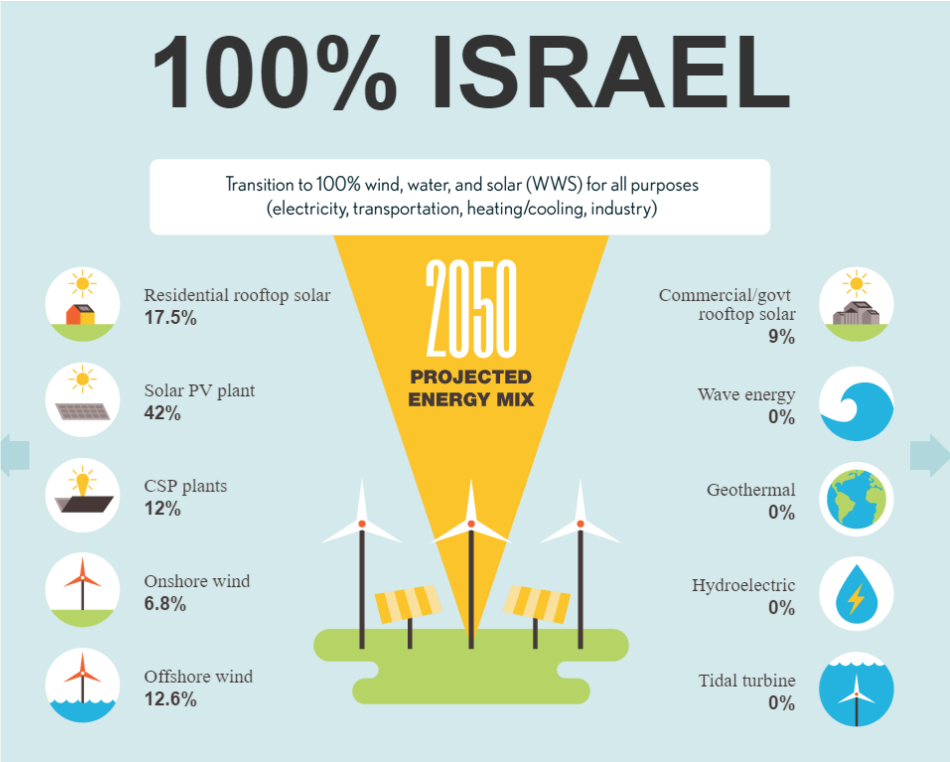
Master Thesis

Israel's practical transition plan to 100% all-sector clean renewable energy by 2050



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Hiermit erkläre ich, dass ich die vorliegende Arbeit selbstständig und eigenhändig sowie ohne unerlaubte fremde Hilfe und ausschließlich unter Verwendung der aufgeführten Quellen und Hilfsmittel angefertigt habe.

Tel Aviv, Israel, den March 12, 2017

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Abstract

Israel is a country rich with renewable energy resources such as solar and wind. Yet, Israel currently lags behind other OECD countries with a mere 2% of its energy produced by renewable energy resources. Future plans to increase the share of renewable energy are at the very best modest or non-concrete. At the same time, Israel has a high-risk profile with regards to climate change. Given its long coastline and vulnerability to rising sea levels and its dry climate, Israel is prone to heatwaves and droughts. Other than climate change effects, the continued use of fossil fuels as an energy resource has additional negative effects such as air pollution causing health issues and premature deaths.

This thesis proposes a clear, actionable, and validated plan to convert Israel's all-purpose energy infrastructure into 100% renewable energy of Wind-Water-Sunlight (WWS) technologies by 2050. The proposed plan is based on Prof. Jacobson's "world plan",'100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World.' While Jacobson et al. (2016) presents a cogent plan for Israel (as well as the other 138 countries) the World Plan does not account for Israel's specific topographic, environmental, and statutory limitations. Accounting for such limitations is critical in order to validate Israel has enough suitable area to develop the aforementioned WWS technologies. Thus, meeting the expected all-purpose end use power by 2050 by relying entirely on WWS is questionable, hereby placing another hurdle for Jacobson's et al. (2016) plan. Closing this gap is important as decision makers in general are more likely to adopt Jacobson's et al. (2016) plan the more detailed and targeted it is towards their country.

This thesis, based on Jacobson's et al. (2016) World Plan, presents for the first time a full comprehensive validated plan to convert Israel's all-purpose energy infrastructure to one derived entirely from WWS by 2050, which includes spatial analysis.

In the analysis, residential rooftop photovoltaics (PV), utility-scale PV, and Concentrating Solar Power (CSP) technologies practical potential were found to be sufficiently greater than the nameplate capacity needed according to Jacobson's et al. (2016) proposed energy mix. Onshore wind practical potential was validated to be very close to the nameplate capacity needed by the World Plan. Since the analysis accounts only for limited topographic, environmental, and statutory limitations and many other factors exist that influence the success of wind development in Israel (such as economic and social factors), Jacobson's et al. (2016) energy mix was not found to be "safely" validated. As such, a second 'alternative' proposal was introduced, offering an energy mix based on Jacobson's et al. (2016) plan but slightly modified so that all energy sources were safely validated to meet projected demand.

Abstrakt

Israel ist ein Land, dass viele erneuerbare Energiequellen besitzt, wie Solar- und Windenergie. Das Land bezieht jedoch nur 2% seiner Energie von erneuerbaren Energiequellen. Dies ist verglichen mit anderen OECD sehr wenig. Ist gibt für die Zukunft derzeit keine konkreten Pläne, die einen größeren Bezug von erneuerbaren Energie vorsehen. Zudem stellt der Klimawandel derzeit ein Risiko für Israel dar. Da das Land einen langen Küstenstreifen besitzt, ist es sehr schadenanfällig bei steigendem Meeresspiegel und besitzt zudem ein trockenes Klima mit Hitzewellen und Dürren. Neben den Effekten des Klimawandels, gehen mit der andauernden Benutzung fossiler Brennstoffe als Energiequelle viele negative Effekte einher, wie Luftverschmutzung, welche Gesundheitliche Probleme und frühzeitige Tode als Folge haben können

In dieser Arbeit wird ein verständlicher, verfolgbarer und stichhaltiger Plan aufgeführt, der Israel 100 % Umwandlung auf erneuerbare Energien bis zum Jahr 2050, basierend auf Prof Jacobsons „World Plan“, 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World` erörtert. Obwohl Jacobson et. Al (2016) einen überzeugenden Plan für Israel (sowie die anderen 138 Länder) vorlegt, geht der World Plan nicht auf Israels spezifische Topografie, Umwelt und gesetzliche Bestimmungen ein. Diese sind jedoch kritisch für die Beurteilung, ob Israel genug geeignete Flächen hat, um die genannten WWS Technologien zu entwickeln. Daher ist das alleinige Verlassen auf WWS fraglich, wenn es darum geht bis 2050 den Energiebezug komplett auf Erneuerbare Energien zu umzustellen. Die schafft eine weitere Hürde für Jacobson’s et al . (2016) Plan. Dies ist insofern wichtig, da wichtige Entscheidungsträger generell mit größerer Wahrscheinlichkeit Jacobson’s et al. (2016) annehmen, je detaillierter und länderspezifisch er ist.

Diese Arbeit bezieht sich auf Jacobson et al . (2016) World Plan und präsentiert zum ersten Mal einen kompletten, umfassenden validierten Plan der Israels komplette Energieinfrastruktur bis 2050 auf erneuerbare Energien beschreibt. Hierfür wird auch eine räumliche Analyse durchgeführt.

In der durchgeführten räumlichen Analyse wurde ermittelt, dass das praktische Potential von Photovoltaikanlagen in Wohngebieten (PV); Versorgungsunternehmen (PV), und konzentrierte Solarkraft (CSP) als hinreichend größer ermessen wurde, als die Nennkapazität durch Jacobson’s et al. (2016) vorgeschlagenen Energiemix. Das praktische Potential von Seewind ist der ermittelten Nennkapazität aufgeführt im Worldplan sehr ähnlich. Da die Analyse nur auf limitierte topografische, umwelt und gesetzliche Bestimmungen eingeht und viele andere Faktoren existieren, die den Erfolg der Windentwicklung in Israel beeinflussen (die ökonomische und soziale), wurde Jacobson’s et al. (2016) Energie Mix als unzureichend empfunden. Es wurde aus diesem Grund eine zweiter ‘alternativer’ Vorschlag aufgeführt, der einen Energie Mix erläutert, der auf Jacobson’s et al. (2016) Plan basiert, aber ein wenig modifiziert wurde, damit alle Energiequellen sicher validiert werden konnten, um der prognostizierten Nachfrage gerecht zu werden.

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List of abbreviations

BAU	Business as Usual
AC	Alternating Current
AWPR	Advanced pressurized-water reactor
BEV	Battery Electric Vehicles
CBS	Central Bureau of Statistics
CC	Carbon Capture
CO_2	Carbon dioxide
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiance
EEZ	Exclusive Economic Zone
EGS	Enhanced Geothermal Systems
EIA	Energy Information Agency
FTE	Full Time Equivalents
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiance (the sum of direct and diffuse Irradiance)
GIS	Geographic Information System
GW	Gigawatt
HCLB	High Cost Low Benefits
HVAC	Heating, Ventilation and Air Conditioning
HVDC	High Voltage Direct Current
IGCC	Integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
JEDI	Jobs and Economic Development Impact
JNF	Jewish National Fund (Keren Kayemeth LeIsrael)
km	Kilometer
km^2	Square Kilometer
kWh	Kilowatt hour
LCHB	Low Cost High Benefits
LCOE	Levelized Costs Of Energy
m/s	Meter per second
MNI	Ministry of National Infrastructures
MoEP	Ministry of Environmental Protection
MW	Megawatt
n.a	Not available
NIS	Israeli New Shekel
NOP	National Outline Plan
NOP 10/D/10	National Outline Plan for photovoltaic installations
NOP 22	National Outline Plan for Forests and Afforestation
NOP 35	Integrated National Outline Plan for Building, Development and Conservation
O_3	Ozone
$PM_{2.5}$	Particulate Matter
PSH	Pumped-storage hydroelectricity
PV	Photovoltaic

R&D	Research and Development
SMR	Small Modular Reactor
TWh	Terawatt-hours
VSL	Value of Statistical Life
WWS	Wind-Water-Sunlight

Terms

This section briefly describes some of the words and terms used in this project in order to make the thesis approachable to readers from a variety of technical backgrounds. The terms are presented in alphabetical order.

