actor are presented in Figure 81. In the sustainable scenario, the weights of the four dimensions are the same. All actors gave a higher weight to the economic dimension with a value exceeding 0.3 except for the young-researchers actor which gave a higher weight to the social dimension. For the actor "Experts", the social dimension comes in the second preference order, then the technical dimension and finally the environmental one. However, the actor "Investors" has the technical preference in the second position, then the environmental dimension and finally the social dimension, which seems to be a logic thinking of any investor. For the actor "Policy-makers", the technical and the social dimensions have the same weights occupying the second preference position then the environmental dimension comes in the last preference order. For the actor "Young-researchers", the preference of the economic dimension comes after that of the social dimension, then the technical preference is in the third position and finally the environmental dimension. It can be noticed that in all tested actors, the environmental dimension has the lowest preference as compared to the other dimensions except for the actor "Investors". Another observation is that the values of the weights of each dimension are not the same among the actors which reflects the individual variation of preferences among the actors although they belong to the same agent category of energy planning.

A second output of the questionnaire is the initial preferences of the technologies (see Figure 82) which are necessary as an initial input of the model. Again the sustainable scenario applies the hypothesis of unbiased analysis with equal preferences of the technologies. It has been found that all of the tested four actors show a higher preference to three renewable energy technologies which are wind, CSP and PV with different values and order of preferences between the actors. Investors gave completely no support to coal and nuclear. However, Policy-makers show some preferences to nuclear which is even more than that of NG and very close to PV. Young-researchers show some preferences to nuclear but at a lower extent than that of policy-makers and it is lower than that of NG. They justified this preference as a kind of diversification of supply and gaining experience of the technology from the point of view of energy security. Experts, investors and young-researchers show a considerable preference to NG as a fossil fuel resource but all actors have a very low preference to coal. There is no preference to biomass by all actors since it was not included in the questionnaire. However, I applied it in the sustainable scenario.

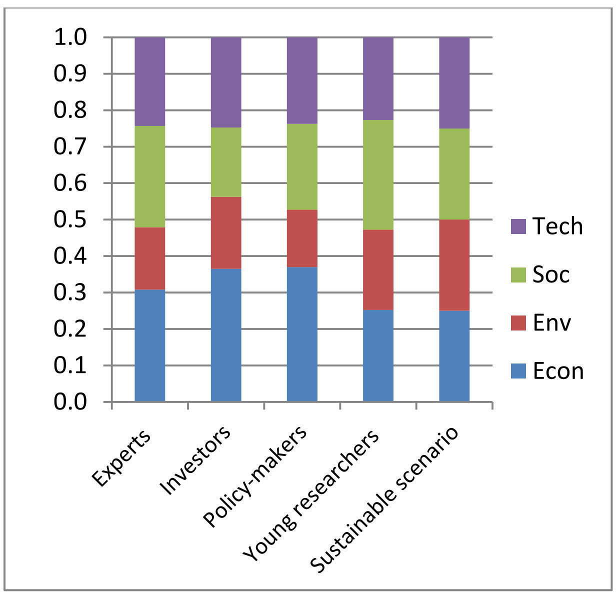


Figure 81: The weights of the sustainability dimensions per actor

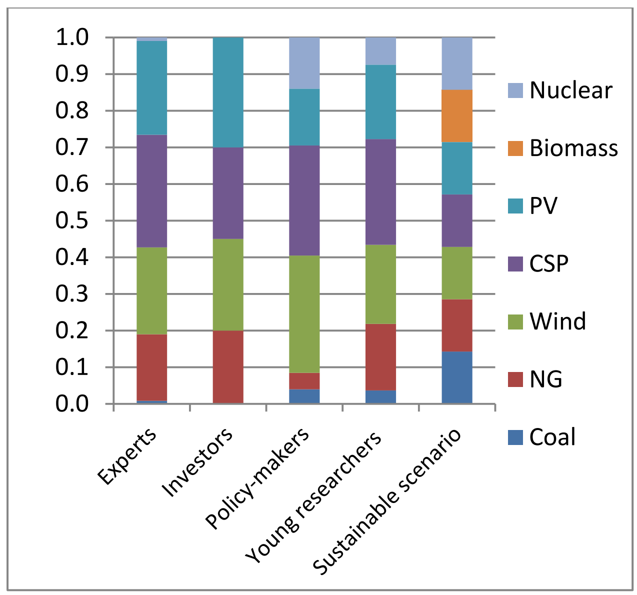


Figure 82: The initial preferences of the technologies per actor

By distributing the weights of the sustainable dimensions on the used assessment indicators and integrating them with the normalized values of the indicators using the WSM, I was able to get a general sustainability index of each technology per actor type covering the subjective and objective analysis. The values of these indices for each technology per actor are shown in Figure 83. From these indices, I ranked the technologies in a ranking order from 1 – 7, where 1 is the highest general integrated sustainable index technology as shown in Figure 84. The difference between the general sustainable indices of the technologies as well as the rankings of the technologies across the actors, although very small, exists. However, this analysis will be significant in extreme preference condition as will be shown sooner. All actors including the sustainable scenario ranks NG as the highest sustainable technology followed by wind. CSP and PV occupy the third and fourth ranking according to the actor type. Although in the sustainable scenario, biomass constitutes the fifth ranking position, three of the tested actors ranked coal in the fifth place before biomass. However, the general sustainable indices of both coal and biomass are very close. Moreover, all actors show nuclear as the lowest ranking technology in the seventh position except for the sustainable scenario which ranks coal at the lowest position after nuclear.

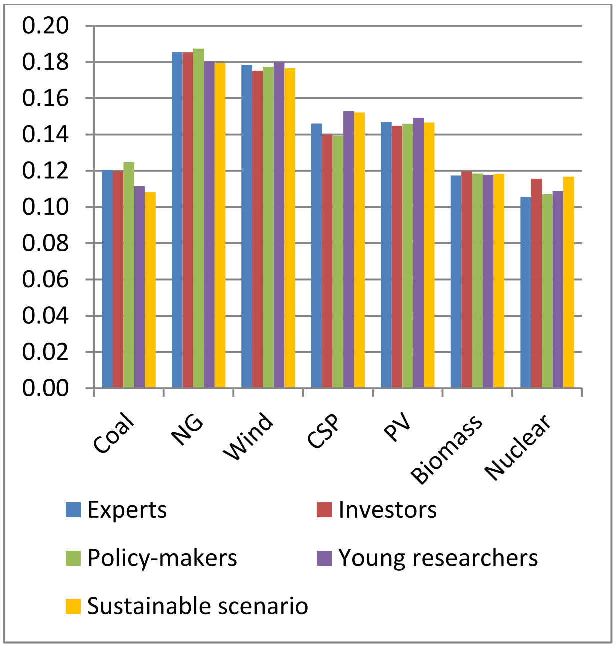


Figure 83: The integrated general sustainability indices of each technology per actor

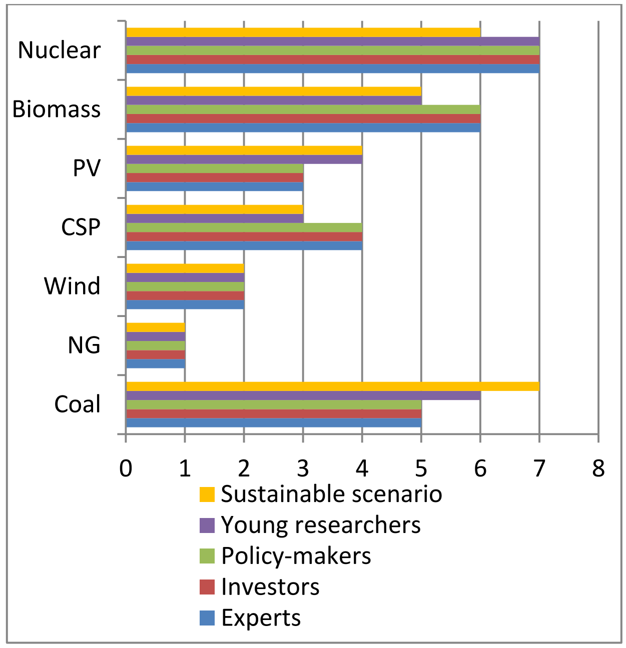


Figure 84: The ranking of the technologies per actor (1 being the highest rank)

The results of the validation of the ranking of the technologies by the tested actors using Monte-Carlo simulation methodology over 1000 random simulated observations are shown in (Figure 85 – Figure 88). The color codes reflect the ranking order of the technologies with 1 being the highest rank technology. The charts compare the probability of the resulted technology ranking from the small sample of the contributed individuals in the questionnaire with the simulated probability. The figures show that the simulated probability of technology ranking conforms to the probability of actual ranking. This methodology could be also applied to assess the uncertainty of the results due to the wide range of the values of some assessment indicators.

In order to examine the impact of the weights of the sustainability dimensions on the values of the general sustainability indices and the ranking of the technologies, I performed the MCDA analysis again with four virtual actors. Each of them has a preference to only one of the sustainability dimensions. This is applied also in the agent-based model to see the change in the priorities of the technologies through these virtual actors. This step shows the correlation between the technologies and the sustainability dimensions.

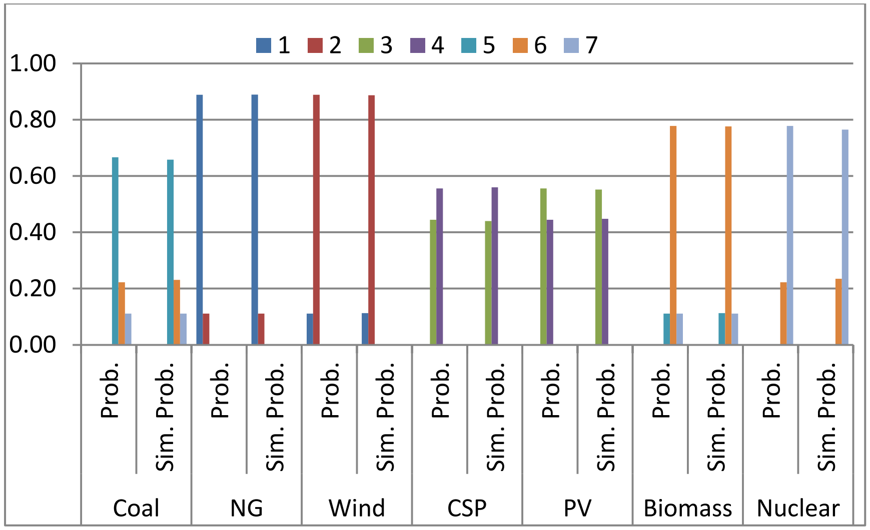


Figure 85: Monte-Carlo results of ranking of the technologies by Experts

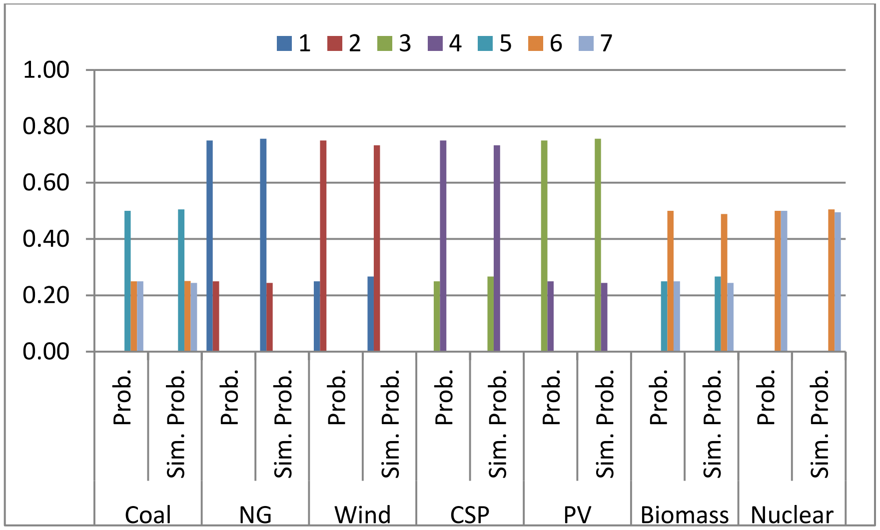


Figure 86: Monte-Carlo results of ranking of the technologies by Investors

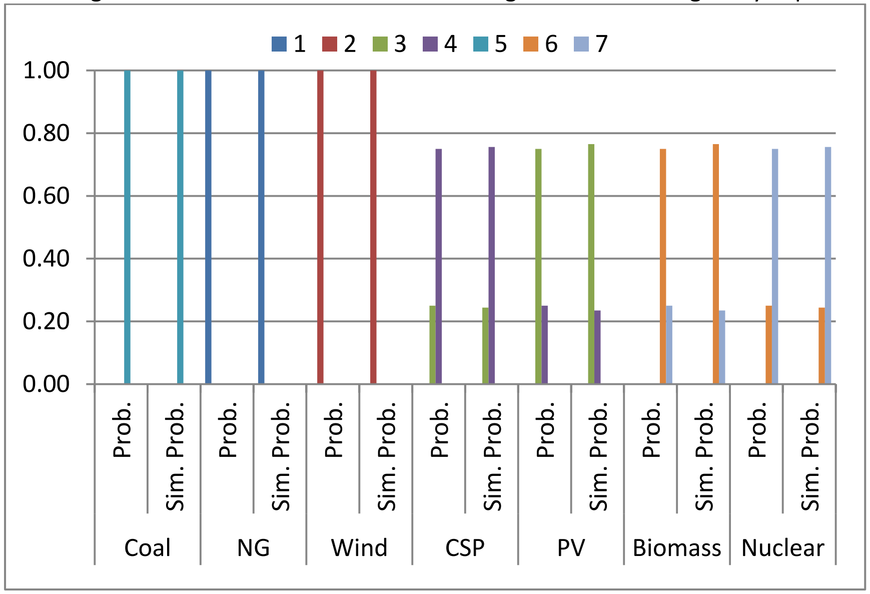


Figure 87: Monte-Carlo results of ranking of the technologies by Policy-makers

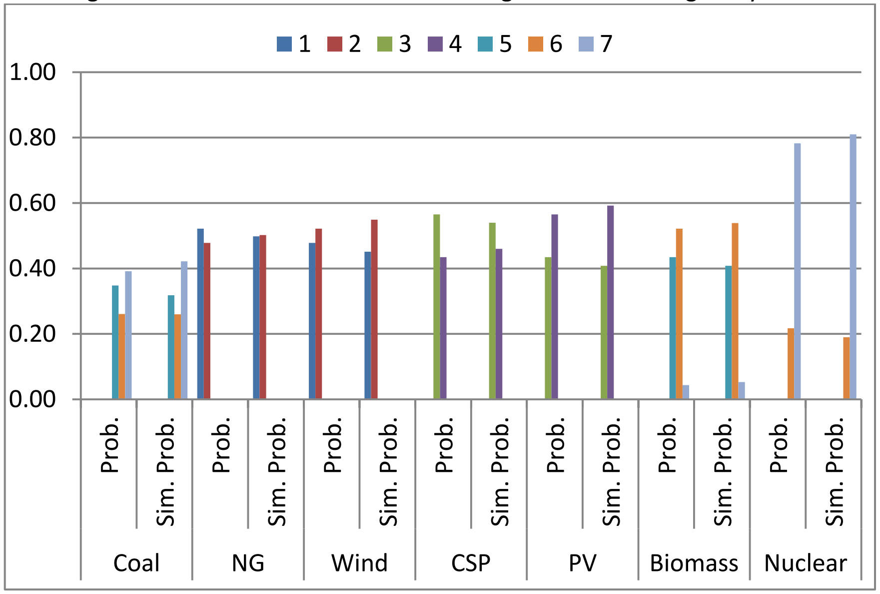


Figure 88: Monte-Carlo results of ranking of the technologies by Young-researchers

Figure 89 shows the general sustainability indices of the technologies with a single sustainability dimension analysis as compared to the sustainable scenario, whereas Figure 90 shows the ranking of the technologies resulting from these indices with 1 being the highest rank technology. Figure 90 shows that actors with only economic, social or technical preference rank NG followed by wind as the highest ranking technology which is not the case with environmentally oriented actors who rank NG in the fifth position and wind in the first position. Economically and technically biomass represents the last ranking technology, while environmentally and in the sustainable scenario, coal is the last ranking technology, however, nuclear is the last ranking technology by socially oriented actors. From this analysis one can deduce the technology to which one most probably will be directed, when one changes the preference to a certain sustainablility dimension. Moreover, it explains the degree of cooperation or conflicts that could results from a group of actors with different assessment preferences while deciding in technology selection or investment allocation in technologies. For instance, the environmental actor could have strong conflicts with the other actors in selecting NG which will not be the same degree of conflicts in case of wind since the ranking difference is not too much.

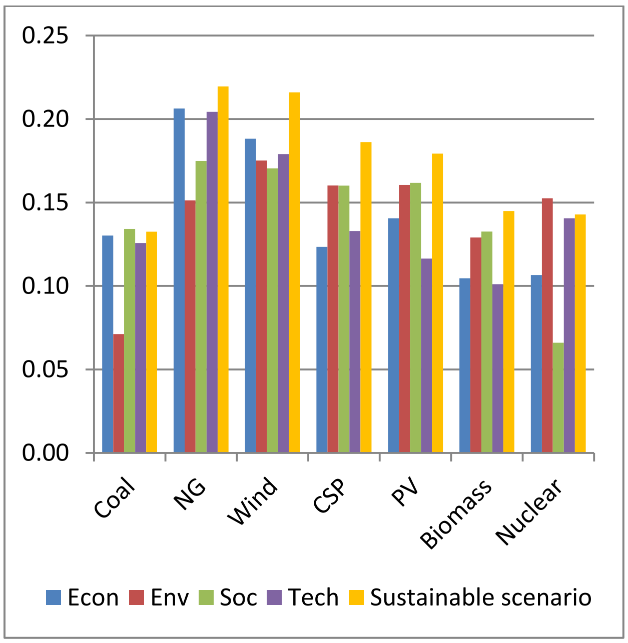


Figure 89: The integrated general sustainability indices of each technology with single sustainability dimension preference

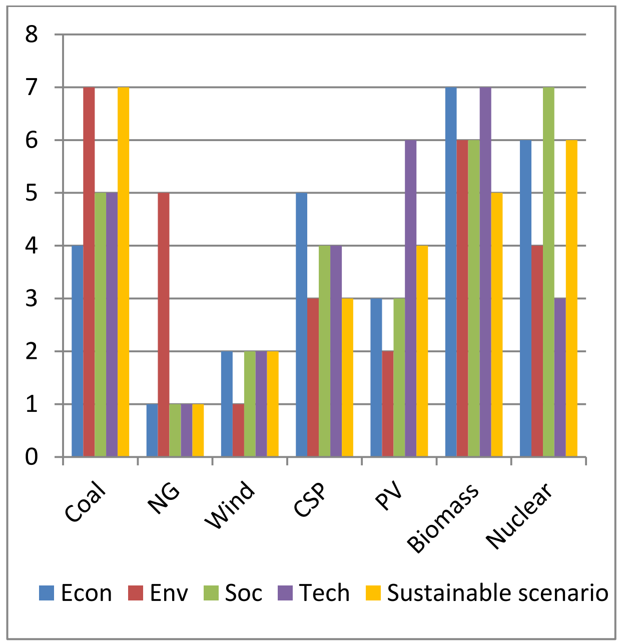


Figure 90: The ranking of the technologies after applying a single sustainability dimension MCDA

These previously resulted MCDA indices are used partly in my model in identifying the marginal value by which actors change their priorities towards the technologies with time. However, they are presented here to set up the static ranking of the sustainability of the technologies in Egypt in a general concept without considering the time and space impact on changing the values of the assessment indicators. Regarding the temporal effect, the time function equations for some indicators are integrated into the model instead of using a constant value. Regarding the influence of the spatial factors, the values of the spatial factors have been investigated and presented in section 3.2, whereas the second important issue to be included is the weights of these factors according to technology type since some factors are of low importance to some technologies while they are of a very high importance to other technologies. For example the resource potential as a spatial factor has a very high importance to solar- and wind-dependent technologies as they cannot be imported or even transported from one place to another. However, for fossil fuel resources as well as nuclear technology, the resource potential is not of that much importance since they can be easily imported but this will add some costs. Figure 91 shows the weights of the spatial factors per technology according to the results of applying the AHP methodology based on my own assessment. So here the factors are pair-wise compared for each technology type.

It can be observed that coal, NG and nuclear give more importance to the population density, the negative impacts on crops and the political stability because it is advisable for these types of power plants to be installed apart from the populated and the farming areas as well as away from any areas with a high susceptibility to any kinds of attacks. For wind and CSP, the resource potential factor has the highest weight whereas for PV, the political stability has a high importance as compared to the other factors. Grid availability is also important to wind while water availability shows more importance to CSP in comparison with other technologies. Although it is advisable to install biomass power plants near to the biomass resources which mostly come from agricultural and animal wastes, the negative impacts on crops due to GHG emissions should be considered to some extent. As I mentioned, these analysis of the spatial factors weights are justified based on my own perspective which might be different from other analysts. Thus, they should not be considered as standard weights.

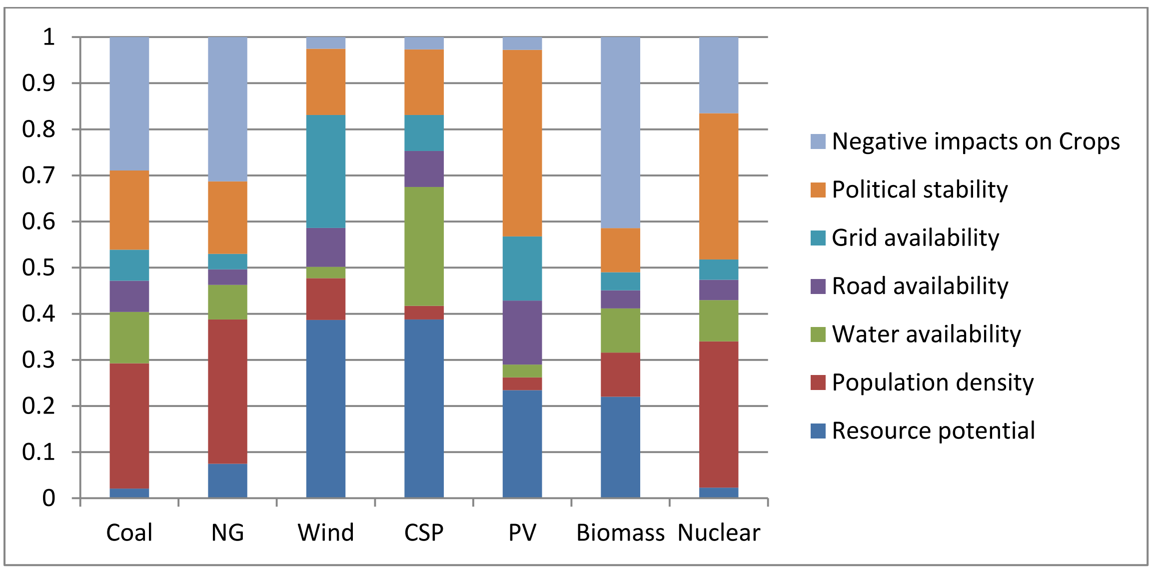


Figure 91: The weights of the spatial factors per technology

4.2. Simulation and assessment of energy landscape under different scenarios

In this section I present the results of integrating the three methodologies in Netlogo. I investigate several possible scenarios which will be basically classified according to the actor type. Therefore, I have four tested actor types which are experts, investors, policy-makers and young-researchers. Moreover, I have another four virtual actors representing a single sustainability dimension oriented actors which are economic, environmental, social and technical actors. Each of these two four-actors-groups will be compared to the sustainable scenario which has equal weights of the sustainability dimensions and will be compared also to the game scenario. The first game scenario reflects the interaction between the four actual actors and the sustainable scenario. The second game scenario reflects the interaction between the four virtual actors and the sustainable scenario. So according to actor's classification, I have 11 possible scenarios. For each of these actor-based scenarios, I analyze the change in priorities of the spatial DM for each of the seven assessed technologies, the change in the average priorities of each of these technologies over the whole country, the predominance of the highest priority technology across the spatial DM, and the winning actor type in the game scenario across the spatial DM. In the next subsection, I present the GHG emissions from the priority-mix decided by the spatial DM. All these analyses could be done at different adaptation rates (alpha) (alpha), however, I present here only the results at α = 1.

4.2.1. The average priorities of the technologies

Figure 92 compares the adaptive change in the average priorities of the technologies across the four tested actors, the sustainable scenario and the game scenario of this group throughout the years 2015 – 2100 (i.e. 0 – 85 time steps in Netlogo). In the scenario of experts, it can be observed that the model starts with the highest average priority to CSP followed by PV, wind and NG which matches with the initial preferences of the technologies. One should not be confused with the ranking obtained from applying the MCDA with the priorities of the technologies because the general sustainability indices of the technologies obtained through the MCDA is the driver of changing the priorities of the technologies. However, this initial priority corresponds to the results of the preferences of the technologies that obtained from the questionnaire but after considering the local spatial factors. Nuclear and coal are almost of zero priority throughout the run period of the model for both experts and investors, however, they started in the policy-makers and young-researchers scenario at a small level above zero but again they decrease drastically approaching zero. In general, there is a gradual increase in the priorities of both wind and NG which starts to decrease again after approximately 40 years with an opposite pattern to both CSP and PV. This implies that the potential tendency towards both CSP and PV will start after 2050 giving less attention to wind and NG by these actors. However, this changing pattern exists at different levels between actors.

In the scenario of policy-makers, the priority of wind is higher than that of other actors showing a more affinity towards this technology. This scenario also shows a lower priority curve of NG than that of CSP and PV. In the sustainable scenario, the priorities of wind and NG are almost coinciding whereas for CSP and PV, they bifurcate starting from the middle of the model running period showing an increasing trend to CSP and a decreasing trend to PV but at a lower rate than that of CSP. Since the initial preference of biomass for the test actors was zero, therefore it will remain zero constantly while running the model, but this is not the case with the sustainable scenario where biomass is set up at an equal preference like that of all other technologies. For this reason, the priority of biomass can be seen clearly in the game scenario above zero level. This has been done by selecting the maximum priority value of biomass between the five actors in each cell which will be in this case for the sustainable scenario, then taking the average of these values over all cells and finally normalizing it over the sum of the average maximum priority of other technologies. This applies similarly to nuclear which justifies the considerable priority of nuclear in the game scenario that seems to be negligible in other actors. However, wind, NG, CSP and PV in the game scenario follow the same pattern like in other scenarios. These priority measures are to be used in projecting the future energy-mix scenario in Egypt from the perspectives of different actors and scenarios as will be shown later.

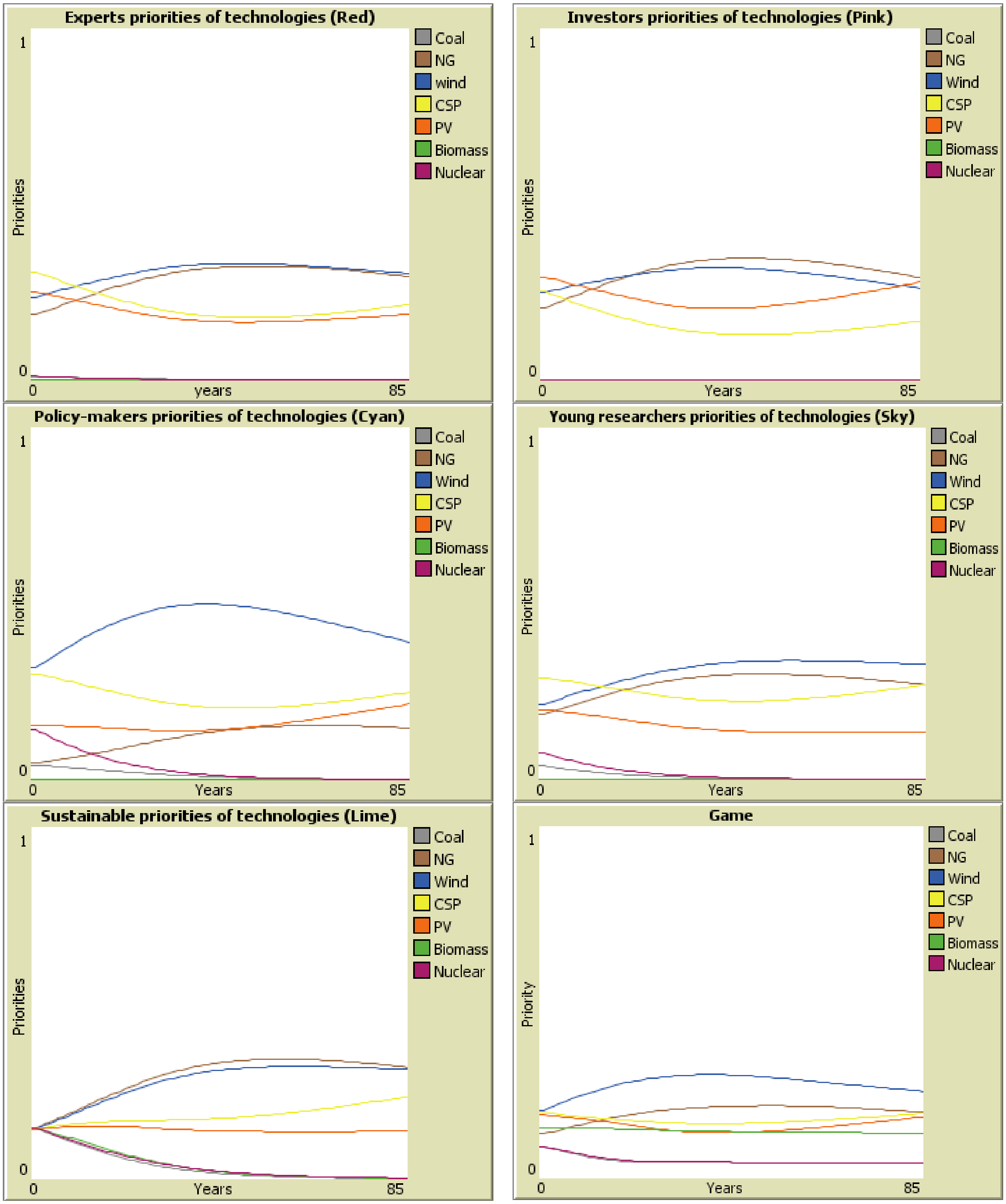


Figure 92: The average priorities of the technologies per actor type changing with time

4.2.2. Single technology analysis

The analyses of the change in the landscape of each of the assessed technology by each actor are shown in Appendix G. The analyses show the percentage of coverage of the cells at 10 levels of priorities and the map view of the energy landscape in 2020 and 2100 for NG, wind, CSP and PV. However, I do not show the results of coal, biomass and nuclear, since their priorities across the cells do not exceed 0.1 over the running period. This analysis is important in investigating the spatial agents of one actor where they show different priority levels to the same technology, although they start with the same initial preferences of the technology and the sustainability dimensions.

4.2.3. Energy landscape analysis

Figure 93 elucidates the percentage of spatial DM (cells) with the maximum priority technology in the four tested actors scenarios and in the sustainable scenario (a – e) changing with time. In the game scenario (f), the plot shows the percentage of spatial DM having the maximum priority technology across the five actors in each cell. Figure (g) is an exported version to an excel sheet from Figure (f) so that the scale of the axis is more visible and understandable.

In the “Experts” scenario, CSP starts with a predominating priority in almost 80% of the spatial DM having the rest being distributed between PV, wind and NG showing PV coverage exceeds that of wind by two times. As the model runs, the percentage of CSP decreases till it reaches 13% coverage after about 35 years (at year 2050). Then, it starts again to increase after 70 years (at year 2085) till it covers almost 25% of the map. The wind and NG coverage increases with time till each of them reaches about 40% coverage after approximately 35 years. Wind reaches this level at an earlier time step and remains almost constant, however, NG reaches this level at a later time step and starts to decrease when CSP starts to increase ending up with about 30% coverage. PV coverage jumped to some few percentages at a short duration then it decreases soon again till it disappears from the map for a long period then it covers about 3% during the last 10 years. This analysis shows the influence of the spatial factors on the priorities of the technologies since in the previous example; I have the same actor with the same assessment preferences in all spatial cells that represent the spatial DMs, however, the maximum priority technology is not the same between these spatial DMs.

In the “Investors” scenario, the landscape starts with about 85% coverage with PV while having the rest being distributed between CSP, wind and NG. However, this enormous coverage comes to zero after about 20 years (at year 2035), whereas the coverage of NG and wind increases simultaneously covering 50% and 44% of the cells, respectively. CSP remains at a coverage of about 4% till approximately year 2073. After this year, the technology coverage starts to change again where NG decreases to the wind coverage level, then both decreases together until NG covers 36% of the cells and wind covers 26% of the cells. At the same time CSP and PV start to increase gradually, where the former reaches at the end of the model run 10% while the latter reaches 26% coverage.

In the “policy-maker” scenario, the landscape performs in a different way than that of the previous two scenarios. Instead of starting with an overwhelming coverage of one technology, the scenario starts with close percentage coverage between CSP (40%) and wind (60%). The coverage of wind increases at a slow rate with time while it decreases for CSP until after 35 years they behave in opposite way but with keeping wind at a higher coverage percentage than CSP till 2100. NG coverage starts after about 20 years with only 2% coverage and increases gradually till it reaches 7% at year 2100. PV coverage starts to increase after about 60 years at a high rate for about 10 years. Then, the rate of increase of PV coverage slows down ending up with almost 20% coverage.

In the “Young-researchers” scenario, the landscape starts with CSP coverage of about 85% and 10% coverage of wind with remaining 5% distributed between NG and PV. While the CSP coverage decreases as the model runs, the wind and NG coverage increases until reaching an equilibrium with a predominating wind coverage of 43%, NG coverage of 33% and CSP coverage of 23% after 25 years. This equilibrium lasts with this approximate coverage distribution till 2090 where the priority of CSP exceeds over that of NG in about 7% of the cells. The PV coverage is very low to be considered.

In the “sustainable” scenario, the landscape starts with a balanced mix including all technology types except coal. This is because the priorities are affected only by the spatial factors without including the technology assessment at the setup step. However, this distribution changes drastically after the model runs showing abrupt drop of biomass, PV and nuclear coverage leaving the landscape with major coverage by NG, wind and CSP at a value of 51%, 40% and 9%, respectively. After 50 years CSP takes place of some of the NG-predominated cells ending up with 33% NG and 23% CSP coverage and almost no changes in wind coverage.

In the “game” scenario, the landscape starts with approximately 40% coverage by wind, 40% coverage by CSP and the remaining 20% is covered by PV. The priority of wind exceeds over that of PV in some cells at a very short time and also exceeds that of CSP but over a longer period till it reaches its peak coverage of 70% at 2032, then NG priorities starts to get over that of wind in some cells. This occurs also with CSP where its coverage increases again gradually after it was decreasing.

In this type of analysis, I would like to add some remarks. First, it assumes that each DM (cell or patch) decides independently on which technology to supply its demand, to be installed or which energy-mix will be present at that cell. This is not a practical application in the energy planning especially in Egypt where a centralized electricity grid is applied. This means that the government assesses the possible technologies generally, and then it checks for the best location for installation for the selected technology. In my analysis, I include the spatial and temporal assessment of the technologies as I explained in Figure 92. However, from this landscape analysis, if one of the actors first selects the location for any reason and this actor wants to know the best technology to be installed at that location at a certain time step, then, in this case, this analysis will help. The second remark is that the energy demand in Egypt does not need to be supplied through the overall coverage of the land. This means that when I have 80% CSP coverage, this does not mean that in all of these cells the CSP technology should be installed but it reflects only the maximum priority in these cells. A third remark is that the spatial agents of all actors show a high affinity to three main technologies which are wind, CSP and NG but at different coverage levels across the actors. The map visualization of energy landscape in an interpretation of the previously explained plots in Figure 93 showing the maximum priority technology across the spatial DMs for each actor at year 2015 and 2100 are presented in Figure 94 and Figure 95, respectively.

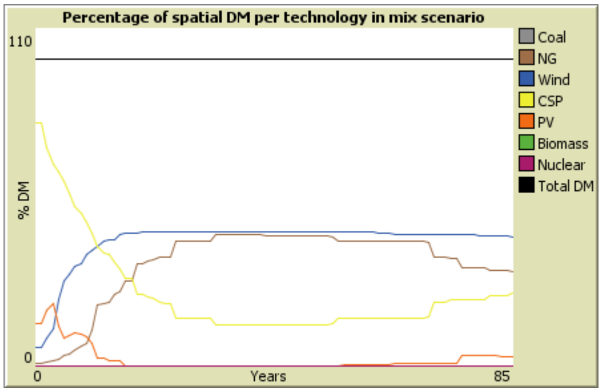


Figure 93-a: Experts

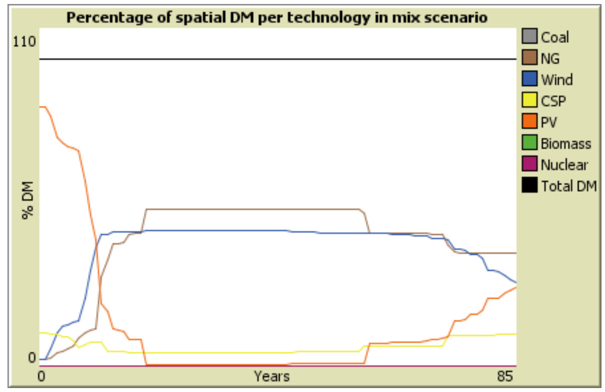


Figure 93-b: Investors

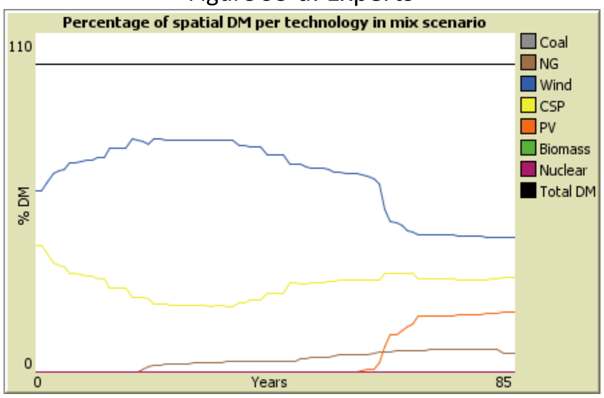


Figure 93-c: Policy-makers

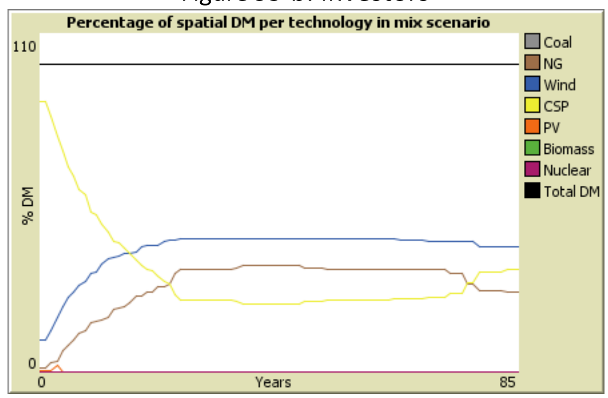


Figure 93-d: Young-researchers

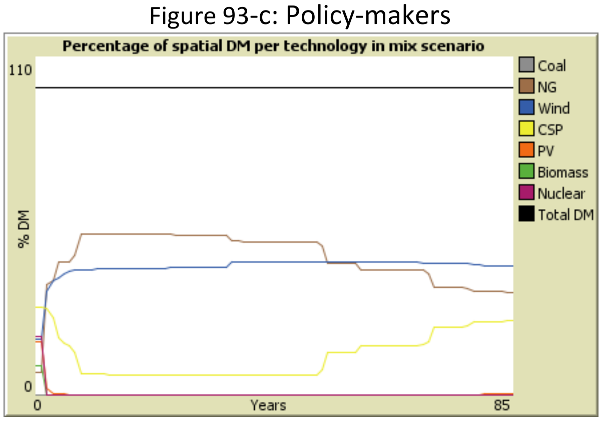


Figure 93-e: Sustainability scenario

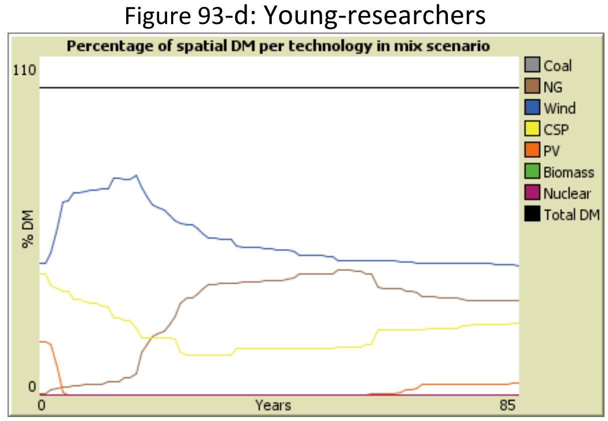


Figure 93-f: Game scenario

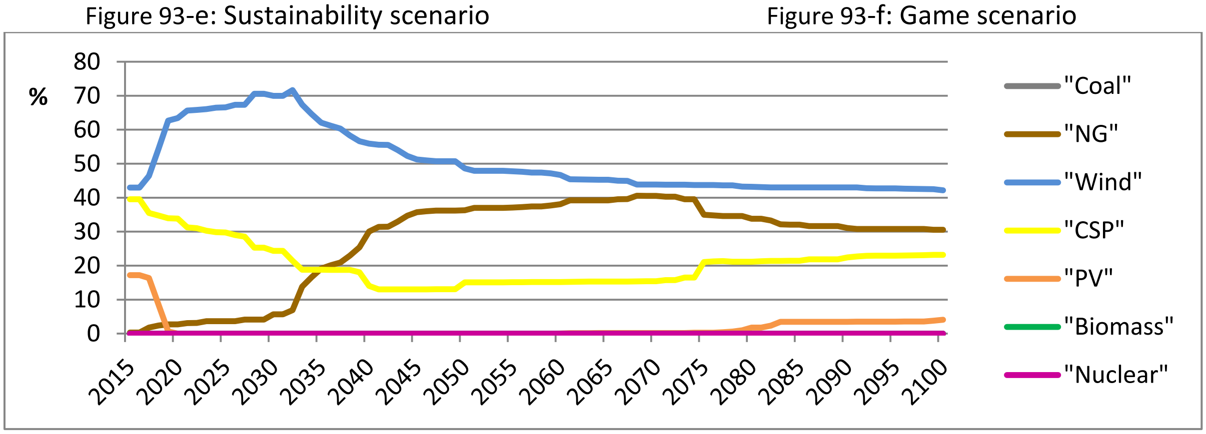


Figure 93-g: Game scenario exported to Excel

Figure 93: Percentage of DM patches having the maximum priority technology per each actor type (a – g)