Capacity factor: The proportion of the electrical energy produced by a generating unit for a period of time to the maximum electrical energy that could have been produced by the (same) generating unit at perfect conditions during the same period of time (U.S. Energy Information Administration)

Diffuse Horizontal Irradiation (DHI): The solar energy received by a unit area of surface from all directions when radiation is scattered off the atmosphere or surrounding area. (International Finance Corporation (IFC) 2012)

Direct Normal Irradiation (DNI): The solar energy received by a unit area of surface directly facing the sun. (International Finance Corporation 2012)

Electrification: Transformation of services such as heating, cooling, lighting, and transportation to be powered directly by electricity instead of other fuels. For example, shifting to use battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (HFCVs) instead of fueled vehicles (Jacobson et al. 2016)

End-use load: The power in delivered electricity or fuel that is actually used to provide services to a firm or individual. It disregards losses during electricity generation or fuel production and transmission but includes industry self-energy-use such as mining, transporting, and refining fossil fuels (Jacobson et al. 2016)

Footprint area: The physical area on the top surface of the ground or water needed for each generating unit (Jacobson et al. 2016)

Global Horizontal Irradiation (GHI): The total solar energy, direct beam and diffuse irradiation, which a unit area of surface receives (International Finance Corporation 2012)

Installed nameplate capacity: The maximum rated output of a generating unit (device or plant) under specific conditions designated by the manufacturer (U.S. Energy Information Administration)

Rated power (of a device or plant): The rated or maximum capacity at which rate an electric power production equipment will produce power (U.S. Energy Information Administration)

Spacing area: The area between generating units (Jacobson et al. 2016)

1. Introduction

The earth's ecosystem has been changing as a result of human activity since the beginning of the industrial revolution. Most scientists attribute the cause of climate change to the combustion of fossil fuels, which releases greenhouse gases into the earth's atmosphere (Moomaw et al. 2011).

Without any active change in the current energy resource consumption, fossil fuel consumption is expected to increase, leading to rising levels of greenhouse gas (GHG) and other pollutants that cause climate change like carbon dioxide (the leading climate change pollutant), black carbon, methane, tropospheric ozone precursors, carbon monoxide, and nitrous oxide. Jacobson et al. (2016) developed a roadmap to convert the energy recourses of 139 countries of the world to 100% WWS recourses by 2050 with a mid-goal of 80% by 2030. Implementation of the roadmap will avoid increases in CO_2 levels and in other climate change pollutants with the aim to delay, and ultimately prevent, reaching the climate change tipping point. Figure 1 demonstrates the impact of implementation of the roadmap on global carbon dioxide levels, as well as the impact of less intensive conversion of 80% WWS by 2050 and 100% by 2100. In both cases CO_2 levels will be reduced below today's level. Furthermore, Figure 1 presents Intergovernmental Panel on Climate Change (IPCC) estimations of CO_2 levels in five case of Business as Usual (BAU) illustrating that without any active change, CO_2 levels are expected to be much higher than in WWS scenarios (Jacobson et al. 2016).

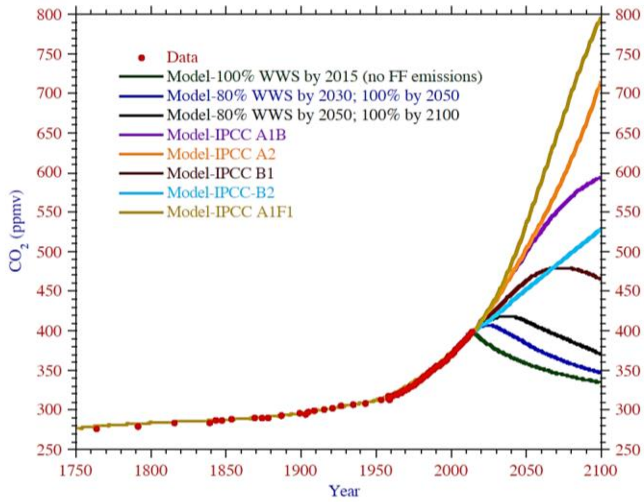

Figure 1. Observed CO_2 mixing ratios (ppmv) between 1751-2014 and model projections from 2015-2100 for five Intergovernmental Panel on Climate Change (IPCC) scenarios and three WWS cases: an unattainable 100% WWS by 2015 case; a 80% WWS by 2030 and 100% by 2050 case and a less-aggressive 80% by 2050 and 100% by 2100 case. Source: Jacobson et al. 2016

1.1 Predicted climate change effects on Israel

Israel is a small, developed country, with 8.3 million citizens, which contributes about 0.2% of global emissions (Israel 2015; Central Bureau of Statistics 2015b). Although Israel's contribution to the world's emission is relatively small, climate change places Israel at a high risk due to the country's long coastline which makes it vulnerable to rising sea levels and its already dry climate increasing vulnerability to heat waves and droughts (Lelieveld et al. 2012).

Israel is located in western Asia in the eastern part of the Mediterranean Sea. The Eastern Mediterranean is expected to warm up faster than the global mean rate of 2.8°C by the end of the century. A regional climate assessment predicts that in case of intermediate IPCC SRES scenario A1B, the mean temperatures at the Eastern Mediterranean are expected to rise by 3-5°C by 2050 and 3.5-7°C by the end of the century (see Figure 2). Such rises could lead to consequences for human health and energy usage. Warmer temperatures are predicted to result in an increase in energy consumption for cooling purposes. Furthermore, a decrease of 10-50% of rainfall during this century is predicted which leads to about 5-10 extra dry days per year by 2050 and 10–20 extra dry days per year by the end-of-century (See Figure 3). Water scarcity is predicted to increase energy demand due to the need to desalinate sea water (Lelieveld et al. 2012).

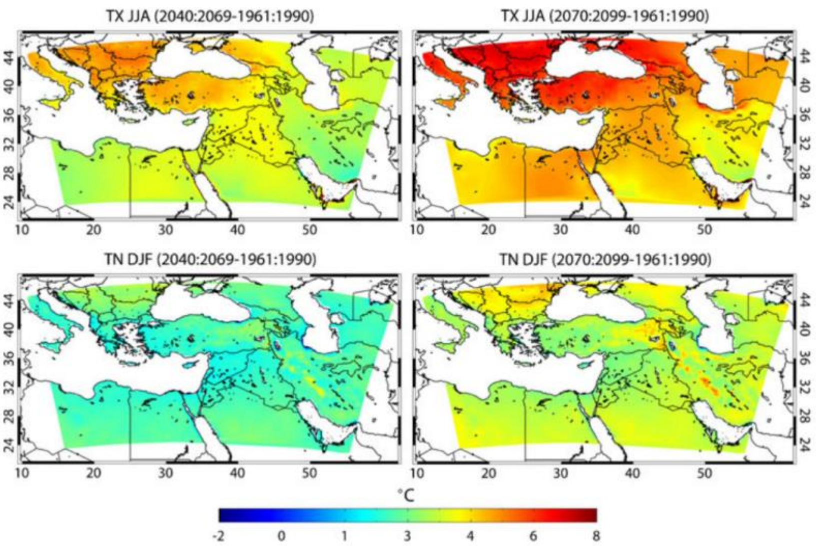

Figure 2. "Patterns of changing mean summer maximum (JJA) and mean winter minimum (DJF) temperatures, TX (top) and TN (bottom), respectively... The left panels shoe the mean changes for 2040-2069 and the right panels for 2070-2099 relative to the 1961-1990 control period " Lelieveld et al. 2012

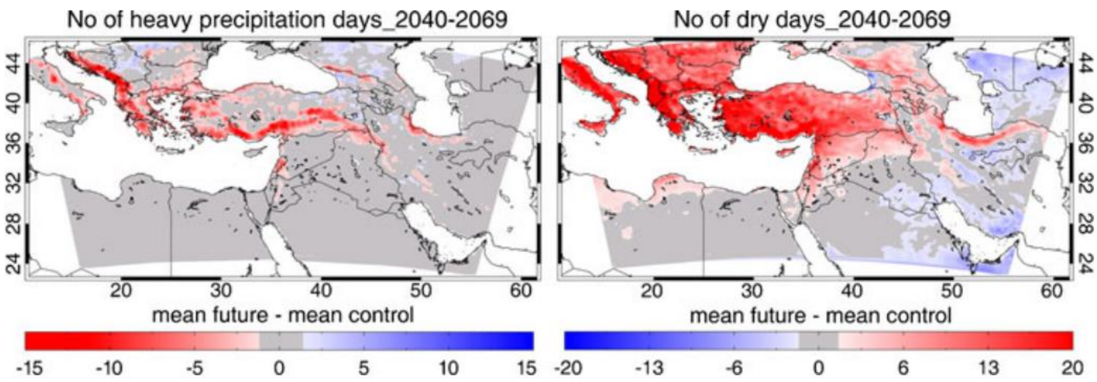

Figure 3. "Patterns of changing number of days per year with heavy precipitation (RR>10mm, left panel) and number of dry days (RR<1 m, right panel)… showing the mean changes for 2040-2069 relative to the control period 1961-1990" Lelieveld et al. 2012. RR = Rain Rate

The Mediterranean Sea level on Israel's shore is predicted to increase by about 1-1.4 meters by 2100 due to climate change. Rising sea levels will lead to several problems, including pushing the coastal strip east causing cliff collapses that will endanger a stripe of about 50 m east of the current cliff line. The cliff collapse and rising sea level will cause Israel's land area to decrease by 1.1-2.25 km^2 (1,125-2,250 dunam) in the next 50 years, which will harm existing assets, infrastructures, and coastal antiquities sites. The costs due to cliff collapse for the next 50 years are estimated to be about 65-208 million dollars (250-800 million NIS), depending on the growth rate of the risked stripe, which is estimated to be of 0.5-1 meters per year. Furthermore, rising sea levels will cause higher waves and stronger storms (Bein et al. 2010).

Climate change is also expected to influence the Levant basin's unique marine ecosystem. The eastern Mediterranean land-locked basin structure causes a rapid increase of the sea surface temperature. In the past two decades, higher temperatures were detected at the sea surface and this trend is expected to continue to in the future, including in deep waters (Lelieveld et al. 2012).

1.2 Other negative effects to Israel from current BAU energy policy

Continued use of fossil fuels as an energy resource has several negative effects on Israel other than climate change effects. First, combustion of fossil fuels such as oil, coal or natural gas releases air pollutants, such as sulfur dioxide and nitrogen oxides, into the atmosphere causing health issues_ (Meindertsma et al. 2012). Furthermore, fossil fuel emissions of particulate matter ($PM_{2.5}$) and ozone (O_3) were found to have a relative risk in causing premature deaths due to cardiovascular disease, respiratory disease, and complications from asthma (Jacobson et al. 2016)

Second, Israel’s energy security is actually a matter of national security. Israel is politically an island state and cannot rely on its neighbor countries for energy. A disruption to Israel’s energy supply can impact its ability to provide water for domestic, agricultural, and industrial uses due to Israel’s dependency on desalination plants for clean water that operate on electricity from the grid. Currently, Israel's power plants are located on several limited locations along the Mediterranean coast for technical reasons such as supply of cooling water and due to better access for ships transporting fossil fuels. Israel Electric Corporation (IEC), a governmental company that generates most of Israel’s electricity, has 63-generation units and 17 power stations (See Figure 4 ; Israel Electric Corporation Strategic Aspects Overview 2012). The geographical concentration of energy resources increases Israel’s vulnerability to threats, such as potential terrorist attacks or weather hazards. Deployment of energy resources with renewable energy technologies over many locations will strengthen Israel’s energy immunity from such threats (Willner 2014).

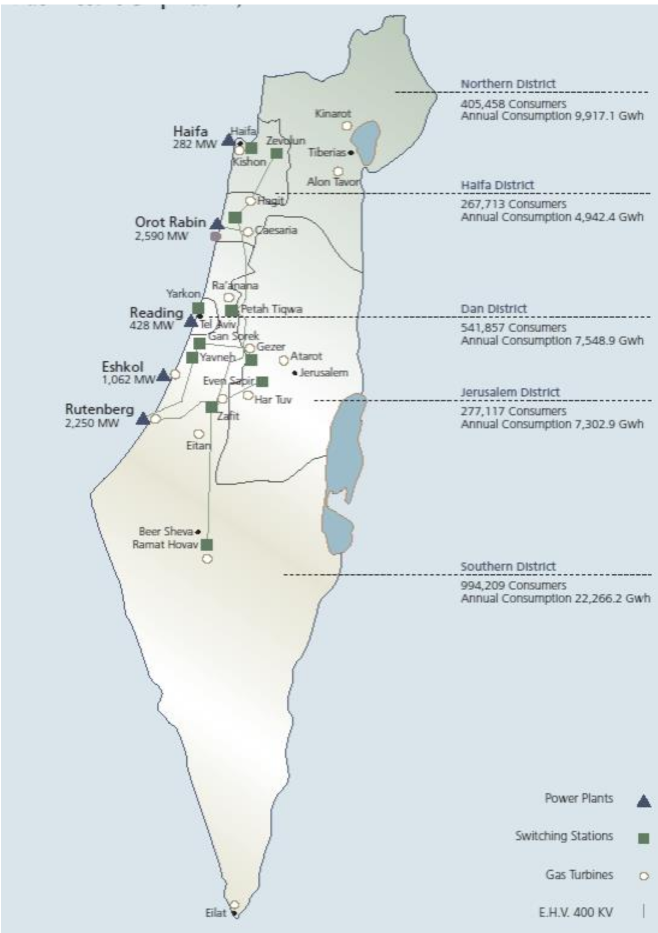

Figure 4. Electricity generation system of Israel Electric Corporation (True for 2010) Source: Israel Electric Corporation Strategic Aspects Overview 2012

Lastly, since fossil fuel availability is limited and the power demand is projected to rise by 49% in the next 25 years, fossil fuel costs are expected to increase. Thus, Israel is expected to pay higher prices for its energy resources if no active changes are made to Israel's energy grid (Uyan 2013).

To review Israel's energy demand growth to date, over the past 6 decades since Israel's establishment in 1948, Israel's installed capacity and energy demand grew greatly from 69 MW of installed capacity to 13,750 MW in 2012 (Israel Electric Corporation Strategic Aspects Overview 2012). While both (installed capacity and energy demand) grew throughout the years, Israel's ability to supply peak demand has declined. The gap between the two is illustrated in Figure 5. Figure 6 demonstrates that Israel's electricity consumption grew linearly with the country's Gross Domestic Product (G.D.P).

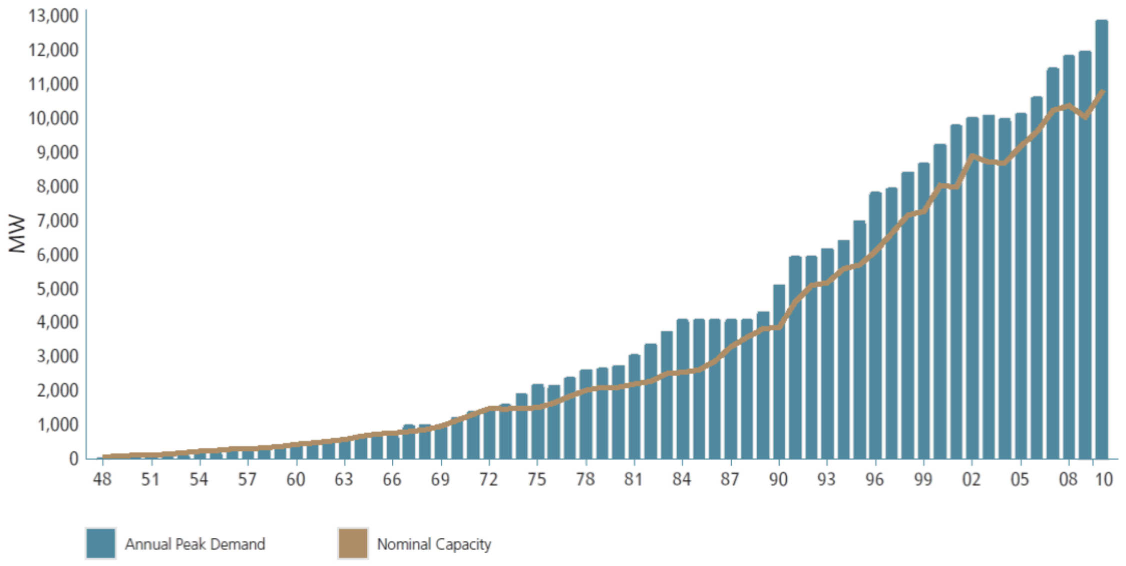

Figure 5. Israel's Annual peak demand vs. nominal installed capacity through the years 1948-2011. Source: The Israel Electric Corporation 2010

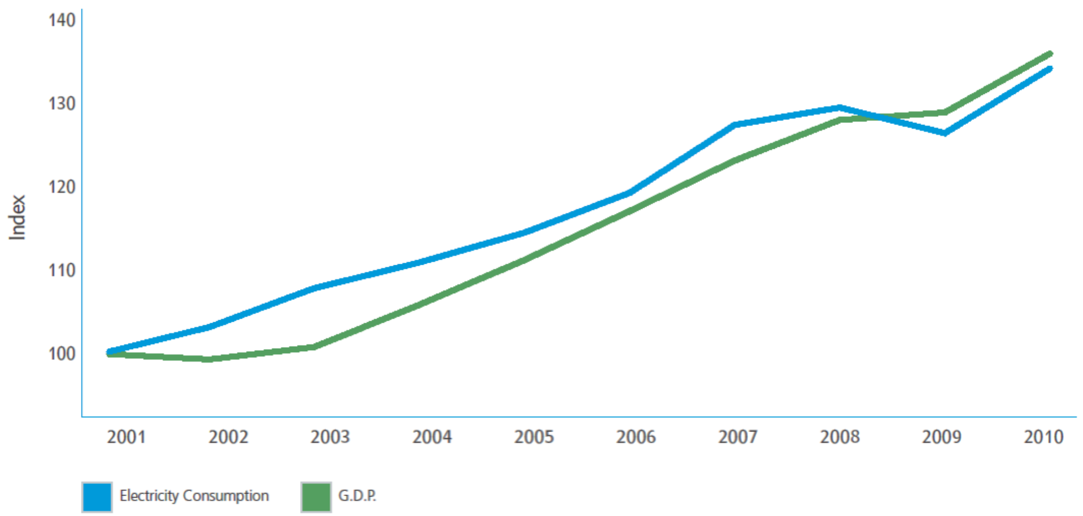

Figure 6. "Growth in GDP. vs. growth in total electricity consumption. 2001=100". Source: The Israel Electric Corporation 2010

1.3 Renewable energy as a solution

As a clean energy resource that is becoming more cost-effective, renewable energy has been increasingly utilized to fulfill the growing global energy demand and is expected to take on an increasingly significant role in meeting rising energy demands as the global community works together to reduce greenhouse gas emissions in order to stop climate change (Renewable Energy Policy Network for 21st Century (REN21) 2016). Wind, solar photovoltaics (PV), and concentrating solar power (CSP) with storage are clean, commercially proven, scalable technologies that in combination can ensure reliable renewable energy supply during the day and night (Wright, Hearps 2011).

Wind turbines generate electricity from the energy of the wind. It converts mechanical energy of the rotating blades to electrical energy. Over the years wind turbines have increased their sizes and capacities and today they are the cheapest renewable energy technology to deploy (Wright, Hearps 2011). Wind turbines can be developed on land or offshore. Increased world-wide offshore wind energy development is expected over the next decades in the hopes of becoming an important source of energy in the near future (Bilgili et al. 2011).

Solar photovoltaics (PVs) is clean renewable energy that coverts solar radiation (Global Horizontal Irradiation) to electricity. The modules are made up of PV cells which are typically made from silicon. The modules must be mounted on a structure that can be either fixed or tracking. Even though tracking systems are more expensive they are usually cost-effective in locations with a high direct irradiation. PV modules costs have dropped significantly over the last decade, which has made solar a cost competitive resource and the world's fastest growing energy source. Solar PVs are constructed in arrays in variety of sizes based on the application used, ranging from residential rooftops, to commercial rooftop, to utility scale plants (Wright, Hearps 2011)

CSP plants generate electricity by exploiting solar power. First, DNI (component of solar irradiance that travels directly from the sun) is focused by mirrors and then it is either converted to heat energy in concentrating solar thermal systems or directly to electricity in concentrating photovoltaic (CPV) systems. If converted to heat, a turbine and generator are then used to produce electricity in concentrating solar thermal systems. Molten salts are usually used as a heat transfer fluid and heat storage medium that can be used in times with no sun or at high pick demand. CSP technologies use sun-tracking technology since they have to face the sun at all times. CSP is still relatively expensive when compared to other renewable resources and its scalability depends on extensive cost reductions, combined with government-driven economic support (Wright, Hearps 2011).