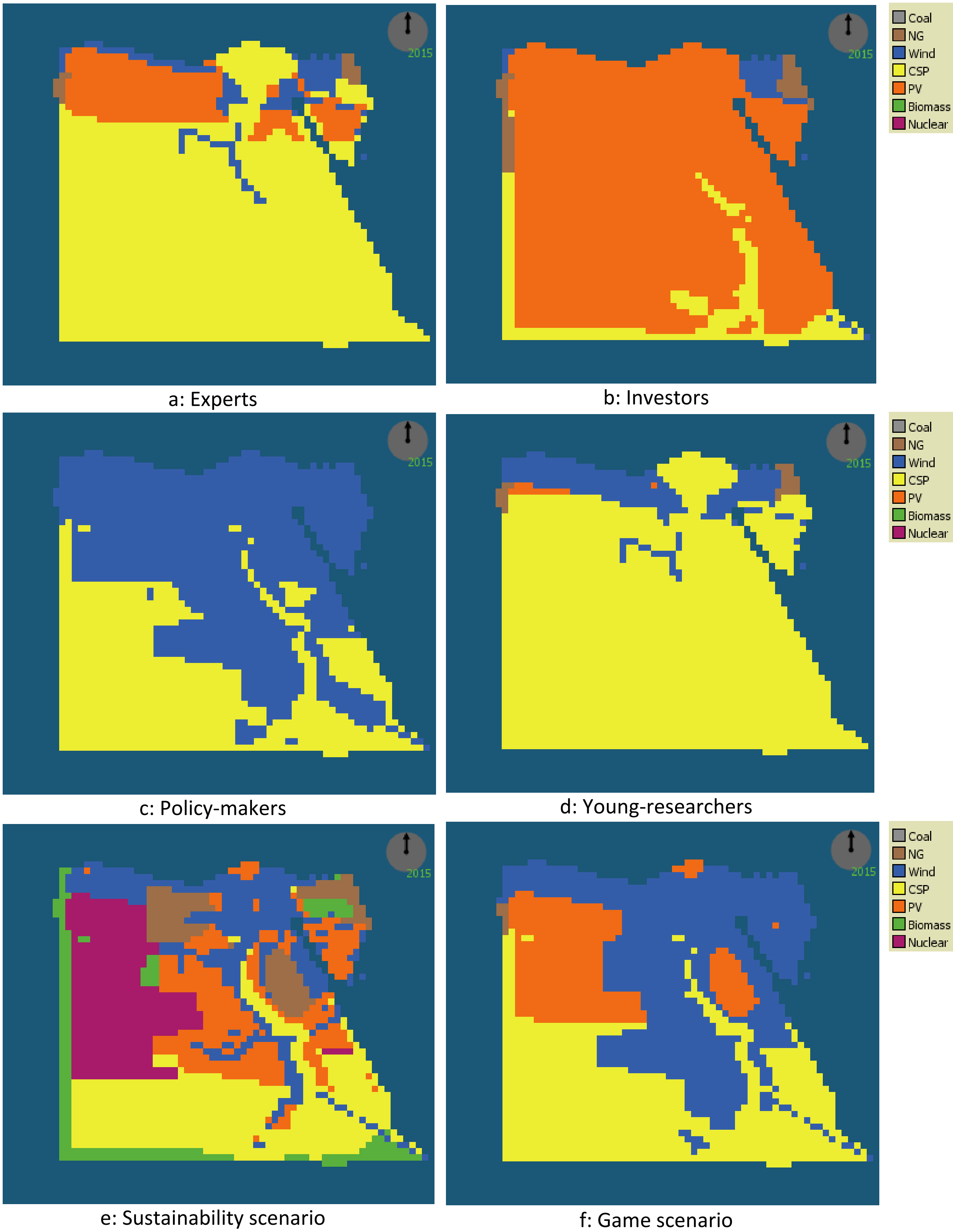
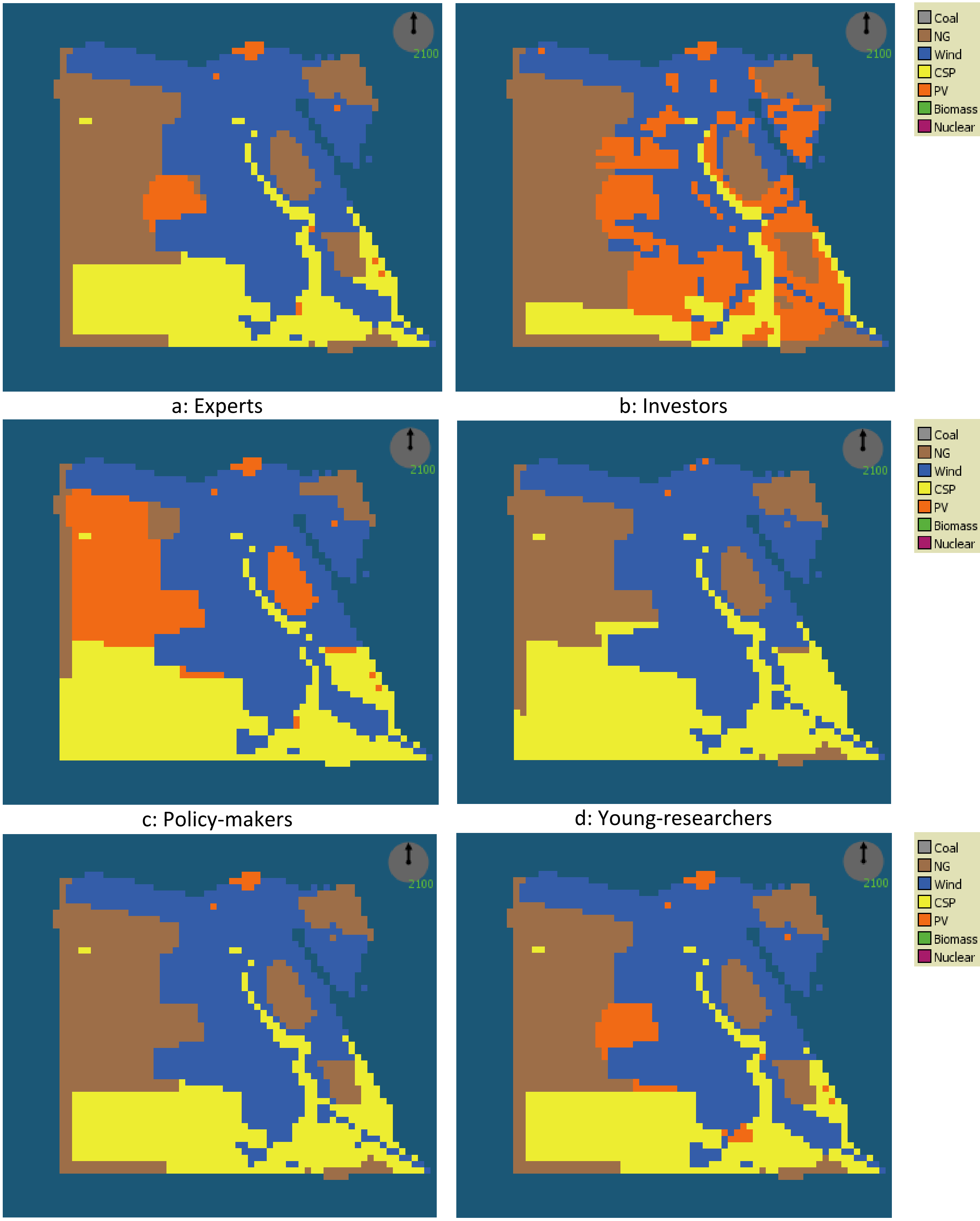


Figure 94: The map view displaying the maximum priority technology per actor type (a – f) at year 2015



a: Experts b: Investors

c: Policy-makers d: Young-researchers

e: Sustainability scenario f: Game scenario

Figure 95: The map view displaying the maximum priority technology per actor type (a – f) at year 2100

4.2.4. The game scenario

In the game scenario, each actor has set up an initial preference of the sustainability dimensions and played the game with a probability of winning or losing the game in each spatial cell. In order to control the compliance of each actor strategy with the results in the game scenario, there are several possibilities. The first is to compare the average priorities of the technologies of the actor with those of the game scenario. The second is to compare the landscape coverage percentage of each technology of the actor with that in the game scenario. The third is to compare the map view of the energy landscape of the actor with that of the game scenario. In each step each actor can observe how much deviation exists from the actor's plan. These ways are useful in conforming to the main target of the game that is concerned with the energy technology to be selected where the winning actor could select the same technology as another losing actor who "loses" the game because of a lower priority value of that technology. According to this logic conflicts between the actors can be avoided. However, if the game runs subjectively, where each actor is concerned with just winning the game even if two actors have the same selected technology, as in a tendering process, then there will be strong competition. In order to visualize the winning actor in each spatial cell, the "players?" button should be switched on. Moreover, the "improve?" button could be switched on, so that the preference of the sustainability dimensions could be modified by each actor in order to sustain the winning status or increase the winning chance. Thus, here the actors compare between sticking to their initial preferences of the technology assessment and modifying their preferences to win the game.

According to the game rule that the spatial actor who has the highest priority technology win the game, the results are displayed in the plots shown in Figure 96, whereas the landscape visualizations of the winning spatial actors at year 2100 are shown in Figure 97. Figure 96 shows 6 plots with different game strategies, where the first plot (a) is based on the preferences of the sustainability dimensions that are given by the actors from the questionnaire and after applying the AHP methodology. The following 4 plots (b-e) are based on the change of the preferences of the sustainability dimensions by each of the tested actors, where in each plot the actor plays the game with another preference of the sustainability dimensions instead of the initial one as shown in Table 16. Actually, there are many possibilities of changing the preferences of the dimensions and it could be changed in each time step until the actor wins the game. Here I give an example of applying one of the changes in the preferences of the sustainability dimensions which is estimated to enable an actor to win the game as far as the other actors do not change their strategies. Thus, the initial preferences of the technologies by the other actors are kept unchanged. The last plot (f) represents a game including six actors instead of five, where I added the "New-DM" actor in the game and set up the initial preferences of both the sustainability dimensions and the technologies to be the same like in the sustainable scenario. In other words, the game is played with two actors having a similar strategy but with different identities.

As I mentioned before, the target of the game here for each actor is to achieve the highest value of the priority of the technology. There are two variables that influence this action. The first is the initial preference of the technology by each actor which will not be modified here. The second is the preference of the sustainability dimensions which will be modifiable here. So if two actors have the same preferences of the sustainability dimensions but they have different initial preferences of the technologies, then they will not have the same priorities of the technologies. This could be best explained in the following example; if one actor has no initial preference to nuclear, then the priority of this technology will be forever zero. If another actor has an initial preference to nuclear of 0.1, then there will be a priority to this technology at some time steps even if both of these actors start the game with the same preferences of the sustainability dimensions. So the trick of the game is that, if the initial preference is given more to NG, for instance, and I know that technically NG is better than the other technologies but has a lower environmental aspects, therefore my strategy will be to change my preferences of the sustainability dimensions by increasing the technical score and reducing the environmental score. But each actor should consider that the other actors will also change their performance since it is a game. Moreover, the change by one actor could be in favor of other actors to win the game. At the end, the actors will be directed to the most sustainable technologies by changing their preferences of assessment.

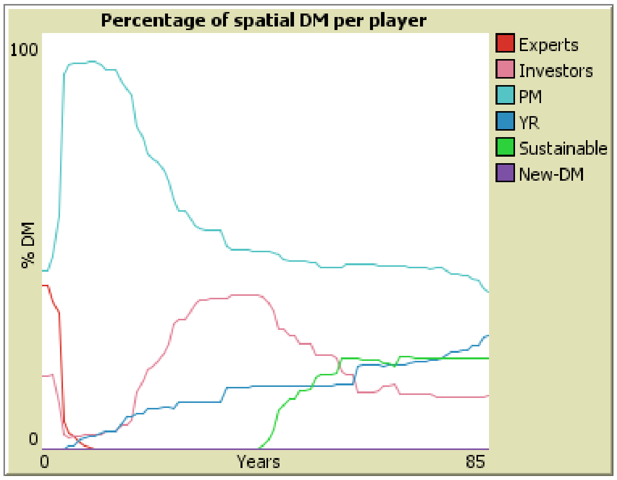
Table 16: The old and new preferences of the sustainability dimensions by the tested actors

Dimension	Economic		Environmental		Social		Technical	
Actors	old	new	old	new	old	new	old	new
Experts	0.31	-	0.17	0.50	0.28	0.50	0.24	-
Investors	0.37	1	0.20	-	0.19	-	0.25	-
PM	0.37	-	0.16	0.50	0.24	0.50	0.24	-
YR	0.25	-	0.22	0.50	0.30	0.50	0.23	-

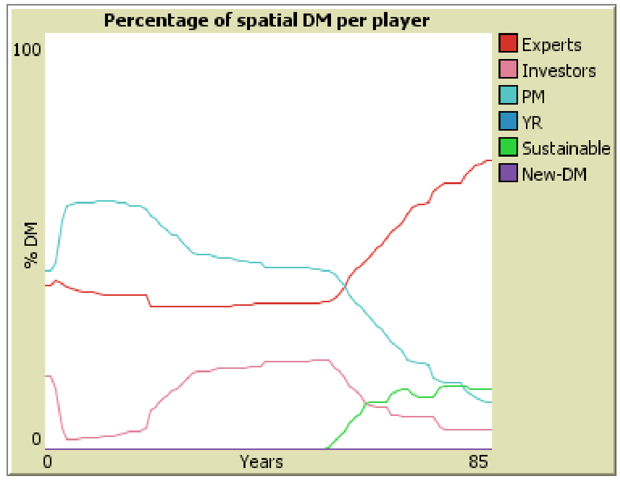
By investigating these plots, we can see in plot (a) the “Policy-makers” (PM) actor represents the highest winning actor over the whole period especially in the first 15 years where the actor wins in about 93% of the spatial cells and persists in 40 – 50% of the cells as the winning actor. “Experts” actor drops down abruptly, although it started with a winning coverage of about 40% of the cells. For the “Investors” actor, the winning coverage starts with about 15% then it falls down to 2% for a short period then it increases again to contribute to 35% winning coverage after 30 years, then again it decreases gradually until it reaches 13%. The winning coverage of the “Young-researchers” actor (YR) increases gradually till it reaches a coverage of 27% of the cells. The sustainable scenario contributes in the game to involve unbiased actor with equal opportunities to all technologies. Here, it shows some winning opportunities but after about 37 years (shortly after 2050) which reflects the failure of the strategies of other actors to achieve the maximum priority technologies in these cells according to their preferences.

In the next step each actor changes the preference of the sustainability dimensions in a way allowing a higher probability of winning the game. The “Experts” actor has initially more preference to the economic and the social dimensions but with this strategy the actor fails to have a considerable winning coverage. The actor, however, made changes by concentrating only on the environmental and social dimension. By this modification, the actor was able not only to persist on the initial winning coverage for a long period but also to increase the coverage to around 70% of the cells as shown in plot (b) Figure 96 and Figure 97 (b). It is not necessary that the actor changes to this extreme preference distribution, but the actor can run the game several times with changing between the initial and the new preferences until the actor compromises between them.

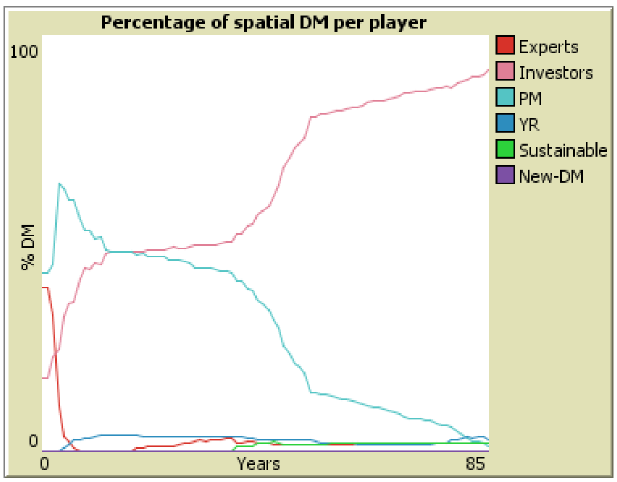
For the “Investors” actor the initial winning coverage is fine but would be better improved. The actor concentrates on only the economic dimension, although it is considerably high in the old preference value. This improvement produces a rapid increase in the winning coverage of about 50% in a short period that sustains for another period then increases again till it ends with more than 90% winning coverage in 2100 as shown in plot (c) Figure 96 and Figure 97 (c).



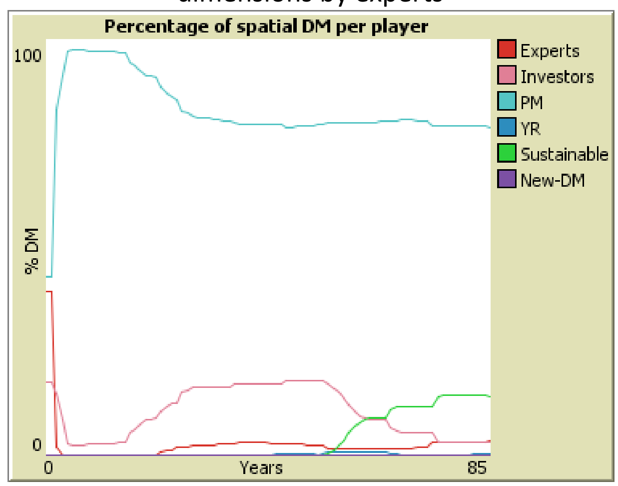
a-Basic preferences with only 5 actors game



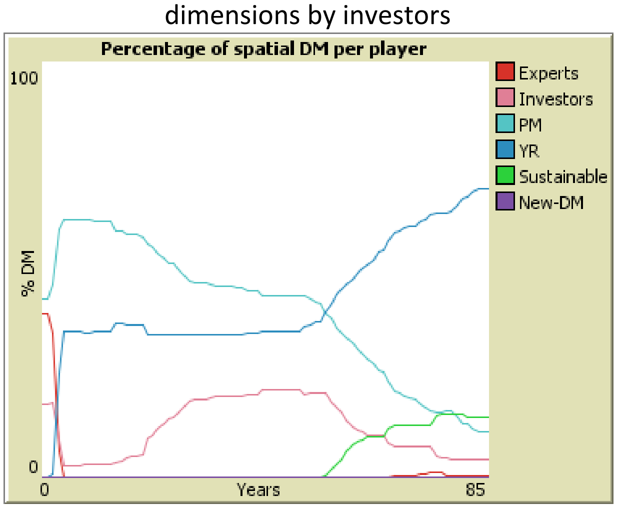
b-Changed preferences of sustainability dimensions by experts



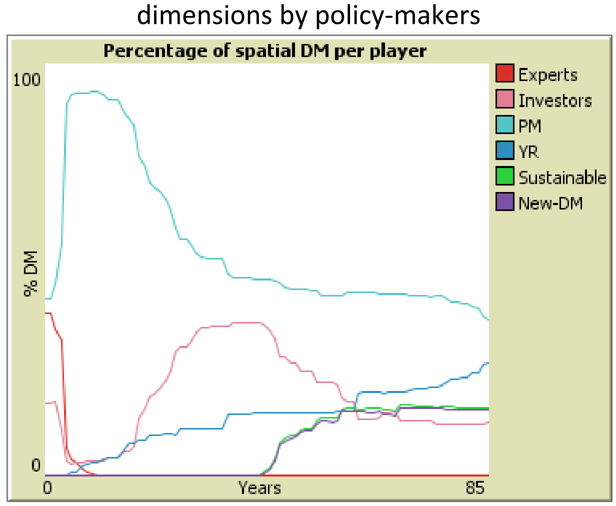
c-Changed preferences of sustainability dimensions by investors



d- Changed preferences of sustainability dimensions by policy-makers

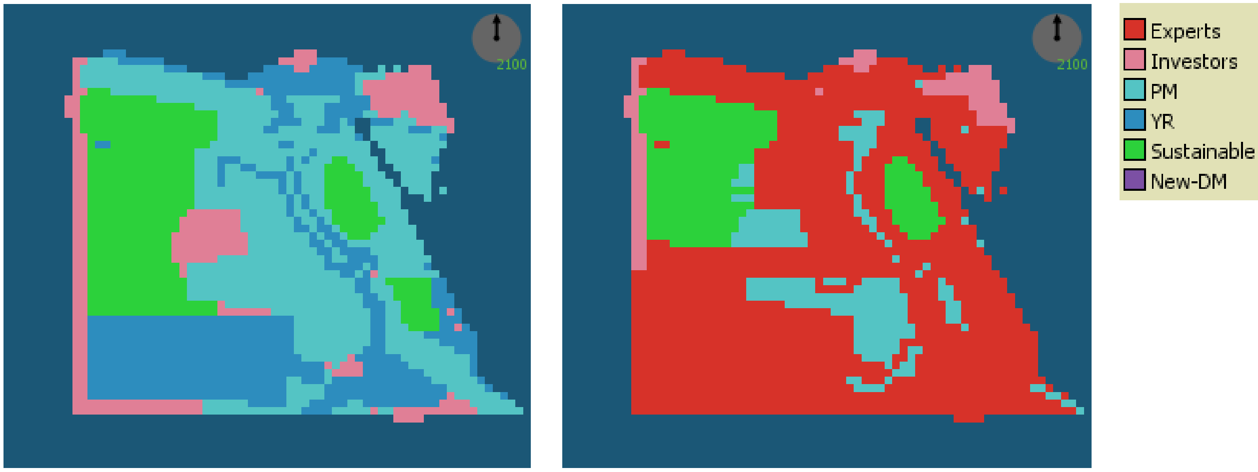


e-Changed preferences of sustainability dimensions by young-researchers



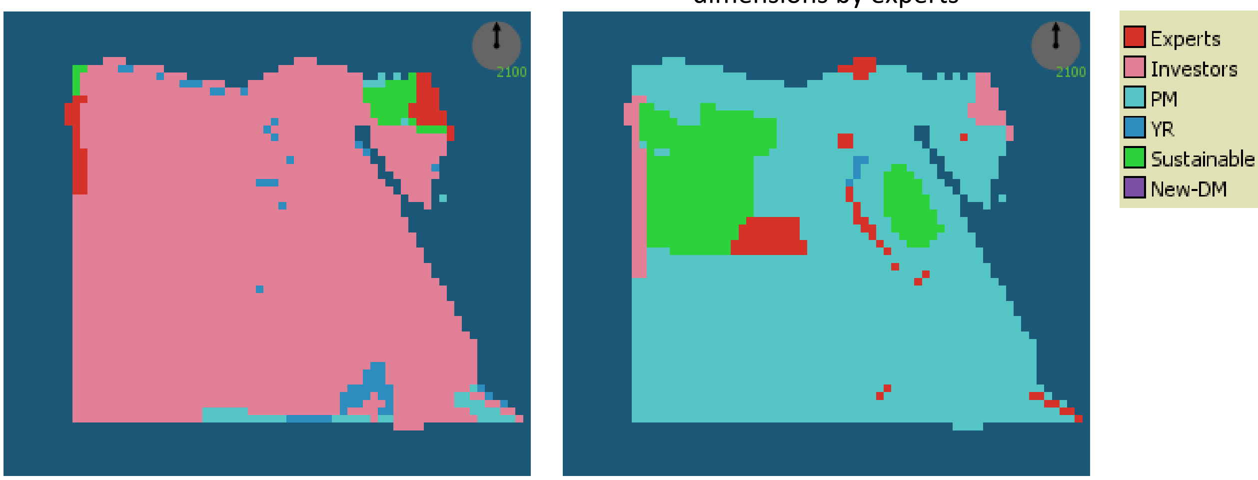
f-Adding the New-DM actor in the game with the same initial input of the sustainability scenario

Figure 96: Percentage of DMs having the actor with the maximum priority technology in the game scenario under basic and changed preferences of the sustainability dimensions conditions



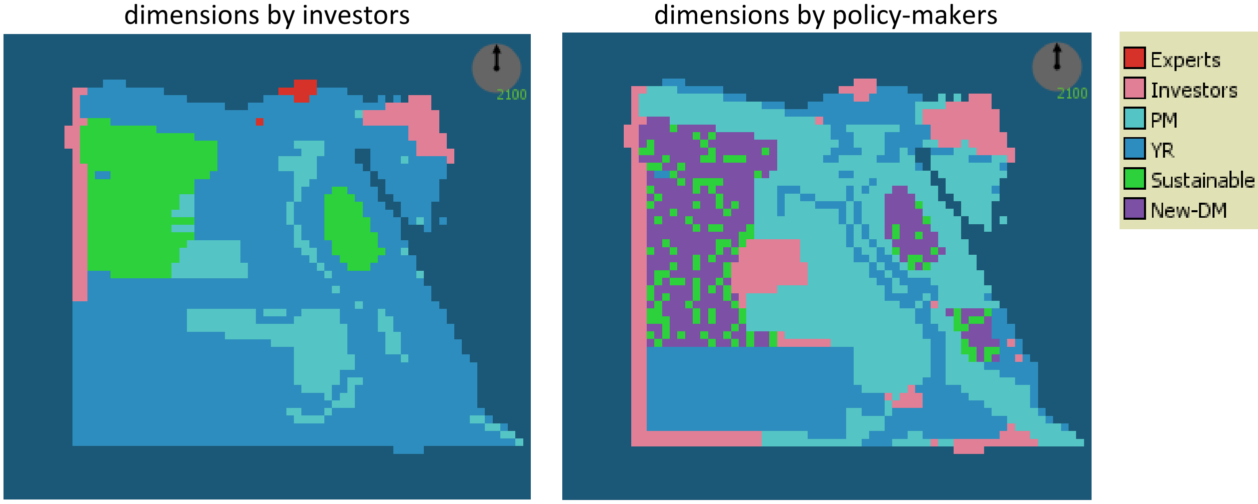
a-Basic preferences with only 5 actors game

b-Changed preferences of sustainability dimensions by experts



c- Changed preferences of sustainability dimensions by investors

d- Changed preferences of sustainability dimensions by policy-makers



e- Changed preferences of sustainability dimensions by young-researchers

f-Adding the New-DM actor in the game with the same initial input of the sustainability scenario

Figure 97: Map view displaying the winning actor with the maximum priority technology in the game scenario under basic and changed preferences of the sustainability dimensions at year 2100

For the “Policy-makers” actor, the winning coverage is originally satisfactory according to the given preferences of the sustainability dimensions. However, in order to sustain and increase this coverage, the actor concentrates the preference on both the social and environmental dimensions ending up with an overall winning coverage of about 80% of the cells along the whole period as can be observed in plot (d) Figure 96 and Figure 97 (d).

The same preference improvement strategy of the “Policy-makers” actor is implemented by the “Young-researchers” actor showing a widespread winning coverage of the actor as presented in plot (e) Figure 96 and Figure 97 (e). From these previously mentioned improvement examples, one can deduce that how the decision in the preferences of the sustainability dimensions by one actor can influence on the decision of other actors if they just compete subjectively on winning the game even if it will not end up with the previously selected technology. This kind of game resembles the competition between parties in the parliament election process where they adapt their agenda to the winning situation even if it does not match with their actual vision. For this reason the game will be more productive and meaningful if it is controlled through the visualization of the winning technology as it could be the same as the preferred technology of a non-winning actor, enabling a cooperative instead of a conflicting interaction.

In the last tested game scenario, it has been found that the addition of a new actor with similar preferences as an occurring actor will have no influence on the winning coverage of the other actors, but rather will share the winning coverage with the similarly occurring actor as shown in plot (f) Figure 96 and Figure 97 (f).

4.2.5. The Energy-mix scenarios

The following section describes the most important objective of this study which is the electricity-mix scenarios based on the preferences made by the actors and the dynamic assessment of the technologies. Based on the average priorities of the technologies that are presented in Figure 92, I calculate the future projected energy-mix. In 2015, I use the actual energy-mix in Egypt at year 2014 based on the shares of the electricity generated in TWh not based on the shares of the installed capacity which are shown in Table 17 in the fifth column. I use the predicted future electricity consumption that I showed in Figure 5 and calculate the amount of the needed electricity during each time plan (i.e. the amount between 2015 and 2020 as a short-term plan, between 2020 and 2040 as a medium-short term plan,…etc). The priority-mix of the technologies for each actor is multiplied by the needed amount giving a new energy-mix distribution. For instance, if 30 TWh will be needed between 2015 and 2020, therefore the priorities will be distributed on this amount, and then it will be added to the previously existing amount. In other words, I assume in this study that the old systems will be included in the energy-mix and not substituted or decommissioned. Another remark is that I assume no additional installation of hydro and oil-fired power plants. The last thing is for biomass where it is not visible in the energy-mix of the actors not because they do not prefer it but because they were not questioned about it. However, it is present in the sustainable scenario. I calculate the predicted electricity-mix in the form of percentage and installed capacity where the latter is calculated according to the predicted future electricity generated and the full load hours for each technology type.

Table 17: Electricity-mix data of Egypt in 2014 (EEHC 2014)

	MW	TWh	% MW[1]	% TWh[1]	FLH[1]
Hydro	2800	13.352	8.745900359	7.9455381	4769
NG	22288	119.3	69.61736686	70.993311	5353
Oil	6360	34.04	19.86568796	20.256599	5352
Wind	547	1.332	1.708574106	0.7926495	2435
Solar	20	0.02	0.062470717	0.0119016	1000

[1] These are calculated values, FLH= Full load hours

Figure 98 depicts the predicted energy-mix in percentage in Egypt by the tested actors, the sustainable scenario and the game scenario from 2015 till 2100, whereas the interpreted energy-mix in terms of installed capacity is shown in Figure 99. Although the charts seem to be quite similar, there are still some differences which can be observed in the values of the energy-mix in percentage shown in Table 18 and Table 19 for the years 2020 and 2100, respectively and in the values of the energy-mix in terms of installed capacity for the same years shown in Table 20 and Table 21. As I mentioned before, this kind of similarity is based on the close tendency of preferences in the assessment between the tested actors since they have the same objective and are from the same group of agents in the field of energy sector. However, still some variations exist which are related to the individual variation even among the same group of people. In this sense, I highlight the major variations between these actors in 2020 and 2100. The values in Table 18 and Table 19 which are highlighted in light red represent the minimum values while the ones highlighted in light blue represent the maximum values. For hydro and oil, the values are constant between actors. For biomass, the expected share is included only in the sustainable and the game scenario.

It has been found that coal in 2020 ranges between completely absent in the energy-mix as preferred by investors to about 2% in the sustainable scenario which corresponds to 0.8 GW but 0.5 GW would be accepted to all actors according to the game scenario. In 2100 coal would be accepted not to exceed 4% of the energy-mix with an installed capacity in the range of 5 GW. For NG which currently constitutes about 70% of the energy mix, its share is expected to be reduced to about 60 % with an installed capacity of about 23 GW in 2020. There is no big difference in the prediction levels of NG between actors in 2020, however, in 2100, the gap increases between actors regarding this technology where it ranges between 25 – 40% share in the energy-mix which corresponds to a predicted installed capacity ranging between 36 – 58 GW. Wind share is predicted to have an average value of 5% with a range of 3.5 – 7% in 2020 of the generated energy and an installed capacity of about 5 GW. These values should not confuse with the values stated in the national plan of 12% share of wind as the latter value is based on the installed capacity share which is almost close to my calculation which shows approximately 10% share based on the installed capacity. In 2100, there is also a big difference between actors' predictions where the share of wind ranges between 20 – 35%, which corresponds to an installed capacity range of 70 – 113 GW. For CSP, the share ranges between 2.7 – 5% with an installed capacity ranging between 5.5 – 10.5 GW. The value of the installed capacity for CSP is almost double that of wind although the share of CSP is lower than that of wind because the full load hours of CSP is less than half that of wind.

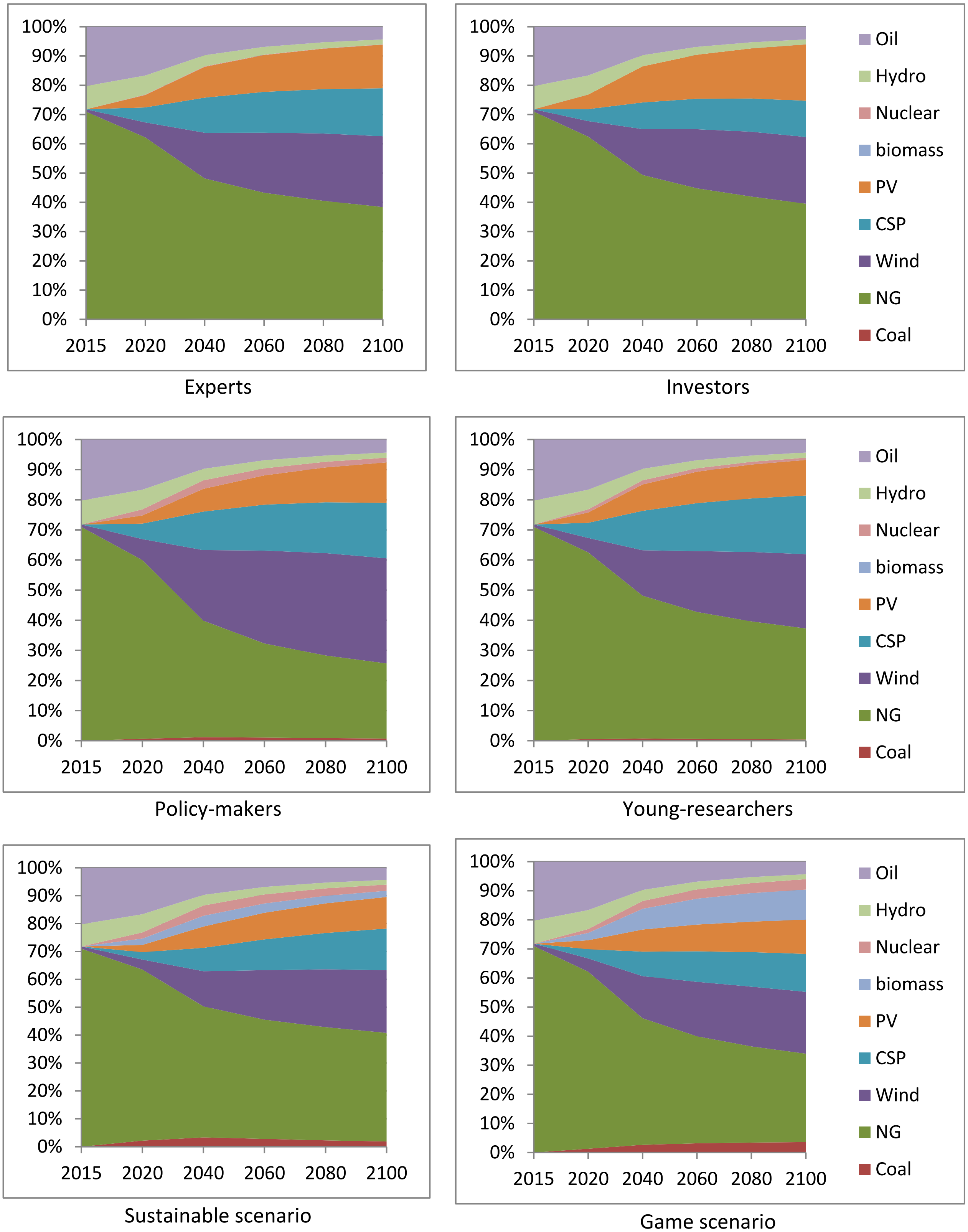


Figure 98: Predicted energy-mix for Egypt in percentage according to actors' priorities

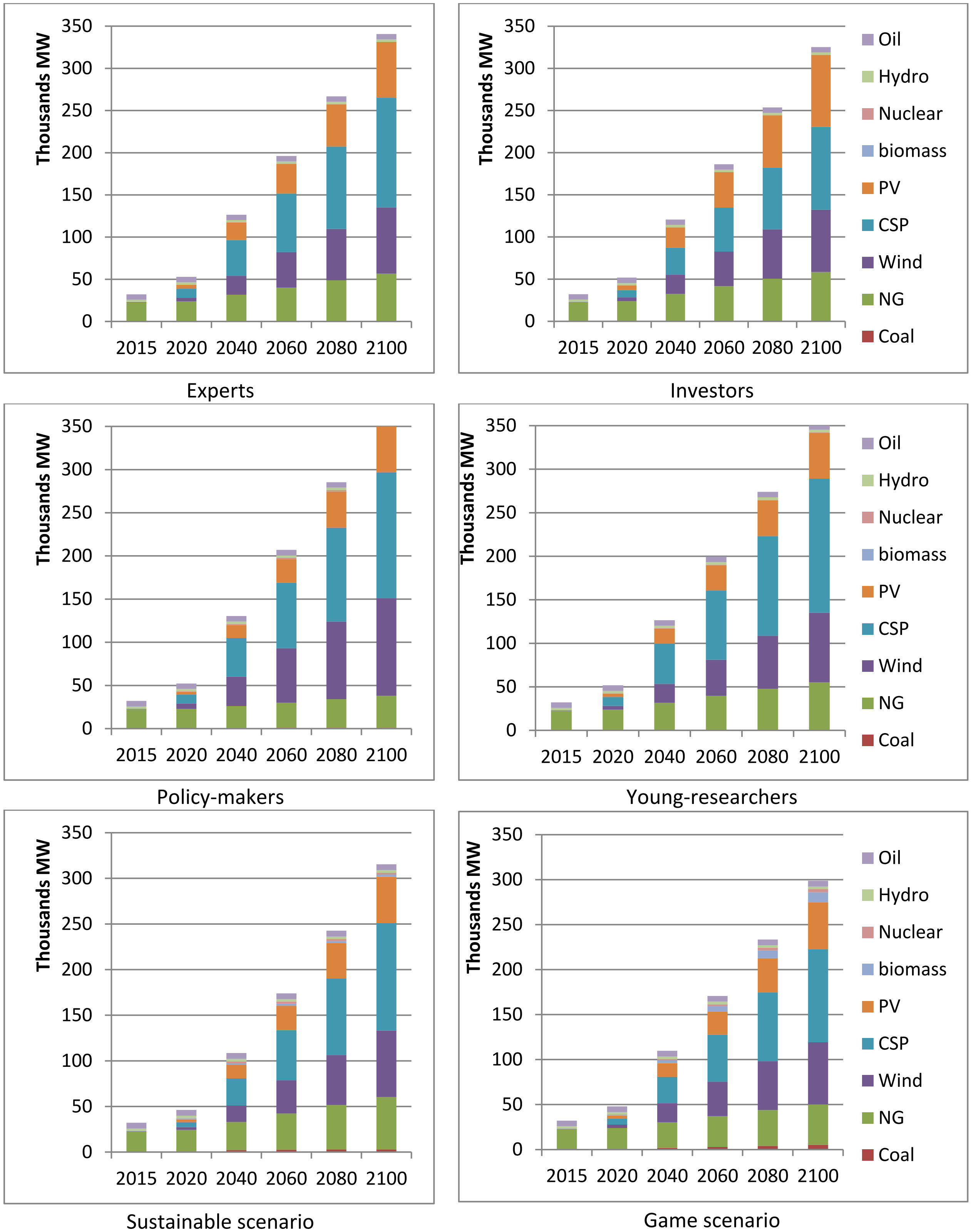


Figure 99: Predicted energy-mix for Egypt in GW according to actors' priorities

Table 18: Electricity-mix scenarios in percentage for different actor types of Egypt in 2020

	Experts	Investors	Policy-Makers	Young-Researchers	The Sustainable scenario	The Game scenario
Coal	0.14%	0.00%	0.65%	0.53%	2.16%	1.30%
NG	62.03%	62.43%	59.32%	62.00%	61.35%	60.87%
Wind	5.13%	5.32%	6.97%	4.79%	3.57%	4.56%
CSP	5.12%	4.10%	5.15%	5.02%	2.67%	3.17%
PV	4.25%	4.97%	2.71%	3.43%	2.58%	3.08%
biomass	0.00%	0.00%	0.00%	0.00%	2.28%	2.51%
Nuclear	0.14%	0.00%	2.02%	1.05%	2.21%	1.34%
Hydro	6.53%	6.53%	6.53%	6.53%	6.53%	6.53%
Oil	16.65%	16.65%	16.65%	16.65%	16.65%	16.65%

Table 19: Electricity-mix scenarios in percentage for different actor types of Egypt in 2100

	Experts	Investors	Policy-Makers	Young-Researchers	The Sustainable scenario	The Game scenario
Coal	0.12%	0.00%	0.72%	0.41%	1.86%	3.56%
NG	38.27%	39.53%	24.94%	36.87%	38.94%	30.41%
Wind	24.18%	22.79%	34.89%	24.65%	22.49%	21.26%
CSP	16.40%	12.41%	18.43%	19.48%	14.90%	13.05%
PV	14.92%	19.25%	13.46%	11.82%	11.32%	11.78%
biomass	0.00%	0.00%	0.00%	0.00%	2.24%	10.33%
Nuclear	0.08%	0.00%	1.54%	0.75%	2.22%	3.58%
Hydro	1.70%	1.70%	1.70%	1.70%	1.70%	1.70%
Oil	4.33%	4.33%	4.33%	4.33%	4.33%	4.33%

Table 20: Electricity-mix scenarios as installed capacity in MW for different actor types of Egypt in 2020

	Experts	Investors	Policy-Makers	Young-Researchers	The Sustainable scenario	The Game scenario
Coal	51.97	0.00	248.21	205.13	829.42	497.10
NG	23,807.14	23,960.29	22,765.20	23,792.79	23,545.29	23,360.70
Wind	4,330.34	4,486.63	5,881.26	4,043.30	3,010.85	3,844.92
CSP	10,526.66	8,418.76	10,570.57	10,307.09	5,483.80	6,504.81
PV	4,909.55	5,731.92	3,131.18	3,957.66	2,979.04	3,552.64
biomass	0.00	0.00	0.00	0.00	636.12	701.27
Nuclear	35.28	0.00	526.37	272.47	574.65	348.13
Hydro	2,812.16	2,812.16	2,812.16	2,812.16	2,812.16	2,812.16
Oil	6,391.76	6,391.76	6,391.76	6,391.76	6,391.76	6,391.76
Total	52,864.86	51,801.53	52,326.72	51,782.35	46,263.09	48,013.50

Table 21: Electricity-mix scenarios as installed capacity in MW for different actor types of Egypt in 2100

	Experts	Investors	Policy-Makers	Young-Researchers	The Sustainable scenario	The Game scenario
Coal	172.31	0.00	1,068.74	598.98	2,746.71	5,267.10
NG	56,553.09	58,412.73	36,854.66	54,484.94	57,543.76	44,940.64
Wind	78,552.26	74,013.71	113,321.81	80,080.65	73,054.90	69,067.88
CSP	129,710.88	98,136.29	145,754.35	154,068.85	117,890.54	103,204.76
PV	66,315.98	85,559.46	59,792.52	52,518.65	50,306.48	52,352.12
biomass	0.00	0.00	0.00	0.00	2,408.70	11,105.97
Nuclear	83.55	0.00	1,547.56	751.50	2,227.11	3,588.07
Hydro	2,812.16	2,812.16	2,812.16	2,812.16	2,812.16	2,812.16
Oil	6,391.76	6,391.76	6,391.76	6,391.76	6,391.76	6,391.76
Total	340,592.01	325,326.10	367,543.56	351,707.49	315,382.12	298,730.48

The full load hours are calculated according to the currently installed power plants in Egypt and their generated electricity. The difference in the full load hours roots from the difference in the capacity factors and the availability of the technologies. This also justifies the differences in the total installed capacities between the actors as they have different energy-mixes. In 2100 the share of CSP will rise to a range of 12 – 20% with an average installed capacity of about 120 GW. PV share is expected to have the same range like that in CSP in 2020 and 2100 in accordance to the preferences of different actors. Moreover, the installed capacity will be in the range of 3 – 6 GW in 2020 to 50 – 85 GW in 2100 which differs from that of CSP due to the differences in the full load hours also. It is recommended by the sustainable scenario to include a share of 2.2% of biomass in 2020 and 2100 as a diversification tool of the technologies like in coal. The same applies to nuclear technology where it shows a range of sharing in 2020 between 0 – 2.2% with an average installed capacity of 0.4 GW. Although the share range is preferred to be kept unchanged, however, the installed capacity will be increased to an average value of 2 GW in 2100. The tendency towards nuclear between actors varies to some extent like in coal where it is completely absent in the energy-mix of the “Investors” actor but is supported in the sustainable scenario and by “Policy-makers”.