Hydropower is another clean commercially proven technology but its development is limited due to environmental considerations (Wright, Hearps 2011). Hydropower classifies into three categories: run-of-river, reservoir or storage, and pumped storage plants. Hydroelectric plants generate electricity through the use of gravitational force of falling or flowing water. The most common types are the reservoir or storage dams that produce power from water falling from dams. Run-of-river plants produce electricity from water flowing down a river (Willner 2014).

Most pumped-storage hydroelectricity (PSH) methods combine pump station with hydroelectric plants. This combination exploits the potential energy between different elevation levels. PSH is storage in the form of reservoir pair, where the water is pumped to a higher elevation reservoir at times of low cost and low peak demand and used to generate electricity at times of high peak demand. It is not a "source" of electric power since it uses slightly more energy than it produces but it allows the peak power demand to be met reliably and cost-effectively (Jacobson et al. 2014). PSH is essentially another form of energy storage. PSH helps manage the grid at times when other energy sources such as solar and wind are less effective like when there is no sun or wind or in times of other problems with the grid. Another benefit of PSH is helping to control the grid frequency since the response time of turning on the system and generating electricity is relatively short. PSH response time stands at 70 seconds while gas turbine response time is half an hour.

Currently, ocean energy technologies are under development and range from Research and Development (R&D) to prototype and demonstration stages. Only tidal range technology is considered mature (Moomaw et al. 2011). Wave, tidal and enhanced geothermal power are technologies with large potentials but need to overcome technical obstacles to be used in the future on a large scale (Wright, Hearps 2011).

Geothermal energy is generated by extracting heat from natural hot resources such as volcanoes, geysers, hot springs, thermal conduction from Earth's internal heat, and ground heat produced by solar radiation. This heat can then be used to generate electricity or for direct heating. Geothermal systems are expected to be extensively developed in the near future because of their affordable power prices and reliable production of base-load power (International Energy Agency (IEA) 2011). Geothermal energy could be generated in most areas with Enhanced Geothermal Systems (EGS) technology. EGS allows generation of geothermal energy at high depths at areas with dry rock by fracturing impermeable rock with cold high-pressure water. The water flows through the fracks of the hot rock capturing its heat and returns to surface through production to spin turbines and creates electricity (U.S. Department of Energy 2012). EGS is still a relatively new technology. The first private commercial EGS plant for large-scale electricity production started in Australia in 2013 and only few commercial developments have been done at depths between 2-5 km (Olasolo et al. 2016).

While Israel can use resource available on land (land size of 21,640 km^2), it can also use resources available in its offshore area. Israel's enjoys Exclusive Economic Zone (EEZ) of about 26,000 km^2 with a coastline of about 273 km (Jacobson & Delucchi 2016), Technion 2014). Within the EEZ, Israel does not have full sovereignty but enjoys exclusive economic rights such as the right to use waves, currents, and wind for renewable energy production.

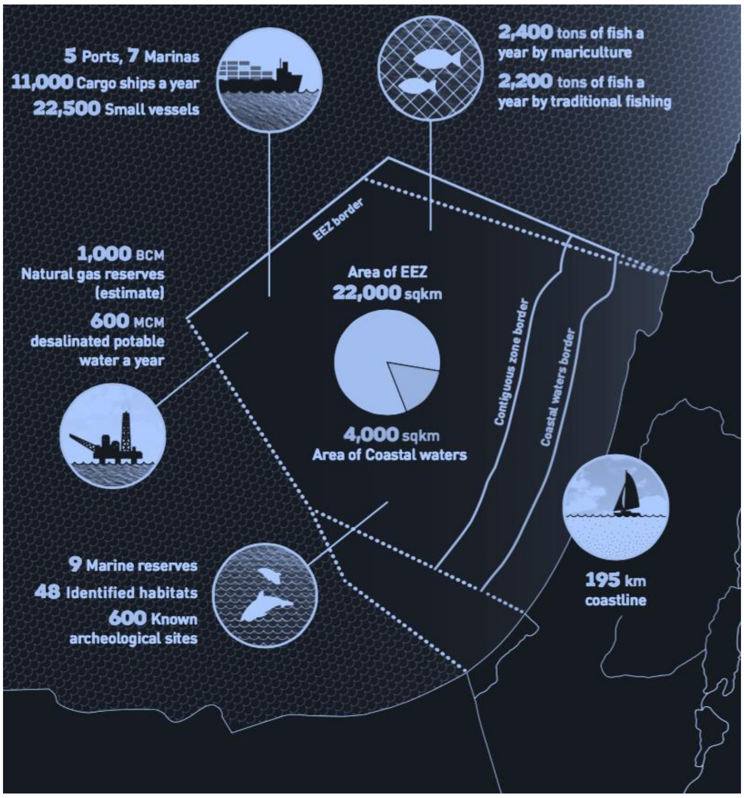

Figure 7. Israel's EEZ provide a variety of social, economic, and environmental services. Source: Technion 2014

With the aid of new technological developments, converting Israel's energy sources from fossil fuels to clean renewable energy can mitigate climate change and other negative effects, such as environmental consequences and health related issues (Meindertsma et al. 2012). While further research and development keeps improving cost-effectiveness of renewable energy technologies, some are already cost-competitive when compared with conventional energy generation, especially when taking into account climate change effects and other health externalities (Jacobson et al. 2016; Proaktor et al. 2015).

The question remains – If a technical and economic solution already exists today that can mitigate and possibly even prevent the dire threats of rising sea levels, extreme storms, and heat waves that scientists warn us about as the consequences of climate change, why is the global community so slow to convert to renewable energy?

A large gulf exists between the scientific world and decision makers. Climate change could be halted if decisions makers were informed, or willing to listen, to reliable, scientific and unbiased information that consists of specific solutions to climate change that outline feasible long-term actions with clear economic and social benefits.

2. Motivation

The motivation behind the topic of this thesis relies on the following three observations: Firstly, Israel currently is doing very poorly from a renewable energy perspective. Secondly, it has all the necessary environmental factors to have the potential have a robust renewable energy sector. Lastly, Israel can greatly benefit from making the transition to relying on renewable energy.

Let’s elaborate on these three points:

2.1 Israel’s current energy consumption by sources

Although Israel takes an active role in the international effort of stopping climate change, it still lags behind considering that its electricity is almost entirely generated from fossil fuels. In 2010, based on Israel’s Central Bureau of Statistics, Israel’s main fuels for electricity generation were 61% coal, 36.6% natural gas, 1.5% fuel oil, and 0.9% gas oil (Central Bureau of Statistics 2015a). In 2015, only 2% of Israel’s total energy was generated by renewable energy, a very small percentage compared to its technical potential with solar and wind resource availability (Gutman 08/20/16, Willner 2014). The change in energy production by different sources is illustrated in Figure 8.

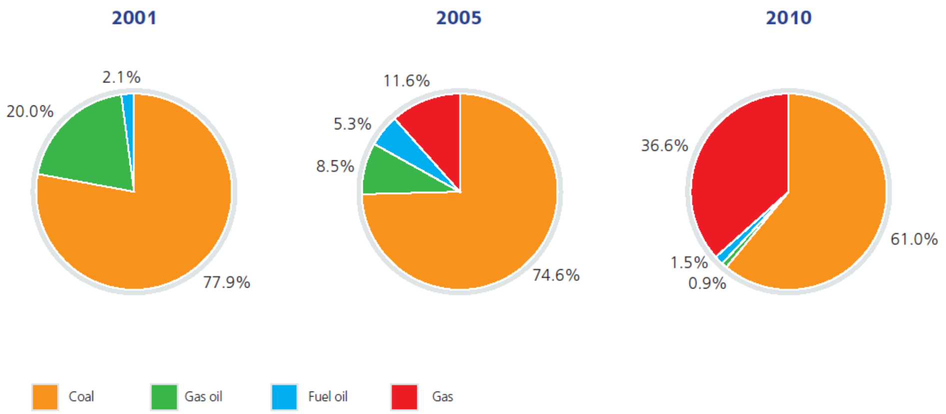

Figure 8. Israel's annual electricity production by fuel type for the years 2001, 2005, 2010. Source: The Israel Electric Corporation 2010.

Problem Statment

Currently there are several renewable energy plants under development. A Concentrated Solar Plant (CSP) facility of 121 MW that combines parabolic trough and tower technologies is under construction in Ashalim. Ashalim is expected to connect to the grid in 2017 and an additional 110 MW is expected to be added in 2018 (Renewable Energy Policy Network for 21st Century (REN21) 2016). Yet still, these additions are a “drop in a bucket” (less than 0.5%) when compared to Israel’s total energy production of ~21,200 MW.

One cannot discuss Israel’s energy supply mix without mentioning the recent discovery of natural gas at the coast of Israel, which has had a significant impact on the future of Israel’s energy production. Over 30 trillion cubic feet of natural gas, an amount that is expected to be sufficient to fulfill Israel’s energy demand for the next decades, has been discovered in recent years within Israel’s EEZ. Israel plans to export some of this resource and use it to generate about 65% of its energy (Technion 2014). The natural gas discovery allows Israel to stop relying on imported fossil fuels from foreign countries and become an energy independent country. This kind of energy independency could also be achieved using renewable energy. The latter will also benefit Israel through better air quality that will lead to reductions in mortality and environmental benefits, such as protecting its marine ecosystem while extracting the gas and, of course, reducing GHG emissions. From an energy security perspective, Israel would be safer since renewable energy will be based at many individual sites, as opposed to a single high-vulnerability site.

In 2014, only 1% of Israel’s nameplate capacity required for a 100% WWS system by 2050 was installed. Compared to other world countries Israel ranked 97th in 2014 for its ability to reach 100% WWS power for all-purposes energy demand by 2050 (see figure 2) (Jacobson et al. 2016).

Problem Statment

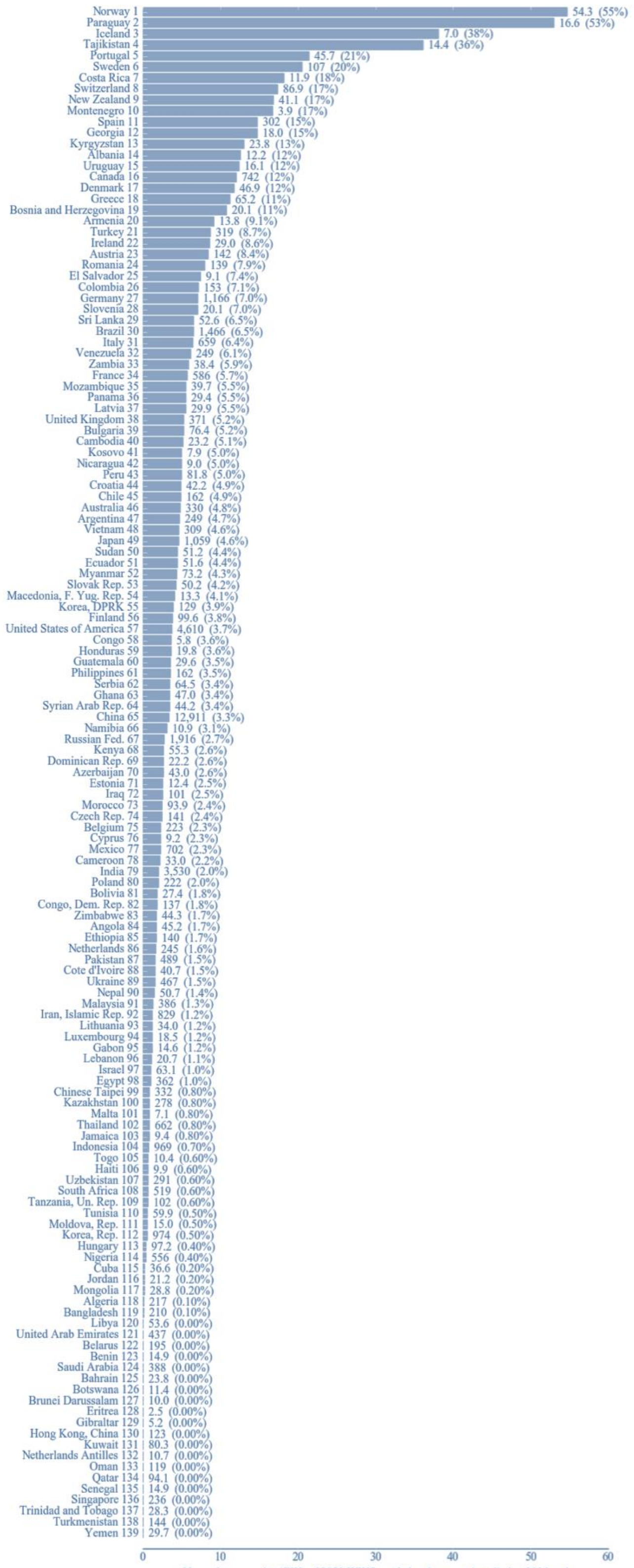

Figure 9. Comparison between 139 countries in 2014 for their ability to reach 2050 WWS all-purposes energy demand. Source: Jacobson et al. 2016

2.1 Israel's renewable resource availability

Relative to other parts of the world, Israel has high annual Global Horizontal Irradiation (GHI) of about 6 kWh/m^2/day as can be seen in Figure 10. Israel's richness of solar resource, the maturity of solar technologies over the last decade, as well as the massive reductions in price of solar panels that have made them cost comparative to fossil fuels makes solar energy a great resource for Israel to rely on (Wright, Hearps 2011; Jacobson et al. 2016). Utility-scale PV can operate in any country because it can use global solar irradiance (direct plus diffuse) (Jacobson et al. 2016). CSP is feasible only in countries with strong DNI of at least an annual average of 5 KWh/m^2/day. Some areas in Israel do have significant DNI where CSP can be developed (see Figure 11) (Schmalensee et al. 2015).

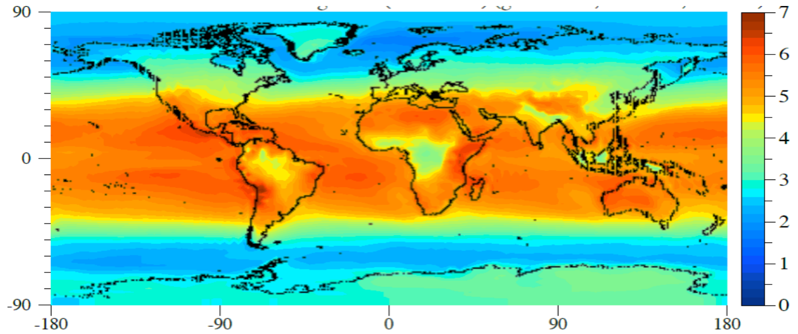

Figure 10. Worldwide annually averaged global solar irradiance (direct plus diffuse) at the ground (kWh/m^2/day) generated by GATOR-GCMOM model, which simulates clouds, aerosols gases, weather, radiation fields, and variations in surface albedo over time. Horizontal resolution of 2.5o W-E x 2.0o S-N. Source: Jacobson et al. 2016

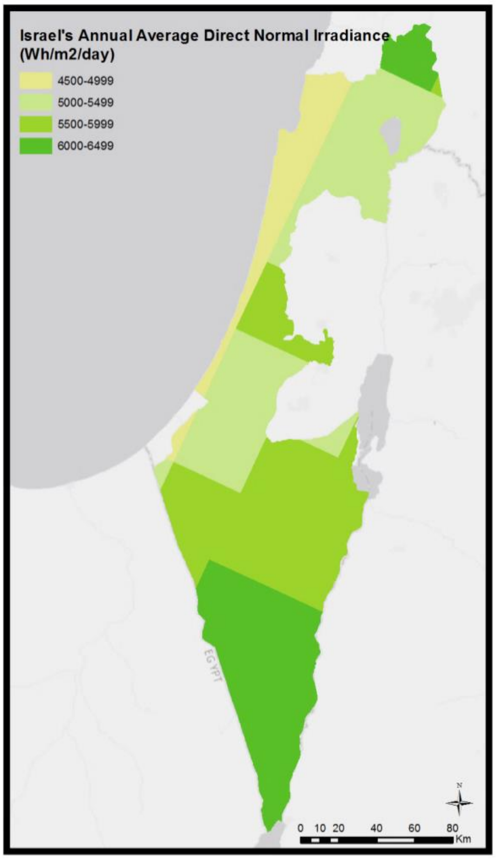

Figure 11. Israel's annual average direct normal (DNI), at 40 km resolution. The data was developed by NREL's Climatological Solar Radiation (CSR) Model. Data source for creating this map: OpenEI

Interestingly, while Israel is behind on its renewable energy production, with less than 2% of its energy produced by renewable (solar and wind) energy, Israel is actually ranked third in the world in solar water heating collector capacity per capita, after Austria and Cyprus. This further illustrates Israel's renewable energy resources availability and potential.

Wind is another resource available for Israel to generate clean energy. Figure 12 and figure 13 indicates that the annual wind speed at 100 meter above ground level (AGL) in Israel's area is about 6 m/s and the annual [1]capacity factor at that height, assuming 5 MW turbines with 126-meter rotor diameter, is about 0.3. When compared to other countries, Israel's annual wind speeds and capacities are average. Although Israel does not enjoy the highest annual wind speeds and capacities when compared to other locations, the region might have in some locations high enough wind speeds to generate electricity using wind turbines.

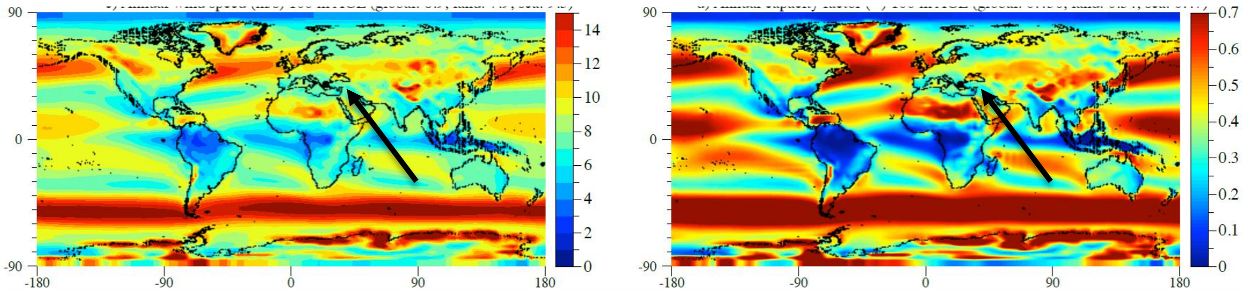

Figure 12. On the left, the world's annual wind speed (m/s) and on the right, annual capacity factor (--)generated by GATOR-GCMOM 4-year-average modeled at 100 meter above ground level (AGL) at 2.5o W-E x 2.0o S-N resolution (Israel's location is on the eastern part of the Mediterranean Sea. It is marked by the error). Source: Jacobson et al. 2016

A detailed evaluation of areas with sufficient solar irradiance and wind speed for development of solar and wind technologies will be made as part of this project.

2.2 Value of converting to renewable energy

Converting Israel's energy resource to renewable energy has the potential to mitigate many of the negative effects caused by fossil fuel emissions of particulate matter ($PM_{2.5}$) and ozone (O_3) such as environmental consequences, premature deaths, and health related issues (e.g cardiovascular disease, respiratory disease, and complications from asthma) (Jacobson et al. 2016; Meindertsma et al. 2012).

Prof. Jacobson "world plan",'100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World' (Jacobson et al. 2016)), present a transition plan to 139 countries of the world to rely entirely on WWS. Israel energy resource mix in 2050 is suggested to rely almost mainly (99.97%) on wind and solar technologies. This section presents Israel's benefits from implementing transitioning to WWS taken from Prof. Jacobson "world plan" such as, reduction in future energy costs (due to transforming to WWS system), avoided global-warming costs, mortality and morbidity due to air-pollution, and estimations of cost reductions associated with conversion to 100% renewable energy of wind-water-solar (WWS) technologies. Additionally, this part presents Jacobson et al. (2016) estimations for job creation potentials versus loss.