4.2.6. Sensitivity analysis

The previous analysis deals with the real actors who are involved and interested in the energy sector in Egypt. It is necessary to investigate the model in a sensitivity analysis for the extreme cases in the assessment of the technologies. So, I run the model using four virtual actors each has a preference to only one of the sustainability dimensions. This type of analysis guides to the correlation between the technologies and the sustainability dimensions based on the indicators used in this study. The following figures and tables are a repetition to the previously presented ones but for analyzing these four virtual actors in comparison with the sustainable scenario and it includes also the game scenario 2 which reflects the interaction between these actors. Figure 100 compares the average priorities of the technologies throughout the running period between the virtual actors. Figure 101 shows the percentage of coverage by the highest priority technology for each of these actors which is again visualized on the energy landscape of the map for the years 2020 and 2100 in Figure 102 and Figure 103, respectively. Figure 104 and Figure 105 present the predicted energy-mix scenarios at different identified years in terms of percentage and installed capacity, respectively. The values corresponding to the energy-mix figures in 2020 and 2100 are presented in Table 22, Table 23, Table 24 and Table 25.

Briefly, I found that PV would be the most economic technology in a future outlook as compared to other technologies. This means that actors who are more interested in the economic impacts of the technologies should support the PV technology than the others. Surprisingly, it has been found that nuclear is the most environment-friendly technology but based on only CO_2, SO_2 and NO_x emissions followed by CSP, wind and PV. However, this ranking would be greatly affected if we include the radioactive material disposal and emissions and their impact on the ecosystem. Wind represents the first priority technology to be socially accepted and has low risks on safety followed by CSP. However, the acceptance of NG comes before PV. Technically, NG technology predominates over all other technologies at a very large extent in the near and long term which sounds plausible.

These extreme actors show how the priorities of the technologies could change differently generating also heterogeneous energy-mix scenarios along the tested period which would most probably induce conflicts between these kinds of actors. Therefore, there are a wide range of energy-mix scenarios that could be proposed by modifying the preferences of the sustainable dimensions and the adaptation rate (alpha) which also change with time and actors showing how the complexity of setting up a strategic energy plan is while including different actors.

4.2.7. Complied energy-mix scenarios analysis

Figure 106 shows a comparison between the energy-mix of the compiled technologies based on their resources (i.e. Fossil fuels – renewables – nuclear) between the actual and virtual actors in addition to the sustainable and the game scenarios for the years 2020 and 2100. In the upper left figure, it is clear that all actors agree on having 20% of the energy supply from renewable resources which agrees with the national plan of Egypt for renewable energy while 80% from fossil fuels with the inclusion of approximately 2% of nuclear for some actors in 2020. In 2100 in the upper right figure, the share of renewables accounts for 50 – 70% having the complementary supply from fossil fuels but also with about 3% nuclear for some actors. In the lower left figure, the virtual actors show a lower renewable energy share in 2020 as compared to the actual actors where it is in the level of 17%. Fossil fuels and nuclear supply the rest of the demand showing the majority is given to fossil fuels while nuclear share does not exceed 3%. In the lower right figure, a variety of energy-mix scenarios can be explicitly observed where the most prominent one is with the technical actor where it predicts only 11% renewable, 87% fossil fuels and approximately 2% nuclear.

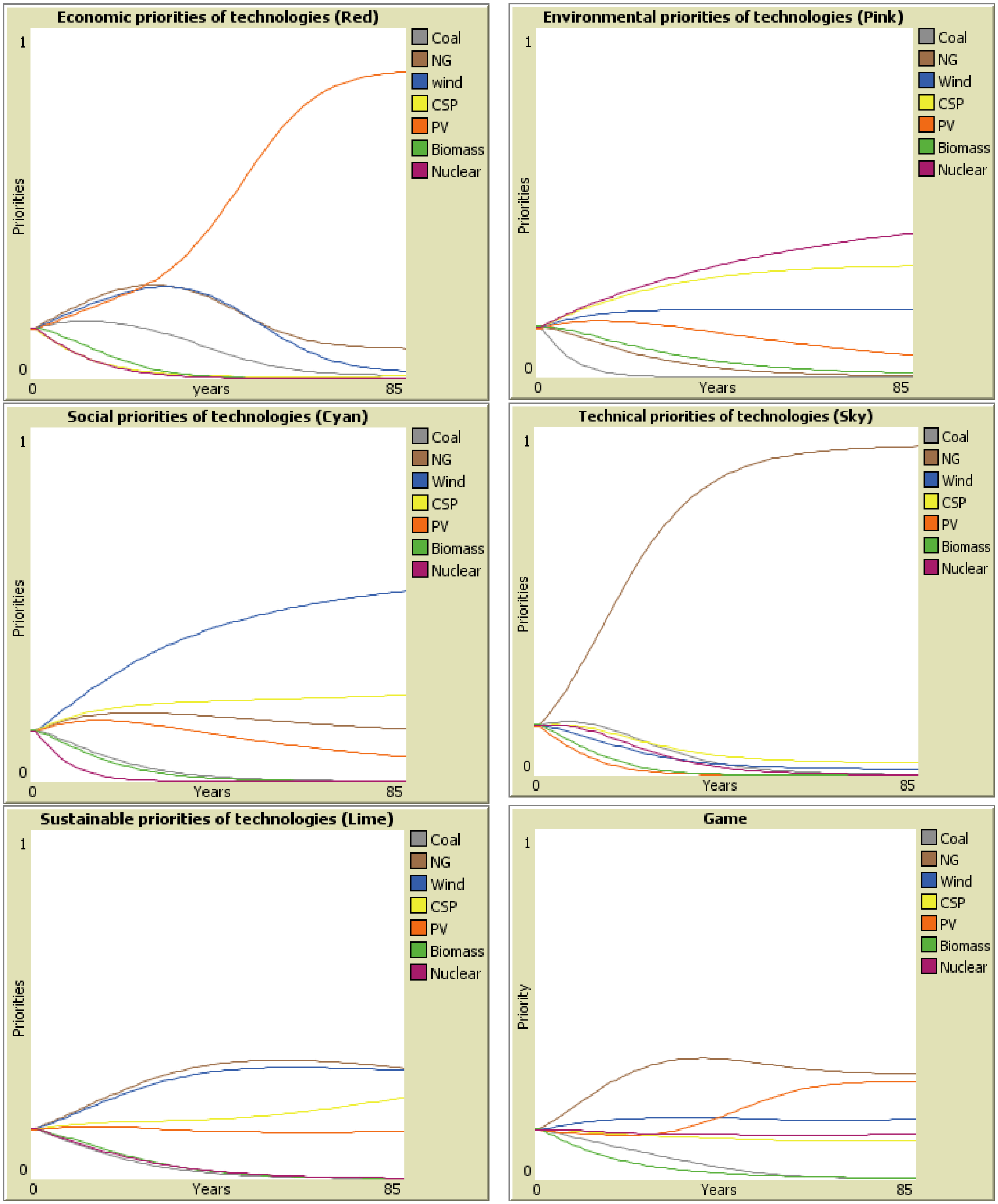
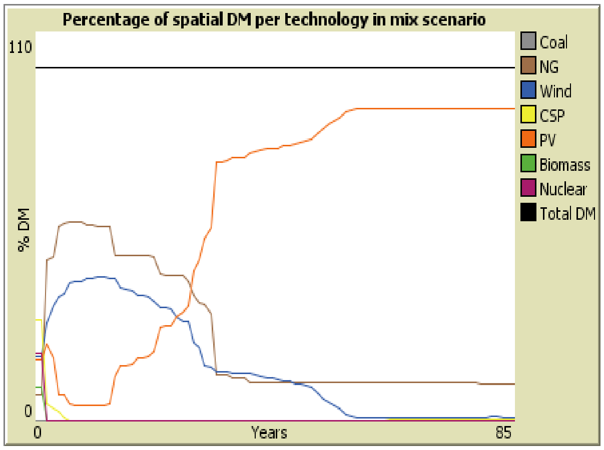
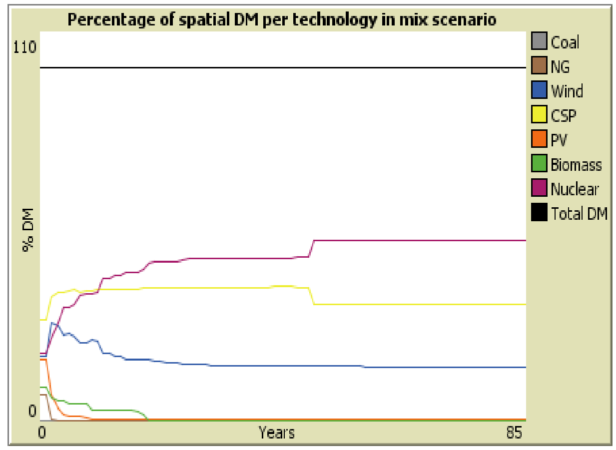


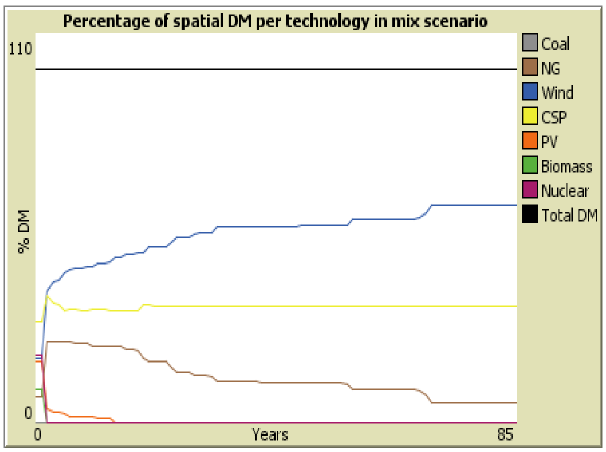
Figure 100: The average priorities of the technologies per actor type in a single dimension analysis changing with time



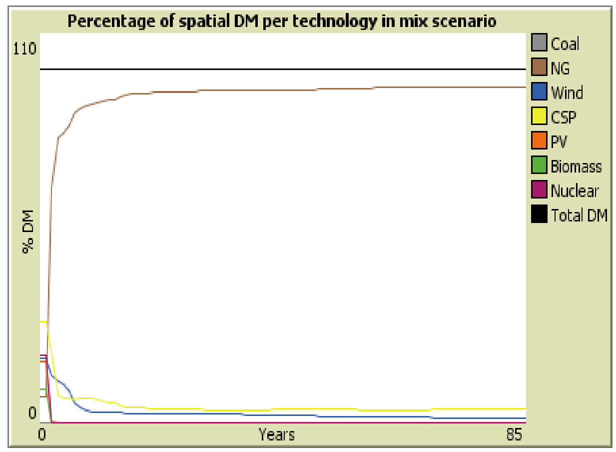
a: Economic



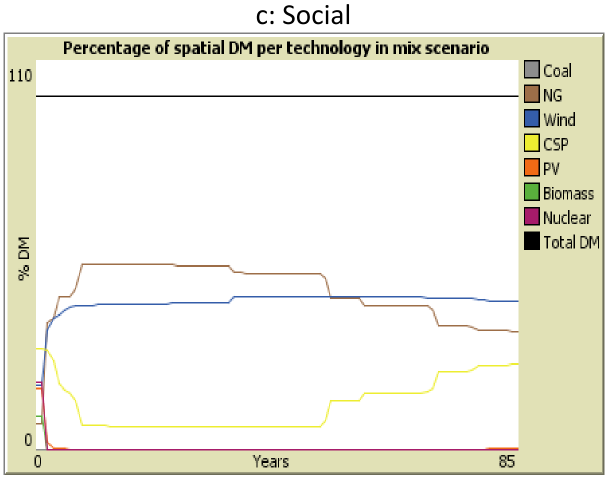
b: Environmental



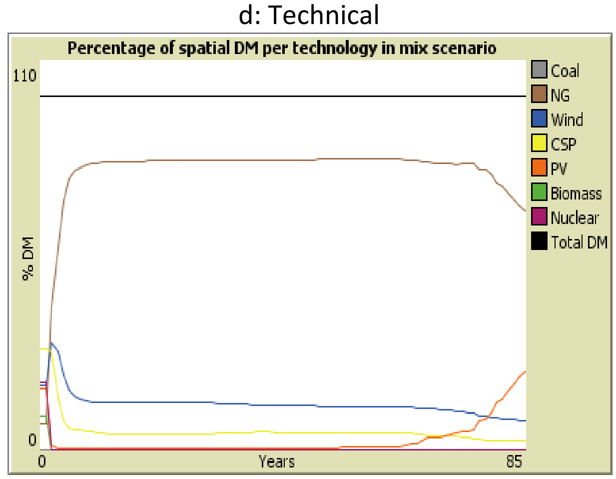
c: Social



d: Technical



e: Sustainability scenario



f: Game scenario 2

Figure 101: Percentage of DMs having the maximum priority technology in the single dimension analysis

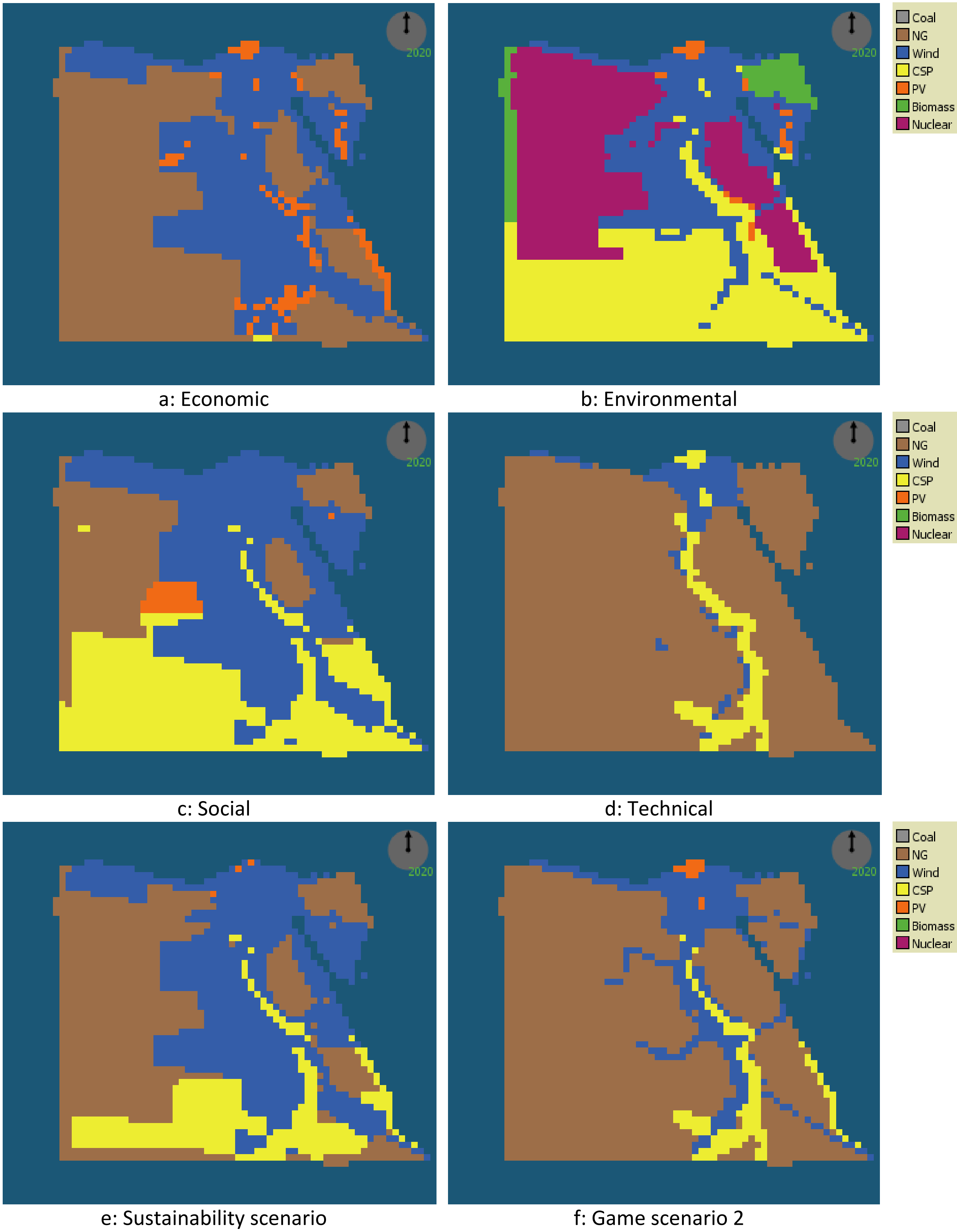
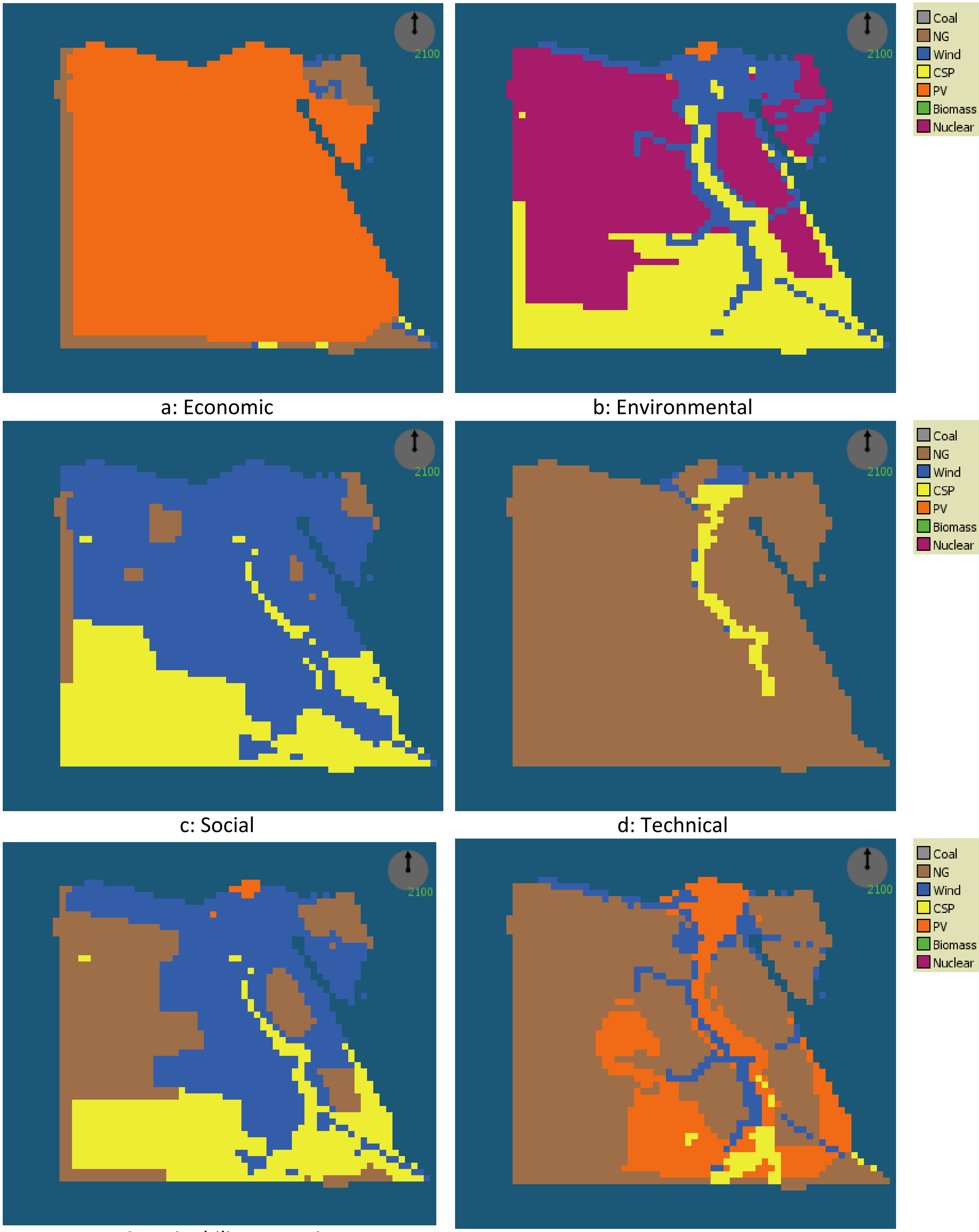


Figure 102: The map view displaying the maximum priority technology per actor type (a – f) at year 2020 according to a single dimension analysis



a: Economic b: Environmental c: Social d: Technical e: Sustainability scenario f: Game scenario 2

Figure 103: The map view displaying the maximum priority technology per actor type (a – f) at year 2100 according to a single dimension analysis

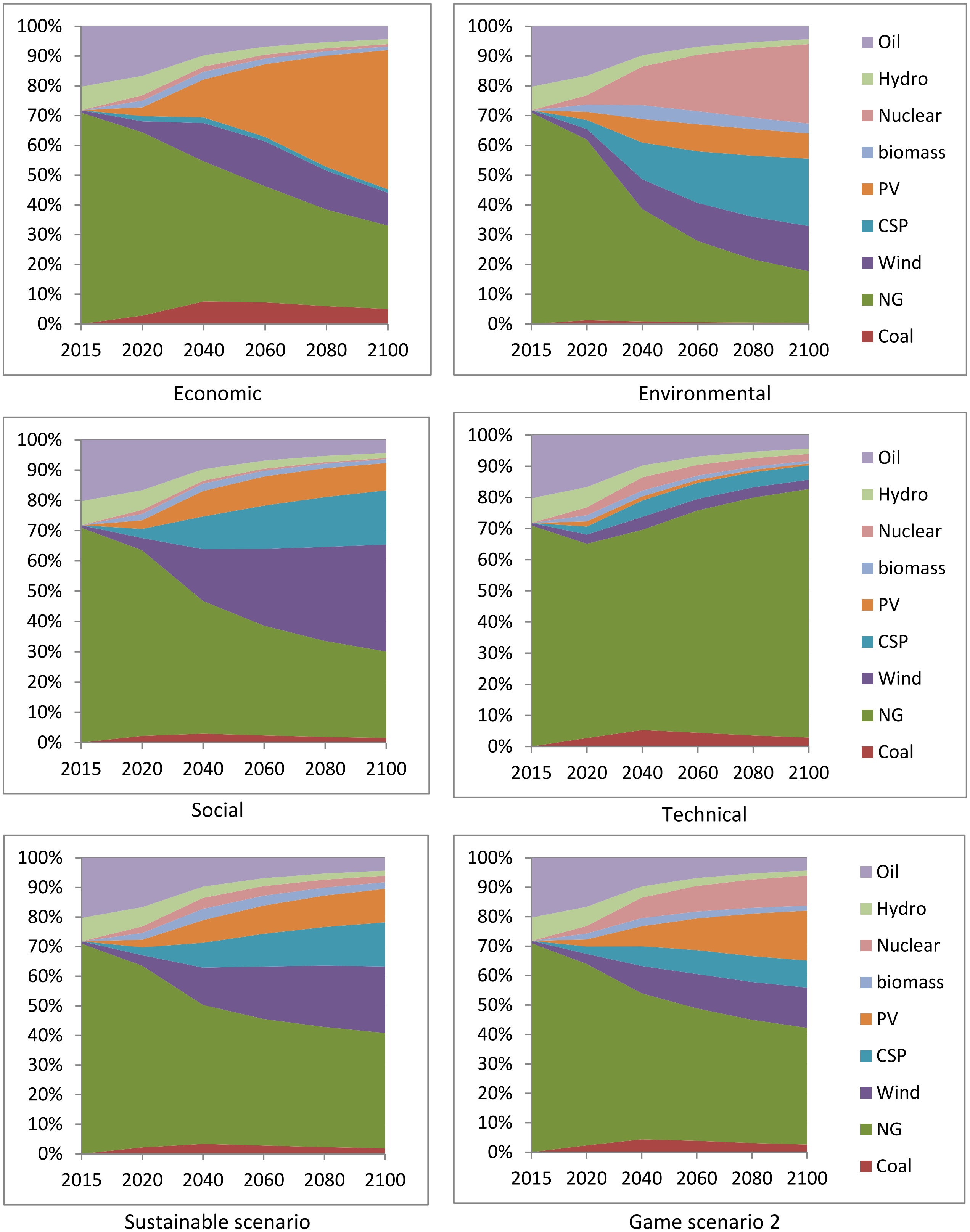


Figure 104: Predicted energy-mix for Egypt in percentage according to a single dimension analysis

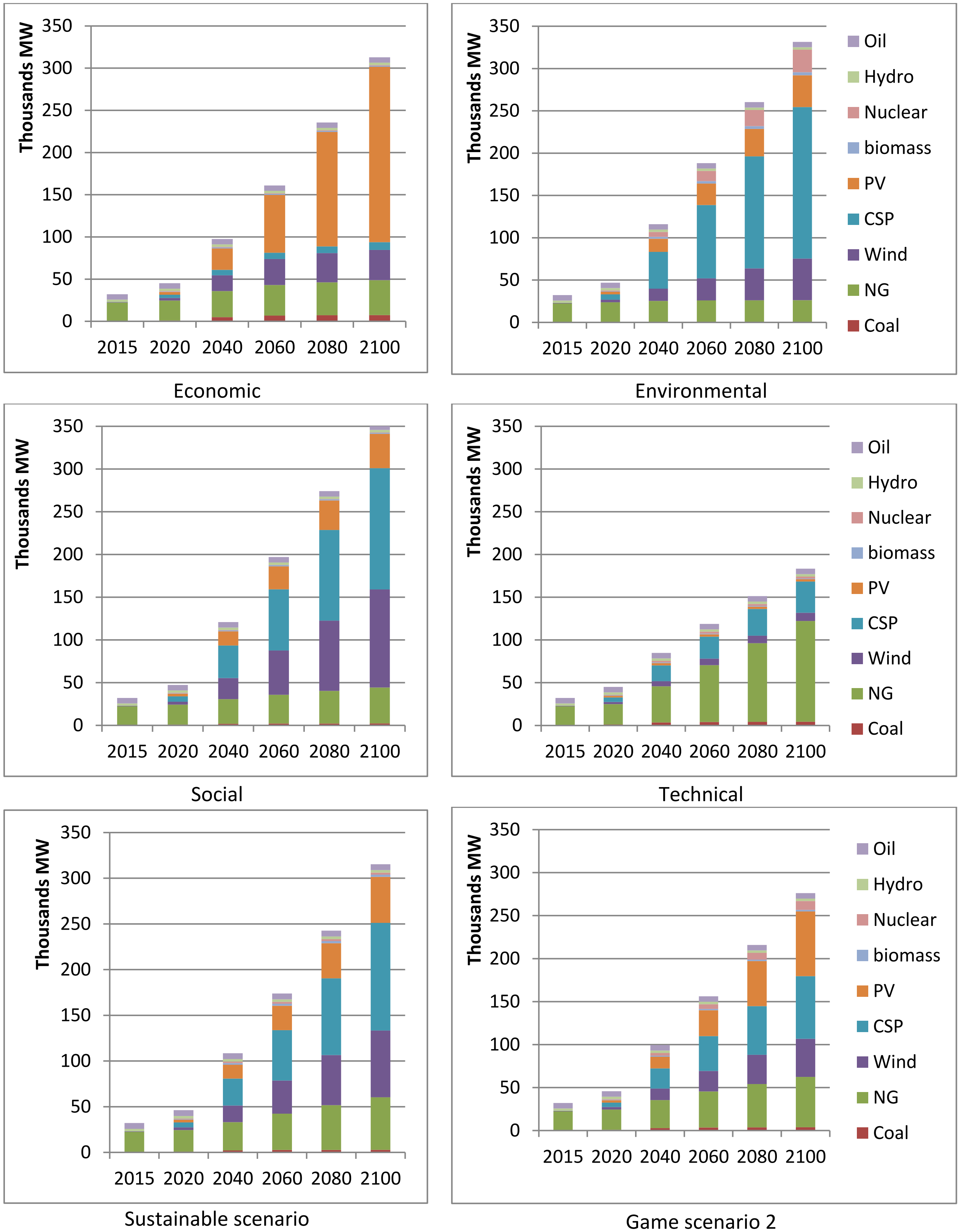


Figure 105: Predicted energy-mix for Egypt in GW according to a single dimension analysis

Table 22: Electricity-mix scenarios in percentage for Egypt in 2020 by virtual extreme actors

	Economic	Environmental	Social	Technical	The Sustainable scenario	The Game scenario 2
Coal	2.81%	1.25%	2.20%	2.72%	2.16%	2.31%
NG	61.54%	60.65%	61.31%	62.39%	61.35%	61.64%
Wind	3.71%	3.53%	4.02%	2.96%	3.57%	3.40%
CSP	1.78%	3.08%	3.03%	2.58%	2.67%	2.52%
PV	2.94%	2.74%	2.84%	1.66%	2.58%	2.40%
biomass	2.24%	2.45%	2.09%	1.98%	2.28%	2.00%
Nuclear	1.80%	3.12%	1.32%	2.54%	2.21%	2.55%
Hydro	6.53%	6.53%	6.53%	6.53%	6.53%	6.53%
Oil	16.65%	16.65%	16.65%	16.65%	16.65%	16.65%

Table 23: Electricity-mix scenarios in percentage for Egypt in 2100 by virtual extreme actors

	Economic	Environmental	Social	Technical	The Sustainable scenario	The Game scenario 2
Coal	5.02%	0.37%	1.54%	2.89%	1.86%	2.59%
NG	28.02%	17.36%	28.53%	79.81%	38.94%	39.67%
Wind	11.01%	15.17%	35.30%	2.99%	22.49%	13.65%
CSP	1.16%	22.63%	17.94%	4.61%	14.90%	9.21%
PV	46.77%	8.44%	9.04%	0.61%	11.32%	16.94%
biomass	1.21%	3.34%	1.24%	0.85%	2.24%	1.68%
Nuclear	0.79%	26.66%	0.40%	2.23%	2.22%	10.25%
Hydro	1.70%	1.70%	1.70%	1.70%	1.70%	1.70%
Oil	4.33%	4.33%	4.33%	4.33%	4.33%	4.33%

Table 24: Electricity-mix scenarios as installed capacity in MW for Egypt in 2020 by virtual extreme actors

	Economic	Environmental	Social	Technical	The Sustainable scenario	The Game scenario 2
Coal	1,078.99	480.01	845.14	1,044.12	829.42	886.17
NG	23,616.39	23,275.92	23,530.25	23,943.20	23,545.29	23,656.73
Wind	3,128.07	2,974.78	3,392.57	2,493.87	3,010.85	2,868.08
CSP	3,650.36	6,325.49	6,219.37	5,289.84	5,483.80	5,169.08
PV	3,392.28	3,159.96	3,281.26	1,912.01	2,979.04	2,773.45
biomass	625.67	684.36	583.90	553.06	636.12	558.53
Nuclear	469.74	813.23	343.49	661.45	574.65	663.31
Hydro	2,812.16	2,812.16	2,812.16	2,812.16	2,812.16	2,812.16
Oil	6,391.76	6,391.76	6,391.76	6,391.76	6,391.76	6,391.76
Total	45,165.45	46,917.68	47,399.90	45,101.48	46,263.09	45,779.27

Table 25: Electricity-mix scenarios as installed capacity in MW for Egypt in 2100 by virtual extreme actors

	Economic	Environmental	Social	Technical	The Sustainable scenario	The Game scenario 2
Coal	7,421.67	548.39	2,270.12	4,271.53	2,746.71	3,823.66
NG	41,403.24	25,649.68	42,156.66	117,936.71	57,543.76	58,617.83
Wind	35,745.56	49,274.07	114,674.36	9,707.47	73,054.90	44,322.23
CSP	9,212.88	179,026.98	141,886.21	36,425.29	117,890.54	72,841.48
PV	207,817.21	37,518.61	40,156.37	2,693.26	50,306.48	75,290.10
biomass	1,304.07	3,592.90	1,327.94	913.15	2,408.70	1,803.91
Nuclear	789.10	26,745.72	399.19	2,234.07	2,227.11	10,279.14
Hydro	2,812.16	2,812.16	2,812.16	2,812.16	2,812.16	2,812.16
Oil	6,391.76	6,391.76	6,391.76	6,391.76	6,391.76	6,391.76
Total	312,897.65	331,560.28	352,074.78	183,385.41	315,382.12	276,182.27

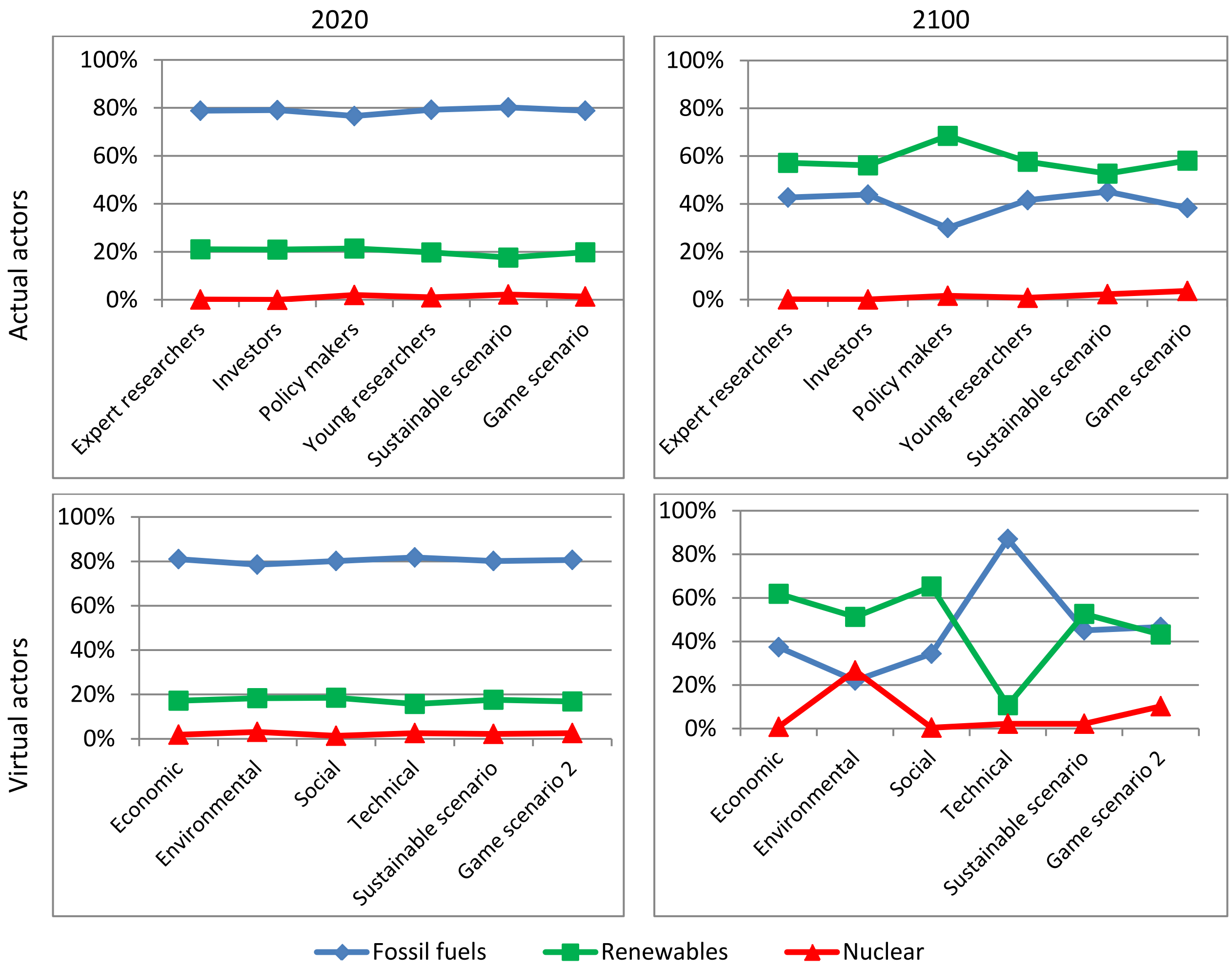


Figure 106: A comparative analysis of the compiled technologies of the generated energy-mixes between actual and virtual actors in 2020 and 2100

4.3. GHGs assessment results

The last output of the model represents a comparative investigation of the contribution to climate change and global warming from the different energy-mix scenarios as obtained from the analysis of the decisions made by actors in the assessment of the technologies. Figure 107 illustrates this comparison in four graphs, where the upper row represents the GHG emissions in percentages based on the average priority-mix of the technologies while the lower row represents the GHG emissions in million tons CO_2 equivalent (Mio tons CO_2 eq.) from the energy-mix estimated by each actor over the whole period. The left column investigates the actual actors whereas the right column investigates the virtual actors. It has been found that the proposed energy-mix scenario by policy-makers emits lower GHGs as compared to other scenarios while the sustainable scenario shows the highest probability of GHG emissions due to the inclusion of biomass and a higher value of coal. However, the emission from the sustainable scenario approaches to that of the other three actors. On the other hand, the technical actor shows the highest GHG emissions that could reach more than 400 Mio tons CO_2 eq. by 2100 which is four times that of the environmental actor. We can conclude from these graphs that the average GHG emissions could reach 200 Mio tons CO_2 eq. from the electricity supply sector only which worth to be considered in climate change projection analysis. The GHG emissions from the priority-mix of the technologies of the spatial DM of different actors in 2015 and 2100 showing the hot spot cells are shown in Figure 108.

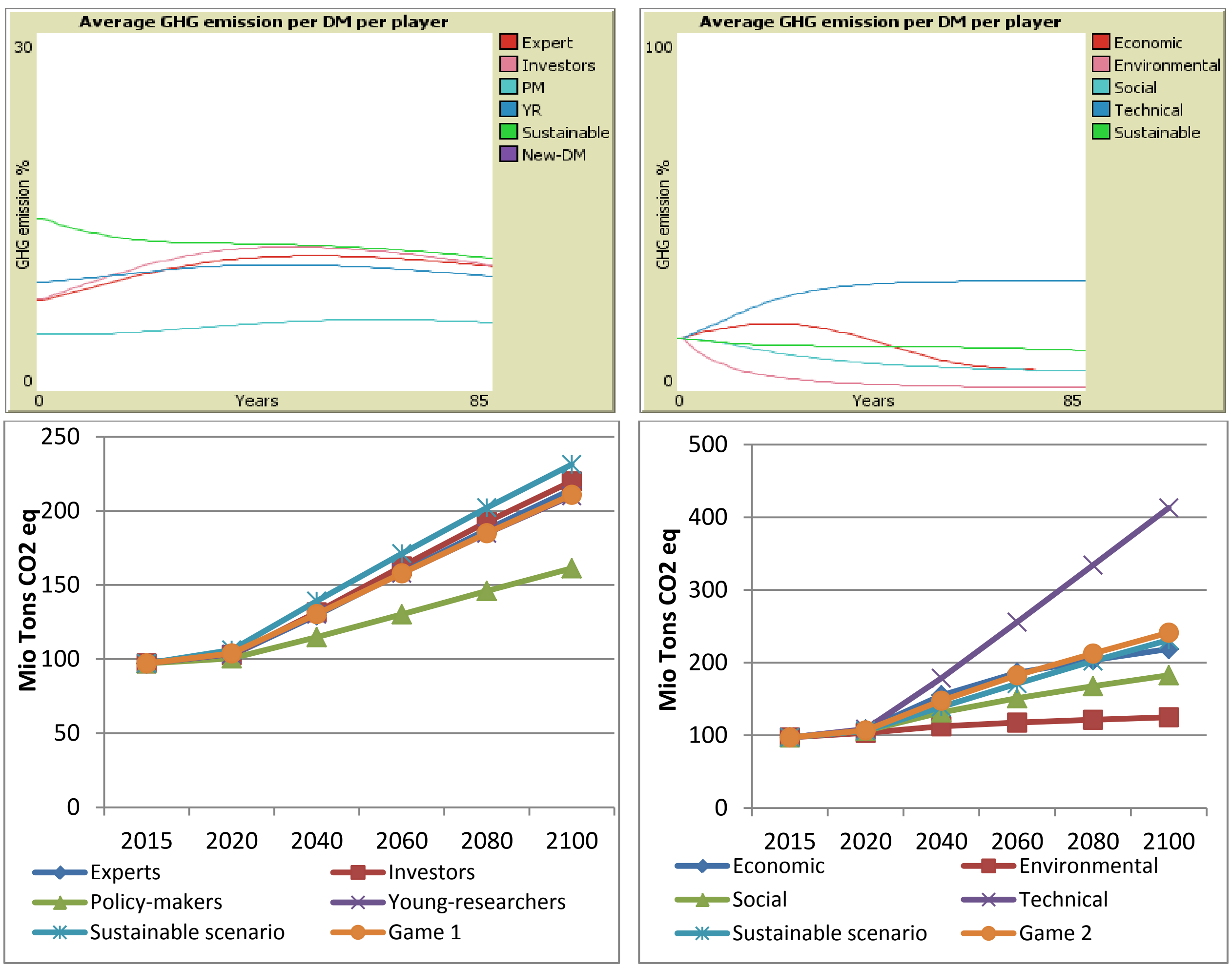


Figure 107: A comparison of the GHG emissions of the priority-mix and the energy-mix of the technologies per each actual and virtual actor

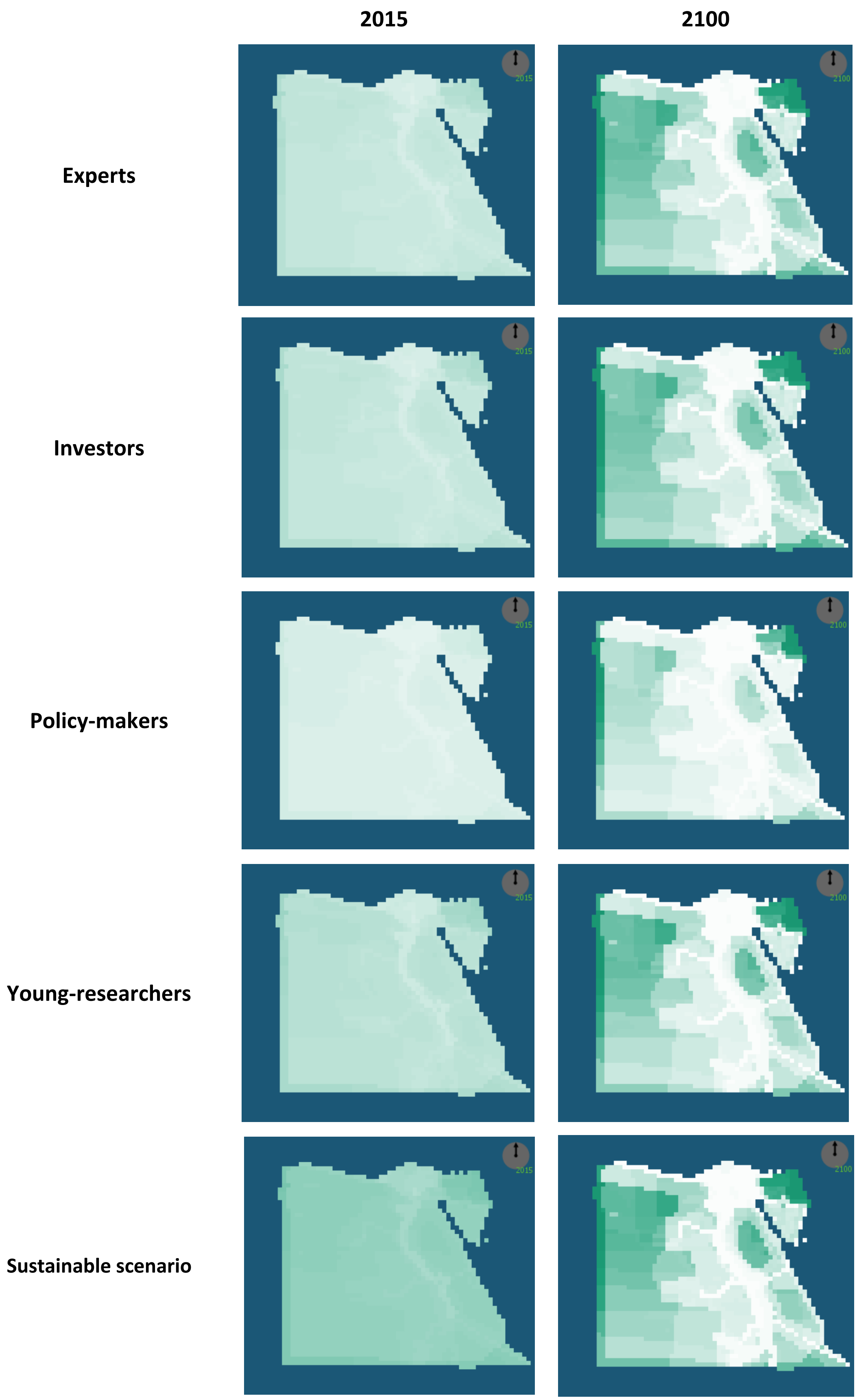


Figure 108: Map view of GHG emissions from the priorities of energy-mix at each spatial DM per each actor

4.4.A comparison with the results of TARES project

As I mentioned in the problem statement section, a study project which is called "*Technical Assistance to support the reform of the Energy Sector"* (TARES) has been conducted by the electric utility in Egypt to anticipate different energy-mix scenarios till the year 2035 using the TIMES energy model generator. However, this model is mainly based on the technical and economic assessment of energy systems. The aim of the project is developing the 20 year energy strategy, understanding and responding to the powerful drivers that will force changes throughout the energy system of Egypt in the medium to long-term. According to the final report of this study, Egyptera (2015), five scenarios have been proposed in setting up the future energy-mix in Egypt as follows:

Baseline scenario - Business as usual (BaU)

In the Baseline scenarios, the most likely forecast for indigenous oil and NG production is used. The level of subsidies of July 2014 is kept constant until 2035 in a sub-scenario, while it is reduced by 50% over 5 years (till 2020) and are removed in ten years (by 2025) in another sub-scenario. In the electricity sector, coal fired power plants are available to be installed after 2020, the current national program for nuclear energy is applied and it is assumed that the introduction of renewable energy for electricity production follows a low rate considering that no more than 1 GW of PV, 1 GW of wind and 400 MW of CSP could be added in the system per year.

Scenarios 1 - Different renewable development policy

In Scenarios 1, the most likely forecast for indigenous oil and NG production is used. Energy subsidies are reduced according to the same approach as in the second sub-scenario in the Baseline scenario. Coal and nuclear power plants are available. Renewables are to be introduced according to three sub-scenarios:

a. In Scenario 1-a the 20% Target Scenario is applied;

b. In Scenario 1-b the Delayed Reference Scenario of the Combined Renewable Energy Masterplan (CREMP) is applied;

c. In Scenario 1-c the Minimum Fuel Scenario of the Combined Renewable Energy Masterplan is applied.

Scenario 2 - Delayed development and high energy efficiency policy

In Scenario 2, the indigenous production, the development of subsidies and the availability of coal in the power sector are the same as in Scenarios 1. The deployment of nuclear power plants is delayed by five years compared to the existing national plan in order to examine the effect that this could have on the power system. The introduction of renewable energy follows the Delayed Reference Scenario of the CREMP (i.e. scenario 1-b). Finally the introduction of higher rates of energy efficiency is included in this scenario, representing the immediate implementation of policy measures to promote more efficient equipment and behavioral changes.

Scenario 3 - High renewables policy

Scenario 3 examines the possibility of a policy combining high penetration of renewables in the power sector and in the final energy consumption sector, together with a non-diversification with respect to the conventional sources for electricity production (coal and nuclear is not included in the electricity mix).

Scenario 4 - Least cost policy

Scenario 4a is intended as a "least cost" analysis scenario in which subsidies are eliminated by 2020 and all the alternative sources are competing on the basis of their relative cost. Coal fired power plants and nuclear power plants are available to the model and free to compete with all alternative

technologies. The potential for the introduction of renewable energy is set as an upper bound to the level of the Minimum Fuel scenario and high energy efficiency measures are available.
Scenario 4b enforces an updated nuclear program with two units operating in 2025 (2.4GW) the third unit operating in 2026 and the forth unit in 2027.

In this subsection, I present a comparison of the energy-mix of the potential electricity supply technologies (see Figure 109) between the five previously mentioned scenarios that have been investigated in TARES project and ten scenarios from my research project (Experts, Investors, Policy-makers (PM), Young-researchers (YR), the sustainable scenario, the game scenario, the economic scenario, the environmental scenario, the social scenario and the technical scenario) for the year 2035/40[7].

Figure 109 shows that the share of coal in electricity production ranges between 30 – 50% in BaU, scenario 1 and 4. This very high percentage indicates a high affinity to include coal in the energy-mix of Egypt from the governmental side. However, in other scenarios it does not exceed 10% as in the economic scenario. The share of NG and oil together are estimated to be reduced to a range of 17 – 36% according to TARES study, which does not match with my scenarios that show the minimum share of NG and oil is 47%. There is no significant difference in the share of hydropower between all scenarios with a range of 3-4% and the same applies to wind with a range of 12 – 17% except in PM scenario it reaches 23% and in the technical scenario it reaches 4%. There is a wide range for the share of CSP and PV across the scenarios, where CSP ranges between 2 – 26% and PV ranges between 1.5 – 19%. Biomass is completely absent in the estimates of TARES study. Nuclear is recommended in TARES study in the same scenarios where coal is also recommended at a range of 2 – 8% share.

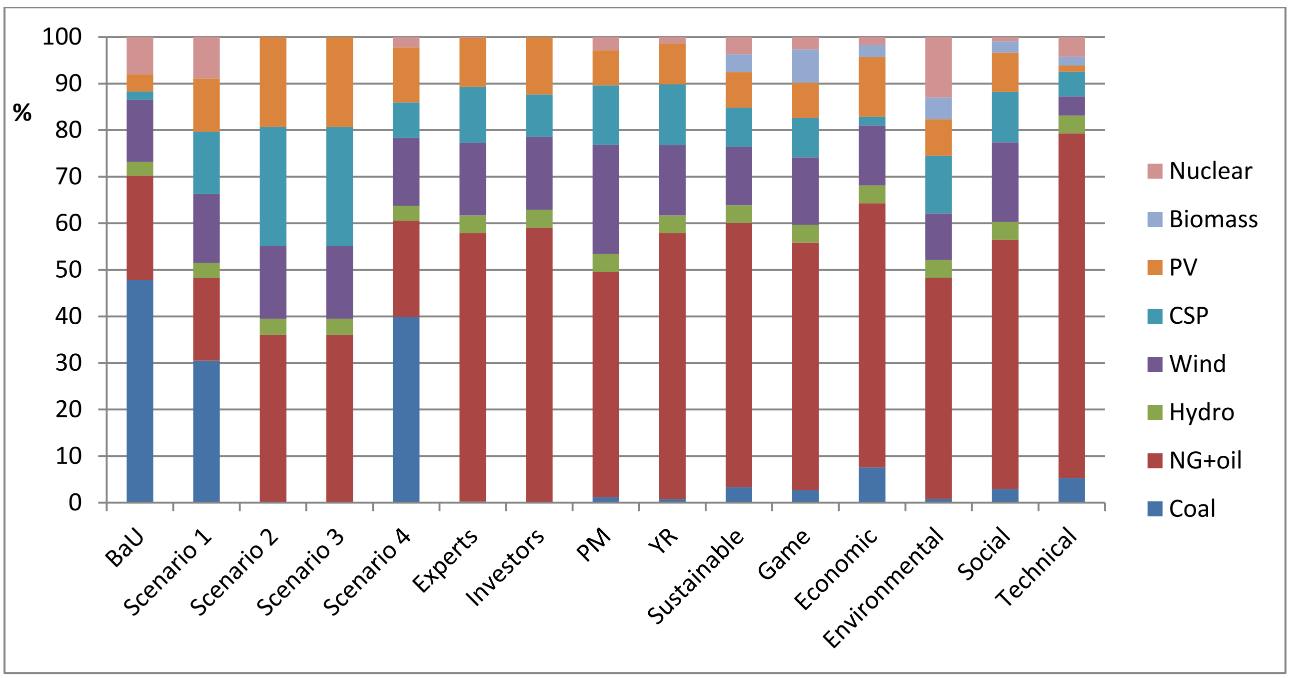


Figure 109: A comparison of different energy-mix scenarios for the year 2035/40

[7] I use the shares of the technologies in 2035 for scenarios from TARES study and in 2040 for scenarios from my study

5. Conclusion and Future Recommendations

According to the results obtained from this study, I conclude that the decision making process in the energy sector in order to secure a future electricity supply for the coming generations is a complex process. It involves a multi-dimensional analysis of all possible potential technologies through the evaluation of indicators whose values change in space and time. Moreover, the actors involved in the decision making process have different preferences for these indicators and their decisions could be affected by the decisions of other actors. Additionally, they adapt in practice at a different rate to the changes in the values of the technologies. Although the sustainable scenario represents a normative decision approach with unbiased affinity towards any of the sustainability dimensions making it a target for all countries in their energy planning, in practice, there are many actors who decide differently and interact with each other. Therefore, I cannot state that the energy-mix obtained from any of the tested actors including the sustainable scenario is the best, but rather a harmonized energy-mix resulting from the interaction of the actors in the game scenario could represent a realistic and better approach of predicting the acceptable, sustainable and secure future energy-mix in Egypt. The results of the game scenario show how important it is for the Egyptian government to show more concern for the renewable energy projects and the transition of the energy landscape from the fossil fuel-fired energy systems to the renewable ones. Energy diversification, through the inclusion of other resources like coal or nuclear in a limited amount, adds more security through gaining the knowledge and experience of their operation.

In this study, I was able to develop a novel model integrating three methodologies: MCDA, GIS and ABM. It is worth mentioning that the model is a prototype, therefore, the results lack of a high accuracy as the investigations have been done at a very low resolution perspective. It is recommended to extend the model by including a larger number of assessment indicators, spatial factors and other actors. Moreover, the spatial factors should be analyzed at a higher resolution and should exclude the locations that could not be used in all cases for the installation of power plants. However, this last thing is difficult to be implemented, since the area of Egypt is more than 1 million km^2 and the area required for power plants installation is not so big. As more variables, in terms of indicators, spatial factors and actors, and higher resolution analysis are included in the model, the higher the accuracy of the results will be. This is a principle in any scenario prediction model.

Therefore this model could be used as a building block for future projects as follows:

- A high resolution and accuracy assessment of the energy systems in Egypt or in any other countries.
- The dynamic decision making process in sectors other than the energy sector like farming, transportation, housing….etc.
- The analysis of the interaction between actors in a decision making process and the resulting pathways of conflict or cooperation from this interaction.
- The analysis of the behavior of different actors in response to action taken by other actors in the energy sector, and this could include:
    - Electricity planning and climate change.
    - Energy, water and food nexus.
    - Electricity planning and migration.

Thus, the model could be handled in a way to cover a wide scope of studies through changing the alternatives, the assessment indicators, the external spatial factors, the country of study and the actors. From this point, I would like to shed the light briefly on some of these future projects.

5.1.Cooperation – conflict response of the interaction of actors

As I mentioned in the game scenario, I have five actors ranking the technologies from their preferences of assessment. At the end, each of these actors will select the highest priority technology to be installed in the spatial location cell. I mentioned also that the rule of the game states that the highest priority technology between these actors win the game. Now, how will the other actors response in case they lose the game? First we should identify the main objective of the game since this objective could lead to three possibilities. The first objective is based on the value of the priority of the technology. In this objective, the actors are concerned on the value rather than on the type of the technology, since this value represents the benefits they get out of the technology. Thus, if the winning technology is not the same like the highest priority technology but the values are very close, then the actor will accept it. Basically, this matches with the objectives of this study where the actors change their technology selection according to the value of the priority. The second objective is based on the type of the technology more than on the value of the priority. In this case, the actors keen to have the winning technology in the game scenario matches with the highest priority technology of their individual ranking regardless the values are close or not. The third possibility is based on the winning actor regardless of the technology. Here, the actors are concerned only on winning the game as a player, so they can change their preferences of the assessment even to a scheme that is completely different from their actual preferences and norms. In conclusion, the first is value-wise, the second is technology-wise and the third is actor-wise, moreover, the first objective has a wide range of probability of the outcomes, whereas the other two objectives have only two probabilities of outcomes. However, in all possibilities there is an interaction between the actors, and according to the outcome of this interaction there is either a cooperation or conflict response.

Since in the last two objectives, there is a clear-cut outcome which could be easily interpreted into a cooperation or conflict response, I will introduce a qualitative measurement tool for the response of the interaction for the first objective which is value-wise. I simulate the interaction between two agents as two intersecting circles as shown in Figure 110. The intersecting area represents the amount of agreements between the decisions of the two actors, whereas, the un-intersected area represents the amount of disagreement. If we assume that the border-line between cooperation and conflict is when the circles intersect at their centers. In other words, 50% of the diameter of the two circles is shared between them as shown in the upper example of Figure 110. If the circles come closer to each other, so that they share more than 50% of the diameter of each, this will lead to a cooperation response as shown in the lower right example of Figure 110. If the circles go further from each other, so that they share less than 50% of the diameter of each, this will lead to a conflict response as shown in the lower left example of Figure 110. In order to interpret this diagram into the form of a quantitative measure, I proposed this equation:

$$I_{CopCon} = \frac{|v_a - v_b|}{v_{max}}, \quad \begin{cases} \leq 0.5 & \rightarrow cooperation \\ = 0.5 & \rightarrow decisive\ value \\ > 0.5 & \rightarrow conflict \end{cases}$$

Where,

I_{CopCon} is the cooperation-conflict index, $v_a and v_b$ are the values of the outcome of the decision of two interacting actors (in this study this value corresponds to the highest priority technology value of two actors) and v_{max} is the maximum value of these two values. The decisive value is the minimum threshold value at which the actor decides to be in the cooperation side. This value differs from one person to another. The maximum decisive value is one and this applies with very flexible actors who accept the decision of other actors in all cases. The minimum decisive value is zero and this applies with very extremely distinctive actors who accept only their decisions like the case of the second two objectives of the game scenario that I mentioned before shortly. In between these two values a huge number of agents exist ranging between extremist and flexible. In my opinion this decisive value depends on the matter of the decision and the person who makes the decision. Here, I assume a decisive value of 0.5.

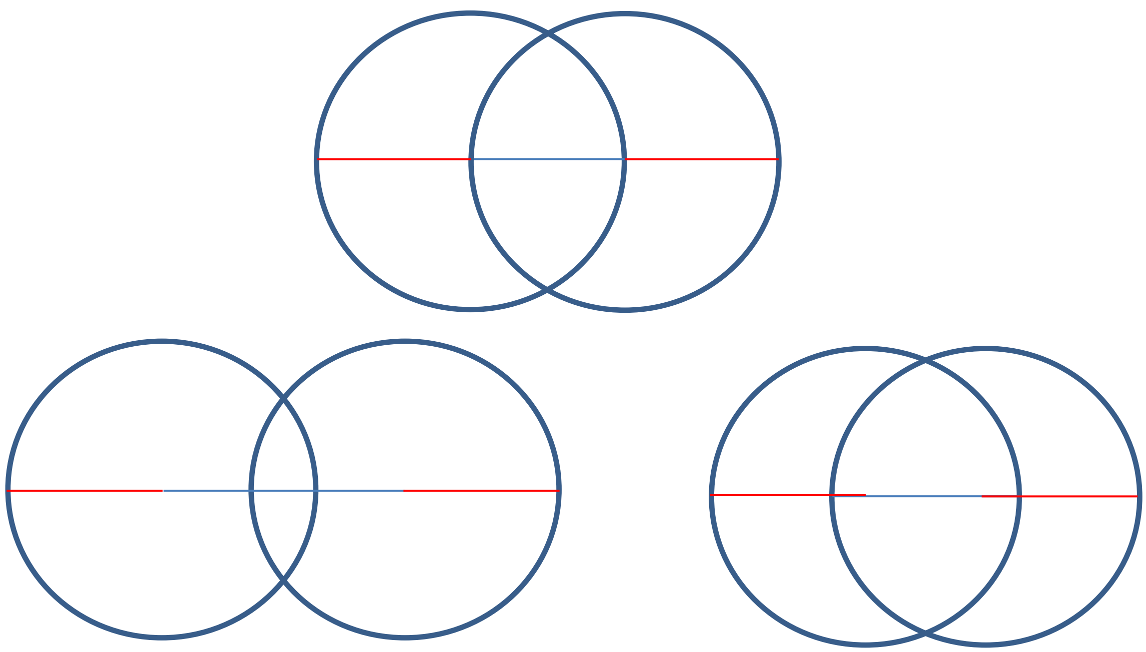


Figure 110: Illustrative diagram of the cooperation-conflict concept

I will give two examples to explain it more. The first example is from the real life between a salesman and a buyer of a product. If the cost of the product is 5 Euros and the salesman wants to sell it at a price of 10 Euros but the decisive value is 0.5. So if the buyer asked to buy it at a price of 7 Euros, then this would be in a more cooperative deal as it will generate a win-win situation and the index will be 0.3. If the buyer asked to buy it at a price of 3 Euros, then this would be in a more conflict deal as it will generate a win-lose situation and the index will be 0.7. If the buyer asked to buy it at a price of 5 Euros, then it will be still in the side of cooperation deal, not always, because the salesman will gain other values although the profit of the product is zero. This gain could be, for instance, that the product could expire at a near date or this activity could attract other customers with different negotiating behavior. The second example is related to this study but the values mentioned here is illustrative and not the actual values as shown in Table 26.

Table 26: An illustrative example of calculation and significance of the cooperation-conflict index

Actors	Highest priority technology value	Interactions	I_{CopCon}
A	0.9	A and B	0.22 < 0.5
B	0.7	A and C	0.77 > 0.5
C	0.2	B and C	0.71 > 0.5

Therefore we can identify the interaction response between the actors in the game scenario according to this quantitative analysis and visualize the cooperation-conflict landscape transition by analyzing the interaction response of each two actors in the game scenario. This also would assist in the final decision on the winning game, since if we have 5 actors then we have 10 interactions responses. If more than five responses are cooperation ones, then the acceptance of the decision will be more stable. This type of analysis could be applied also for other actors especially when they are from different sectors or in the assessment of other alternatives.

The analysis could include also the possible consequences of the responses especially if these responses are conflicts. These consequences could be a passive or active one and the active could be in a positive or a negative reaction. This is controlled by two major variables: power and tolerance. Thus, the actor could possess:

- high power and high tolerance; this is the best criteria of handling a conflict in an active way
- low power and high tolerance; this is still better than the next two possibilities
- high power and low tolerance; this usually leads to more conflicts
- low power and low tolerance; this is the worst case in reacting to conflicts

The power does not mean only money or force but also could be in terms of knowledge, wisdom, believes or confidence. This is briefly an example of a recommended extension of the study that could be investigated in the future.

Table 27: The steps of cooperation-conflict concept in response to the interaction of two actors

Steps	**Interaction of two actors**		
Objective	Value-wise	Technology-wise	Actor-wise
Decisive value	> 0, < 1	= 0	= 0
Cooperation	I_{CopCon} ≤ Decisive value	Same technology	Same actor
Conflicts	I_{CopCon} > Decisive value	Another technology	Another actor
Consequence	Active		Passive
Response	Positive	Negative	
Power	High, low	High, low	
Tolerance	High	Low	

5.2.Electricity planning and Climate Change

This topic deals with the interaction between actors in the energy sector who make decisions about future energy-mix and actors in the environmental protection sector who are concerned with climate change and their consequences. I already explained in this study the GHG emissions projected from the different scenarios but I did not include actors from the environmental protection sector and their interaction with each other. Generally, the GHG emissions from Egypt should not necessarily have a direct impact on climate change manifestations in Egypt, but rather it is a global phenomenon where the emissions of some countries could impact on others. It could be investigated such that the environmental actor follows up the GHG emissions from the scenarios and react when the emissions exceed the permitted limit for each country. This reaction could be in the form of imposing penalties or taxes on the contributing technologies. At the same time, there could be some incentive programs for the technologies with lower GHG emissions. This kind of interaction would force a change in the priority of the technologies given by the actors of the energy sector. Moreover, the projected impacts of climate change could induce some geographical and meteorological changes which could be in favor of some technologies and against other technologies. I will present here some of the projected impacts of climate change in Egypt.

Projections of climate change and their impacts in Egypt

Egypt is one of the vulnerable countries to climate change. It has been projected 3 – 3.5 °C increase in temperature and 20% decrease in precipitation over Egypt as shown in Figure 111 and Figure 112. These projected climate change will impact on different vital sectors. Crop yields, for instance, is projected to suffer from deficits in the yields of three major crops of Egypt: wheat, rice and maize. This impact will increase the pressure on food security.

Moreover, It is projected an increase in water stress as an impact of a declined discharge of the Nile River with a high potential of inducing droughts. Importantly, Egypt is highly vulnerable to 1 meter sea level rise. Egypt was ranked the 2nd highest with respect to the coastal population affected, 3rd highest for coastal GDP affected and 5th highest for proportion of urban areas affected.

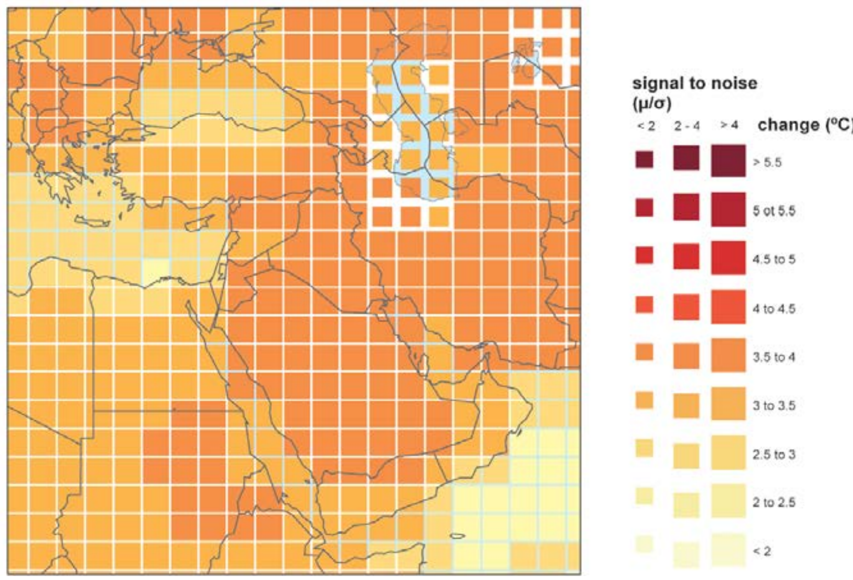


Figure 111: Percentage change in average annual temperature by 2100 from 1960-1990 baseline climate (Met Office 2011)

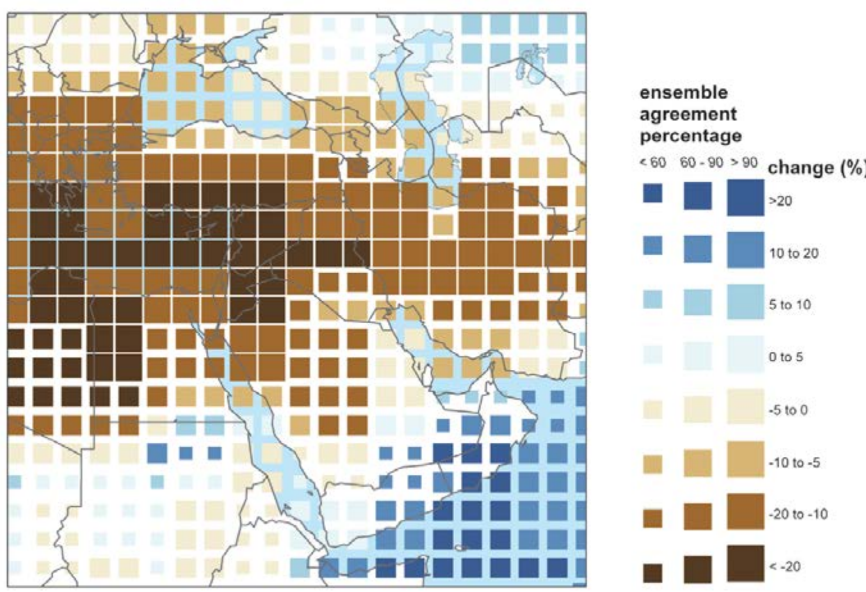


Figure 112: Percentage change in average annual precipitation by 2100 from 1960-1990 baseline climate (Met Office 2011)

Around 15% (2.7 million people) of Egypt's coastal population could be affected by a 10% intensification of the current 1-in-100-year storm surge combined with a 1m sea level rise. It is suggested also that the total area of the Nile Delta affected in 2025, 2050, 2075 and 2100, could be 153, 256, 450, and 761 km^2, respectively, (Met Office 2011). These projections of impacts will influence also on major social aspects like social stability of citizens inducing internal and external migration which will in turn increases the national and international conflicts and stresses. Link et al. (2013) investigated the social and economic impacts of accelerated sea level rise on the coastal zones of Egypt. Thus, there is a tight interlinkage between the decisions of technology selection in the energy sector and climate change projections and impacts which is recommended to be included in the model for future investigation.

5.3.Energy, water and food nexus (EWFN)

Another important topic that I suggest to be included in this study in the future is investigating the EWFN and its influence on future energy-mix in Egypt. As I showed in this study, I included water consumption by power plants as one of the important assessment indicators. Moreover, I included in the spatial factors the negative impacts on crops which is closely linked to livestock. Energy, water and food represent three vital resources to human beings, although some other issues like land, atmosphere and health are important as well. This concept is concerned with fresh water. Water is needed for drinking and cleaning by human (labor, residents) as well as livestock, land irrigation and farming in the food sector. It is needed also in the energy sector where it is used in thermal power plants, for cooling condensation of the exhausted steam, cleaning, as the main driver of hydropower and also for drinking by labor. Food is needed for the nutrition of persons working in both water and energy sector. Food wastes from agriculture and animals represent a biomass resource. In the past, human and animal-power were the major sources of energy needed in the water and food sector. However, in the modern era, electricity took place of many of these activities. Electricity is needed for the treatment of water, distribution to demand centers through pumping and for the electrification of other devices used by the labor. In the food sector, electricity became an important requirement in food processing industries and modern agriculture techniques. Sometimes it is needed for warming the weather for livestock during cold weather, but this in Egypt is mostly supplied by gas heaters, or for conditioning the extreme hot weather also for livestock during summer to protect them from death due to extreme weather. If actors from each of these three sectors are included in the study, then we can investigate the reaction of each of them to the decision made by one of them. For example, if the actor from the energy sector chose an energy-mix which will include technologies that consume too much water. The actor in the water sector will raise the price of water which will in turn increase the price of food products. Then, the actor in the energy sector has two choices: either to raise the cost of electricity or to shift to other technologies. Of course the first choice is the easiest one; however, there is another actor, which is the end consumer of these three sectors, who will mostly response in a conflict way with low tolerance and low power ending up with internal political instability.

In the end, decision making process for securing the future of vital sectors in any country should be performed carefully with the inclusion of all stakeholders who are affected either directly or indirectly and with the consideration of the spatial and temporal variations.

6 References

AbdulRazek, Y., 2009. Uranium resources in Egypt.

Abu Taha, R., Daim, T., 2013. Multi-Criteria Applications in Renewable Energy Analysis, a Literature Review, in: Daim, T., Oliver, T., Kim, J. (Eds.), Research and Technology Management in the Electricity Industry. Springer London, London, pp. 17–30.

Afgan, N.H., Carvalho, M.G., 2002. Multi-criteria assessment of new and renewable energy power plants. Energy 27, 739–755. doi:10.1016/S0360-5442(02)00019-1

Afgan, N.H., Carvalho, M.G., Jovanovic, M., 2007. Biomass-fired power plant: the sustainability option. Int. J. Sustain. Energy 26, 179–193. doi:10.1080/14786450701550434

Amer, H.A., Shawky, S., Hussein, M.I., Abd El-Hady, M.L., 2002. Radiological study of exposure levels in El Maghara underground coal mine. J. Environ. Monit. 4, 583–587. doi:10.1039/b202693g

Begić, F., Afgan, N.H., 2007. Sustainability assessment tool for the decision making in selection of energy system—Bosnian case. Energy 32, 1979–1985. doi:10.1016/j.energy.2007.02.006

Bellhouse, D., 2007. The problem of Waldegrave. J. Électronique Hist. Probab. Stat. 3.

Billari, F.C., Fent, T., Prskawetz, A., Scheffran, J. (Eds.), 2006. Agent-Based Computational Modelling, Contributions to Economics. Physica-Verlag HD, Heidelberg.

Burgherr, P., Eckle, P., Hirschberg, S., 2011. Final report on severe accident risks including key indicators (Security of Energy Considering its Uncertainity, Risk and Economic implications No. 213744). Paul Scherrer Institut (PSI).

Burgherr, P., Hirschberg, S., 2005. Comparative Assessment of Natural Gas Accident Risks (Comprehensive Assessment of Energy Systems). Paul Scherrer Institut (PSI), Switzerland.

Burton, J., Hubacek, K., 2007. Is small beautiful? A multicriteria assessment of small-scale energy technology applications in local governments. Energy Policy 35, 6402–6412. doi:10.1016/j.enpol.2007.08.002

CAPMAS, 2016. Governorates population [WWW Document]. Cent. Agency Public Mobilization Stat. URL http://www.capmas.gov.eg/Pages/populationClock.aspx (accessed 11.6.16).

Cartelle Barros, J.J., Lara Coira, M., de la Cruz López, M.P., del Caño Gochi, A., 2015. Assessing the global sustainability of different electricity generation systems. Energy 89, 473–489. doi:10.1016/j.energy.2015.05.110

Central Intelligence Agency, 2017. The World Factbook _Egypt [WWW Document]. URL https://www.cia.gov/library/publications/the-world-factbook/geos/eg.html (accessed 2.13.17).

Chaouki Ghenai, 2012. Life Cycle Analysis of Wind Turbine. INTECH Open Access Publisher.

del Río, P., Burguillo, M., 2009. An empirical analysis of the impact of renewable energy deployment on local sustainability. Renew. Sustain. Energy Rev. 13, 1314–1325. doi:10.1016/j.rser.2008.08.001

Demirtas, O., 2013. Evaluating the Best Renewable Energy Technology For Sustainable Energy Planning. Int. J. Energy Econ. Policy 3, 23–33.

Diakoulaki, D., Karangelis, F., 2007. Multi-criteria decision analysis and cost–benefit analysis of alternative scenarios for the power generation sector in Greece. Renew. Sustain. Energy Rev. 11, 716–727. doi:10.1016/j.rser.2005.06.007

Diehl, T.H., 2013. Methods for estimating water consumption for thermoelectric power plants in the United States, Scientific Investigations report. U.S. Department of the Interior, U.S. Geological Survey, Reston, Virginia.

Dombi, M., Kuti, I., Balogh, P., 2014. Sustainability assessment of renewable power and heat generation technologies. Energy Policy 67, 264–271. doi:10.1016/j.enpol.2013.12.032

Doukas, H.C., Andreas, B.M., Psarras, J.E., 2007. Multi-criteria decision aid for the formulation of sustainable technological energy priorities using linguistic variables. Eur. J. Oper. Res. 182, 844–855. doi:10.1016/j.ejor.2006.08.037

Doukas, H., Papadopoulou, A., Savvakis, N., Tsoutsos, T., Psarras, J., 2012. Assessing energy sustainability of rural communities using Principal Component Analysis. Renew. Sustain. Energy Rev. 16, 1949–1957. doi:10.1016/j.rser.2012.01.018

Dubey, S., Sarvaiya, J.N., Seshadri, B., 2013. Temperature Dependent Photovoltaic (PV) Efficiency and Its Effect on PV Production in the World – A Review. Energy Procedia 33, 311–321. doi:10.1016/j.egypro.2013.05.072

EEHC, 2014. Egyptian Electricity Holding Company annual report. Ministry of electricity and renewable energy, Cairo.

EGAS [WWW Document], 2013. URL http://egas.com.eg/Egyptian_Natural_Gas/Establishing_gas.aspx (accessed 10.6.16).

Egyptera, 2015. Integrated sustainable energy strategy to 2035. Cairo.

Egyptera, 2014. Energy strategy in Egypt.

Eisenack, K., Lüdeke, M., Petschel-Held, G., Scheffran, J., Kropp, J., 2007. Qualitative Modelling Techniques to Assess Patterns of Global Change, in: Kropp, J., Scheffran, J. (Eds.), Advanced Methods for Decision Making and Risk Management in Sustainability Science. Nova Science Publishers, New York, pp. 99–146.

El-Nahrawy, M.A., 2011. Country Pasture/Forage Resource Profiles: Egypt. FAO.

ElSobki, M.S., 2015. Full Scale Program for Renewable Energy in Egypt.

ESI-Africa, 2016. Egypt: Ministry of Electricity invests $4.5bn in coal-fired power. ESI-Afr.

EURELECTRIC, VGB, 2003. Efficiency in Electricity Generation. Brussels.

European Nuclear Society, 2017. Fuel comparison [WWW Document]. URL https://www.euronuclear.org/info/encyclopedia/f/fuelcomparison.htm (accessed 3.19.17).

Evans, A., Strezov, V., Evans, T.J., 2009. Assessment of sustainability indicators for renewable energy technologies. Renew. Sustain. Energy Rev. 13, 1082–1088. doi:10.1016/j.rser.2008.03.008

Frauenhofer ISE, 2016. Frauenhofer ISE annual report. Freiburg.

GEO, 2016. Egypt Energy Map Data in GEO [WWW Document]. Glob. Energy Obs. URL http://globalenergyobservatory.org/constructNetworkIndex.php (accessed 10.6.16).

Georgia Power's Plant Scherer, 1982. A Coal-Fired Thermoelectric Power Plant.

Gilbert, G.N., 2008. Agent-based models, Quantitative applications in the social sciences. Sage Publications, Los Angeles.

GIS-Lab, 2014. VMap0 data in ESRI shape format [WWW Document]. URL http://gis-lab.info/qa/vmap0-eng.html (accessed 10.6.16).

Global Energy Network Institute, 2016. Map of Egyptian Electricity Grid [WWW Document]. Map Egypt. Electr. Grid - Egypt - Natl. Energy Grids - Libr. - GENI -. URL http://www.geni.org/globalenergy/library/national_energy_grid/egypt/egyptiannationalelectricitygrid.shtml (accessed 10.6.16).

Góralczyk, M., 2003. Life-cycle assessment in the renewable energy sector. Appl. Energy 75, 205–211. doi:10.1016/S0306-2619(03)00033-3

Gylling Mortensen, N., Egypten, New and Renewable Energy Authority, Egyptian Meteorological Authority, Forskningscenter Risø, 2006. Wind atlas for Egypt: measurements and modelling 1991-2005. New and Renewable Energy Authority : Egyptian Meteorological Authority ; Risø National Laboratory, Cairo; Roskilde.

Haapala, K.R., Prempreeda, P., 2014. Comparative life cycle assessment of 2.0 MW wind turbines. Int. J. Sustain. Manuf. 3, 170. doi:10.1504/IJSM.2014.062496

Hall, D.O., 1976. Photobiological energy conversion. FEBS Lett. 64, 6–16. doi:10.1016/0014-5793(76)80236-0

Hansson, S.O., 2005. Decision theory: A brief introduction. Royal Institute of Technology (KTH), Stockholm.

Hasegawa, A., Ohira, T., Maeda, M., Yasumura, S., Tanigawa, K., 2016. Emergency Responses and Health Consequences after the Fukushima Accident; Evacuation and Relocation. Clin. Oncol. 28, 237–244. doi:10.1016/j.clon.2016.01.002

Hasegawa, A., Tanigawa, K., Ohtsuru, A., Yabe, H., Maeda, M., Shigemura, J., Ohira, T., Tominaga, T., Akashi, M., Hirohashi, N., Ishikawa, T., Kamiya, K., Shibuya, K., Yamashita, S., Chhem, R.K., 2015. Health effects of radiation and other health problems in the aftermath of nuclear accidents, with an emphasis on Fukushima. The Lancet 386, 479–488. doi:10.1016/S0140-6736(15)61106-0

Hatch, 2014. Lifecycle Assessment Literature Review of Nuclear, Wind and Natural Gas Power Generation. Canadian Nuclear Association, Canada.

Hersch, P., Zweibel, K., 1982. Basic photovoltaic principles and methods (No. SERI/SP-290-1448, 5191389).

Hirschberg, S., Bauer, C., Burgherr, P., Dones, R., Simons, A., Schenler, W., Bachmann, T., Gallego Carrera, D., 2008. Final set of sustainability criteria and indicators for assessment of electricity supply options (EU-Project NEEDS New Energy Externalities Developments for Sustainability), Deliverable n° D3.2 – RS 2b. Paul Scherrer Institut (PSI).

Hirschberg, S., Burgherr, P., Spiekerman, G., Cazzoli, E., Vitazek, J., Cheng, L., 2003. Comparative Assessment of Severe Accidents in the Chinese Energy Sector (China Energy Technology Program). Paul Scherrer Institut (PSI).

Hirschberg, S., Dones, R., Heck, T., Burgherr, P., Schenler, W., Bauer, C., 2004. Sustainability of electricity supply technologies under German conditions : a comparative evaluation (Comprehensive Assessment of Energy Systems). Paul Scherrer Institut (PSI), Switzerland.

IAEA, 2007. ENERGY INDICATORS FOR SUSTAINABLE DEVELOPMENT: Country Studies on Brazil, Cuba, Lithuania Mexico, Russian Federation, Slovakia and Thailand. International Atomic Energy Agency, Vienna.

IAEA, 2005. Energy indicators for sustainable development: guidelines and methodologies. International Atomic Energy Agency, Vienna.

IEA, 2014. Snapshot of Global PV Markets: Photovoltaic Power Systems Programme. International Energy Agency.

Ileana, 2015. Bioenergy: 5 facts you must read about. Convert News.

IPCC, 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva.