[1] Defined in Terms

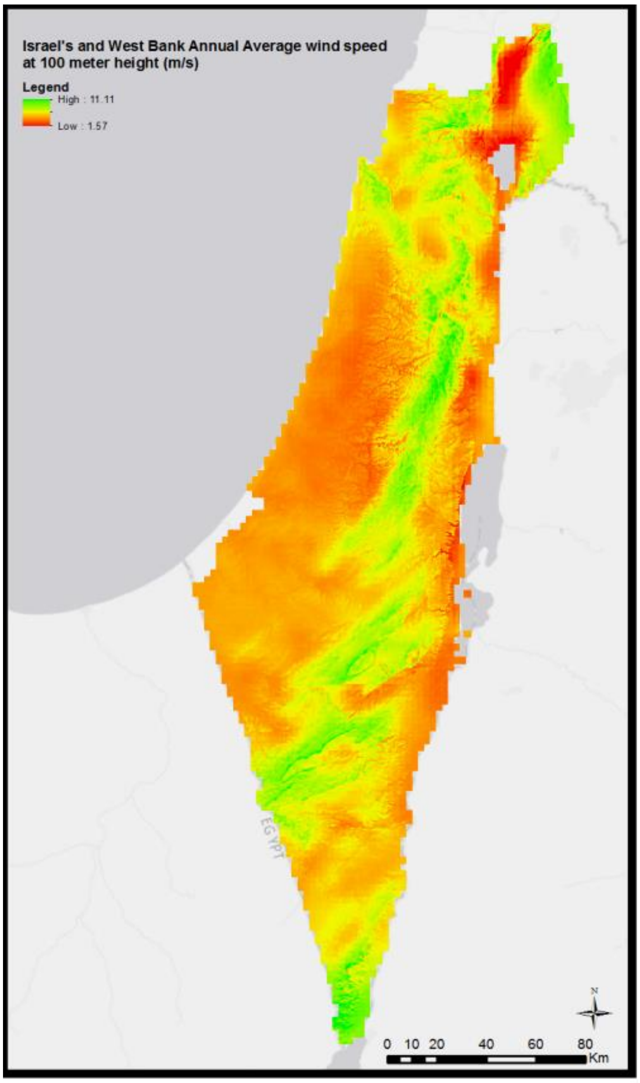

Figure 13. Map of annual mean wind speed (m/s) at 100 meter height above the topographical surface in Israel and the West Bank. The data was provided by Israel Meteorology Center as raster file of 100 meter resolution created by using regional model (COSMO) and micro model (WAsP). Data source: Israel Meteorology Center

2.2.1 Prevention of premature deaths

Converting Israel's all-purpose energy infrastructure to WWS by 2050 will prevent on average 2674 premature deaths per year due to the reduction of air pollution. Israel's premature deaths were calculated by Jacobson et al. (2016) by using modeled concentrations of $PM_{2.5}$ and O_3 that were combined with the relative risk of mortality as a function of concentration and with population in a health effects equation. Mortalities due to emissions in 2050 were then extrapolated while accounting for expected future efficiencies under the BAU scenario (Jacobson et al. 2016).

2.2.2 Jobs

Converting Israel to 100% WWS system will create 62,408 new jobs from 2015 to 2050. Those include both short term construction jobs and long-term operation and maintenance jobs. Jobs lost due to lack of further development of fossil-fuel infrastructures are also taken into account. Moreover, additional job creation due to conversion to WWS system for research and development of WWS technologies and storage can also be accounted for but is not included in Jacobson's calculations (Jacobson et al. 2016).

For each WWS technology an estimate of job creation and change in earnings in 2050 was calculated by Jacobson et al. (2016) for both construction and operation jobs in scenario of transition of Israel to 100% WWS system. The average estimate for construction and operation (Jobs/MW) for each year for each technology were calculated by averaging yearly high and low estimates for construction and operation. These estimates used Jobs and Economic Development Impact (JEDI) models for each technology assuming steady construction from 2015-2050 (1/35th of the WWS infrastructure is built each year). JEDI are economic input-output models with several assumptions and uncertainties. JEDI models integrate three levels of impacts: project development and onsite labor impacts, local revenue and supply chain impacts, and induced impacts. JEDI models report job creation as full-time equivalents (FTE) which equal to 2,080 hours of work per year per FTE. Jacobson et al. (2016) makes the following assumptions for the calculation of jobs associated with new transmission lines: 80% of new lines will be 500 kV high-voltage direct current (HVDC) lines and 20% 230 kV alternating current (AC) lines; total line length simply equals five times the circular radius of Israel (Jacobson et al. 2016). The total construction and operation jobs were calculated by summing up the construction and operation job creation needed for new WWS generator capacity for each technology plus new jobs for transmission and storage.

Table 1. New jobs created and earnings from construction and operations due to conversion to WWS system from 2015 to 2050, jobs lost in the conventional fuels and nuclear energy industries and net jobs and earning change due to conversion to WWS system from 2015 to 2050.

New WWS construction jobs	New WWS operations jobs	Constraction jobs lost in conventional fuels and nuclear energy industries due to conversion to WWS	Operations jobs lost in due to conversion to WWS	Net jobs: new WWS jobs created minus jobs lost	Average earnings from new WWS construction jobs (B $2013/yr)	Average earnings from new WWS operation jobs (B $2013/yr)	Average earnings from net jobs (B $2013/yr)
38,891.89	45,184.25	4,279.22	17,388.57	62,408.34	3.25	3.78	5.22

Note: The jobs are FTE equivalent. One FTE is equivalent to 2,080 hours a year. Data derived from Jacobson and Delucchi (2016) Spreadsheets of calculations for 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World.

Estimates for construction and operation jobs and earnings are based on the number of new generators required for each type of annual average power and peaking or storage. Earnings take into account wages, services, and supply-chain impacts. Jobs lost account for current jobs plus future jobs lost from a decreased developing fossil-fuel infrastructure in the oil, gas, coal, nuclear, and bioenergy industries because WWS plants will replace them.

2.2.3 Energy security

Currently, Israel's power plants are geographically concentrated on several limited locations along the Mediterranean coast for technical reasons, which makes Israel vulnerable to threats, such as potential terrorist attacks or weather hazards. The Deployment of energy resources with renewable energy technologies over many locations will contribute to Israel’s energy immunity from such threats. Furthermore, renewable energy contributing to energy resource diversification is an acute factor in increasing energy security which leads to stronger economic security and national security (Willner 2014). Israel is politically an island state and cannot rely on its neighbor countries for energy. Considering Israel’s delicate political situation, energy security should also be taken into consideration when evaluating the benefits from converting to renewable energy.

2.2.4 Cost reduction

Another benefit from converting to renewable energy is independency from rising and fluctuating world fossil fuels costs. Israel could avoid paying higher prices for fossil fuels as its power demand is projected to rise by 49% in the next 25 years since their availability is limited (Uyan 2013). LCOE for conventional fuels are expected to increase by 2050 due to higher labor and transport costs and constant processing of the fuels. While the costs of all WWS technologies by 2050 are expected to drop due to technology improvements, cheaper manufacturing costs, and improved efficiency of project deployment caused by scaling .Jacobson et al. (2016) estimates the cost of converting to all-purpose energy infrastructure with WWS by 2050 and in case of further usage of fossil fuel (BAU). Current and future full social costs of WWS electricity generators and conventional energy generators were estimated. Table 2 presents weighted average estimates of fully annualized levelized business costs of electricity generation (LCOE) for fossil fuels such as coal and gas, for nuclear and biomass and for each of the WWS technologies in 2013 and 2050. WWS LCOE in 2050 were calculated by averaging low cost, high benefits (LCHB) case and high cost, low benefits case (HCLB). The costs include generation, short and long distance transmission, distribution and storage, but they do not include externality costs.

Table 2 shows that in 2013 the LCOE for generating electricity by hydropower, onshore wind, utility-scale solar PV, and solar thermal for heat are lower than traditional fuels.

Table 2. Estimated fully annualized, unsubsidized 2013 and 2050 U.S.-averaged costs of electricity to end-users ($2013/MWh). The costs include generation, short- and long-distance transmission, distribution, and storage, but do not include external costs.

	Base year 2013			Target year 2050		
Technology	Average	LCHB	HCLB	Average	LCHB	HCLB
Advanced pulverized coal	92.75	81.48	104.01	89.30	77.37	101.23
Advanced pulverized coal w/CC	134.89	112.28	157.50	117.69	97.93	137.46
IGCC coal	106.84	92.98	120.69	95.97	83.34	108.60
IGCC coal w/CC	176.59	138.32	214.87	114.85	95.51	134.19
Diesel generator (for steam turbine)	215.39	185.45	245.32	309.70	247.25	372.14
Gas combustion turbine	284.44	182.68	386.20	280.49	186.94	374.05
Combined cycle conventional	87.53	81.20	93.87	118.43	103.85	133.00
Combined cycle advanced	n.a	n.a	n.a	106.23	95.21	117.24
Combined cycle advanced w/CC	n.a	n.a	n.a	125.70	111.19	140.21
Fuel cell (using natural gas)	154.89	120.72	189.05	165.93	132.61	199.26
Microturbine (using natural gas)	133.80	122.55	145.04	171.23	151.73	190.73
Nuclear, APWR	102.97	80.91	125.03	90.83	73.20	108.46
Nuclear, SMR	108.00	92.94	123.06	91.34	79.59	103.09
Distributed generation (using natural gas)	n.a	n.a	n.a	315.14	246.88	383.41
Municipal solid waste	229.49	202.27	256.70	196.05	179.05	213.05
Biomass direct	149.22	130.94	167.50	115.61	104.80	126.43
Geothermal	106.87	86.34	127.40	93.89	79.16	108.61
Hydropower	72.38	61.14	83.62	63.27	54.19	72.34
On-shore wind	87.44	74.06	100.82	77.25	66.14	88.35
Off-shore wind	153.45	108.89	198.02	140.22	100.81	179.63
CSP no storage	157.94	124.32	191.56	115.63	90.10	141.16
CSP with storage	97.02	80.77	113.27	77.92	64.23	91.62
PV utility crystalline tracking	82.92	71.10	94.73	74.91	64.53	85.30
PV utility crystalline fixed	89.70	75.34	104.05	69.10	59.86	78.35
PV utility thin-film tracking	81.63	70.51	92.74	73.77	64.00	83.53
PV utility thin-film fixed	89.27	74.48	104.05	68.82	59.29	78.35
PV commercial rooftop	118.88	95.41	142.36	102.77	83.47	122.07
PV residential rooftop	161.91	130.38	193.43	138.59	113.11	164.06
Wave power	204.26	131.05	277.47	197.48	125.18	269.77
Tidal power	159.06	102.57	215.56	153.04	97.28	208.81
Solar thermal (water or glycol solution)	61.85	56.68	67.03	57.48	52.34	62.62

Explanation for the calculation can be found in Jacobson et al. (2016). For the year 2050 BAU scenario, costs of WWS are slightly different. CC = carbon capture; IGCC = integrated gasification combined cycle; AWPR = advanced pressurized-water reactor; SMR = small modular reactor; PV = photovoltaics. n.a = not available. Data derived from Jacobson and Delucchi (2016) Spreadsheets of calculations for 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World. The source of the footnotes of the table is Jacobson et al. 2016.

Table 3 displays Jacobson et al. (2016) estimates for LCOE per unit energy (converted to kWh) produced in all sectors for conventional fuels in (BAU) scenario in 2013 and 2050 and for WWS energy sources in 2050. Also shown are end-use power delivered in BAU and WWS scenarios together with average electricity cost savings due to conversion to WWS in 2050. As presented in Table 3, in 2050 Israel's weighted LCOEs among all generators in WWS scenario is estimated to be 9.91 ¢/kWh and 10.5 ¢/kWh for BAU. Since the estimate for LCOE for 2050 BAU scenario does not account for transportation, heating and cooling, or industry energy costs, it is not directly comparable with the LCOE in 2050 WWS that takes these factors into account. Due to switching from BAU electricity to WWS electricity average electricity cost saving in 2050 is expected to be 2.46 billion dollar (2013 USD) per year and 227 dollar per person a year (2013 USD).

Table 3. Levelized costs of energy (LCOE) for conventional fuels in business as usual (BAU) scenario in 2013 and 2050 and for WWS energy sources in 2050. Also shown are average electricity cost savings due to conversion to WWS system in 2050

(a)	(b)	(c)	(d)	(e)
2013	**2050**			
Average LCOE of BAU (¢/kWh)	Average LCOE of BAU (¢/kWh)	Average LCOE of WWS (¢/kWh)	Average Electricity Cost Savings with WWS (B $2013/yr)	Average energy cost savings with WWS ($2013/person/yr)
9.90	10.50	9.91	2.46	227.08

Data derived from Jacobson and Delucchi (2016) Spreadsheets of calculations for 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World. The source of the footnotes of the table is Jacobson et al. 2016

a. The 2013 LCOE for conventional fuels combines the distribution of conventional and WWS generators in 2013 with 2013 averaged LCOEs for WWS technologies. Costs include generation, short- and long-distance transmission, distribution, and storage, but they exclude externalities for conventional fuels and WWS power (2013 USD/MWh-delivered electricity)
b. Same as (a), but for a 2050 BAU scenario. LCOE for 2050 BAU includes existing WWS together with future increases in WWS and energy efficiency
c. The 2050 LCOE of WWS scenario includes the 2050 distribution of WWS technologies of all energy sectors with 2050 averaged LCOEs for each WWS technology (The LCOE accounts for transmission and distribution)
d. The 2050 averaged electricity cost savings per year due to switching to WWS system. It is calculated as the product of BAU electricity use and the 2050 BAU LCOE less the annualized cost of the expected efficiency improvements in the WWS case less the total cost of BAU electricity converted to WWS (product of WWS electricity use replacing BAU electricity and the 2050 WWS LCOE)
e. The 2050 averaged electricity cost savings per capita a year due to switching to WWS system, calculated by dividing (d) by Israel's 2050 population

When accounting for externality costs such as air pollution health costs and climate change damage cost (e.g. loss of coastline, fishery and agricultural, heat stress mortality and morbidity, food scarcity, drought, wildfires, and severe weather), the total cost of electricity generation for each of the WWS technologies is even further less than conventional fuels in 2050.

Israel's total air pollution damage cost in 2050 in BAU scenario is estimated to be on average 27 billion dollars (2013 USD) per year and account for mortality costs, morbidity costs, and non-health costs such as loss caused by a decrease in agricultural output. The mortality cost was calculated by multiplying the number of mortalities by the value of statistical life (VSL). The morbidity and non-health costs were calculated by multiplying the mortality cost by the ratio of the value of total air-pollution damages (mortality plus morbidity plus other damages) (Jacobson et al. 2016).

Climate change damage costs for Israel in 2050 caused by greenhouse gas (GHG) emissions created by burning fossil fuels in BAU scenario is 36 billion dollars (2013 USD) per year and 3300 dollars (2013 USD) per person a year (Table 4). GHG emissions are defined by Jacobson et al. (2016) as carbon dioxide (CO_2), air pollution particles that cause global warming and other GHGs. Climate change costs was calculated by the sum of coastal flood and real estate damage costs, agricultural loss costs, energy-sector costs, water costs, health costs due to heat stress and heat stroke, influenza and malaria costs, famine costs, ocean acidification costs, increased drought and wildfire costs, severe weather costs, and increased air pollution health costs (Jacobson et al. 2016).

Total cost savings due to damage prevention of air pollution and climate change together with energy saving due to better efficiency is on average 65 billion dollars (2013 USD) per year and 6029 dollars (2013 USD) per person a year. Thus, converting to a WWS system will produce electricity, health and climate change cost-savings in 2050 with a total average of 6029 dollars per person a year. Thus the upfront investment due to conversion to a WWS system is expected to be returned on average after 2 years when accounting for the sum of the aforementioned cost-savings (Jacobson et al. 2016; Jacobson & Delucchi 2016).

Table 4. Israel's air pollution ($PM_{2.5}$ plus O_3) premature mortalities per year in 2050, avoided air pollution costs and climate change costs due to conversion to WWS in 2050. Also, Israel's total cost benefit due to conversion to a WWS system and the payback period are presented.

	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
	Premature Mortality caused by Air Pollution in 2050 (Deaths/yr)	Avoided air-pollution damage costs in 2050 (B 2013-$/yr)	Avoided air-pollution damage costs in 2050 ($2013/person /yr)	Avoided Climate Change damage costs in 2050 (B 2013-$/yr)	Avoided Climate Change damage costs in 2050 ($2013/person /yr)	Energy+Air-pollution+CC benefits of converting to WWS in 2050 (B 2013-$/yr)	Energy+Air-pollution+CC benefits of converting to WWS in 2050 ($2013/person/yr)	Energy + Air-pollution + CC Payback period (Years)
Average	2,674	27	2,502	36	3,300	65	6,029	2.1
HCLB	653	4	377	20	1,860	27	2,465	5.0
LCHB	5,897	88	8,148	76	7,023	167	15,398	0.8

Data derived from Jacobson and Delucchi (2016) Spreadsheets of calculations for 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World. The source of the footnotes of the table is Jacobson et al. 2016

a. Israel's 2050 premature mortalities due to air pollution of particulate matter ($PM_{2.5}$) and Ozone (O_3) per year in BAU scenario. Israel's premature deaths were calculated by using modeled concentrations of $PM_{2.5}$and O_3 in 2015 that were combined with low, medium, and high relative risks of mortality and with Israel's population. The results for 2015 were than extrapolated for 2050. The threshold concentration of zero was used for $PM_{2.5}$while concentrations below 8 μg/m3 were down-weighted and for ozone a concentration threshold of 35 ppbv was assumed.
b. Israel's 2050 total avoided costs per year from mortalities, morbidities and non-health costs such as lost visibility and agricultural output that were prevented due to conversion to WWS system. Calculated by multiplying Israel's value of statistical life (VSL) (can be found in Jacobson & Delucchi 2016) by the low, medium, and high values of premature mortalities due to $PM_{2.5}$ and ozone). Values are projected to 2050 based on GDP per capita projections for the U.S. then scaled for Israel as a nonlinear function of GDP per capita relative to the U.S. The result is then used to calculate morbidity and non-health cost caused by air pollution.
c. Israel's total climate cost saving per year due reduction in emissions in 2050 with WWS scenario.
d. The sum of averaged electricity cost saving from Table 3, and columns (b) and (d).
e. The cost savings due to converting to WWS when accounting air pollution (health) and climate change is equal the upfront installation cost of WWS generators on average after 2 years.

Thus, converting Israel to rely only on WWS resources will be more economical than continuing to burn fossil fuels in BAU scenario. This is due 1) cost savings from prevention of mortality, morbidity and non-health costs caused by air pollution, 2) cost saving due to climate change damages 3) energy cost savings due to better efficiency from switching from BAU electricity to WWS electricity (Jacobson et al. 2016; Jacobson & Delucchi 2016).

Furthermore, converting Israel's all-purpose energy infrastructure to WWS by 2050 will not only contribute to the prevention of climate change but also benefit Israel directly by preventing health issues caused by air pollution, creating new jobs from 2015 to 2050, and contributing to energy resource diversification and energy independency, which are acute factors in strengthening Israel's energy security leading to stronger economic and national security. Also, Israel's energy independency will help ensure that expected rising and fluctuating fossil fuels fluctuation prices will not affect Israel.

3. Problem statement

While the negative effects on Israel due to consumption of fossil fuels such as climate change effects, health issues and energy security are discussed in the scientific literature, Israel is relying and expected to keep relying on fossil fuels for its energy resource as a long-term plan. As discussed, Israel's current energy plan versus it's potential is the genesis of this paper - creating an actionable alternative energy plan for Israel that is based on renewable energy sources. Although previous work with assessments on Israel resource availability for different renewable resources exists, it is still unclear whether Israel has enough available land to construct renewable energy technologies that will allow conversion to 100% renewable energy in an economic manner, and if so what constitutes the right transition plan for Israel.

3.1 Purpose statement

This work aims to eventually decrease Israel's GHG emissions and other pollutants that contribute to climate change and other negative effects to zero by presenting a clear roadmap for Israel, which could be easily adopted by Israel's decision makers. The thesis suggests a roadmap to convert Israel's all-purpose energy infrastructure to one derived entirely from WWS by 2050 while focusing on the siting aspect of WWS development.

3.1.1 Main research question

What practical transition plan can convert Israel to 100% all-sector renewable energy by 2050?

3.1.2 Sub-research question

When accounting for technical, environmental, and regulatory limitations, does Israel have sufficient area for development of wind and solar installations that will allow Israel to fulfill its all-purpose energy demands by 2050?

4. State of art

The state of art review will cover: (a) previous renewable energy plans for Israel and (b) Jacobson's work globally, and will further show (c) there is a gap. Namely, that previous Israel-specific plans are far from detailed or comprehensive enough, and Jacobson's work, while promising, isn't validated, and further isn't specific and actionable yet in terms of specific siting of different WWS technologies for Israel.

4.1 Israel's previous renewable energy plans

In prior decades several governmental decisions targeted a specific percentage of electricity generation from renewable energy sources. Many of the targets, however, were not met. In this following section previous documents discussing Israel's GHG reduction targets or renewable energy development are presented such as governmental decisions and national plans that hoped to achieve a specific percentage of energy generation from renewables or reducing GHG emission by a specific year.