Islam, M.T., Shahir, S.A., Uddin, T.M.I., Saifullah, A.Z.., 2014. Current energy scenario and future prospect of renewable energy in Bangladesh. Renew. Sustain. Energy Rev. 39, 1074–1088. doi:10.1016/j.rser.2014.07.149

Jovanović, M., Afgan, N., Radovanović, P., Stevanović, V., 2009. Sustainable development of the Belgrade energy system. Energy 34, 532–539. doi:10.1016/j.energy.2008.01.013

Kahraman, C., Kaya, İ., Cebi, S., 2009. A comparative analysis for multiattribute selection among renewable energy alternatives using fuzzy axiomatic design and fuzzy analytic hierarchy process. Energy 34, 1603–1616. doi:10.1016/j.energy.2009.07.008

Kaya, T., Kahraman, C., 2011. Multicriteria decision making in energy planning using a modified fuzzy TOPSIS methodology. Expert Syst. Appl. 38, 6577–6585. doi:10.1016/j.eswa.2010.11.081

Kaya, T., Kahraman, C., 2010. Multicriteria renewable energy planning using an integrated fuzzy VIKOR & AHP methodology: The case of Istanbul. Energy 35, 2517–2527. doi:10.1016/j.energy.2010.02.051

Khalil, A.K., Mubarak, A.M., Kaseb, S.A., 2010. Road map for renewable energy research and development in Egypt. J. Adv. Res. 1, 29–38. doi:10.1016/j.jare.2010.02.003

K. Ibrahim, T., Rahman, M.M., 2012. Effect of Compression Ratio on Performance of Combined Cycle Gas Turbine. Int. J. Energy Eng. 2, 9–14. doi:10.5923/j.ijee.20120201.02

Kowalski, K., Stagl, S., Madlener, R., Omann, I., 2009. Sustainable energy futures: Methodological challenges in combining scenarios and participatory multi-criteria analysis. Eur. J. Oper. Res. 197, 1063–1074. doi:10.1016/j.ejor.2007.12.049

Link, P.M., Kominek, J., Scheffran, J., 2013. Impacts of accelerated sea level rise on the coastal zones of Egypt. Mainz. Geogr. Stud. 55, 79– 94.

Liu, G., 2014. Development of a general sustainability indicator for renewable energy systems: A review. Renew. Sustain. Energy Rev. 31, 611–621. doi:10.1016/j.rser.2013.12.038

Loulou, R., Goldstein, G., Noble, K., 2004. Documentation for the MARKAL Family of Models. ETSAP.

Loulou, R., Remne, U., Kanudia, A., Lehtila, A., Goldstein, G., 2005. Documentation for the MARKAL Model-Part I. ETSAP.

Macal, C., North, M., 2006. Introduction to Agent-based Modeling and Simulation.

Mainali, B., Silveira, S., 2015. Using a sustainability index to assess energy technologies for rural electrification. Renew. Sustain. Energy Rev. 41, 1351–1365. doi:10.1016/j.rser.2014.09.018

Matteson, S., 2014. Methods for multi-criteria sustainability and reliability assessments of power systems. Energy 71, 130–136. doi:10.1016/j.energy.2014.04.042

McMaster University, 1996. The McMaster Nuclear Reactor [WWW Document]. URL https://mnr.mcmaster.ca/index.php/about/how-does-it-work (accessed 4.7.17).

Met Office, 2011. Climate: Observations, projections and impacts (Egypt) (Country factsheet). Met Office, United Kingdom.

Meyer, L., Brinkman, S., van Kesteren, L., Leprince-Ringuet, N., van Boxmeer, F., 2014. IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of theIntergovernmental Panel on Climate Change. Geneva, Switzerland.

MIT SDEP, 1997. What is System Dynamics? [WWW Document]. URL http://web.mit.edu/sysdyn/sd-intro/ (accessed 2.9.17).

Myerson, R.B., 2004. Game theory: analysis of conflict, 6. print. ed. Harvard Univ. Press, Cambridge, Mass.

National Research Council (U.S.), National Academies (U.S.), Zhongguo ke xue yuan, Zhongguo gong cheng yuan, National Academies Press (U.S.) (Eds.), 2010. The power of renewables: opportunities and challenges for China and the United States. National Academies Press, Washington, D.C.

Ness, B., Urbel-Piirsalu, E., Anderberg, S., Olsson, L., 2007. Categorising tools for sustainability assessment. Ecol. Econ. 60, 498–508. doi:10.1016/j.ecolecon.2006.07.023

Neumann, J. von, 1928. Zur Theorie der Gesellschaftsspiele. Math. Ann. 100, 295–320.

Neves, A.R., Leal, V., 2010. Energy sustainability indicators for local energy planning: Review of current practices and derivation of a new framework. Renew. Sustain. Energy Rev. 14, 2723–2735. doi:10.1016/j.rser.2010.07.067

NREA, 2015. Annual report. New and Renewable Energy Authority.

NREL, 2015. Reported timeline of solar cell energy conversion efficiencies.

NREL, 2013a. Life Cycle Greenhouse Gas Emissions from Electricity Generation (Fact sheet). NREL, USA.

NREL, 2013b. Energy Analysis - Energy Technology Cost and Performance Data [WWW Document]. URL http://www.nrel.gov/analysis/tech_lcoe_documentation.html (accessed 3.12.16).

OECD/IEA, 2015. Key World Energy STATISTICS 2015. International Energy Agency, Paris.

OECD/IEA, 2014. World Energy Investment Outlook (Special Report). International Energy Agency, Paris.

OECD/NEA, 2016. Uranium 2016: Resources, Production and Demand.

Onat, N., Bayar, H., 2010. The sustainability indicators of power production systems. Renew. Sustain. Energy Rev. 14, 3108–3115. doi:10.1016/j.rser.2010.07.022

Open Energy Information, 2015. Transparent Cost Database_Capcity factor [WWW Document]. URL http://en.openei.org/apps/TCDB/#blank (accessed 3.19.17).

Paul J. H. Schoemaker, 1982. The Expected Utility Model: Its Variants, Purposes, Evidence and Limitations. J. Econ. Lit. 20, 529–563.

Paul Scherrer Institut, 2016. Risk Assessment [WWW Document]. psi.ch. URL http://psi.ch/i8zb (accessed 4.4.16).

Pehnt, M., 2006. Dynamic life cycle assessment (LCA) of renewable energy technologies. Renew. Energy 31, 55–71. doi:10.1016/j.renene.2005.03.002

Pohekar, S.D., Ramachandran, M., 2004. Application of multi-criteria decision making to sustainable energy planning—A review. Renew. Sustain. Energy Rev. 8, 365–381. doi:10.1016/j.rser.2003.12.007

Reuters, 2016a. Japan's Marubeni may build coal power plant in Egypt [WWW Document]. URL http://www.reuters.com/article/marubeni-egypt-plant-idUSL3N16A3LG (accessed 4.22.16).

Reuters, 2016b. Egypt warns citizens from participating in foreign polls. Reuters.

Reuters, 2015. Egypt, Russia sign deal to build a nuclear power plant. Reuters.

Rovere, E.L.L., Soares, J.B., Oliveira, L.B., Lauria, T., 2010. Sustainable expansion of electricity sector: Sustainability indicators as an instrument to support decision making. Renew. Sustain. Energy Rev. 14, 422–429. doi:10.1016/j.rser.2009.07.033

Rutovitz, J., Harris, S., 2012. Calculating global energy sector jobs: 2012 Methodology (For Greenpeace International). Institute for Sustainable Futures, University of Technology, Sydney.

Saaty, T.L., 1980. The analytic hierarchy process: planning, priority setting, resource allocation. McGraw-Hill International Book Co, New York ; London.

Scheffran, J., 2013. Conditions for Cooperation and Trading in Value-Cost Dynamic Games, in: Křivan, V., Zaccour, G. (Eds.), Advances in Dynamic Games. Springer International Publishing, Cham, pp. 173–203.

Scheffran, J., 2010. Criteria for a Sustainable Bioenergy Infrastructure and Lifecycle, in: Mascia, P.N., Scheffran, J., Widholm, J.M. (Eds.), Plant Biotechnology for Sustainable Production of Energy and Co-Products. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 409–447.

Scheffran, J., 2008. Adaptive management of energy transitions in long-term climate change. Comput. Manag. Sci. 5, 259–286. doi:10.1007/s10287-007-0044-1

Scheffran, J., BenDor, T., 2009. Bioenergy and land use: a spatial-agent dynamic model of energy crop production in Illinois. Int. J. Environ. Pollut. 39, 4. doi:10.1504/IJEP.2009.027140

Scheffran, J., Hannon, B., 2007. From complex conflicts to stable cooperation: Cases in environment and security. Complexity 13, 78–91. doi:10.1002/cplx.20201

Schröder, A., Kunz, F., Meiss, J., Mendelevitch, R., von Hirschhausen, C., 2013. Current and Prospective Costs of Electricity Generation until 2050. Deutsches Institut für Wirtschaftsforschung, Berlin.

SE4All, 2011. Sustainable Energy for All [WWW Document]. URL http://www.se4all.org/our-vision (accessed 5.3.16).

Servert, J.F., Cerrajero, E., 2015. Assessment on Egypt's CSP Components Manufacturing Potential. Energy Procedia 69, 1498–1507. doi:10.1016/j.egypro.2015.03.100

Shaaban, M., Scheffran, J., 2017. Selection of sustainable development indicators for the assessment of electricity production in Egypt. Sustain. Energy Technol. Assess. 22, 65–73. doi:10.1016/j.seta.2017.07.003

Singh, R.K., Murty, H.R., Gupta, S.K., Dikshit, A.K., 2009. An overview of sustainability assessment methodologies. Ecol. Indic. 9, 189–212. doi:10.1016/j.ecolind.2008.05.011

SourceWatch, 2016. Hamarawein Port power station [WWW Document]. URL http://www.sourcewatch.org/index.php/Hamarawein_Port_power_station (accessed 2.14.17).

Spang, E.S., Moomaw, W.R., Gallagher, K.S., Kirshen, P.H., Marks, D.H., 2014. The water consumption of energy production: an international comparison. Environ. Res. Lett. 9, 105002. doi:10.1088/1748-9326/9/10/105002

Stambouli, A.B., Khiat, Z., Flazi, S., Kitamura, Y., 2012. A review on the renewable energy development in Algeria: Current perspective, energy scenario and sustainability issues. Renew. Sustain. Energy Rev. 16, 4445–4460. doi:10.1016/j.rser.2012.04.031

Steele, K., Stefánsson, H.O., 2016. Decision Theory, in: Zalta, E.N. (Ed.), The Stanford Encyclopedia of Philosophy. Metaphysics Research Lab, Stanford University.

Terrapon-Pfaff, J., Dienst, C., König, J., Ortiz, W., 2014. A cross-sectional review: Impacts and sustainability of small-scale renewable energy projects in developing countries. Renew. Sustain. Energy Rev. 40, 1–10. doi:10.1016/j.rser.2014.07.161

The Global Wind Energy Council, 2015. GLOBAL STATISTICS.

The World Bank, 2014a. Total population [WWW Document]. Population. URL http://data.worldbank.org/indicator/SP.POP.TOTL (accessed 4.22.16).

The World Bank, 2014b. Electric power consumption [WWW Document]. Electr. Power Consum. URL http://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC (accessed 4.22.16).

Trieb, F., 2005. MED-CSP: Concentrating Solar Power for the Mediterranean Region. German Aerospace Center (DLR), Stuttgart.

Troldborg, M., Heslop, S., Hough, R.L., 2014. Assessing the sustainability of renewable energy technologies using multi-criteria analysis: Suitability of approach for national-scale assessments and associated uncertainties. Renew. Sustain. Energy Rev. 39, 1173–1184. doi:10.1016/j.rser.2014.07.160

Tsai, W.-T., 2010. Energy sustainability from analysis of sustainable development indicators: A case study in Taiwan. Renew. Sustain. Energy Rev. 14, 2131–2138. doi:10.1016/j.rser.2010.03.027

Turconi, R., Boldrin, A., Astrup, T., 2013. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renew. Sustain. Energy Rev. 28, 555–565. doi:10.1016/j.rser.2013.08.013

United Nations, 2016. United Nations sustainable development agenda. U. N. Sustain. Dev.

U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, n.d. The main parts of wind turbine.

US EIA, 2017a. International Energy Statistics: Data_Egypt_Natural gas [WWW Document]. US Energy Inf. Adm. URL https://www.eia.gov/beta/international/data/browser/#/?pa=00000000000000000004&c=0000000000001&ct=0&tl_id=3002-A&vs=INTL.3-6-EGY-TCF.A&cy=2014&vo=0&v=H&start=1980&s=INTL.7-1-EGY-TST.A (accessed 3.19.17).

US EIA, 2017b. How much coal, natural gas, or petroleum is used to generate a kilowatthour of electricity? - FAQ - U.S. Energy Information Administration (EIA) [WWW Document]. US Energy Inf. Adm. URL https://www.eia.gov/tools/faqs/faq.php?id=667&t=6 (accessed 3.19.17).

US EIA, 2016. Biomass explained [WWW Document]. US Energy Inf. Adm. URL https://www.eia.gov/energyexplained/index.cfm?page=biomass_home (accessed 4.7.17).

US EIA, 2015. Egypt energy analysis [WWW Document]. US Energy Inf. Adm. URL https://www.eia.gov/beta/international/analysis.cfm?iso=EGY (accessed 3.14.16).

US EIA, 2014. International Energy Statistics: Data_Egypt_Coal [WWW Document]. US Energy Inf. Adm. URL https://www.eia.gov/beta/international/data/browser/#/?pa=000000000000000000000000000000000000000000000000003101&c=0000000000001&ct=0&tl_id=1-A&vs=INTL.1-6-EGY-MST.A&vo=0&v=H&start=2014&end=2014&showdm=y (accessed 3.19.17).

US EIA, 2013. International [WWW Document]. US Energy Inf. Adm. URL http://www.eia.gov/beta/international/ (accessed 4.6.16).

Varun, Bhat, I.K., Prakash, R., 2009a. LCA of renewable energy for electricity generation systems—A review. Renew. Sustain. Energy Rev. 13, 1067–1073. doi:10.1016/j.rser.2008.08.004

Varun, Prakash, R., Bhat, I.K., 2009b. Energy, economics and environmental impacts of renewable energy systems. Renew. Sustain. Energy Rev. 13, 2716–2721. doi:10.1016/j.rser.2009.05.007

Vera, I., Langlois, L., 2007. Energy indicators for sustainable development. Energy 32, 875–882. doi:10.1016/j.energy.2006.08.006

VGB, 2011. Investment and Operation Cost Figures – Generation Portfolio. Germany.

Wang, C., Mu, D., 2014. An LCA study of an electricity coal supply chain. J. Ind. Eng. Manag. 10. doi:10.3926/jiem.1053

Wang, J.-J., Jing, Y.-Y., Zhang, C.-F., Zhao, J.-H., 2009. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renew. Sustain. Energy Rev. 13, 2263–2278. doi:10.1016/j.rser.2009.06.021

Wei, M., Patadia, S., Kammen, D.M., 2010. Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US? Energy Policy 38, 919–931. doi:10.1016/j.enpol.2009.10.044

Weisser, D., 2007. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. Energy 32, 1543–1559. doi:10.1016/j.energy.2007.01.008

Weston, K.C., 1992. Energy conversion. West Pub. Co, St. Paul.

Worldometers, 2017. Egypt Population (2017) [WWW Document]. URL http://www.worldometers.info/world-population/egypt-population/ (accessed 2.13.17).

7 Appendices

Appendix A: Questionnaire design

Version 1

STUDY OBJECTIVES

In my study "*The Roadmap to Energy Security in Egypt*", I conduct a sustainability analysis of different electricity supply resources in terms of technical, socio-economic and environmental analysis for Egypt.
The aim of this questionnaire is to measure the importance and the weight of the selected sustainability criteria for future electricity planning, and ranking the different electricity production technologies for future supply.
This data is important to me as it will be further used for analyzing the sustainability extent of each electricity supply resource. Furthermore, it will be used for designing future electricity mix scenarios for Egypt.
You as experts, decision makers, investors, researchers, consumers and citizens play an important role in designing and shaping future energy that is strictly linked to the future quality of life. The questionnaire will take from you only 15-20 minutes. Please read the instructions on how to fill in the questionnaire before going through it.
After collecting the data, it will be analyzed and surely I will send you a feedback about the results.
For privacy, you will only be asked to choose your gender, nationality and affiliation. No names or contact details should be provided and your participation will be kept confidential.

INSTRUCTIONS ON HOW TO FILL IN THE QUESTIONNAIRE

1- Table 1 measures the importance of the criteria for future electricity planning through pairwise comparison. You should compare the criteria in the first column with those in the first row such that the criterion in the first column, second row is of (…) importance as compared to the criterion in the first row, second column, but not vice versa, then select an item from the drop-down list in the corresponding cell (e.g., Direct employment generation is of (very high / high / equal / low / very low) importance as compared to Investment cost, then compared to Greenhouse gases and particles emissions and so on. You should fill it horizontally, not vertically, starting the sentence in your mind with the criteria in the first column.

2- Table 2 measures your general preference of the electricity supply technologies through the same principle of table 1 which is the pairwise comparison. You should compare the technologies in the first column with those in the first row such that the technology in the first column, second row is of (very high / high / equal / low / very low) preference as compared to the technology in the first row, second column, but not vice versa, then select an item from the drop-down list in the corresponding cell. Again, you should fill it horizontally, not vertically, starting the sentence in your mind with the criteria in the first column.

3- Finally, you will be asked to select your gender, nationality and affiliation.

4- Please, do not use the shaded cells.

Table 1: Importance of criteria

Criteria	Investment cost	Levelized Cost of Electricity	GHGs* and particles emissions	Waste generation	Visual, noise and odor discomfort	Illness due to normal operation	Safety (fatalities/ accident)	Social accept-ability	Area require-ment	Energy efficiency	Water consumpt-ion
Direct employ-ment generation	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Investment cost	Choose an item. 5= very high 4= high 3= equal 2= low 1= very low	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Levelized Cost of Electricity			Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
GHGs* and particles emissions				Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Waste generation					Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Visual, noise and odor discomfort						Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Illness due to normal operation							Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Safety (fatalities/ accident)								Choose an item.	Choose an item.	Choose an item.	Choose an item.
Social accept-ability									Choose an item.	Choose an item.	Choose an item.
Area requirement										Choose an item.	Choose an item.
Energy efficiency											Choose an item.

* Greenhouse Gases

Table 2: Power generation technology preference in electricity planning

Technologies	Hydro-power	Wind power	Solar thermal power	Photovoltaics	Nuclear power
Conventional (fossil fuels based) power plants	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Hydro-power		Choose an item.	Choose an item.	Choose an item.	Choose an item.
Wind			Choose an item.	Choose an item.	Choose an item.
Solar thermal power				Choose an item.	Choose an item.
Photovoltaics					Choose an item.

Choose an item.
5= very high
4= high
3= equal
2= low
1= very low

Gender

Choose an item.

Choose an item.
Female
Male

Nationality

Choose an item.

Choose an item.
Afghanistan
Albania
Algeria
Andorra
Angola
Antigua & Deps
Argentina
Armenia
Australia
Austria
Azerbaijan
Bahamas
Bahrain
Bangladesh
Barbados
Belarus
Belgium
Belize
Benin
Bhutan
Bolivia
Bosnia Herzegovina
Botswana
Brazil
Brunei
Bulgaria
Burkina
Burundi
Cambodia

Affiliation

Choose an item.

Choose an item.
Governmental employee
Private employee
Investor
Undergraduate Student
M.Sc./M.A. Student
PhD Student
Researcher

THANK YOU FOR YOUR TIME

Version 2

Questionnaire

Q1. If you have the opportunity to invest in the installation of power plants in Egypt, how would you allocate your investment over the different technologies in percentage? Please write the number in % below each technology in the following table so that the total will be 100%.

						
Coal fired power plants	Oil fired power plants	Natural Gas fired power plants	Wind power	Solar thermal power	Photovoltaics	Nuclear power plants

Q2. Based on your investment allocation, what are the criteria that are important to you while thinking about investment in power plants in Egypt?
Below are some of the criteria that are taken in consideration while planning for electricity production. Please, rank these criteria from 1 to 9 according to their importance for you, so that **1 means the highest** important **while 9 means the lowest** important. You can give two or more criteria the same importance number.
Additionally, kindly specify other criteria that are not mentioned but seem to be important to you in the fourth column and rank them by specifying their importance position relative to the mentioned criteria in the second column by writing the code letter in column 5, 6 and 7.

Code letter	**Criteria**	**Importance ranking**	**Others**	**Importance ranking**		
				Same as	**Before**	**After**
A	Investment cost					
B	Cost of Electricity					
C	GHGs and particles emissions					
D	Visual, noise and odor discomfort					
E	Safety (fatalities/ accident)					
F	Social acceptability					
G	Area requirements and land use					
H	Plant Energy efficiency					
I	Water consumption					

Q3. Kindly, specify your gender, nationality and position in the table below.

Gender	**Nationality**	**Position**

Q4. (Optional): Name:……………………………… Email:………………………… Thank you for your time☺

Appendix B: Sustainability assessment indicators collected from the literature

Table 28: A set of indicators collected from the literature

Category	Indicator Code	Indicator
Economic Indicators	v1	Average generation cost
	v2	Construction period
	v3	Contribution to economy
	v4	Cost-benefit index
	v5	Creation of a local industry
	v6	Direct employment generated
	v7	Flexibility of dispatch
	v8	Ratio of fuel cost to generation cost
	v9	Investment cost
	v10	Job creation (direct & indirect)
	v11	Cost of electricity
	v12	Medium to long-term independence from foreign energy sources
	v13	Net energy import dependency
	v14	Net Present Cost
	v15	Operation and maintenance cost
	v16	Payback period
	v17	Percentage of imported inputs
	v18	Return on investment
	v19	Service life
	v20	Total average variable cost
	v21	Tourism
Environmental Indicators	v22	Acidification and eutrophication
	v23	Amenity
	v24	CO emission
	v25	CO_2 emission
	v26	Contaminant discharges in liquid effluents from energy systems
	v27	Eco-toxicity
	v28	Greenhouse gas emissions
	v29	Land use impact on biodiversity
	v30	Non-methane volatile organic compounds
	v31	NO_x emission
	v32	Particles emission
	v33	Rate of deforestation attributed to energy use
	v34	Ratio of solid waste properly disposed of to total generated solid waste
	v35	Ratio of solid-waste generation to units of energy produced
	v36	Severe accidents from oil or nuclear leakage
	v37	SO_2 emission
	v38	Soil area where acidification exceeds critical load

Social Indicators	v39	Accessibility
	v40	Affordability
	v41	Average job income level
	v42	Contribution to traffic
	v43	Effects on migration and immigration
	v44	Disparities
	v45	Diversity of primary energy suppliers
	v46	Equitable life conditions
	v47	Flexibility to incorporate technological change
	v48	Likely potential effects of a successful attack
	v49	Local workers education by training
	v50	Maximum consequences of accidents
	v51	Necessity of participative decision-making processes for different technologies
	v52	Non-fatal illness due to normal operation
	v53	Perceived risk characteristics for accidents
	v54	Perceived risk characteristics for normal operation
	v55	Potential of attack
	v56	Potential of conflict induced by energy systems
	v57	Poverty
	v58	Reduced life expectancy due to normal operation
	v59	Safety
	v60	Social acceptability
	v61	Social cohesion and human development
	v62	Waste management
	v63	Willingness of NGOs and other citizen movements to act against the realization of an option
	v64	Work quality
Technical Indicators	v65	Area requirements
	v66	Average annual availability
	v67	Efficiency of energy generation
	v68	Resource potential
	v69	Primary energy ratio
	v70	Reliability of energy supply
	v71	Technology maturity
	v72	Water consumption
References	del Río and Burguillo 2009, Wang et al. 2009, Demirtas 2013, Begić and Afgan 2007, Rovere et al. 2010, Mainali and Silveira 2015, Liu 2014, Neves and Leal 2010, Troldborg et al. 2014, Evans et al. 2009, Vera and Langlois 2007, Onat and Bayar 2010, IAEA 2005, Hirschberg et al. 2008, Hirschberg et al. 2004, IAEA 2007, Matteson 2014, Kaya and Kahraman 2010, Cartelle Barros et al. 2015, Diakoulaki and Karangelis 2007, Jovanović et al. 2009, Kowalski et al. 2009, Afgan and Carvalho 2002, Afgan et al. 2007, Burton and Hubacek 2007, Doukas et al. 2007, Varun et al. 2009b, Kahraman et al. 2009, Dombi et al. 2014, Kaya and Kahraman 2011	

Appendix C: The online survey structure and the challenges in data collection

1. The Arabic version below:
   Dear prospective participants,

I investigate the sustainability of different electricity supply technologies that could be installed in Egypt to meet the growing demands through a multi-criteria decision analysis methodology covering the technical, social, economic and environmental dimensions of these technologies. The social acceptability is one of the main criteria of assessment under the social dimension. In order to ensure the sustainability of a new power plant project, it is very crucial to involve all stakeholders' opinions and perspectives in the decision making process and give the feeling of respect and consideration to the public sector which is affected by the project. Thus, I will be delighted to invite you to this simple survey. It will take from you only 3-5 min. After collecting the data, it will be analyzed and of course I will send you an overview about the results.
For privacy, you will only be asked to choose your gender, and city (governorate) of residence in Egypt. No names or contact details should be provided and your participation will be kept confidential.

Thank you very much for your participation

Mostafa Shaaban
University of Hamburg

السادة الأفاضل
تحية طيبة وبعد
نظرا لما تواجهه مصر من الزيادة المستمرة فى معدل استهلاك الطاقة الكهربائية والحاجة إلى توفير ما يسد احتياجات المستهلكين فكان من الحاجة لانشاء محطات جديدة لتوليد الطاقة الكهربائية وتغذية الشبكات بما يسد هذه الاحتياجات. هناك تقنيات كثيرة لتوليد الكهرباء و التي تختلف حسب نوع المصادر الأولية المستخدمة فى توليد الطاقة مثل الوقود الإحفوري (الفحم, البترول, الغاز الطبيعي), الشمس, الرياح, الكتلة الحيوية المتمثلة فى أخشاب الشجر وبعض المحاصيل، الطاقة النووية وغيرها. لكل من هذه الأنظمة خصائص تميز بعضها عن البعض والتي لها دور كبير فى صناعة القرار عند الشروع فى انشاء محطة جديدة. لذلك فإننا نقوم بدراسة مدى استدامة هذه التكنولوجيا المختلفة التي يمكن انشاؤها في مصر لتلبية الاحتياجات المتزايدة من خلال منهجية تحليل معايير الاستدامة التي تشمل الأبعاد التقنية والاجتماعية والاقتصادية والبيئية لهذه التكنولوجيا. و من هذه المعايير التي نستخدمها مدى قبول المجتمع لهذه التكنولوجيا وهو أحد المعايير الرئيسية لتقييم إطار البعد الاجتماعي. فمن أجل ضمان استدامة مشروع محطة جديدة لتوليد الكهرباء، من المهم جدا إشراك آراء ووجهات نظر جميع أفراد المجتمع في عملية صناعة القرار
لذا يسعدني أن أدعوكم لهذا الاستبيان ومشاركتكم فى هذا المبحث الذي يستغرق فقط 3-5 دقائق

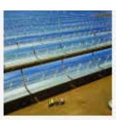
.للخصوصية: سوف يطلب منكم فقط اختيار النوع، ومدينة (محافظة) الإقامة في مصر بدون ذكر أسماء أو طرق الاتصال

شكرا جزيلا لكم على مشاركتكم
مصطفى شعبان
جامعة هامبورغ

Social acceptability of installation of new power plants

⊕ PAGE TITLE

* 2. How much knowledge do you have about each of these technologies?
ماذا لديك من المعلومات عن هذه التقنيات؟

	I have no idea ليس لدي فكرة	I just heard about it in the media سمعت عنها في وسائل الإعلام	Some basic information بعض المعلومات الأساسية	Good knowledge لدي معلومات جيدة	Expert in this technology خبير بهذه التقنية
 Coal-fired power plants فحم	○	○	○	○	○
 Oil-fired power plants بترول	○	○	○	○	○
 Natural gas-fired power plants غاز طبيعي	○	○	○	○	○
 Wind power plants رياح	○	○	○	○	○
 Concentrated solar power plants شمسية حرارية	○	○	○	○	○
 Ground-mounted Photovoltaic شمسية ضوئية	○	○	○	○	○
 Biomass-fired power plants كتلة حيوية	○	○	○	○	○
 Nuclear power plants نووية	○	○	○	○	○

* 3. Do you support the installation of any of these power plant in Egypt?
هل تدعم انشاء إحدى هذه المحطات في مصر؟

	Strongly disagree أرفض بشدة	Disagree أرفض	Neither agree nor disagree محايد	Agree أوافق	Strongly agree أوافق بشدة
Coal-fired power plants فحم					
Oil-fired power plants بترول					
Natural gas-fired power plants غاز طبيعي					
Wind power plants رياح					
Concentrated solar power plants شمسية حرارية					
Ground-mounted Photovoltaic شمسية ضوئية					
Biomass-fired power plants كتلة حيوية					
Nuclear power plants نووية					

* 4. When do you think the installation of each of these technologies should start?
متى تفضل البدأ في انشاء كل من هذه التقنيات في مصر؟

	As soon as possible في أقرب وقت	In 2020	In 2035	In 2050	In 2100
Coal-fired power plants فحم					
Oil-fired power plants بترول					
Natural gas-fired power plants غاز طبيعي					
Wind power plants رياح					
Concentrated solar power شمسية حرارية					
Ground-mounted Photovoltaic شمسية ضوئية					
Biomass power plants كتلة حيوية					
Nuclear power plants نووية					

* 5. How would you feel if any of these technologies were built near where you live?
ما مدى رضاؤك عن انشاء إحدى هذه التقنيات قريبا من محل إقامتك؟

	Strongly disagree أرفض بشدة	Disagree أرفض	Neither agree nor disagree محايد	Agree أوافق	Strongly agree أوافق بشدة
Coal-fired power plants فحم					
Oil-fired power plants بترول					
Natural gas-fired power plants غاز طبيعي					
Wind power plants رياح					
Concentrated solar power plants شمسية حرارية					
Ground-mounted Photovoltaic شمسية ضوئية					
Biomass-fired power plants كتلة حيوية					
Nuclear power plants نووية					

* 6. Kindly, rank the following technologies in order of preference, 1 being your most preferred technology.
فضلا قم بتصنيف هذه التقنيات حسب الأفضلية لديك بحيث أن رقم 1 هو الأفضل

- Coal-fired power plants فحم
- Oil-fired power plants بترول
- Natural gas-fired power plants غاز طبيعي
- Wind power plants رياح
- Concentrated solar power شمسية حرارية
- Photovoltaic شمسية ضوئية
- Biomass power plants كتلة حيوية
- Nuclear power plants نووية

* 7. Gender النوع

* 8. City (governorate) of residence محافظة الإقامة

Thank you for your time

The scoring calculation for each question for each technology in the survey

The answer of each question for each technology has an internal score which has a high value when a more positive answer is selected. For example, in the first question, when the answer is for "expert in this technology" then the score is 5, when it is "I have no idea", then the score is 1. The same applies for the other questions with a higher score to strongly agreeing or soon installation of the technology. For technology ranking, when 1 is selected, this is equivalent to the highest internal score technology. The scores for each technology is multiplied by the number of scoring participants in the questionnaire, then aggregated and averaged over the number of participants to give an integrated score for each technology under each question.

Example: (3x1 + 5x2 + 6x3 + 10x4 + 6x5) / (3+5+6+10+6) = 101/30 = 3.4

Challenges:

5-Minutes Survey on Energy sustainability in Egypt_distribution assistance

Christian Melchert <Christian.Melchert@daadcairo.org> 24 May 2016 at 12:27
To: Mostafa Shaaban <mostafa.shaaban@uni-hamburg.de>
Cc: moustafasha3ban <moustafasha3ban@gmail.com>, Abdelrahman Fatoum <a.fatoum@daadcairo.org>

Dear Mr. Shaaban,

We thank you for contacting us regarding your research and your interest in cooperation. Please excuse the belated reply.

Unfortunately, we will not be able to share your survey link. In general, we do not wish to share surveys and studies from third parties in our distribution list. We hope for your understanding and wish to point to alternative possibilities on social media channels.

We wish you all the best for your future research.

Best regards,

Christian Melchert

Christian Melchert

Coordinator, German Science Centre (DWZ) Cairo

11, Saleh Ayoub St.

Zamalek, Cairo, Egypt

Fon: +20 2 27 35 27 26 - Ext. 108

Email: christian.melchert@daadcairo.org

Deutsches
Wissenschaftszentrum Kairo

Deutschland
Land der Ideen

Survey on Energy sustainability in Egypt_distribution assistance

Research Institute for a Sustainable Environment <rise@aucegypt.edu> 17 May 2016 at 09:54
To: Moustafa Shaaban <moustafasha3ban@gmail.com>

Dear Moustafa,

To conduct research with assistance from AUC you will need to apply for the scholars without stipend program. The research itself will require IRB approval. Please find the link below for more information.

scholars without stipend

Regards,
The RISE Team

WORLD NEWS | Tue Nov 29, 2016 | 2:56pm EST

Egypt warns citizens from participating in foreign polls

The Egyptian government warned citizens on Tuesday against taking part in surveys conducted by foreign media organizations, saying it was a threat to national security.

The interior ministry said on Facebook that it had received complaints indicating that Egyptians had been getting telephone calls from media companies abroad asking their opinions on the country's political, economic and security situation.

"In this regard, the ministry calls on citizens to be cautious around those twisted methods of gathering information about the situation inside the country that aim to harm Egyptian national security," the statement read.

The warning comes amid efforts to quell rising dissent against army general-turned-President Abdel Fattah al-Sisi.

Egypt's parliament on Tuesday overwhelmingly endorsed a law on non-governmental organizations that human rights groups say effectively bans their work and makes it harder for charities to operate.

The law bans NGOs from conducting fieldwork or polls without permission or "from cooperating in any way with any international body without the necessary approval". Human rights groups say that includes the United Nations.

(Reporting by Amina Ismail; Editing by Robin Pomeroy)

Appendix D: Illustration of AHP methodology

	C1	C2	C3	C4	C5	C6	C7
C1	1.00	0.11	0.14	0.20	0.20	0.13	0.11
C2	9.00	1.00	3.00	4.00	4.00	2.00	1.00
C3	7.00	0.33	1.00	2.00	2.00	0.50	0.33
C4	5.00	0.25	0.50	1.00	1.00	0.33	0.20
C5	5.00	0.25	0.50	1.00	1.00	0.33	0.20
C6	8.00	0.50	2.00	3.00	3.00	1.00	0.50
C7	9.00	1.00	3.00	5.00	5.00	2.00	1.00
Total	44.00	3.44	10.14	16.20	16.20	6.29	3.34

	C1	C2	C3	C4	C5	C6	C7	Total	average	Consistency measure
C1	0.02	0.03	0.01	0.01	0.01	0.02	0.03	0.15	0.02	7.04
C2	0.20	0.29	0.30	0.25	0.25	0.32	0.30	1.90	0.27	7.24
C3	0.16	0.10	0.10	0.12	0.12	0.08	0.10	0.78	0.11	7.18
C4	0.11	0.07	0.05	0.06	0.06	0.05	0.06	0.47	0.07	7.10
C5	0.11	0.07	0.05	0.06	0.06	0.05	0.06	0.47	0.07	7.10
C6	0.18	0.15	0.20	0.19	0.19	0.16	0.15	1.20	0.17	7.26
C7	0.20	0.29	0.30	0.31	0.31	0.32	0.30	2.02	0.29	7.27
									CI	0.03
									RI	1.32
									CR	0.02

As can be seen from the above table, the assessment criteria (C1-C7) are sorted in a matrix to enable the pair-wise comparison between them.

Step one: each criterion in the first column is compared with the criteria in the first row. In case the comparison came between identical criteria then the score will be 1 which means equal importance. The scoring is based on the scale presented in Table 14. The cells in the lower left triangle (the blue cells) are the reciprocal of those in the upper right triangle (the red cells) of the matrix. Actually the data required from the questionnaire to apply this methodology are the answers of the pair-wise comparison of the red cells only.

Step two: the scores in each column are summed up vertically.

Step three: a similar matrix is constructed where the score value in each equivalent cell is divided by the total value in each column. For instance, in C1 column, 1 is divided by 44; then 9 is divided by 44 …etc.

Step four: the normalized values in each row are summed up horizontally forming a new column called total.

Step five: another column is constructed beside the total column which is named average column. Here the values in the new total column are divided by the number of criteria forming the average values. These average values are the weights of these criteria.

In case the methodology will be extended to be applied to the ranking of the technologies, then the same table will be constructed but instead of comparing the criteria, the technologies will be pair-wise compared for each criterion.

In order to measure the consistency of our collected data, another column is constructed beside the average column which is named consistency measure. In each cell of this column, the corresponding row in the colored matrix (i.e. the one with the original scores) is multiplied by the average column and divided by the corresponding cell in the average column. For instance, the first cell in the consistency measure column (7.04) equals to the multiplication of C1 row in the colored table (starting with 1 and ends with 0.11) by the average column (starting with 0.02 and ends with 0.29) then divided by the first cell in the average column (0.02). Then, a consistency index value (CI) is calculated through subtracting the number of criteria from the average value of the values in the consistency measure column and divide it by the (number of criteria minus 1);

$$CI= \frac{(Average\ of\ consistency\ measure\ \ column - number\ of\ criteria)}{number\ of\ criteria - 1})$$

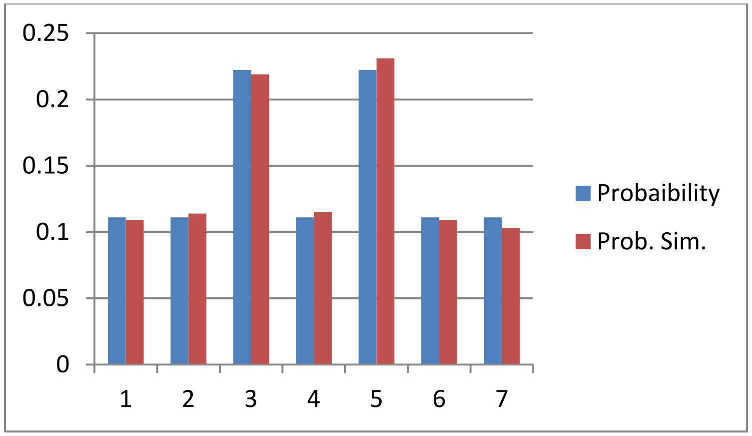
The random index (RI) is the CI of randomly generated pair-wise comparison matrix which in my illustrated example equals to 1.32 since I have 7 criteria (see Table 29). Finally a consistency ratio (CR) is calculated by dividing CI by RI. A CR of a value 0.1 or lower is acceptable (Saaty 1980).

Table 29: Random consistency index (RI) at different number of criteria (n) (Saaty 1980)

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.49

Appendix E: Explanation of Monte-Carlo validation

Technology									
Random	Value	Frequency	Probability	Low value range	Cum. Prob.	Possible Value	value lookup 3	Frequency simulated	Prob. Sim.
0.820153	1	1	0.11	0	0.11	1	6	117	0.117
0.629366	2	1	0.11	0.11	0.22	2	5	138	0.138
0.65743	3	2	0.22	0.22	0.44	3	5	239	0.239
0.53468	4	1	0.11	0.44	0.56	4	4	100	0.1
0.668602	5	2	0.22	0.56	0.78	5	5	207	0.207
0.145975	6	1	0.11	0.78	0.89	6	2	98	0.098
0.039551	7	1	0.11	0.89	1	7	1	101	0.101
0.590085	5	9					5	1000	
0.698039	3						5		
..... n=1000							.....		



Monte-Carlo methodology is a widely used class of computational algorithms for simulating the behavior of various physical and mathematical systems, and for other computations. It is used also to find solutions to mathematical problems that cannot easily be solved. Additionally, it is a statistical simulation technique that provides approximate solutions to problems expressed mathematically. It utilizes a sequence of random numbers to perform the simulation.

The above table and figure do not represent a real analysisbut they are just illustrative. Let's assume that I have 7 ranking possibilities of one of the assessed technology as can be observed in the seventh column in the above table. In the second column, I add the ranking of the technology by the observations contributed in the questionnaire after applying the MCDA methodology. Thus, I have here only 9 observations. In the third column, I calculate the frequency of each possible value in column seven from the ranking values of the observations in column 2. In the fourth column, I calculate the probability of each corresponding value in the frequency column by dividing the frequency value by the number of observations. In the fifth and sixth columns, I convert the probability from a discrete value into a range, where in the fifth column, I add the lower value range and in the sixth column, I add the cumulative probability which is the higher value range. In the first column, I generate a random value from 0 – 1 in a number of cells based on the desired simulated observations, for example, I used here 1000 cells. By this I simulate the survey in a sample of 1000 members. Then, in the eighth column, I pick up the corresponding possible value when the random value falls in the corresponding range. For instance, the first random value equals to 0.820153 which falls in the range between 0.78 and 0.89 which in turn corresponds to the possible value 6. Thus, the first cell in the eighth column will be 6. In the eighth column, I get 1000 values of simulated ranking of the technology. In the ninth column, I repeat calculating the frequency of the possible values but on the 1000 value sample in the eighth column. Finally, I calculate the simulated probability of the frequency simulated in the same manner like previously. The figure compares the probability of technology ranking from the observation values of the sample which might be small with the probability in a simulated large number sample. This method helps in measuring the uncertainty of data results from a small sample data or when there are many possible values for the variables where it could be applied on assessing the ranking of the technologies under different values of the indicators. The order of the table is not important except for the highlighted columns (5^{th} – 7^{th}) where they should be beside each other in the above stated order in order to enable the function in the eighth column.

Appendix F: GIS resource data for some spatial factors

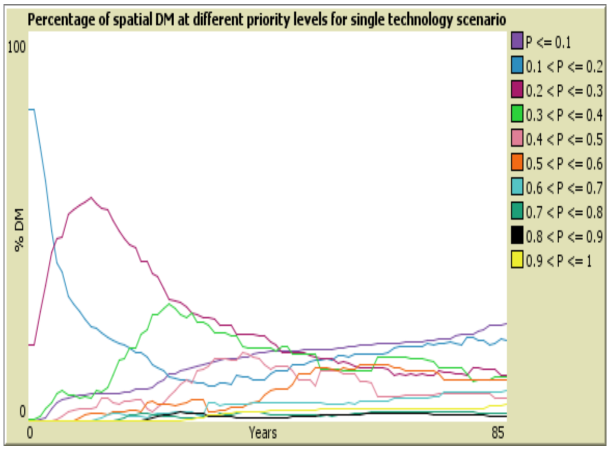
Table 30: Installed NG power plants location and size in Egypt (GEO 2016)

City	longitude	latitude	area km^2	capacity MW
Al Jizah	31.0456	30.054	0.06	600
Alexandria	29.8494244	31.00213392	0.05	100
Al Qalyubiyah	31.2234	30.4974	0.13	750
Cairo	31.266	30.108	0.18	1500
Cairo	31.2908	29.8681	0.07	450
Cairo	31.29139	29.86695	0.06	165
Beheria	30.4293	31.08175	0.04	156
Damiette	31.72358	31.38148	0.12	1200
Damiette	31.7196	31.3822	0.04	500
Al Buhayrah	30.5291	31.1851	0.06	750
Al Iskandariyah	29.99531	31.21585	0.02	200
Al Jizah	30.9471	30.2483	0.31	2250
Red Sea	33.82	27.122	0.05	143
Alexandria	29.914	31.176	0.03	23
Giza	31.2235	29.27127	0.09	750
Giza	31.2242	29.2697	0.06	750
Giza	31.2486	29.2793	0.71	140
Beheria	30.5289	31.1759	0.12	318
Matruh	27.2044	31.3704	0.04	60
El Behaira	30.66712	30.69926	0.91	2250
Port Said	32.52024	31.09952	0.14	682.5
Port Said	32.31711	31.25632	0.01	48
Ismailia	31.9269	30.4659	0.05	100
Ismailia	31.9234	30.4653	0.16	1000
Alexandria	29.6585	31.04325	0.15	682.5
Alexandria	29.6652	31.043	0.08	750
Alexandria	29.7624242	31.02761778	0.03	99
Suez	32.3532	29.6188	0.16	682.5
Dakahlia	31.39015	31.0615	0.04	750
Dakahlia	31.39211	31.06225	0.05	290
Cairo	31.2972593	29.77536662	0.08	700
Cairo	31.3194	29.87567	0.05	100
Dumyat	31.6064	31.4423	0.24	750

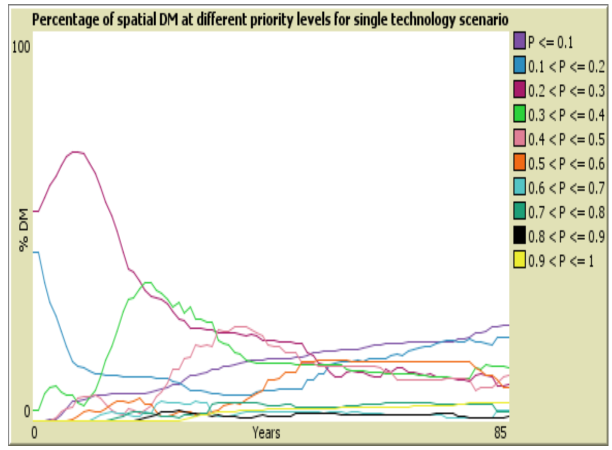
Table 31: Egypt population per governorate (CAPMAS 2016)

Governorate (City)	Population (November 2016)	Area (km^2)	Population density
Ad Daqahliyah	6,183,341	3538	1748
Al Bahr al Ahmar	361,621	119099	3
Al Buhayrah	6,093,222	9826	620
Al Fayyum	3,375,287	6068	556
Al Gharbiyah	4,940,726	1942	2544
Al Iskandariyah	4,979,870	2300	2165
Al Isma`iliyah	1,237,739	5067	244
Al Jizah	7,916,923	13184	600
Al Minufiyah	4,116,537	2499	1647
Al Minya	5,441,413	32279	169
Al Qahirah	9,581,152	3085	3106
Al Qalyubiyah	5,310,468	1124	4725
Al Wadi al Jadid	235,080	440098	1
As Suways	648,973	9002	72
Ash Sharqiyah	6,775,323	4911	1380
Aswan	2,694,634	65136	41
Asyut	4467,142	25926	172
Bani Suwayf	3,019,038	10954	276
Bur Sa`id	688,962	1345	512
Dumyat	1,384,637	910	1522
Janub Sina'	172,122	31272	6
Kafr ash Shaykh	3,315,630	3467	956
Matruh	485,834	166563	3
Qina	3,199,862	10798	296
Shamal Sina'	455,374	28992	16
Suhaj	4,848,029	11022	440

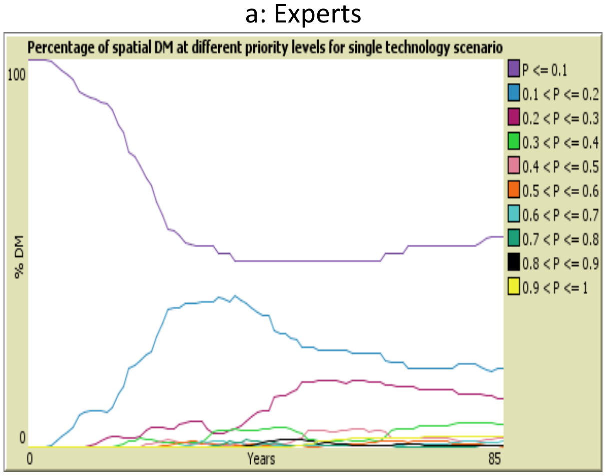
Appendix G: Single technology spatial analysis



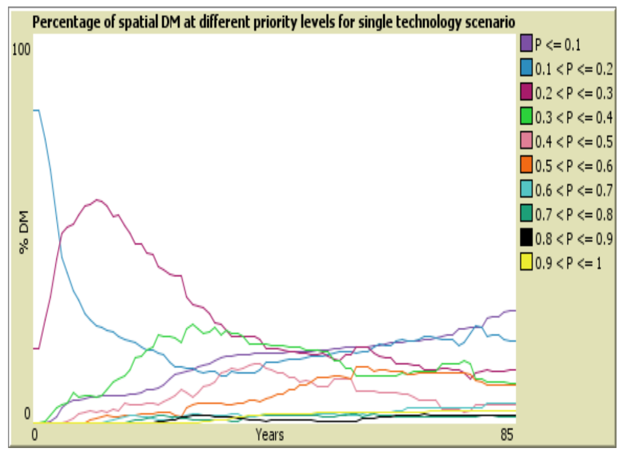
a: Experts



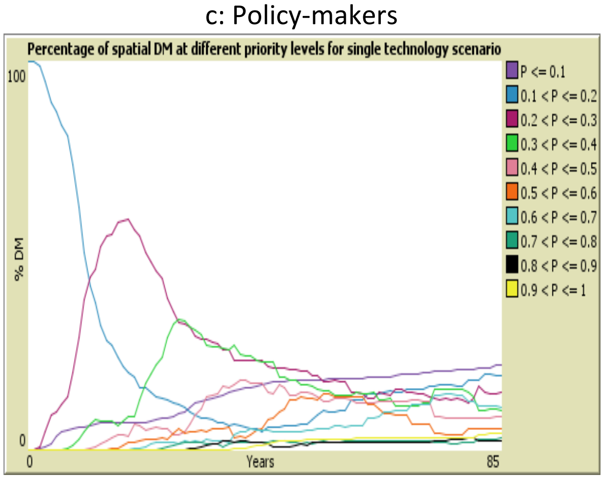
b: Investors



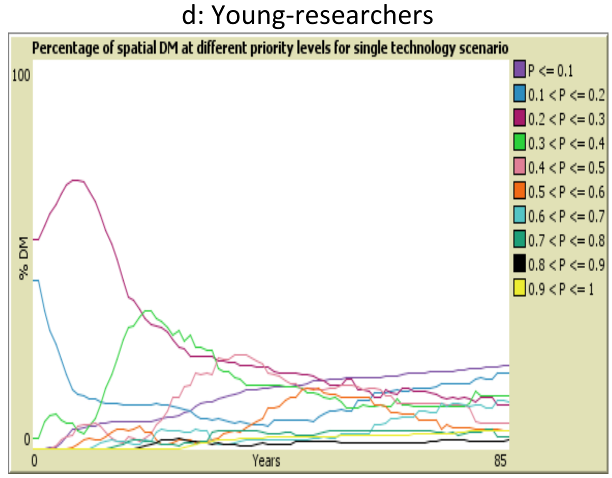
c: Policy-makers



d: Young-researchers

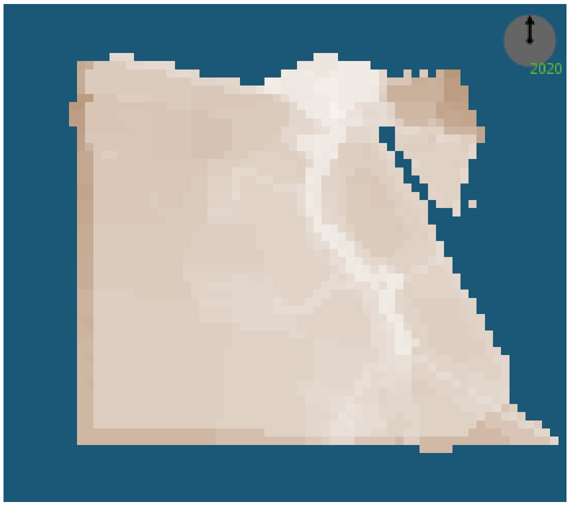


e: Sustainability scenario

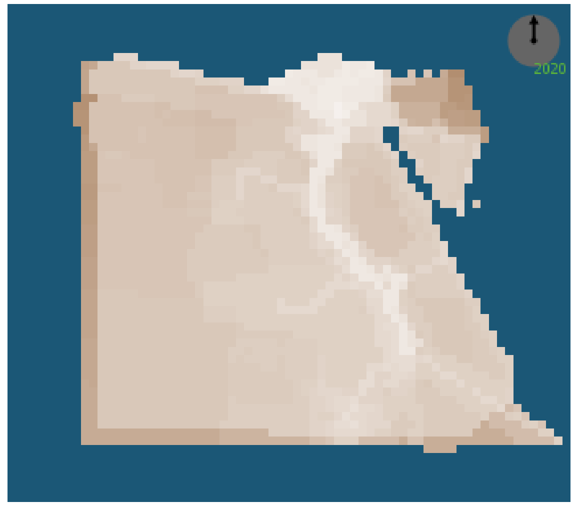


f: Game scenario

Figure 113: Percentage of DM patches at different priority levels for natural gas per each actor type (a – f)

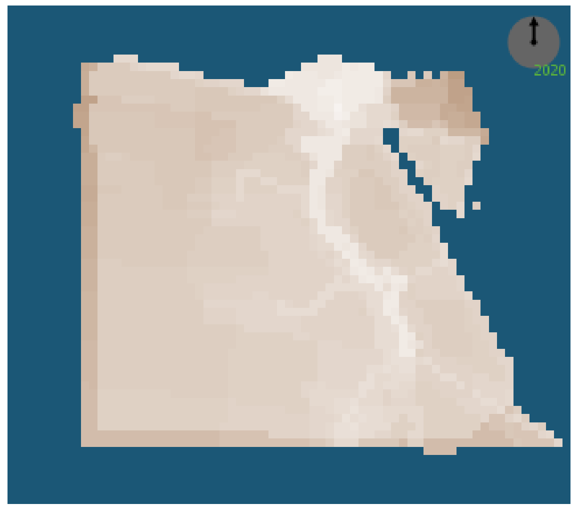


a: Experts

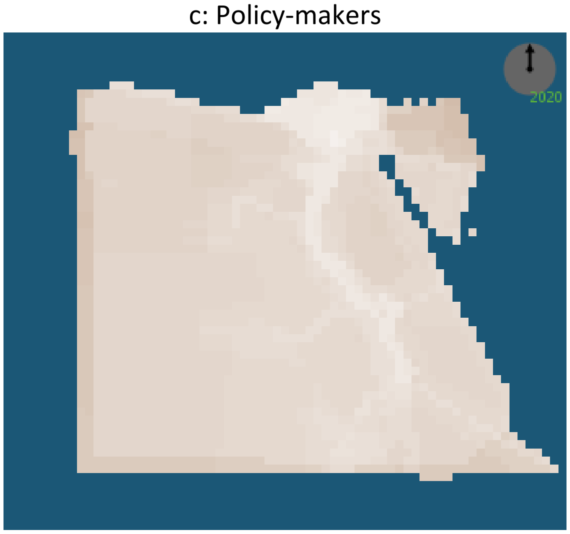


b: Investors

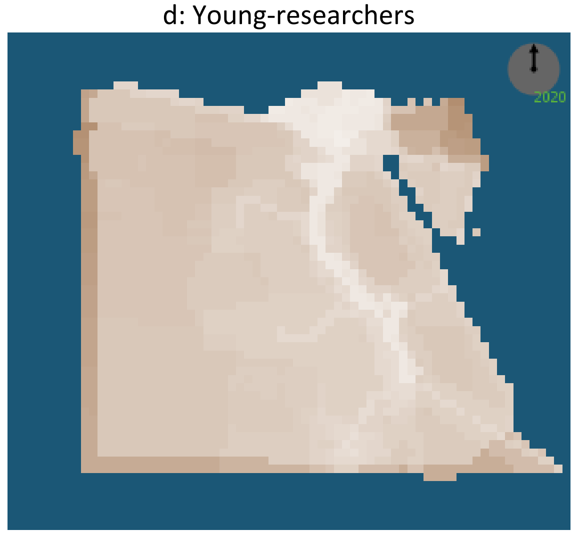
c: Policy-makers



d: Young-researchers

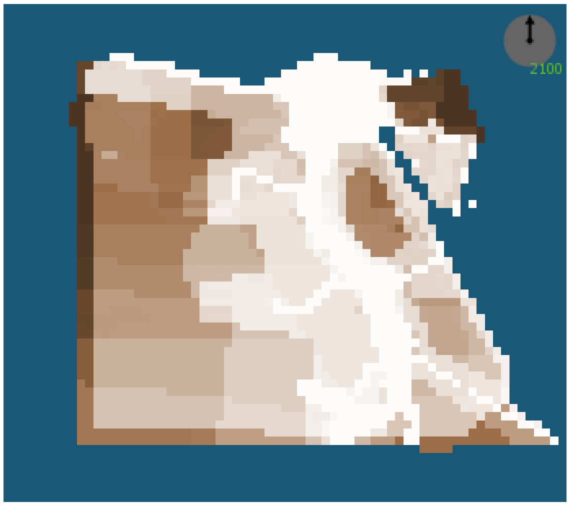


e: Sustainability scenario

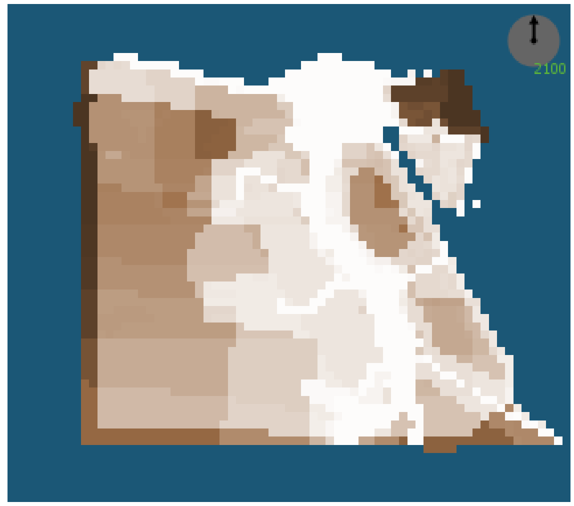


f: Game scenario

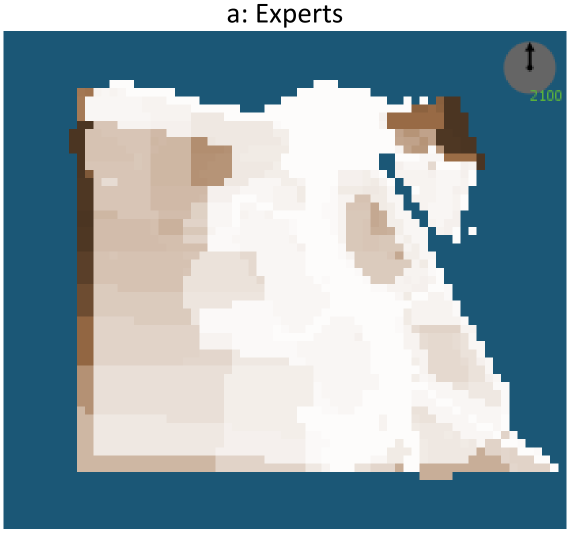
Figure 114: The map view in single technology analysis displaying natural gas priority per actor type (a – f) at year 2020



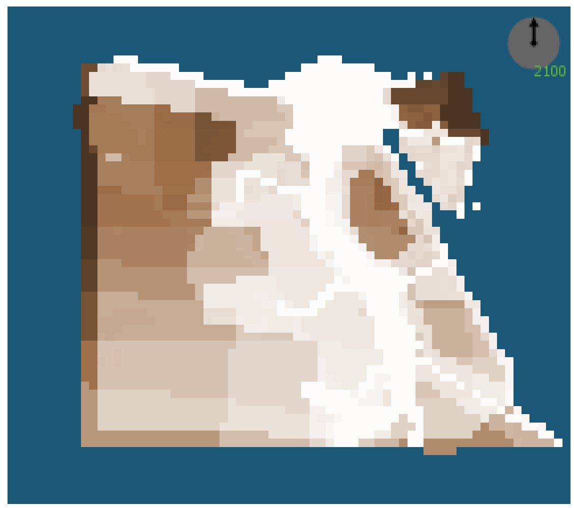
a: Experts



b: Investors



c: Policy-makers



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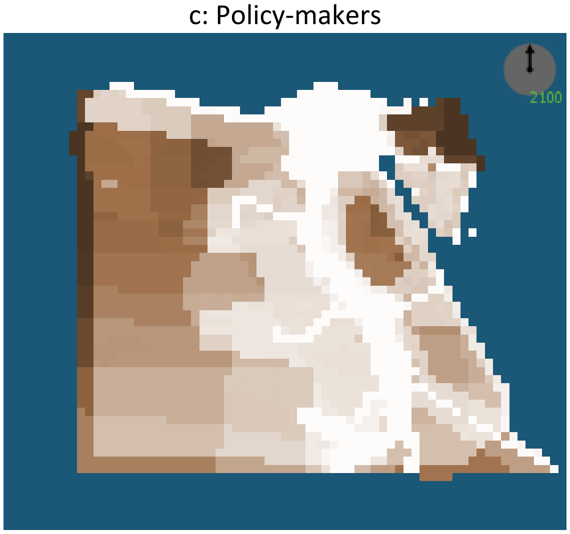
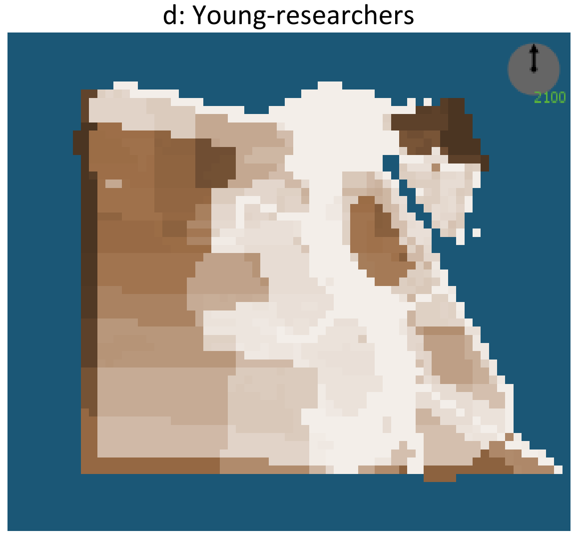


e: Sustainability scenario



f: Game scenario

Figure 115: The map view in single technology analysis displaying natural gas priority per actor type (a – f) at year 2100

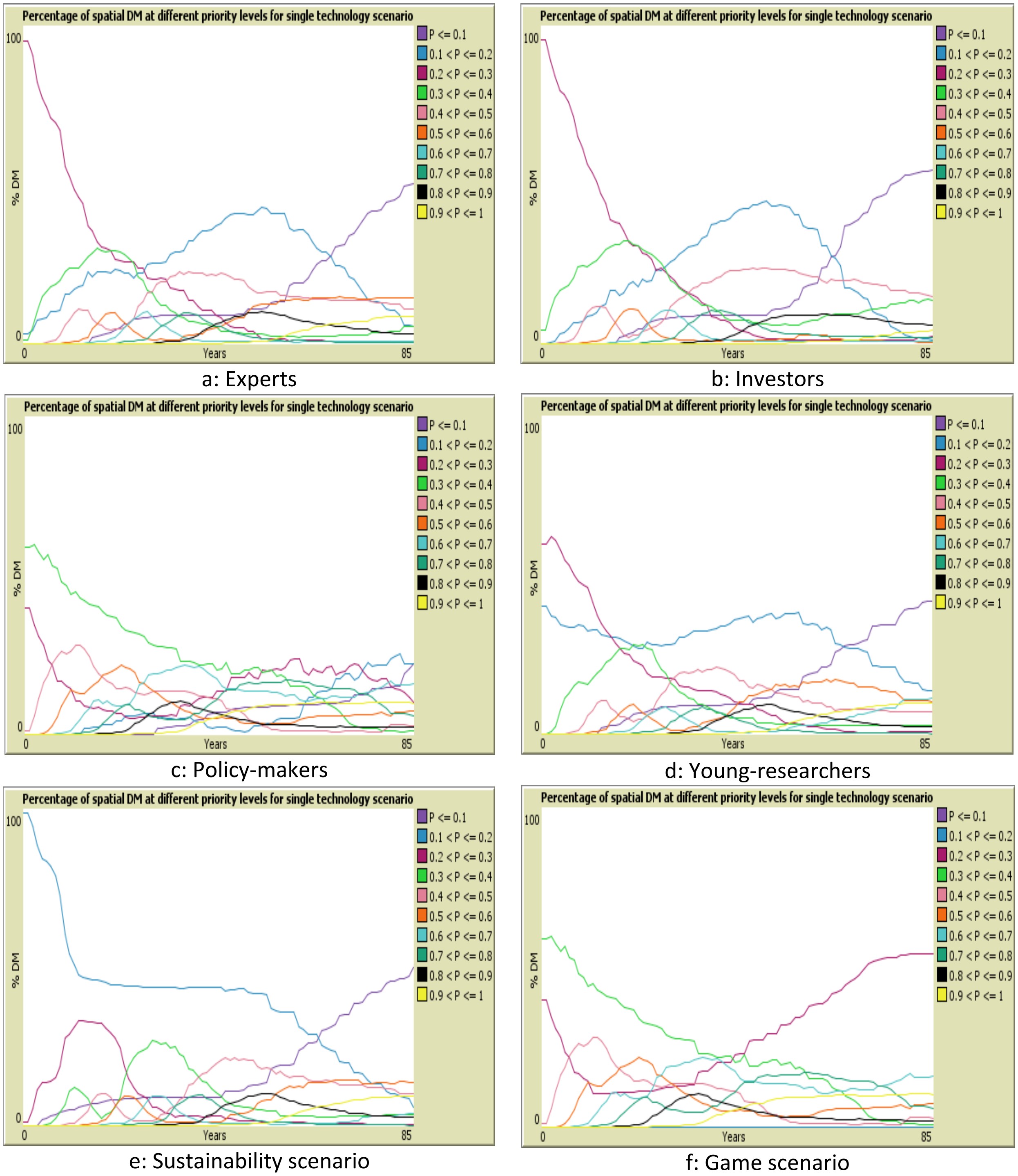


Figure 116: Percentage of DM patches at different priority levels for wind per each actor type (a – f)

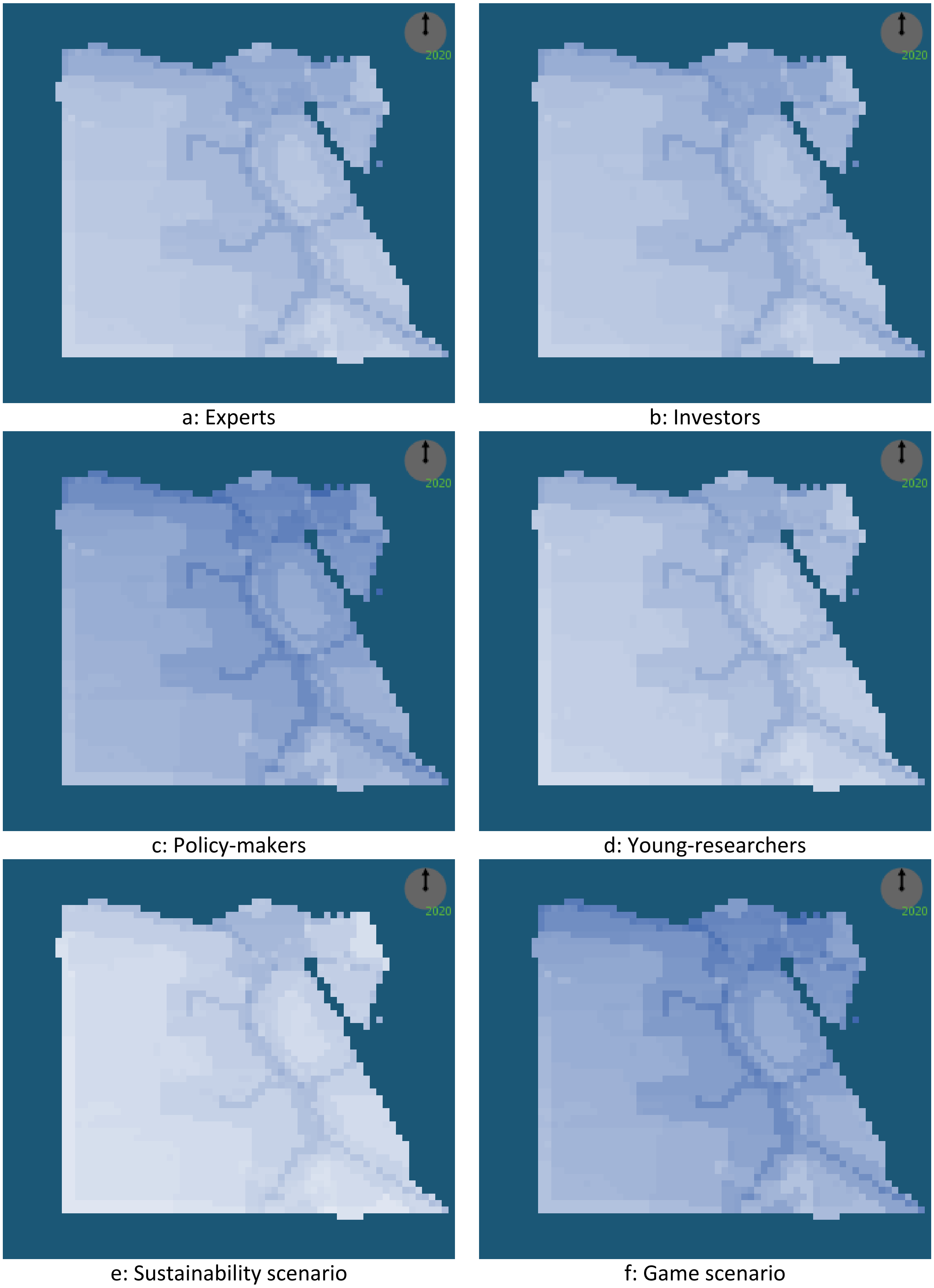
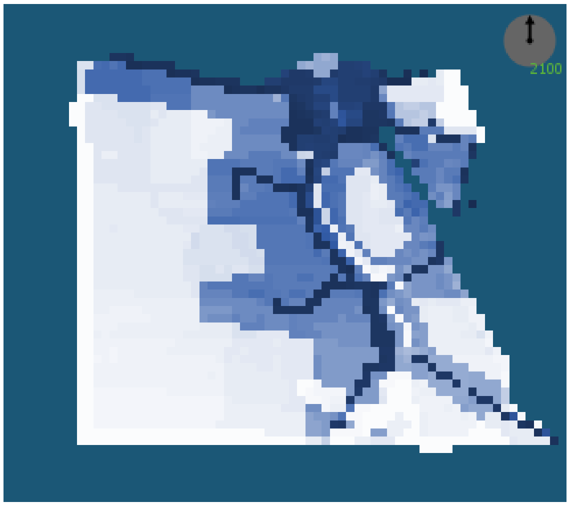
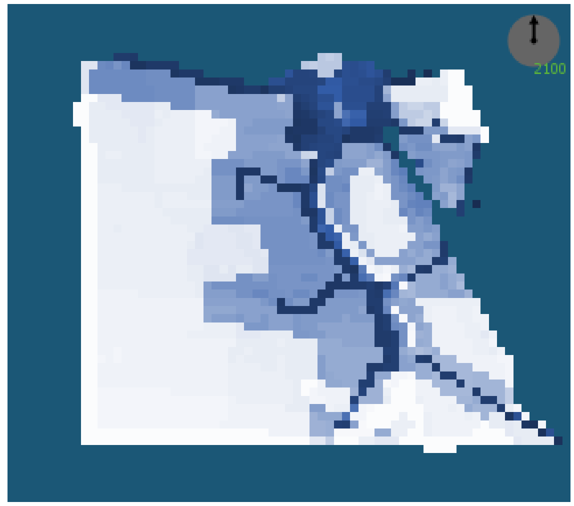


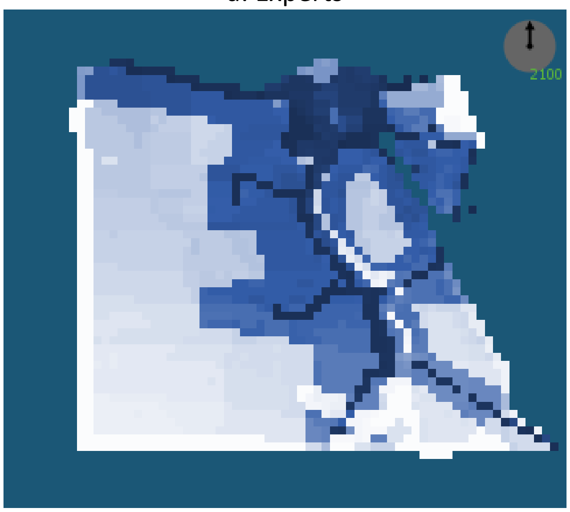
Figure 117: The map view in single technology analysis displaying wind priority per actor type (a – f) at year 2020



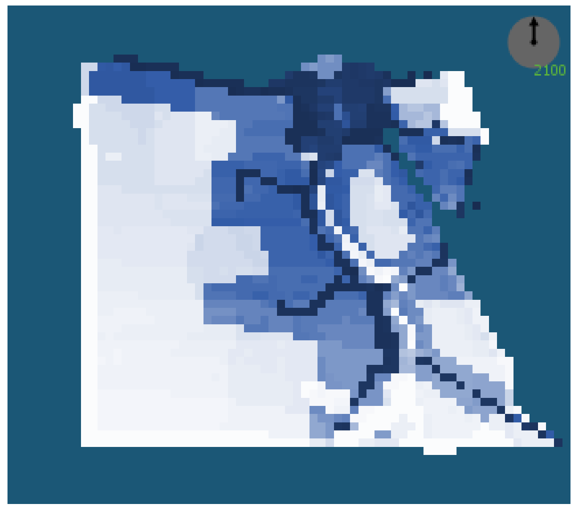
a: Experts



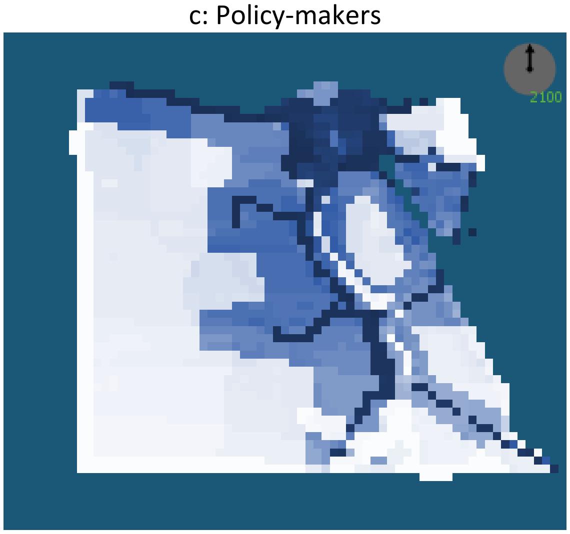
b: Investors



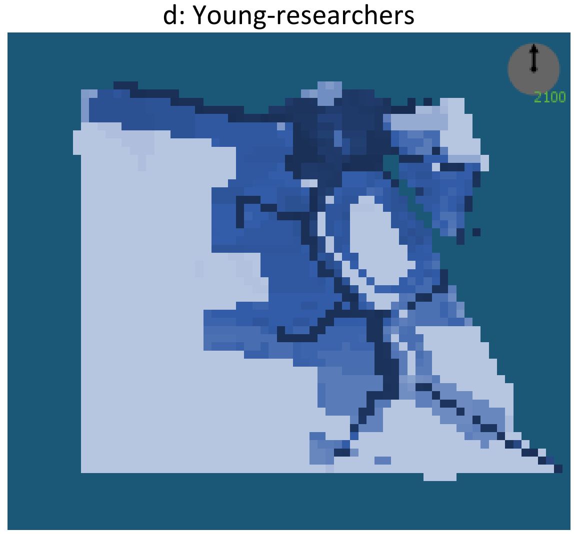
c: Policy-makers



d: Young-researchers

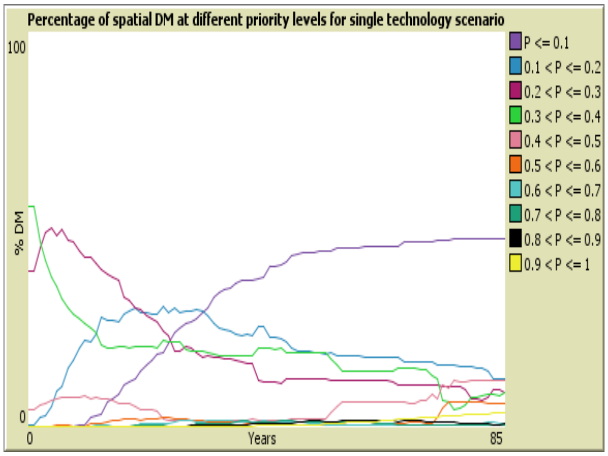


e: Sustainability scenario

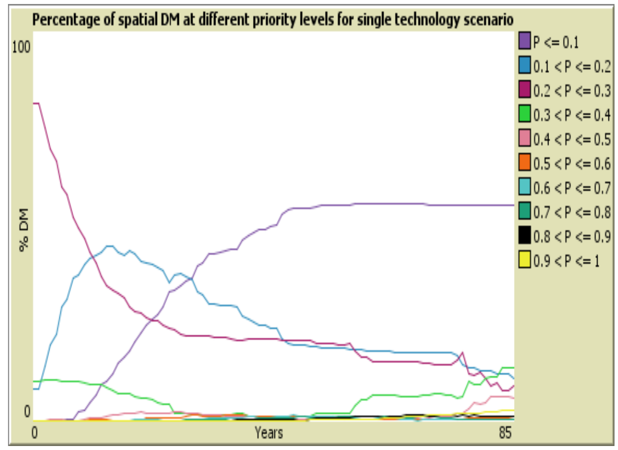


f: Game scenario

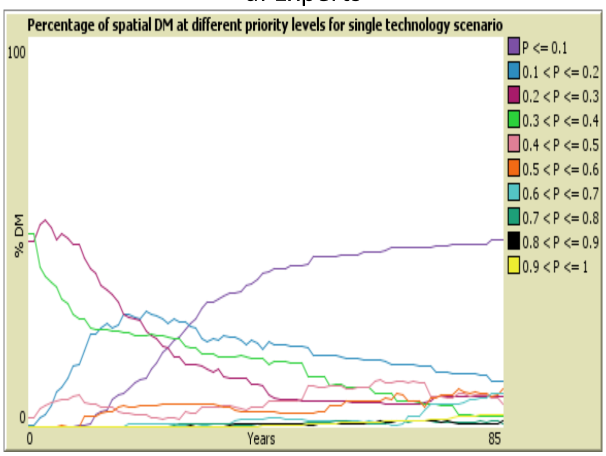
Figure 118: The map view in single technology analysis displaying wind priority per actor type (a – f) at year 2100



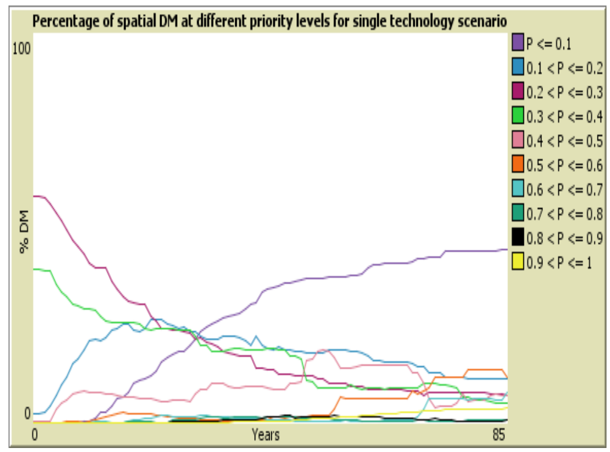
a: Experts



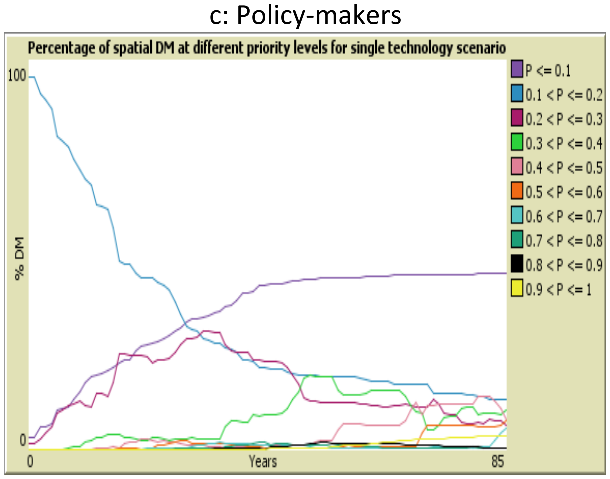
b: Investors



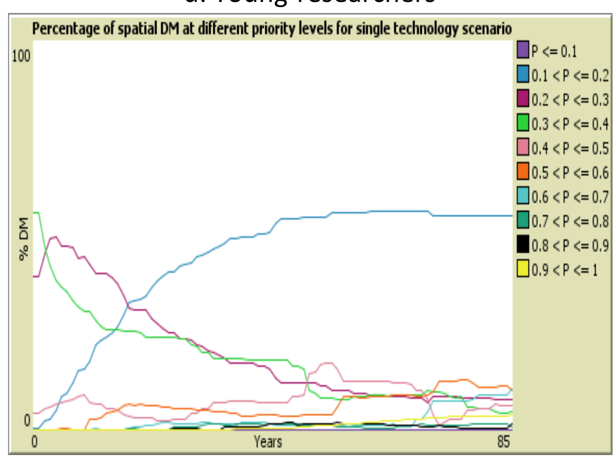
c: Policy-makers



d: Young-researchers

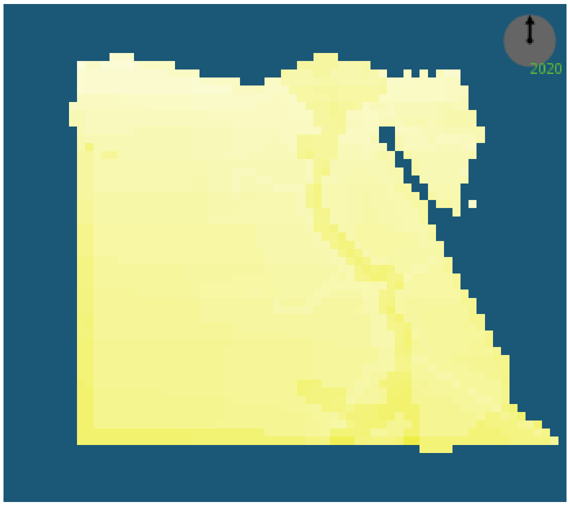


e: Sustainability scenario

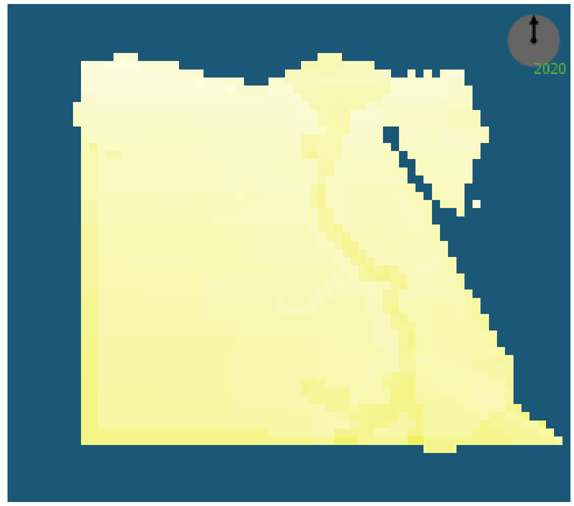


f: Game scenario

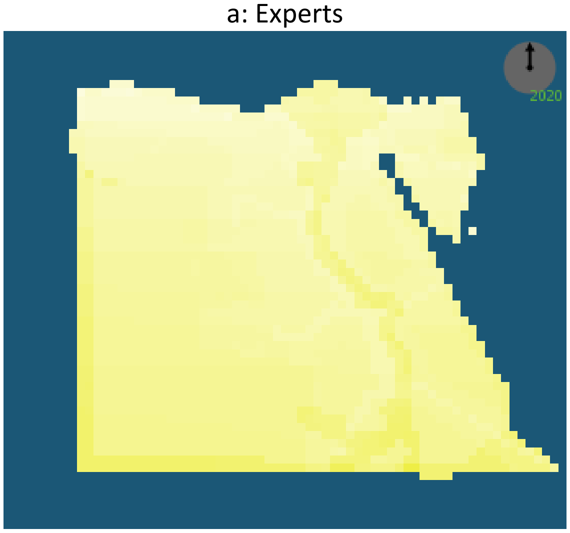
Figure 119: Percentage of DM patches at different priority levels for CSP per each actor type (a – f)



a: Experts



b: Investors



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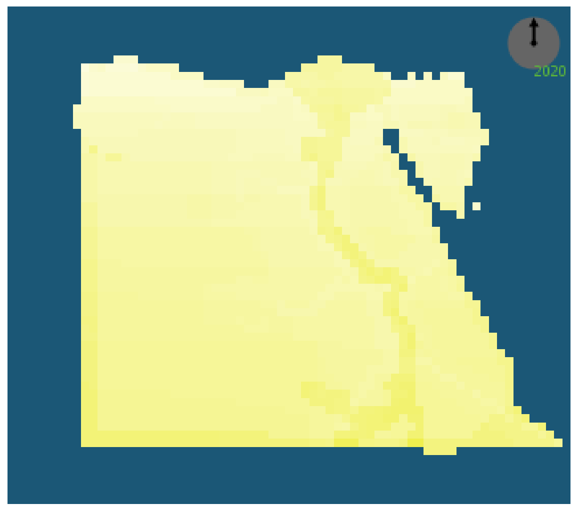
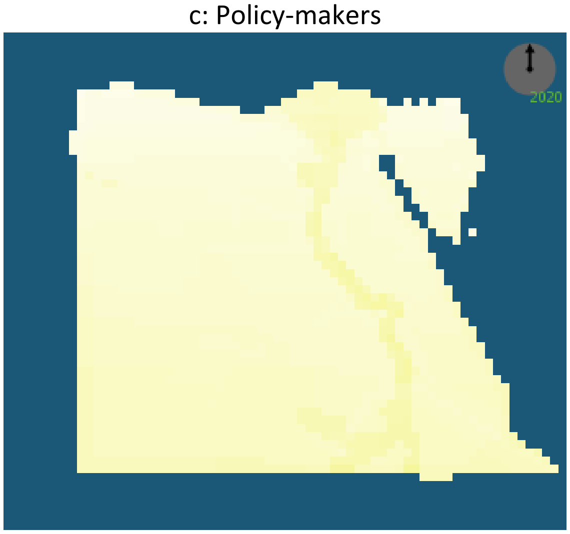
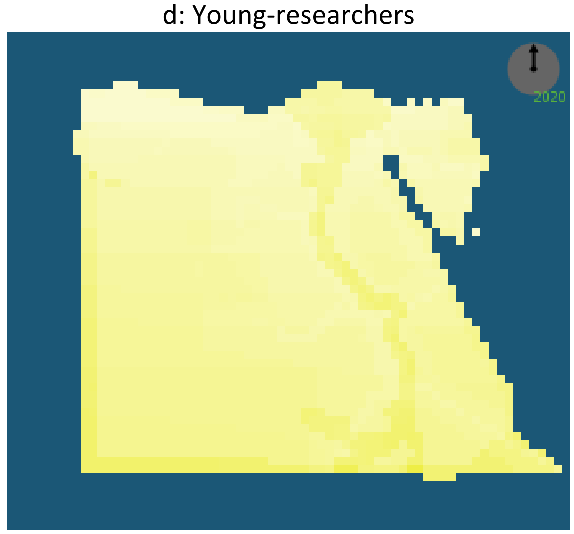


d: Young-researchers

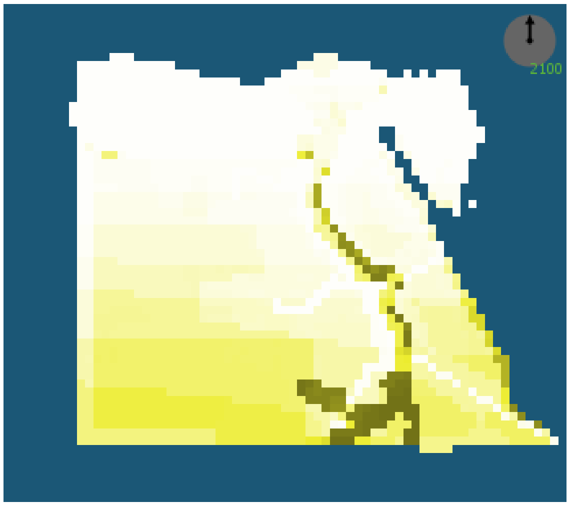


e: Sustainability scenario



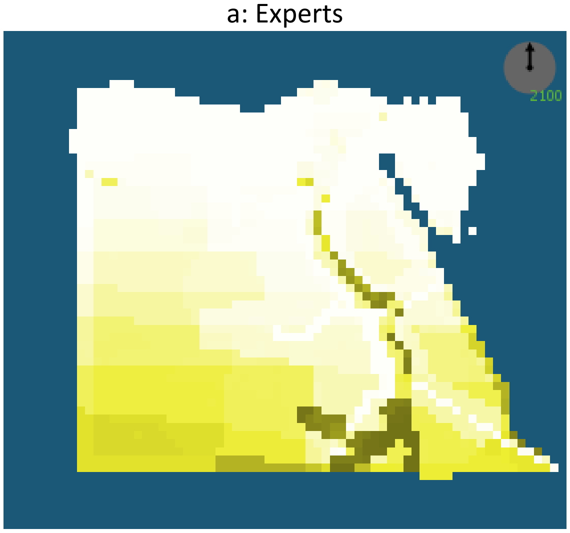
f: Game scenario

Figure 120: The map view in single technology analysis displaying CSP priority per actor type (a – f) at year 2020

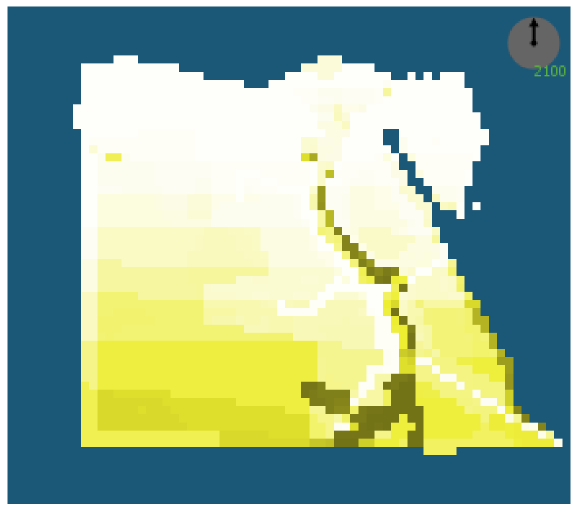


a: Experts

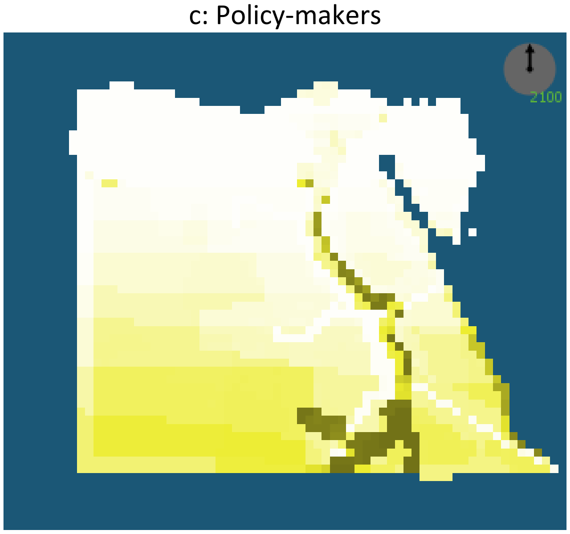
b: Investors



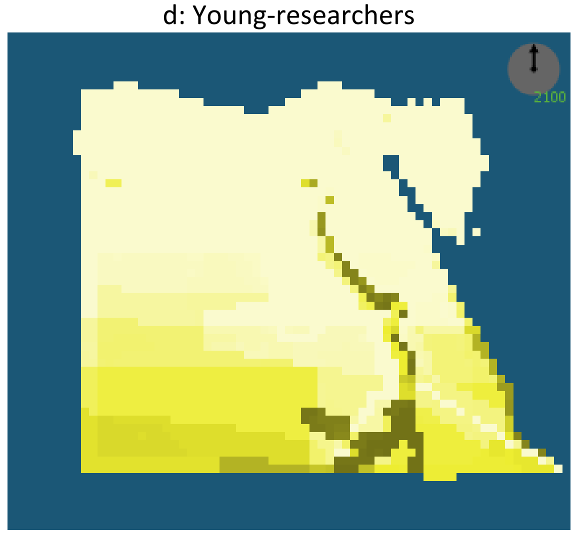
c: Policy-makers



d: Young-researchers

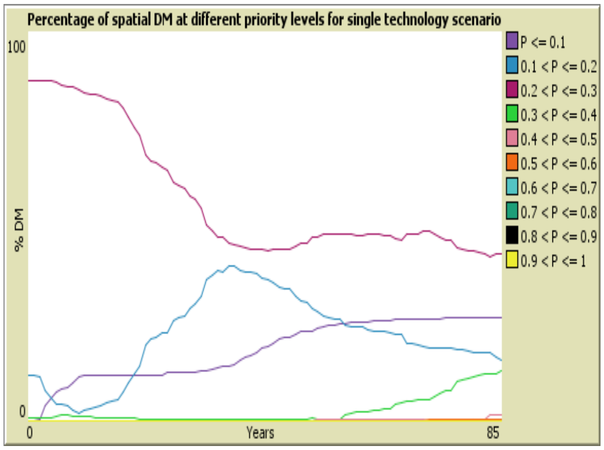


e: Sustainability scenario

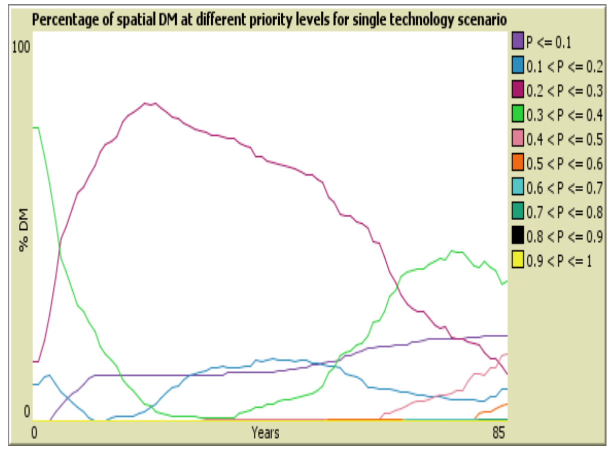


f: Game scenario

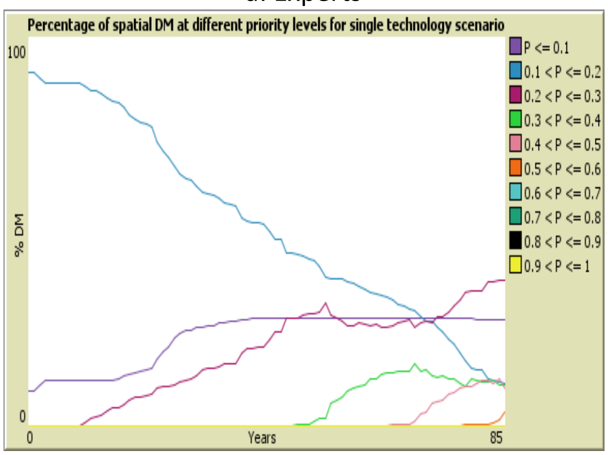
Figure 121: The map view in single technology analysis displaying CSP priority per actor type (a – f) at year 2100



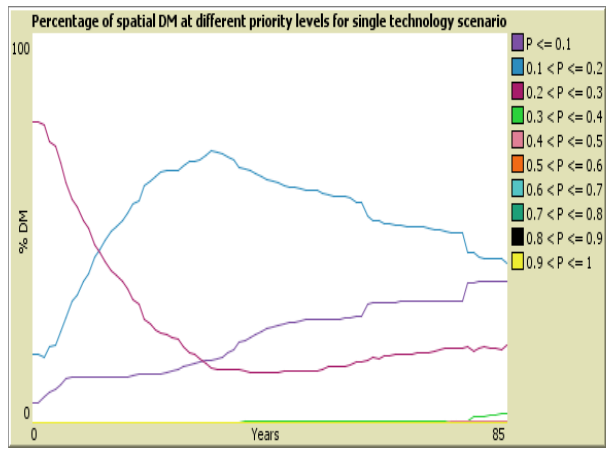
a: Experts



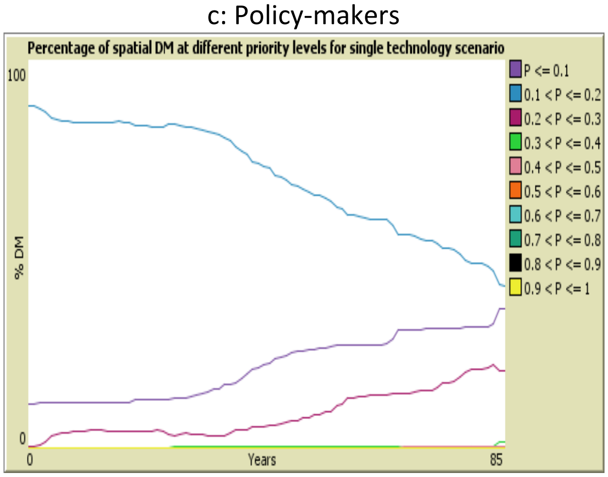
b: Investors



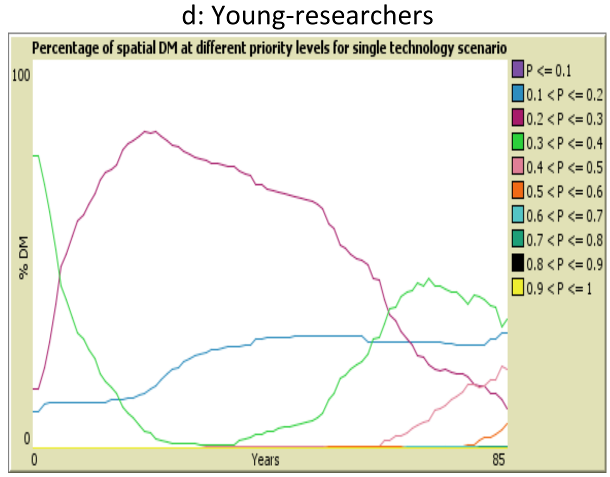
c: Policy-makers



d: Young-researchers

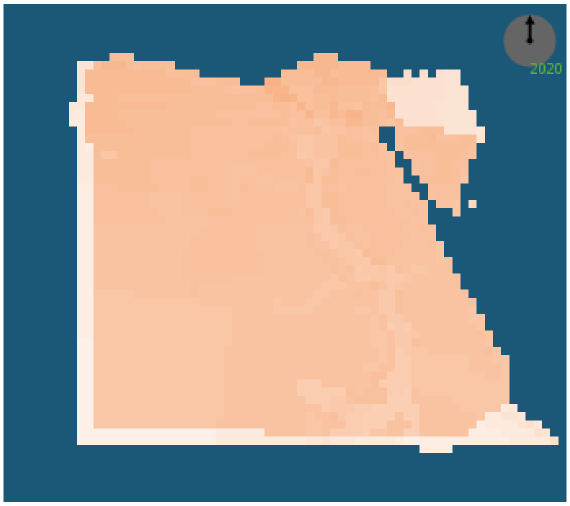


e: Sustainability scenario

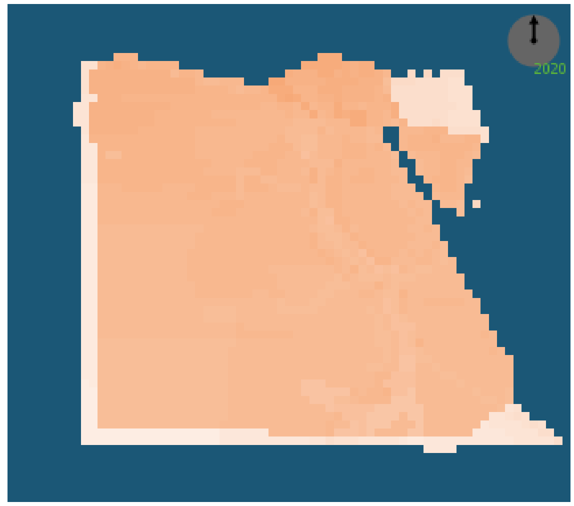


f: Game scenario

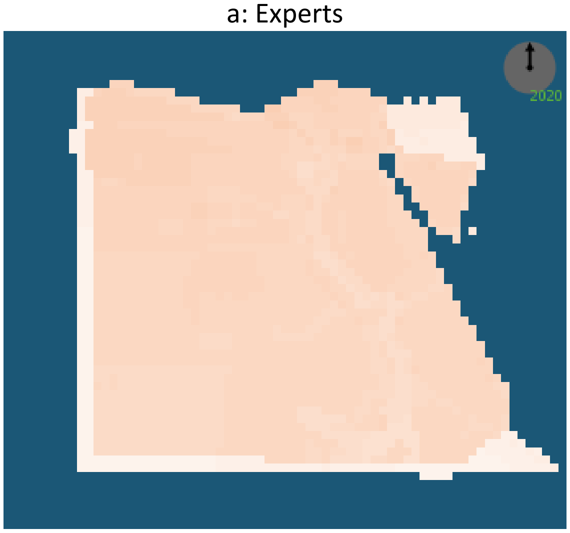
Figure 122: Percentage of DM patches at different priority levels for PV per each actor type (a – f)



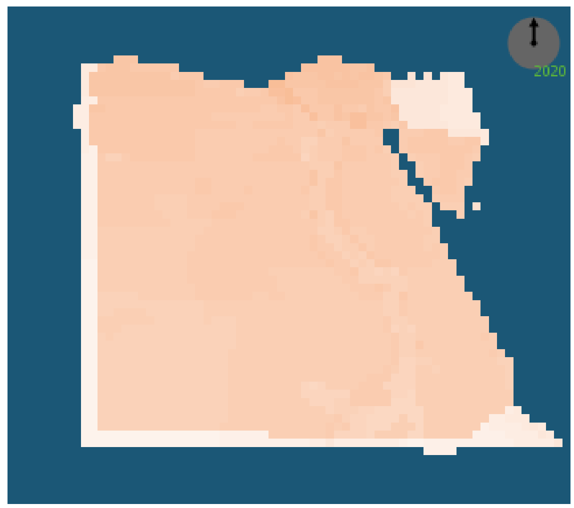
a: Experts



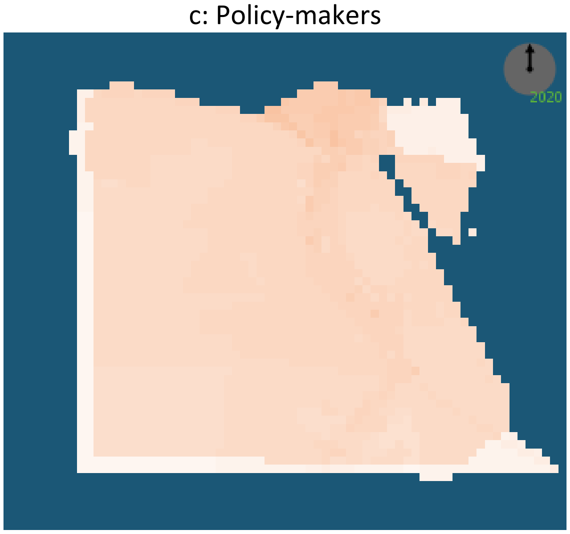
b: Investors



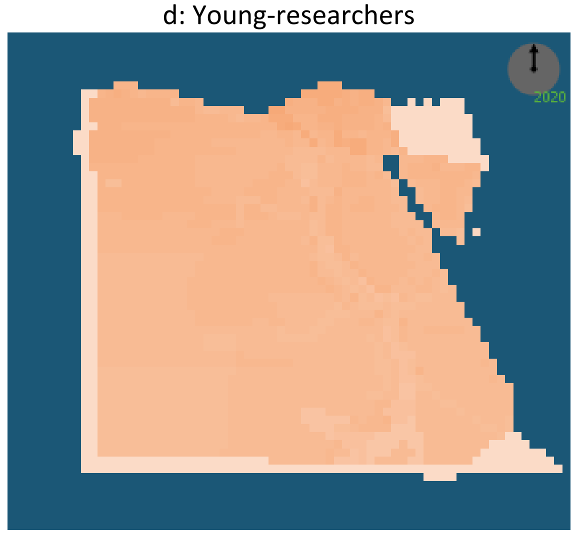
c: Policy-makers



d: Young-researchers

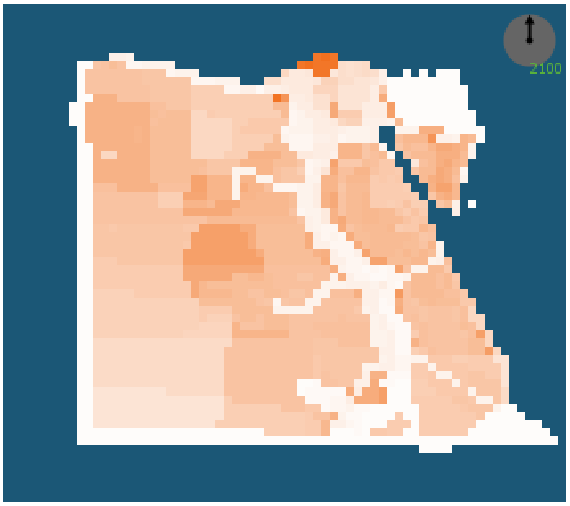


e: Sustainability scenario

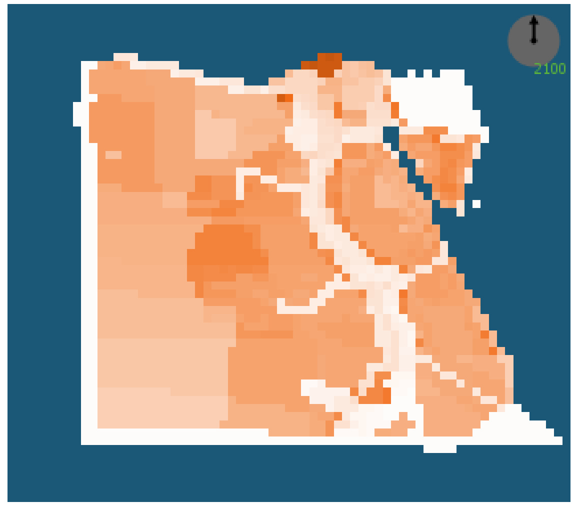


f: Game scenario

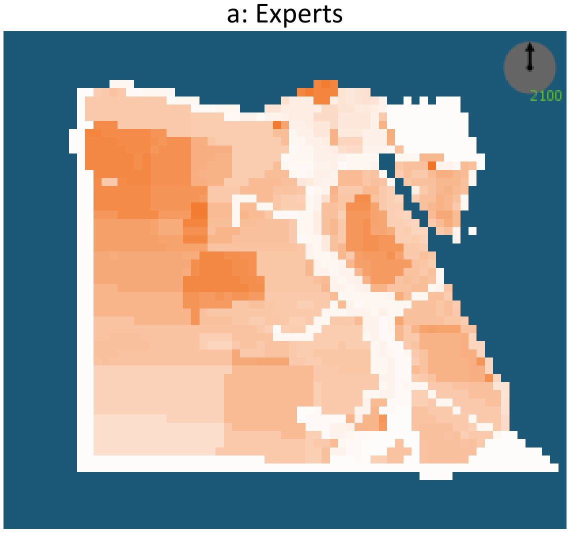
Figure 123: The map view in single technology analysis displaying PV priority per actor type (a – f) at year 2020



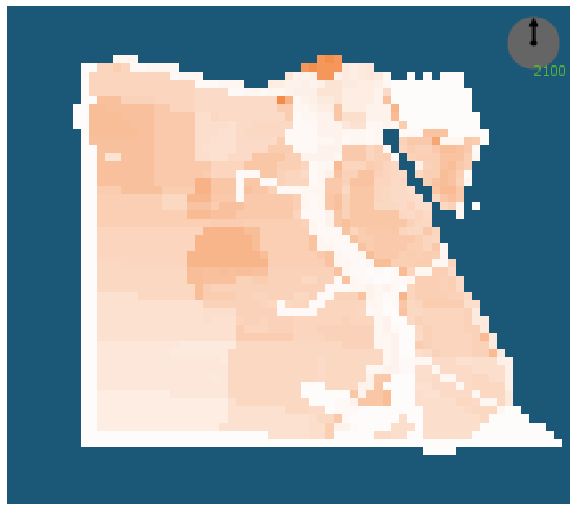
a: Experts



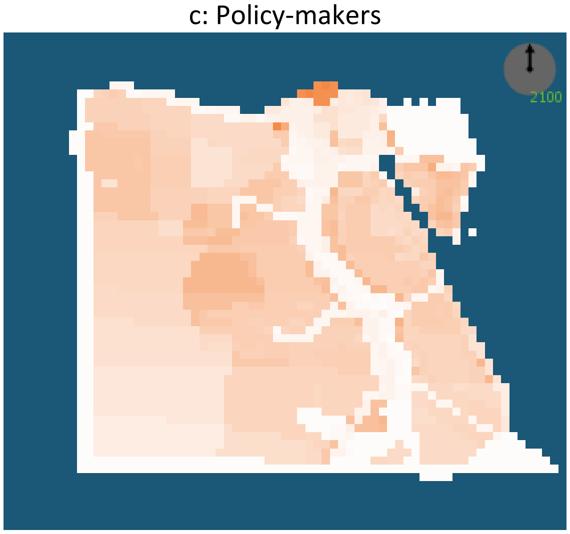
b: Investors



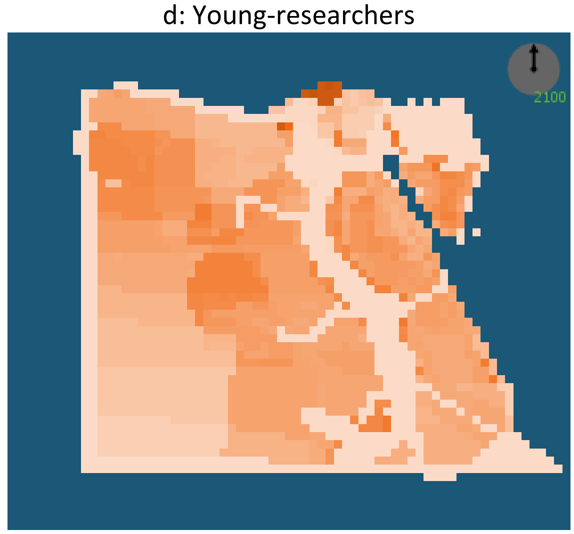
c: Policy-makers



d: Young-researchers



e: Sustainability scenario



f: Game scenario

Figure 124: The map view in single technology analysis displaying PV priority per actor type (a – f) at year 2100

Appendix H: Code of the model

```
extensions [ GIS ]
breed      [ spinners spinner ]
globals    [
DM ; Spatial Decision Makers
DM-type-list ; 0=Expert researchers, 1=Investors, 2=Policy-makers, 3=Young researchers, 4=Sustainable scenario, 5=New-DM input
tech-type-list ; 0=coal, 1=NG, 2=wind, 3=CSP, 4=PV, 5=biomass, 6=nuclear
Wecon Wenv Wsoc Wtech total-weight ; These are the weights of the dimensions for 30 paticipants in the questionnaire plus one sustainable agent representing equal weights of the four dimensions

C1 C2 C3 C4 C5 C6 C7 C8 C9 C10 C11 C12 C13 ; These are the real values of 13 criteria ( 4 Economic, 3 Environmental, 2 Social, 4 Technical) for 7 technologies under assessment
; C1=investment cost, C2=operation and maintenance cost, C3=cost of electricity, C4=job generation, C5=CO2 emission, C6=NOx emission, C7=SO2 emission,
; C8=safety, C9=social aceptability, C10=efficiency, C11=Reliability (capacity factor), C12=Resource potential, C13=water consumption

C1-norm C2-norm C3-norm C4-norm C5-norm C6-norm C7-norm C8-norm C9-norm C10-norm C11-norm C12-norm C13-norm  ; These are the normalized values of 13 criteria

P-coal P-NG P-wind P-CSP P-PV P-biomass P-nuclear P-total-tech ; These are the total average priority over the whole country
GHG-emission
P-coal-initial P-NG-initial P-wind-initial P-CSP-initial P-PV-initial P-biomass-initial P-nuclear-initial
]

patches-own [
S-a-NG S-a-wind S-a-CSP  S-a-PV S-a-biomass S-b S-c S-d S-e S-f S-g ; These are the normalized values of 6 spatial variables (a,b,c,d,e,f,g) imported from GIS
; a=resource potential, b=population, c=water coverage, d=grid coverage, e=stability, f=road coverage, g=negative crop effect
 S-coal S-NG S-wind S-CSP S-PV S-biomass S-nuclear ; These are the integrated spatial factors using the weighted sum method
S-coal-norm S-NG-norm S-wind-norm S-CSP-norm S-PV-norm S-biomass-norm S-nuclear-norm ; These are the integrated spatial factors normalized over the the whole countries
; i.e. The sum of S-coal-norm, for example,  of all DM should equal 1

X-coal X-NG X-wind X-CSP X-PV X-biomass X-nuclear X-total ; These are the weighted sum value of the criteria for each technology multiplied by the spatial factor for each DM
```

SI-coal SI-NG SI-wind SI-CSP SI-PV SI-biomass SI-nuclear ; Theses are the normalized values of the weighted sum values for each DM giving the sustainability index for each technology per each DM

total-preferences-new-DM ; This is the sum of new DM input preferences of technologies

PSI-average ; This is the average value of all technologies with which the value of each technology is compared (i.e. sum (Pi*Vi))

P-coal-previous-year P-NG-previous-year P-wind-previous-year P-CSP-previous-year P-PV-previous-year P-biomass-previous-year P-nuclear-previous-year ; These are the priorities for the previous year.

P-coal-next-year P-NG-next-year P-wind-next-year P-CSP-next-year P-PV-next-year P-biomass-next-year P-nuclear-next-year P-total; These are the priorities for the next year

P0 P1 P2 P3 P4 P5 ; These are patch variable lists each represent one DM type and includes values of technologies priority (i.e. transposition of the technology priority variable lists)
P-game ; represents the winning DM type for each spatial agent as the DM compete on each cell
tmp ; This is a temporary patch variable list for visualization
]
;;##

to load-map

clear-all

gis:apply-raster (gis:load-dataset "data_7/Gas.asc") S-a-NG
gis:apply-raster (gis:load-dataset "data_7/Wind.asc") S-a-wind
gis:apply-raster (gis:load-dataset "data_7/STP.asc") S-a-CSP
gis:apply-raster (gis:load-dataset "data_7/PV.asc") S-a-PV
gis:apply-raster (gis:load-dataset "data_7/biomass.asc") S-a-biomass
gis:apply-raster (gis:load-dataset "data_7/Pop.asc") S-b
gis:apply-raster (gis:load-dataset "data_7/Water.asc") S-c
gis:apply-raster (gis:load-dataset "data_7/Grid.asc") S-d
gis:apply-raster (gis:load-dataset "data_7/Stability.asc") S-e
gis:apply-raster (gis:load-dataset "data_7/Road.asc") S-f
gis:apply-raster (gis:load-dataset "data_7/Crop_n.asc") S-g
gis:set-world-envelope gis:envelope-of (gis:load-dataset "data_7/Gas.asc")

; DM stands for decision makers who are the spatial agents
set DM patches with [S-a-wind >= 0 or S-a-wind <= 0]
output-print word "Count total patches:" count (patches)
output-print word "Count DM:" count (DM)

```
output-print word "Approx. area of DM (km2): "  round ( 1000000 / count DM )
output-print      "Finished loading GIS!"
ask patches [set pcolor 93]
ask DM with [ pycor >= 7 ] [ set pcolor red ] ask DM with [ pycor <= -7 ] [ set pcolor black ] ask DM with [
pycor > -7 and pycor < 7 ] [ set pcolor white ]
ask DM with [ pycor > -3 and pycor < 3 and pxcor > -3 and pxcor < 3 ] [ set pcolor yellow ] ask patch 0 3
[set pcolor  yellow ] ask patch -1 -2 [set pcolor  white ] ask patch 1 -2 [set pcolor  white ]
set spatial-boundaries "Select"
end
;;#########################################################################################
to show-map
ask DM [
        ; These are the individual spatial factors
         if spatial-boundaries = "NG-RP"      [ set tmp S-a-NG      set pcolor scale-color brown  tmp 1.3 0 ]
         if spatial-boundaries = "wind-RP"    [ set tmp S-a-wind    set pcolor scale-color blue   tmp 1.3 0 ]
         if spatial-boundaries = "CSP-RP"     [ set tmp S-a-CSP     set pcolor scale-color yellow tmp 1.3 0 ]
         if spatial-boundaries = "PV-RP"      [ set tmp S-a-PV      set pcolor scale-color orange tmp 1.3 0 ]
         if spatial-boundaries = "biomass-RP" [ set tmp S-a-biomass set pcolor scale-color green  tmp 1.3 0
]
         if spatial-boundaries = "population" [ set tmp S-b        set pcolor scale-color pink   tmp 1.5 0 ]
         if spatial-boundaries = "water"      [ set tmp S-c        set pcolor scale-color cyan   tmp 1.3 0 ]
         if spatial-boundaries = "grid"       [ set tmp S-d        set pcolor scale-color lime   tmp 1.3 0 ]
         if spatial-boundaries = "stability"  [ set tmp S-e        set pcolor scale-color violet tmp 1.3 0 ]
         if spatial-boundaries = "road"       [ set tmp S-f        set pcolor scale-color pink   tmp 1.3 0 ]
         if spatial-boundaries = "crop-neg"   [ set tmp S-g        set pcolor scale-color lime   tmp 1.3 0 ]
; These are the integrated spatial factors for each technology "EFFECTED ONLY AFTER PRESSING
SETUP"
if spatial-boundaries = "S-coal"     [ set tmp S-coal-norm    set pcolor scale-color gray    tmp 0.0008 0 ]
if spatial-boundaries = "S-NG"       [ set tmp S-NG-norm      set pcolor scale-color brown   tmp 0.0008 0 ]
if spatial-boundaries = "S-wind"     [ set tmp S-wind-norm    set pcolor scale-color blue    tmp 0.0008 0 ]
if spatial-boundaries = "S-CSP"      [ set tmp S-CSP-norm     set pcolor scale-color yellow  tmp 0.0008 0 ]
 if spatial-boundaries = "S-PV"      [ set tmp S-PV-norm      set pcolor scale-color orange  tmp 0.0008 0 ]
 if spatial-boundaries = "S-biomass"  [ set tmp S-biomass-norm set pcolor scale-color green   tmp 0.0008
0 ]
 if spatial-boundaries = "S-nuclear"  [ set tmp S-nuclear-norm set pcolor scale-color magenta tmp 0.0008
0 ] ]
end
;;#########################################################################################
to setup
clear-all-plots
clear-turtles
ask DM [set pcolor black]
```

```
create-spinners 1
[ set shape "clock"
  setxy (max-pxcor - 4) (max-pycor - 4)
  set color gray - 1.5
  set size 8
  set heading 0
  set label 2015
  set label-color green ]

set tech-type-list    n-values tech-types [?]
set DM-type-list      n-values DM-types   [?]
set P-total-tech      n-values DM-types   [0]
set P-coal            n-values DM-types   [0]
set P-NG              n-values DM-types   [0]
set P-wind            n-values DM-types   [0]
set P-CSP             n-values DM-types   [0]
set P-PV              n-values DM-types   [0]
set P-biomass         n-values DM-types   [0]
set P-nuclear         n-values DM-types   [0]
set P-coal-initial    n-values DM-types   [0]
set P-NG-initial      n-values DM-types   [0]
set P-wind-initial    n-values DM-types   [0]
set P-CSP-initial     n-values DM-types   [0]
set P-PV-initial      n-values DM-types   [0]
set P-biomass-initial n-values DM-types   [0]
set P-nuclear-initial n-values DM-types   [0]

set C1-norm           n-values tech-types [0]
set C2-norm           n-values tech-types [0]
set C3-norm           n-values tech-types [0]
set C4-norm           n-values tech-types [0]
set C5-norm           n-values tech-types [0]
set C6-norm           n-values tech-types [0]
set C7-norm           n-values tech-types [0]
set C8-norm           n-values tech-types [0]
set C9-norm           n-values tech-types [0]
set C10-norm          n-values tech-types [0]
set C11-norm          n-values tech-types [0]
set C12-norm          n-values tech-types [0]
set C13-norm          n-values tech-types [0]
```

```
ask DM [
  set X-coal        n-values DM-types   [0]
  set X-NG          n-values DM-types   [0]
  set X-wind        n-values DM-types   [0]
  set X-CSP         n-values DM-types   [0]
  set X-PV          n-values DM-types   [0]
  set X-biomass     n-values DM-types   [0]
  set X-nuclear     n-values DM-types   [0]
  set X-total       n-values DM-types   [0]

  set SI-coal       n-values DM-types   [0]
  set SI-NG         n-values DM-types   [0]
  set SI-wind       n-values DM-types   [0]
  set SI-CSP        n-values DM-types   [0]
  set SI-PV         n-values DM-types   [0]
  set SI-biomass    n-values DM-types   [0]
  set SI-nuclear    n-values DM-types   [0]

  set tmp           n-values tech-types [0]
  set P0            n-values tech-types [0]
  set P1            n-values tech-types [0]
  set P2            n-values tech-types [0]
  set P3            n-values tech-types [0]
  set P4            n-values tech-types [0]
  set P5            n-values tech-types [0]
  set P-game        n-values tech-types [0]

  set PSI-average           n-values DM-types [0]
  set P-total               n-values DM-types [0]
  set P-coal-previous-year    n-values DM-types [0]
  set P-NG-previous-year      n-values DM-types [0]
  set P-wind-previous-year    n-values DM-types [0]
  set P-CSP-previous-year     n-values DM-types [0]
  set P-PV-previous-year      n-values DM-types [0]
  set P-biomass-previous-year n-values DM-types [0]
  set P-nuclear-previous-year n-values DM-types [0]]

; assigning the weight values to the variables
;          0     1     2     3    4   5
set Wecon [ 0.31  0.37  0.37  0.25 0.25 "a" ]
set Wenv  [ 0.17  0.20  0.16  0.22 0.25 "b" ]
set Wsoc  [ 0.28  0.19  0.24  0.30 0.25 "c" ]
```

```
set Wtech [ 0.24  0.25  0.24  0.23 0.25 "d" ]


set  total-weight ( economic + environmental + social + technical )
set  Wecon replace-item 5 Wecon (economic      / total-weight )
set  Wenv  replace-item 5 Wenv  (environmental / total-weight )
set  Wsoc  replace-item 5 Wsoc  (social        / total-weight )
set  Wtech replace-item 5 Wtech (technical     / total-weight )

set E-eco 5 set E-env 2 set E-soc 4 set E-tech 3
set I-eco 5 set I-env 3 set I-soc 3 set I-tech 4
set P-eco 5 set P-env 2 set P-soc 3 set P-tech 3
set Y-eco 4 set Y-env 3 set Y-soc 5 set Y-tech 3


; Assigning the initial preference of the technologies according to DM inputs into the questionnaire, equal technology preference and a new DM input
ask DM
  [ set P-coal-next-year    [ 0.009 0.000 0.040 0.037 0.1429 "e"]
    set P-NG-next-year      [ 0.181 0.200 0.045 0.182 0.1429 "f"]
    set P-wind-next-year    [ 0.237 0.250 0.320 0.216 0.1429 "g"]
    set P-CSP-next-year     [ 0.307 0.250 0.300 0.289 0.1429 "h"]
    set P-PV-next-year      [ 0.256 0.300 0.155 0.203 0.1429 "i"]
    set P-biomass-next-year [ 0.000 0.000 0.000 0.000 0.1429 "j"]
    set P-nuclear-next-year [ 0.010 0.000 0.140 0.075 0.1429 "k"]
    set P-total             [   1     1     1     1     1  1   ]

    set  total-preferences-new-DM (coal + NG + wind + CSP + PV + biomass + nuclear)
    set  P-coal-next-year    replace-item 5 P-coal-next-year    (coal    / total-preferences-new-DM )
    set  P-NG-next-year      replace-item 5 P-NG-next-year      (NG      / total-preferences-new-DM )
    set  P-wind-next-year    replace-item 5 P-wind-next-year    (wind    / total-preferences-new-DM )
    set  P-CSP-next-year     replace-item 5 P-CSP-next-year     (CSP     / total-preferences-new-DM )
    set  P-PV-next-year      replace-item 5 P-PV-next-year      (PV      / total-preferences-new-DM )
    set  P-biomass-next-year replace-item 5 P-biomass-next-year (biomass / total-preferences-new-DM )
    set  P-nuclear-next-year replace-item 5 P-nuclear-next-year (nuclear / total-preferences-new-DM )]

; Here below are the initial preference values of technologies per DM type before applying the spatial effect
foreach DM-type-list [
set P-coal-initial    replace-item ? P-coal-initial    ( sum [item ? P-coal-next-year]    of DM  / count (DM))
```

set P-NG-initial replace-item ? P-NG-initial (sum [item ? P-NG-next-year] of DM / count (DM))
set P-wind-initial replace-item ? P-wind-initial (sum [item ? P-wind-next-year] of DM / count (DM))
set P-CSP-initial replace-item ? P-CSP-initial (sum [item ? P-CSP-next-year] of DM / count (DM))
set P-PV-initial replace-item ? P-PV-initial (sum [item ? P-PV-next-year] of DM / count (DM))
set P-biomass-initial replace-item ? P-biomass-initial (sum [item ? P-biomass-next-year] of DM / count (DM))
set P-nuclear-initial replace-item ? P-nuclear-initial (sum [item ? P-nuclear-next-year] of DM / count (DM))]

; Calculating the integrated spatial factor for each technology using the WSM
; Reminder: a=resource potential, b=population, c=water coverage, d=grid coverage, e=stability, f=road coverage, g=negative crop effect
ask DM [
set S-coal ((0.1 * 0.0000004 * 0.021) + (S-b * 0.272) + (S-c * 0.112) + (S-d * 0.067) + (S-e * 0.172) + (S-f * 0.067) + (S-g * 0.289))
set S-NG ((S-a-NG * 1 * 0.075) + (S-b * 0.313) + (S-c * 0.075) + (S-d * 0.034) + (S-e * 0.157) + (S-f * 0.034) + (S-g * 0.313))
set S-wind ((S-a-wind * 0.0844443 * 0.387) + (S-b * 0.091) + (S-c * 0.025) + (S-d * 0.245) + (S-e * 0.144) + (S-f * 0.084) + (S-g * 0.025))
set S-CSP ((S-a-CSP * 0.8130850 * 0.388) + (S-b * 0.030) + (S-c * 0.257) + (S-d * 0.078) + (S-e * 0.142) + (S-f * 0.078) + (S-g * 0.027))
set S-PV ((S-a-PV * 0.0003934 * 0.234) + (S-b * 0.028) + (S-c * 0.028) + (S-d * 0.139) + (S-e * 0.405) + (S-f * 0.139) + (S-g * 0.028))
set S-biomass ((S-a-biomass * 0.0001649 * 0.220) + (S-b * 0.096) + (S-c * 0.096) + (S-d * 0.039) + (S-e * 0.096) + (S-f * 0.039) + (S-g * 0.414))
set S-nuclear ((0.1 * 0.0059180 * 0.023) + (S-b * 0.317) + (S-c * 0.090) + (S-d * 0.044) + (S-e * 0.317) + (S-f * 0.044) + (S-g * 0.165))]

; Normalizing the integrated spatial factor
ask DM [
set S-coal-norm (S-coal / sum [S-coal] of DM)
set S-NG-norm (S-NG / sum [S-NG] of DM)
set S-wind-norm (S-wind / sum [S-wind] of DM)
set S-CSP-norm (S-CSP / sum [S-CSP] of DM)
set S-PV-norm (S-PV / sum [S-PV] of DM)
set S-biomass-norm (S-biomass / sum [S-biomass] of DM)
set S-nuclear-norm (S-nuclear / sum [S-nuclear] of DM)]
foreach DM-type-list [ask DM [; including the integrated spatial factor in initial setup
set P-coal-next-year replace-item ? P-coal-next-year (S-coal-norm * item ? P-coal-next-year)
set P-NG-next-year replace-item ? P-NG-next-year (S-NG-norm * item ? P-NG-next-year)
set P-wind-next-year replace-item ? P-wind-next-year (S-wind-norm * item ? P-wind-next-year)
set P-CSP-next-year replace-item ? P-CSP-next-year (S-CSP-norm * item ? P-CSP-next-year)

```
set  P-PV-next-year     replace-item ? P-PV-next-year     ( S-PV-norm     * item ? P-PV-next-year     )
set  P-biomass-next-year replace-item ? P-biomass-next-year ( S-biomass-norm * item ? P-biomass-next-
year )
set   P-nuclear-next-year replace-item ? P-nuclear-next-year ( S-nuclear-norm * item ? P-nuclear-next-
year )
set  P-total             replace-item ? P-total ( item ? P-coal-next-year + item ? P-NG-next-year + item ? P-
wind-next-year + item ? P-CSP-next-year + item ? P-PV-next-year + item ? P-biomass-next-year + item ?
P-nuclear-next-year)
        ; normalization after considering the spatial factor
        set  P-coal-next-year    replace-item ? P-coal-next-year    (item ? P-coal-next-year    / item ? P-total
)
        set  P-NG-next-year     replace-item ? P-NG-next-year     (item ? P-NG-next-year     / item ? P-total
)
        set  P-wind-next-year    replace-item ? P-wind-next-year    (item ? P-wind-next-year    / item ? P-
total )
        set  P-CSP-next-year    replace-item ? P-CSP-next-year    (item ? P-CSP-next-year    / item ? P-total
)
        set  P-PV-next-year     replace-item ? P-PV-next-year     (item ? P-PV-next-year     / item ? P-total )
        set  P-biomass-next-year replace-item ? P-biomass-next-year (item ? P-biomass-next-year / item ?
P-total )
        set  P-nuclear-next-year replace-item ? P-nuclear-next-year (item ? P-nuclear-next-year / item ? P-
total )
        set  P-total           replace-item ? P-total ( item ? P-coal-next-year + item ? P-NG-next-year + item ?
P-wind-next-year + item ? P-CSP-next-year +
                                    item ? P-PV-next-year + item ? P-biomass-next-year + item ? P-
nuclear-next-year)] ]

       foreach DM-type-list [
        set P-coal      replace-item ? P-coal      ( sum [item ? P-coal-next-year] of DM     / count (DM))
        set P-NG        replace-item ? P-NG        ( sum [item ? P-NG-next-year] of DM       / count (DM))
        set P-wind      replace-item ? P-wind      ( sum [item ? P-wind-next-year] of DM     / count (DM))
        set P-CSP       replace-item ? P-CSP       ( sum [item ? P-CSP-next-year] of DM      / count (DM))
        set P-PV        replace-item ? P-PV        ( sum [item ? P-PV-next-year] of DM       / count (DM))
        set P-biomass     replace-item ? P-biomass     ( sum [item ? P-biomass-next-year] of DM  / count
(DM))
        set P-nuclear    replace-item ? P-nuclear    ( sum [item ? P-nuclear-next-year] of DM  / count (DM))
        set P-total-tech replace-item ? P-total-tech ( sum [item ? P-total] of DM            / count (DM))  ]

       set GHG-emission [ 1.0000  0.5284  0.0041  0.0143  0.0394  0.0439  0.0013 ] ; normalized values

       ; The following is to transpose the list between technologies and DM types so I have a 5 lists of
DMs
```

```
foreach tech-type-list [ ask DM [
 set P0 replace-item 0 P0 ( item 0 P-coal-next-year)
 set P0 replace-item 1 P0 ( item 0 P-NG-next-year)
 set P0 replace-item 2 P0 ( item 0 P-wind-next-year)
 set P0 replace-item 3 P0 ( item 0 P-CSP-next-year)
 set P0 replace-item 4 P0 ( item 0 P-PV-next-year)
 set P0 replace-item 5 P0 ( item 0 P-biomass-next-year)
 set P0 replace-item 6 P0 ( item 0 P-nuclear-next-year)

 set P1 replace-item 0 P1 ( item 1 P-coal-next-year)
 set P1 replace-item 1 P1 ( item 1 P-NG-next-year)
 set P1 replace-item 2 P1 ( item 1 P-wind-next-year)
 set P1 replace-item 3 P1 ( item 1 P-CSP-next-year)
 set P1 replace-item 4 P1 ( item 1 P-PV-next-year)
 set P1 replace-item 5 P1 ( item 1 P-biomass-next-year)
 set P1 replace-item 6 P1 ( item 1 P-nuclear-next-year)

 set P2 replace-item 0 P2 ( item 2 P-coal-next-year)
 set P2 replace-item 1 P2 ( item 2 P-NG-next-year)
 set P2 replace-item 2 P2 ( item 2 P-wind-next-year)
 set P2 replace-item 3 P2 ( item 2 P-CSP-next-year)
 set P2 replace-item 4 P2 ( item 2 P-PV-next-year)
 set P2 replace-item 5 P2 ( item 2 P-biomass-next-year)
 set P2 replace-item 6 P2 ( item 2 P-nuclear-next-year)

 set P3 replace-item 0 P3 ( item 3 P-coal-next-year)
 set P3 replace-item 1 P3 ( item 3 P-NG-next-year)
 set P3 replace-item 2 P3 ( item 3 P-wind-next-year)
 set P3 replace-item 3 P3 ( item 3 P-CSP-next-year)
 set P3 replace-item 4 P3 ( item 3 P-PV-next-year)
 set P3 replace-item 5 P3 ( item 3 P-biomass-next-year)
 set P3 replace-item 6 P3 ( item 3 P-nuclear-next-year)

 set P4 replace-item 0 P4 ( item 4 P-coal-next-year)
 set P4 replace-item 1 P4 ( item 4 P-NG-next-year)
 set P4 replace-item 2 P4 ( item 4 P-wind-next-year)
 set P4 replace-item 3 P4 ( item 4 P-CSP-next-year)
 set P4 replace-item 4 P4 ( item 4 P-PV-next-year)
 set P4 replace-item 5 P4 ( item 4 P-biomass-next-year)
 set P4 replace-item 6 P4 ( item 4 P-nuclear-next-year)

 set P5 replace-item 0 P5 ( item 5 P-coal-next-year)
```

```
set P5 replace-item 1 P5 ( item 5 P-NG-next-year)
set P5 replace-item 2 P5 ( item 5 P-wind-next-year)
set P5 replace-item 3 P5 ( item 5 P-CSP-next-year)
set P5 replace-item 4 P5 ( item 5 P-PV-next-year)
set P5 replace-item 5 P5 ( item 5 P-biomass-next-year)
set P5 replace-item 6 P5 ( item 5 P-nuclear-next-year)

set P-game replace-item 0 P-game ( max P-coal-next-year )
set P-game replace-item 1 P-game ( max P-NG-next-year)
set P-game replace-item 2 P-game ( max P-wind-next-year)
set P-game replace-item 3 P-game ( max P-CSP-next-year)
set P-game replace-item 4 P-game ( max P-PV-next-year)
set P-game replace-item 5 P-game ( max P-biomass-next-year)
set P-game replace-item 6 P-game ( max P-nuclear-next-year)

if GHG?    [ set tech  "N.A."]
if players? [ set tech  "N.A." set DM-type  "Game"]

ifelse DM-type = "Experts" and  GHG?             [set tmp replace-item ? tmp ( item ? P0    * item ? GHG-emission) set pcolor scale-color turquoise sum (tmp) 1 0] [if DM-type = "Experts"             [set tmp replace-item ? tmp ( item ? P0)    ]]
ifelse DM-type = "Investors" and GHG?            [set tmp replace-item ? tmp ( item ? P1    * item ? GHG-emission) set pcolor scale-color turquoise sum (tmp) 1 0] [if DM-type = "Investors"           [set tmp replace-item ? tmp ( item ? P1)    ]]
ifelse DM-type = "Policy-makers" and GHG?        [set tmp replace-item ? tmp ( item ? P2    * item ? GHG-emission) set pcolor scale-color turquoise sum (tmp) 1 0] [if DM-type = "Policy-makers"       [set tmp replace-item ? tmp ( item ? P2)    ]]
ifelse DM-type = "Young-researchers" and GHG?    [set tmp replace-item ? tmp ( item ? P3    * item ? GHG-emission) set pcolor scale-color turquoise sum (tmp) 1 0] [if DM-type = "Young-researchers" [set tmp replace-item ? tmp ( item ? P3)    ]]
ifelse DM-type = "Sustainable" and GHG?          [set tmp replace-item ? tmp ( item ? P4    * item ? GHG-emission) set pcolor scale-color turquoise sum (tmp) 1 0] [if DM-type = "Sustainable"         [set tmp replace-item ? tmp ( item ? P4)    ]]
ifelse DM-type = "New-DM" and GHG?               [set tmp replace-item ? tmp ( item ? P5    * item ? GHG-emission) set pcolor scale-color turquoise sum (tmp) 1 0] [if DM-type = "New-DM"              [set tmp replace-item ? tmp ( item ? P5)    ]]
ifelse DM-type = "Game" and GHG?                 [set tmp replace-item ? tmp ( item ? P-game * item ? GHG-emission) set pcolor scale-color turquoise sum (tmp) 1 0] [if DM-type = "Game"                [set tmp replace-item ? tmp ( item ? P-game)]]

if players? and max P-game = max P0 [set pcolor red   ]  ; Experts
if players? and max P-game = max P1 [set pcolor pink  ]  ; Investors
```

```
    if players? and max P-game = max P2 [set pcolor cyan  ]  ; Policy-makers
    if players? and max P-game = max P3 [set pcolor sky   ]  ; Young-researchers
    if players? and max P-game = max P4 [set pcolor lime  ]  ; Sustainable
    if players? and max P-game = max P5 [set pcolor violet]  ; New-DM


    if tech = "coal"    [ set pcolor scale-color gray    item 0 tmp 1.3 0 ]
    if tech = "NG"      [ set pcolor scale-color brown   item 1 tmp 1.3 0 ]
    if tech = "wind"    [ set pcolor scale-color blue    item 2 tmp 1.3 0 ]
    if tech = "CSP"     [ set pcolor scale-color yellow  item 3 tmp 1.3 0 ]
    if tech = "PV"      [ set pcolor scale-color orange  item 4 tmp 1.3 0 ]
    if tech = "biomass" [ set pcolor scale-color green   item 5 tmp 1.3 0 ]
    if tech = "nuclear" [ set pcolor scale-color magenta item 6 tmp 1.3 0 ]

    if tech = "mix" and item 0 tmp = max tmp [ set pcolor gray]
    if tech = "mix" and item 1 tmp = max tmp [ set pcolor brown]
    if tech = "mix" and item 2 tmp = max tmp [ set pcolor blue]
    if tech = "mix" and item 3 tmp = max tmp [ set pcolor yellow]
    if tech = "mix" and item 4 tmp = max tmp [ set pcolor orange]
    if tech = "mix" and item 5 tmp = max tmp [ set pcolor green]
    if tech = "mix" and item 6 tmp = max tmp [ set pcolor magenta]

    if tech = "mix-scale" and item 0 tmp = max tmp [ set pcolor scale-color gray    item 0 tmp 1.3 0]
    if tech = "mix-scale" and item 1 tmp = max tmp [ set pcolor scale-color brown   item 1 tmp 1.3 0]
    if tech = "mix-scale" and item 2 tmp = max tmp [ set pcolor scale-color blue    item 2 tmp 1.3 0]
    if tech = "mix-scale" and item 3 tmp = max tmp [ set pcolor scale-color yellow  item 3 tmp 1.3 0]
    if tech = "mix-scale" and item 4 tmp = max tmp [ set pcolor scale-color orange  item 4 tmp 1.3 0]
    if tech = "mix-scale" and item 5 tmp = max tmp [ set pcolor scale-color green   item 5 tmp 1.3 0]
    if tech = "mix-scale" and item 6 tmp = max tmp [ set pcolor scale-color magenta item 6 tmp 1.3 0 ]
] ]
   reset-ticks
  end
;;#####################################################################################
  to go
   if ticks >= 85 [ stop ]
   tick

   ;        coal      NG       wind     CSP      PV     biomass    nuclear
   set C1  [ 1867.1429   831.25   1582      4918.3333 3605      2816      4380     ] ; investment costs
   set C2  [    44.326      23.025     36.3575     94.494     35.34      90.115     93.74    ] ; fixed operation and
maintenance costs
   set C3  [    0.061      0.0665    0.0952     0.213     0.3621    0.1154    0.0448 ] ; cost of electricity
```

```
set C4  [    1.675      1.185     2.992      4.4833   12.7917    5.875     1.515  ] ; job generation
set C5  [  926.79     475.8571   45.6714   105.2      110.9      69.5      23      ] ; CO2 emission
set C6  [    1.5329     0.9287    0.0688     0.0148    0.2053    0.6189    0.0297 ] ; NOx emission
set C7  [    2.591      0.0913    0.5418     0.0432    0.517     1.3573    0.0213 ] ; SO2 emission
set C8  [    1.08       0.202     0.0083     0         0.0002    0.0149   13.6301 ] ; Risk
set C9  [    9.4188    23.1793   32.38      24.8166   22.7563    3.7731    8.5977 ] ; Social acceptability
set C10 [   40.3333    47        35.2857    17.3333   12.75      30.4      35      ] ; plant efficiency
set C11 [   85         85        30         35.5      20.5       77        90      ] ; capacity factor
set C12 [    0.4072 90588.2353 7650      73656        36         15.3     536.47   ] ; resource potential
set C13 [   41         41         1          3.4       5.5      102.4167   52.5    ] ; water consumption

; adding the regression equation of C1 (linear)
set C1 replace-item 0 C1 ((80.333  * (1.5 + (ticks / 10))) + 1783.7)
set C1 replace-item 1 C1 ((41.905  * (1.5 + (ticks / 10))) + 743.98)
set C1 replace-item 2 C1 ((-43.833 * (1.5 + (ticks / 10))) + 1644.8)
set C1 replace-item 3 C1 ((-486.57 * (1.5 + (ticks / 10))) + 4995.8)
set C1 replace-item 4 C1 ((-420.53 * (1.5 + (ticks / 10))) + 3147.5)
set C1 replace-item 5 C1 ((109.83  * (1.5 + (ticks / 10))) + 2811.5)
set C1 replace-item 6 C1 ((170.87  * (1.5 + (ticks / 10))) + 4720.8)

; adding the regression equation of C2 (linear)
set C2 replace-item 0 C2 ((-3.3572 * (1.5 + (ticks / 10))) + 45.995)
set C2 replace-item 1 C2 ((-1.3117 * (1.5 + (ticks / 10))) + 24.333)
set C2 replace-item 2 C2 ((-2.9335 * (1.5 + (ticks / 10))) +  37.26)
set C2 replace-item 3 C2 ((-14.579 * (1.5 + (ticks / 10))) + 115.86)
set C2 replace-item 4 C2 ((-4.707  * (1.5 + (ticks / 10))) +  35.25)
set C2 replace-item 5 C2 ((-0.427  * (1.5 + (ticks / 10))) +  88.05)
set C2 replace-item 6 C2 ((-5.034  * (1.5 + (ticks / 10))) + 110.41)

; adding the regression equation of C3 (linear)
set C3 replace-item 2 C3 ((-0.004 * (1.5 + (ticks / 10))) +  0.06)
set C3 replace-item 3 C3 ((-0.017 * (1.5 + (ticks / 10))) + 0.185)
set C3 replace-item 4 C3 ((-0.038 * (1.5 + (ticks / 10))) + 0.262)

; Normalization
foreach tech-type-list [
set C1-norm  replace-item ? C1-norm  (((max C1  + (0.1 * max C1))  - item ? C1)  / ((max C1  + (0.1 * max C1))  - min C1) )
set C2-norm  replace-item ? C2-norm  (((max C2  + (0.1 * max C2))  - item ? C2)  / ((max C2  + (0.1 * max C2))  - min C2) )
set C3-norm  replace-item ? C3-norm  (((max C3  + (0.1 * max C3))  - item ? C3)  / ((max C3  + (0.1 * max C3))  - min C3) )
```

```
    set C4-norm  replace-item ? C4-norm  ((item ? C4  - (min C4  - (0.1 * min C4)))  / (max C4  - (min C4
- (0.1 * min C4))) )
    set C5-norm  replace-item ? C5-norm  (((max C5  + (0.1 * max C5))  - item ? C5)  / ((max C5  + (0.1 *
max C5))  - min C5) )
    set C6-norm  replace-item ? C6-norm  (((max C6  + (0.1 * max C6))  - item ? C6)  / ((max C6  + (0.1 *
max C6))  - min C6) )
    set C7-norm  replace-item ? C7-norm  (((max C7  + (0.1 * max C7))  - item ? C7)  / ((max C7  + (0.1 *
max C7))  - min C7) )
    set C8-norm  replace-item ? C8-norm  (((max C8  + (0.1 * max C8))  - item ? C8)  / ((max C8  + (0.1 *
max C8))  - min C8) )
    set C9-norm  replace-item ? C9-norm  ((item ? C9  - (min C9  - (0.1 * min C9)))  / (max C9  - (min C9
- (0.1 * min C9))) )
    set C10-norm replace-item ? C10-norm ((item ? C10 - (min C10 - (0.1 * min C10))) / (max C10 - (min
C10 - (0.1 * min C10))))
    set C11-norm replace-item ? C11-norm ((item ? C11 - (min C11 - (0.1 * min C11))) / (max C11 - (min
C11 - (0.1 * min C11))))
    set C12-norm replace-item ? C12-norm ((item ? C12 - (min C12 - (0.1 * min C12))) / (max C12 - (min
C12 - (0.1 * min C12))))
    set C13-norm replace-item ? C13-norm (((max C13 + (0.1 * max C13)) - item ? C13) / ((max C13 +
(0.1 * max C13)) - min C13))]

    ; For modifying the weight values to the variables
   if improve? [

    set  Wecon replace-item 0 Wecon (E-eco  / (E-eco + E-env + E-soc + E-tech) )
    set  Wenv  replace-item 0 Wenv  (E-env  / (E-eco + E-env + E-soc + E-tech) )
    set  Wsoc  replace-item 0 Wsoc  (E-soc  / (E-eco + E-env + E-soc + E-tech) )
    set  Wtech replace-item 0 Wtech (E-tech / (E-eco + E-env + E-soc + E-tech) )

    set  Wecon replace-item 1 Wecon (I-eco  / (I-eco + I-env + I-soc + I-tech) )
    set  Wenv  replace-item 1 Wenv  (I-env  / (I-eco + I-env + I-soc + I-tech) )
    set  Wsoc  replace-item 1 Wsoc  (I-soc  / (I-eco + I-env + I-soc + I-tech) )
    set  Wtech replace-item 1 Wtech (I-tech / (I-eco + I-env + I-soc + I-tech) )

    set  Wecon replace-item 2 Wecon (P-eco  / (P-eco + P-env + P-soc + P-tech) )
    set  Wenv  replace-item 2 Wenv  (P-env  / (P-eco + P-env + P-soc + P-tech) )
    set  Wsoc  replace-item 2 Wsoc  (P-soc  / (P-eco + P-env + P-soc + P-tech) )
    set  Wtech replace-item 2 Wtech (P-tech / (P-eco + P-env + P-soc + P-tech) )

    set  Wecon replace-item 3 Wecon (Y-eco  / (Y-eco + Y-env + Y-soc + Y-tech) )
    set  Wenv  replace-item 3 Wenv  (Y-env  / (Y-eco + Y-env + Y-soc + Y-tech) )
    set  Wsoc  replace-item 3 Wsoc  (Y-soc  / (Y-eco + Y-env + Y-soc + Y-tech) )
```

```
set  Wtech replace-item 3 Wtech (Y-tech / (Y-eco + Y-env + Y-soc + Y-tech) )

set  total-weight ( economic + environmental + social + technical )
set  Wecon replace-item 5 Wecon (economic / total-weight )
set  Wenv  replace-item 5 Wenv  (environmental / total-weight )
set  Wsoc  replace-item 5 Wsoc  (social / total-weight )
set  Wtech replace-item 5 Wtech (technical / total-weight ) ]

 ; Calculating the X values (previously identified)
foreach DM-type-list [ ask DM
[ set X-coal replace-item ? X-coal      ( S-coal-norm *
   ((item ? Wecon / 4 * item 0 C1-norm)  + (item ? Wecon / 4 * item 0 C2-norm)  + (item ? Wecon /
4 * item 0 C3-norm)  + (item ? Wecon / 4 * item 0 C4-norm) +
    (item ? Wenv  / 3 * item 0 C5-norm)  + (item ? Wenv  / 3 * item 0 C6-norm)  + (item ? Wenv  / 3
* item 0 C7-norm)  +
    (item ? Wsoc  / 2 * item 0 C8-norm)  + (item ? Wsoc  / 2 * item 0 C9-norm)  +
    (item ? Wtech / 4 * item 0 C10-norm) + (item ? Wtech / 4 * item 0 C11-norm) + (item ? Wtech /
4 * item 0 C12-norm) + (item ? Wtech / 4 * item 0 C13-norm) ) )

  set X-NG replace-item ? X-NG         ( S-NG-norm *
   ((item ? Wecon / 4 * item 1 C1-norm)  + (item ? Wecon / 4 * item 1 C2-norm)  + (item ? Wecon /
4 * item 1 C3-norm)  + (item ? Wecon / 4 * item 1 C4-norm) +
    (item ? Wenv  / 3 * item 1 C5-norm)  + (item ? Wenv  / 3 * item 1 C6-norm)  + (item ? Wenv  / 3
* item 1 C7-norm)  +
    (item ? Wsoc  / 2 * item 1 C8-norm)  + (item ? Wsoc  / 2 * item 1 C9-norm)  +
    (item ? Wtech / 4 * item 1 C10-norm) + (item ? Wtech / 4 * item 1 C11-norm) + (item ? Wtech /
4 * item 1 C12-norm) + (item ? Wtech / 4 * item 1 C13-norm) ) )

  set X-wind replace-item ? X-wind      ( S-wind-norm *
   ((item ? Wecon / 4 * item 2 C1-norm)  + (item ? Wecon / 4 * item 2 C2-norm)  + (item ? Wecon /
4 * item 2 C3-norm)  + (item ? Wecon / 4 * item 2 C4-norm) +
    (item ? Wenv  / 3 * item 2 C5-norm)  + (item ? Wenv  / 3 * item 2 C6-norm)  + (item ? Wenv  / 3
* item 2 C7-norm)  +
    (item ? Wsoc  / 2 * item 2 C8-norm)  + (item ? Wsoc  / 2 * item 2 C9-norm)  +
    (item ? Wtech / 4 * item 2 C10-norm) + (item ? Wtech / 4 * item 2 C11-norm) + (item ? Wtech /
4 * item 2 C12-norm) + (item ? Wtech / 4 * item 2 C13-norm) ) )

  set X-CSP replace-item ? X-CSP        ( S-CSP-norm *
   ((item ? Wecon / 4 * item 3 C1-norm)  + (item ? Wecon / 4 * item 3 C2-norm)  + (item ? Wecon /
4 * item 3 C3-norm)  + (item ? Wecon / 4 * item 3 C4-norm) +
    (item ? Wenv  / 3 * item 3 C5-norm)  + (item ? Wenv  / 3 * item 3 C6-norm)  + (item ? Wenv  / 3
* item 3 C7-norm)  +
```

```
        (item ? Wsoc  / 2 * item 3 C8-norm)  + (item ? Wsoc  / 2 * item 3 C9-norm)  +
        (item ? Wtech / 4 * item 3 C10-norm) + (item ? Wtech / 4 * item 3 C11-norm) + (item ? Wtech /
4 * item 3 C12-norm) + (item ? Wtech / 4 * item 3 C13-norm) ) )

      set X-PV replace-item ? X-PV         ( S-PV-norm *
       ((item ? Wecon / 4 * item 4 C1-norm)  + (item ? Wecon / 4 * item 4 C2-norm)  + (item ? Wecon /
4 * item 4 C3-norm)  + (item ? Wecon / 4 * item 4 C4-norm) +
        (item ? Wenv  / 3 * item 4 C5-norm)  + (item ? Wenv  / 3 * item 4 C6-norm)  + (item ? Wenv  / 3
* item 4 C7-norm)  +
        (item ? Wsoc  / 2 * item 4 C8-norm)  + (item ? Wsoc  / 2 * item 4 C9-norm)  +
        (item ? Wtech / 4 * item 4 C10-norm) + (item ? Wtech / 4 * item 4 C11-norm) + (item ? Wtech /
4 * item 4 C12-norm) + (item ? Wtech / 4 * item 4 C13-norm) ) )

      set X-biomass replace-item ? X-biomass ( S-biomass-norm *
       ((item ? Wecon / 4 * item 5 C1-norm)  + (item ? Wecon / 4 * item 5 C2-norm)  + (item ? Wecon /
4 * item 5 C3-norm)  + (item ? Wecon / 4 * item 5 C4-norm) +
        (item ? Wenv  / 3 * item 5 C5-norm)  + (item ? Wenv  / 3 * item 5 C6-norm)  + (item ? Wenv  / 3
* item 5 C7-norm)  +
        (item ? Wsoc  / 2 * item 5 C8-norm)  + (item ? Wsoc  / 2 * item 5 C9-norm)  +
        (item ? Wtech / 4 * item 5 C10-norm) + (item ? Wtech / 4 * item 5 C11-norm) + (item ? Wtech /
4 * item 5 C12-norm) + (item ? Wtech / 4 * item 5 C13-norm) ) )

      set X-nuclear replace-item ? X-nuclear ( S-nuclear-norm *
       ((item ? Wecon / 4 * item 6 C1-norm)  + (item ? Wecon / 4 * item 6 C2-norm)  + (item ? Wecon /
4 * item 6 C3-norm)  + (item ? Wecon / 4 * item 6 C4-norm) +
        (item ? Wenv  / 3 * item 6 C5-norm)  + (item ? Wenv  / 3 * item 6 C6-norm)  + (item ? Wenv  / 3
* item 6 C7-norm)  +
        (item ? Wsoc  / 2 * item 6 C8-norm)  + (item ? Wsoc  / 2 * item 6 C9-norm)  +
        (item ? Wtech / 4 * item 6 C10-norm) + (item ? Wtech / 4 * item 6 C11-norm) + (item ? Wtech /
4 * item 6 C12-norm) + (item ? Wtech / 4 * item 6 C13-norm) ) )

      set X-total replace-item ? X-total       (item ? X-coal + item ? X-NG + item ? X-wind + item ? X-CSP +
item ? X-PV + item ? X-biomass + item ? X-nuclear)

      ; Recalculating the sustainability index for each technology in each city (the marginal value)
      set SI-coal    replace-item ? SI-coal    ( item ? X-coal    / item ? X-total)
      set SI-NG      replace-item ? SI-NG      ( item ? X-NG      / item ? X-total)
      set SI-wind    replace-item ? SI-wind    ( item ? X-wind    / item ? X-total)
      set SI-CSP     replace-item ? SI-CSP     ( item ? X-CSP     / item ? X-total)
      set SI-PV      replace-item ? SI-PV      ( item ? X-PV      / item ? X-total)
      set SI-biomass replace-item ? SI-biomass ( item ? X-biomass / item ? X-total)
      set SI-nuclear replace-item ? SI-nuclear ( item ? X-nuclear / item ? X-total)
```

set P-coal-previous-year replace-item ? P-coal-previous-year (item ? P-coal-next-year)
set P-NG-previous-year replace-item ? P-NG-previous-year (item ? P-NG-next-year)
set P-wind-previous-year replace-item ? P-wind-previous-year (item ? P-wind-next-year)
set P-CSP-previous-year replace-item ? P-CSP-previous-year (item ? P-CSP-next-year)
set P-PV-previous-year replace-item ? P-PV-previous-year (item ? P-PV-next-year)
set P-biomass-previous-year replace-item ? P-biomass-previous-year (item ? P-biomass-next-year)
set P-nuclear-previous-year replace-item ? P-nuclear-previous-year (item ? P-nuclear-next-year)

set PSI-average replace-item ? PSI-average (((item ? P-coal-previous-year * item ? SI-coal) + (item ? P-NG-previous-year * item ? SI-NG) + (item ? P-wind-previous-year * item ? SI-wind) + (item ? P-CSP-previous-year * item ? SI-CSP) +
(item ? P-PV-previous-year * item ? SI-PV) + (item ? P-biomass-previous-year * item ? SI-biomass) + (item ? P-nuclear-previous-year * item ? SI-nuclear)))
set P-coal-next-year replace-item ? P-coal-next-year (item ? P-coal-previous-year + (Alpha * item ? P-coal-previous-year * ((item ? SI-coal) - item ? PSI-average)))
set P-NG-next-year replace-item ? P-NG-next-year (item ? P-NG-previous-year + (Alpha * item ? P-NG-previous-year * ((item ? SI-NG) - item ? PSI-average)))
set P-wind-next-year replace-item ? P-wind-next-year (item ? P-wind-previous-year + (Alpha * item ? P-wind-previous-year * ((item ? SI-wind) - item ? PSI-average)))
set P-CSP-next-year replace-item ? P-CSP-next-year (item ? P-CSP-previous-year + (Alpha * item ? P-CSP-previous-year * ((item ? SI-CSP) - item ? PSI-average)))
set P-PV-next-year replace-item ? P-PV-next-year (item ? P-PV-previous-year + (Alpha * item ? P-PV-previous-year * ((item ? SI-PV) - item ? PSI-average)))
set P-biomass-next-year replace-item ? P-biomass-next-year (item ? P-biomass-previous-year + (Alpha * item ? P-biomass-previous-year * ((item ? SI-biomass) - item ? PSI-average)))
set P-nuclear-next-year replace-item ? P-nuclear-next-year (item ? P-nuclear-previous-year + (Alpha * item ? P-nuclear-previous-year * ((item ? SI-nuclear) - item ? PSI-average)))
set P-total replace-item ? P-total (item ? P-coal-next-year + item ? P-NG-next-year + item ? P-wind-next-year + item ? P-CSP-next-year + item ? P-PV-next-year + item ? P-biomass-next-year + item ? P-nuclear-next-year)]]

foreach DM-type-list [
set P-coal replace-item ? P-coal (sum [item ? P-coal-next-year] of DM / count (DM))
set P-NG replace-item ? P-NG (sum [item ? P-NG-next-year] of DM / count (DM))
set P-wind replace-item ? P-wind (sum [item ? P-wind-next-year] of DM / count (DM))
set P-CSP replace-item ? P-CSP (sum [item ? P-CSP-next-year] of DM / count (DM))
set P-PV replace-item ? P-PV (sum [item ? P-PV-next-year] of DM / count (DM))
set P-biomass replace-item ? P-biomass (sum [item ? P-biomass-next-year] of DM / count (DM))
set P-nuclear replace-item ? P-nuclear (sum [item ? P-nuclear-next-year] of DM / count (DM))

```
    set P-total-tech replace-item ? P-total-tech ( sum [item ? P-total]         of DM  / count (DM))  ]

  ; The following is to transpose the list between technologies and DM types so I have a 6 lists of
DMs each contains the value for each technology
  foreach tech-type-list [ ask DM [
    set P0 replace-item 0 P0 ( item 0 P-coal-next-year)
    set P0 replace-item 1 P0 ( item 0 P-NG-next-year)
    set P0 replace-item 2 P0 ( item 0 P-wind-next-year)
    set P0 replace-item 3 P0 ( item 0 P-CSP-next-year)
    set P0 replace-item 4 P0 ( item 0 P-PV-next-year)
    set P0 replace-item 5 P0 ( item 0 P-biomass-next-year)
    set P0 replace-item 6 P0 ( item 0 P-nuclear-next-year)

    set P1 replace-item 0 P1 ( item 1 P-coal-next-year)
    set P1 replace-item 1 P1 ( item 1 P-NG-next-year)
    set P1 replace-item 2 P1 ( item 1 P-wind-next-year)
    set P1 replace-item 3 P1 ( item 1 P-CSP-next-year)
    set P1 replace-item 4 P1 ( item 1 P-PV-next-year)
    set P1 replace-item 5 P1 ( item 1 P-biomass-next-year)
    set P1 replace-item 6 P1 ( item 1 P-nuclear-next-year)

    set P2 replace-item 0 P2 ( item 2 P-coal-next-year)
    set P2 replace-item 1 P2 ( item 2 P-NG-next-year)
    set P2 replace-item 2 P2 ( item 2 P-wind-next-year)
    set P2 replace-item 3 P2 ( item 2 P-CSP-next-year)
    set P2 replace-item 4 P2 ( item 2 P-PV-next-year)
    set P2 replace-item 5 P2 ( item 2 P-biomass-next-year)
    set P2 replace-item 6 P2 ( item 2 P-nuclear-next-year)

    set P3 replace-item 0 P3 ( item 3 P-coal-next-year)
    set P3 replace-item 1 P3 ( item 3 P-NG-next-year)
    set P3 replace-item 2 P3 ( item 3 P-wind-next-year)
    set P3 replace-item 3 P3 ( item 3 P-CSP-next-year)
    set P3 replace-item 4 P3 ( item 3 P-PV-next-year)
    set P3 replace-item 5 P3 ( item 3 P-biomass-next-year)
    set P3 replace-item 6 P3 ( item 3 P-nuclear-next-year)

    set P4 replace-item 0 P4 ( item 4 P-coal-next-year)
    set P4 replace-item 1 P4 ( item 4 P-NG-next-year)
    set P4 replace-item 2 P4 ( item 4 P-wind-next-year)
    set P4 replace-item 3 P4 ( item 4 P-CSP-next-year)
    set P4 replace-item 4 P4 ( item 4 P-PV-next-year)
```

```
set P4 replace-item 5 P4 ( item 4 P-biomass-next-year)
set P4 replace-item 6 P4 ( item 4 P-nuclear-next-year)

set P5 replace-item 0 P5 ( item 5 P-coal-next-year)
set P5 replace-item 1 P5 ( item 5 P-NG-next-year)
set P5 replace-item 2 P5 ( item 5 P-wind-next-year)
set P5 replace-item 3 P5 ( item 5 P-CSP-next-year)
set P5 replace-item 4 P5 ( item 5 P-PV-next-year)
set P5 replace-item 5 P5 ( item 5 P-biomass-next-year)
set P5 replace-item 6 P5 ( item 5 P-nuclear-next-year)

set P-game replace-item 0 P-game ( max P-coal-next-year )
set P-game replace-item 1 P-game ( max P-NG-next-year)
set P-game replace-item 2 P-game ( max P-wind-next-year)
set P-game replace-item 3 P-game ( max P-CSP-next-year)
set P-game replace-item 4 P-game ( max P-PV-next-year)
set P-game replace-item 5 P-game ( max P-biomass-next-year)
set P-game replace-item 6 P-game ( max P-nuclear-next-year)

if GHG?     [ set tech  "N.A."]
if players? [ set tech  "N.A." set DM-type  "Game"]

ifelse DM-type = "Experts" and  GHG?              [set tmp replace-item ? tmp ( item ? P0     * item ? GHG-emission) set pcolor scale-color turquoise sum (tmp) 1 0] [if DM-type = "Experts"              [set tmp replace-item ? tmp ( item ? P0)    ]]
ifelse DM-type = "Investors" and GHG?             [set tmp replace-item ? tmp ( item ? P1     * item ? GHG-emission) set pcolor scale-color turquoise sum (tmp) 1 0] [if DM-type = "Investors"            [set tmp replace-item ? tmp ( item ? P1)    ]]
ifelse DM-type = "Policy-makers" and GHG?         [set tmp replace-item ? tmp ( item ? P2     * item ? GHG-emission) set pcolor scale-color turquoise sum (tmp) 1 0] [if DM-type = "Policy-makers"        [set tmp replace-item ? tmp ( item ? P2)    ]]
ifelse DM-type = "Young-researchers" and GHG?     [set tmp replace-item ? tmp ( item ? P3     * item ? GHG-emission) set pcolor scale-color turquoise sum (tmp) 1 0] [if DM-type = "Young-researchers" [set tmp replace-item ? tmp ( item ? P3)    ]]
ifelse DM-type = "Sustainable" and GHG?           [set tmp replace-item ? tmp ( item ? P4     * item ? GHG-emission) set pcolor scale-color turquoise sum (tmp) 1 0] [if DM-type = "Sustainable"          [set tmp replace-item ? tmp ( item ? P4)    ]]
ifelse DM-type = "New-DM" and GHG?                [set tmp replace-item ? tmp ( item ? P5     * item ? GHG-emission) set pcolor scale-color turquoise sum (tmp) 1 0] [if DM-type = "New-DM"               [set tmp replace-item ? tmp ( item ? P5)    ]]
```

```
        ifelse DM-type = "Game" and GHG?                [set tmp replace-item ? tmp ( item ? P-game * item
? GHG-emission) set pcolor scale-color turquoise sum (tmp) 1 0] [if DM-type = "Game"                  [set
tmp replace-item ? tmp ( item ? P-game)]]

        if players? and max P-game = max P0 [set pcolor red   ]  ; Experts
        if players? and max P-game = max P1 [set pcolor pink  ]  ; Investors
        if players? and max P-game = max P2 [set pcolor cyan  ]  ; Policy-makers
        if players? and max P-game = max P3 [set pcolor sky   ]  ; Young-researchers
        if players? and max P-game = max P4 [set pcolor lime  ]  ; Sustainable
        if players? and max P-game = max P5 [set pcolor violet]  ; New-DM

        if tech = "coal"    [ set pcolor scale-color gray    item 0 tmp 1.3 0 ]
        if tech = "NG"      [ set pcolor scale-color brown   item 1 tmp 1.3 0 ]
        if tech = "wind"    [ set pcolor scale-color blue    item 2 tmp 1.3 0 ]
        if tech = "CSP"     [ set pcolor scale-color yellow  item 3 tmp 1.3 0 ]
        if tech = "PV"      [ set pcolor scale-color orange  item 4 tmp 1.3 0 ]
        if tech = "biomass" [ set pcolor scale-color green   item 5 tmp 1.3 0 ]
        if tech = "nuclear" [ set pcolor scale-color magenta item 6 tmp 1.3 0 ]

        if tech = "mix" and item 0 tmp = max tmp [ set pcolor gray]
        if tech = "mix" and item 1 tmp = max tmp [ set pcolor brown]
        if tech = "mix" and item 2 tmp = max tmp [ set pcolor blue]
        if tech = "mix" and item 3 tmp = max tmp [ set pcolor yellow]
        if tech = "mix" and item 4 tmp = max tmp [ set pcolor orange]
        if tech = "mix" and item 5 tmp = max tmp [ set pcolor green]
        if tech = "mix" and item 6 tmp = max tmp [ set pcolor magenta]

        if tech = "mix-scale" and item 0 tmp = max tmp [ set pcolor scale-color gray    item 0 tmp 1.3 0]
        if tech = "mix-scale" and item 1 tmp = max tmp [ set pcolor scale-color brown   item 1 tmp 1.3 0]
        if tech = "mix-scale" and item 2 tmp = max tmp [ set pcolor scale-color blue    item 2 tmp 1.3 0]
        if tech = "mix-scale" and item 3 tmp = max tmp [ set pcolor scale-color yellow  item 3 tmp 1.3 0]
        if tech = "mix-scale" and item 4 tmp = max tmp [ set pcolor scale-color orange  item 4 tmp 1.3 0]
        if tech = "mix-scale" and item 5 tmp = max tmp [ set pcolor scale-color green   item 5 tmp 1.3 0]
        if tech = "mix-scale" and item 6 tmp = max tmp [ set pcolor scale-color magenta item 6 tmp 1.3 0 ]
] ]

       ask spinners
       [ set heading ticks * 72
         set label ticks + 2015 ]
     end
```

Appendix I: List of publications and scientific activities

Shaaban, M., Scheffran, J., 2015. An empirical analysis of the impact of renewable energy deployment in MENA deserts on CO2 emission reduction. Presented at the EWACC 2015 building bridge conference, Nicosia, Cyprus.

Shaaban, M., 2015. Economic Impact Assessment of Desertec in terms of GDP. Presented at the European Association of Environmental and Resource Economists 21st Annual Conference, Helsinki, Finland.

Shaaban, M., Scheffran, J., 2017. A dynamic sustainability analysis of energy landscapes in Egypt: An agent-based model combined with multi-criteria decision analysis. Presented at the 1st Hamburg Workshop on Agent-based Modeling of Environmental Challenges and Climate Policy, Hamburg, Germany.

Shaaban, M., Scheffran, J., 2017. Selection of sustainable development indicators for the assessment of electricity production in Egypt. Sustain. Energy Technol. Assess. 22, 65–73. doi:10.1016/j.seta.2017.07.003.

Future projects:

A dynamic sustainability assessment of electricity supply technologies in Germany: A spatial agent-based model combined with multi-criteria decision analysis. Accepted funding by Center for a Sustainable University (KNU), Funding Channel #4 “Project Support”.