In 2002, Israel's government passed Resolution 4450, setting a target of 2% of electricity generation from renewable energy resources by 2007, and 5% by 2016. In 2009, Israel set a new target of reaching 5% of electricity generation from renewable energy resources by 2014, and 10% by 2020 which is already on its track to fail (Ronen 2013).

In 2010, the Ministry of National Infrastructures published a policy document on the integration of renewable energy sources into the Israeli electricity sector for the years 2010-2020 with the aim of implementing Government Resolution No. 4450 (SE/176) concerning the generation of 10% of Israel's electricity from renewable energy sources by 2020 (Ministry of National Infrastructures 2010). While both the ministry's plan as well as the one brought forth by this thesis offer predictions for electricity demand, offer estimated costs of generating electricity using renewable energy technologies, and provide a forecast of installed capacity from renewable energy sources, the ministry plan aims for low renewable energy target (10% versus end goal of 100%) and is short termed. The ministry's plan forecasts through only 2020 while this plan looks through 2050. The ministry suggested limited sites for development of renewable energy technologies and preliminary mapping of land in the Negev (a desert area in the south of Israel) has been conducted. While both, the ministry plan and this roadmap, identifying potential siting for deployment of renewable energy, this thesis presents a through spatial analysis for all of Israel while the ministry was only specific sites. In 2012, Rebecca A. Yasner from Carnegie Mellon University, criticized the Ministry of National Infrastructures (2010) in her thesis, concluding that the short term goal that was set by the Ministry of National Infrastructures plan was too low and that the plan falls short of setting Israel on track for large-scale, integrated deployment of renewable electricity technologies (Yasner 2012).

In 2015, on behalf of the Israel Ministry of Environmental Protection, an assessment of Greenhouse Gas Emission Reduction Potential was conducted in order to recommend to the Israeli government a national GHG emissions reduction target for 2030 (Proaktor et al. 2015). The report included projection of GHG emissions and electricity consumption under a business-as-usual (BAU) scenario through 2030,. It identified the key technological abatement measures most relevant to Israel and their economic impacts. It studied two scenarios- one with a conservative target which could be achieved only through the implementation of cost-effective abatement measures without a price of carbon, and a second one with a more ambitious target scenario, which includes the maximum reasonable level of implementation of all the abatement measures that were found to be feasible, including a number of measures that are not cost effective without accounting for the price of carbon. This report focuses on different measures of GHG reduction and the evaluation of the maximum reasonable level of deployment for the renewable energy technologies a "a reflection of the team's best assessment " which is based on review of published literature and data but fails to include spatial analysis as seen in this thesis (Proaktor et al. 2015).

4.2 Jacobson's work, which provides framework but does not "validate"

Recently a roadmap to convert 139 countries of the world (including Israel) to entirely Wind Water and Sunlight (WWS) technologies was published by Jacobson et al. (2016). The goal of the roadmap is to minimize air pollutants, greenhouse gases, and particle emissions. The roadmap presents a scenario that energy in all sectors including electricity, transportation, heating/cooling, industry, agriculture, forestry, and fishing will be completely converted to WWS technologies by 2050, with a mid-goal of 80% by 2030. The roadmap presents an energy mix for each of the 139 countries that will allow them to rely entirely on WWS technologies and accounts for their energy demand and resource availability. Jacobson et al. (2016) roadmap does not attempt to present the least-cost future energy mix or satisfy grid reliability constraints but does estimate the number of additional generators needed to ensure reliable electric power grid.

Jacobson (2009) found that in terms of addressing pollution, public health, global warming, and energy security, the following WWS technologies - wind, concentrated solar power (CSP), solar PV, geothermal, tidal, wave, and hydroelectric power, were found to be the most suitable to generate electricity when compared to all overall energy options. Due to increased air pollution, emissions contributing to climate change and other issues, Jacobson’s roadmap excludes the use of nuclear power, coal with carbon capture, liquid or solid biofuels, or natural gas (Jacobson et al. 2014; Jacobson et al. 2016).

Jacobson et al. (2016) suggest a WWS scenario where all end-uses will be electrified and will use WWS power directly (with exception to some transportation that suggested to be run on hydrogen produced from WWS electricity). For short distance ground transportation, Jacobson (2009) found the best option to be battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (HFCVs), where the hydrogen is produced by electrolysis from WWS electricity. The best option for long distance ground transportation was found to be BEVs with fast charging or battery swapping. For heavy-duty ground transportation BEV-HFCV hybrids will be used. Although electrolytic hydrogen for transportation is less efficient and more costly than electricity for BEVs, hydrogen-energy storage might be preferred over battery energy storage in cases of ships, aircraft, and long-distance freight, for example. Furthermore, in the WWS scenario the heating or cooling would be powered primarily by electric heat pumps and high-temperature industrial applications would be powered by electric arc furnaces, induction furnaces, dielectric heaters and resistance heaters (Jacobson et al. 2014; Jacobson et al. 2016).

Electrification of end-uses in the WWS scenario will allow lower end-use power demand due to “(a) the high energy-to-work conversion efficiency of electricity used for heating and electric motors and (b) because WWS eliminates the energy needed to mine, transport, and refine coal, oil, gas, biofuels, bioenergy, and uranium. Also, (c) the use of WWS electricity to produce hydrogen for fuel cell vehicles, while less efficient than the use of WWS electricity to run BEVs, is more efficient and cleaner than burning liquid fuels for vehicles…. On the other hand, burning electrolytic hydrogen is slightly less efficient but cleaner than burning fossil fuels for direct heating” (Jacobson et al. (2016)).

Jacobson et al. (2016) projects Israel’s and the other 138 countries of the world expected end-use energy demand in 2050 in Business As Usual (BAU) and in a scenario of converting its all-purpose energy infrastructures to one powered by Wind, Water, and Sunlight (WWS). End-use power is the power in electricity or fuel that people actually use (e.g. heating and transportation) and it does not account for power losses during production and transmission. The projections consider increasing energy demands, shifts from coal to gas, and improvements in end-use energy efficiency. The end-use energy demand also account for international transportation and shipping. The estimates for 2050 are based on extrapolation of data from the IEA starting in 2012. The BAU projections were extrapolated using the EIA’s 2050/2012 ratio for energy consumption by sector and fuel (Jacobson & Delucchi 2016). EIA’s projections in the International Energy Outlook (Energy Information Agency 2015) are until 2040 while Jacobson et al. extended their projections to 2075 using a ten-year moving linear extrapolation. The WWS projections in 2050 were estimated from 2050 BAU values.

Based on the estimated 2050 end-use power demand and technical potential capacity, the total nameplate capacity, and total nameplate capacity per each of the WWS technologies, as well as the number of needed units for each of the WWS technologies needed in 2050 in order to meet the demand was calculated (considering that all sectors have been electrified). by Jacobson et al. (2016). For onshore and offshore wind the nameplate capacity needed was calculated by accounting for each country’s power demand and technical potential available for onshore and offshore wind. For hydropower, the nameplate capacity is assumed to be the same as in 2015 and for geothermal, tidal, and wave power the nameplate capacity is limited by each country’s technical potentials. For rooftops, utility scale PV and CSP the total nameplate capacity needed to be installed in 2050 is calculated by dividing the end-use power delivered in 2050 by the product of 2050 capacity factors and overall transmission and distribution efficiency in 2050.. Power losses during energy transmission and distribution, generator maintenance, and competition among wind turbines for limited kinetic energy were accounted for.

Grid reliability and energy exchanges among countries were not considered. While grid reliability was not part of the calculations, the number of additional generators needed to ensure reliable electric power grid was estimated using the results of a grid reliability study for the U.S (Jacobson et al. 2015c). Jacobson et al. (2015) concluded that maintaining grid reliability in a 100% WWS system in the U.S. can be solved by integrating multiple low-cost solutions. CSP with molten storage will provide Israel power demand in peaking times by storing electricity or heat. Furthermore, solar thermal and geothermal are used for direct heat or heat storage in soil. Also presented are the needed capacities for additional peaking power and storage. The calculations account for power losses due to storage (Jacobson et al. 2016).

Jacobson et al. (2016) assumes that Israel will generate all of its' annually averaged power independently. This is an ideal scenario considering Israel's political conflicts with neighboring countries. However, import and export of electricity with other countries might be profitable for Israel considering energy generation costs that might be cheaper due to better resource availability in neighboring countries.

For wind turbine calculations characteristics Senvion's RePower 5M wind turbine at the 100-m hub is used. For solar PV calculations Sun Power E20 panels characteristic were used, where the estimated panel rated power output is 200.53 W/m^2, the sample solar panel rated power = 327 W and the area of panel itself = 1.63 m^2. Utility-scale PV power plants are assumed to be sized relatively small (50 MW) to allow for placement in most available sites. For CSP, characteristics mimic the device used at Ivanpah Solar Power Facility in California Mojave Desert with assumed storage of maximum charge to discharge rate of 2.62:1. Their technical potentials limit their use in geothermal, tidal, and wave energy technologies (Jacobson et al. 2016; Jacobson & Delucchi 2016).

Footprint area is defined by Jacobson et al. (2016) as: "the physical area on the top surface of the ground or water needed for each energy device.", while 'spacing area' is defined as: "the area between some devices, such as wind, tidal, and wave turbines, needed to minimize interference of the wake of one turbine with downwind turbines." While Rooftop PV and offshore technologies do not take up new land, onshore wind, hydropower, geothermal, solar PV plants, and CSP plants require new land footprints. Jacobson et al. (2016) chose not to account for additional footprints or spacing areas for added transmission lines since: "Transmission systems have virtually no footprint on the ground because transmission towers are four metal supports connected to small foundations, allowing grass to grow under the towers. Further, the rights-of-way under transmission lines can typically accommodate many uses; more than can the rights-of-way under gas and oil pipelines and other conventional infrastructure that new transmission lines will replace" (Jacobson et al. 2016).

The technical potential capacity for onshore wind was calculated by multiplying areal power density of onshore wind systems by the total onshore land area with a wind resource that can provide what was defined as the minimum acceptable capacity factor, where the capacity factor and the areal power density are a function of the hub height of the turbines. The technical potential for offshore wind was estimated as the product of the areal power density for offshore wind systems and Israel's coastal length. Wave technical potential capacity was estimated as a function of the wave power available per unit of coastline, the fraction of the coastline that can be exploited for wave power, the efficiency of the wave-energy converter (WEC), and the capacity factor without consideration of the availability of the WEC. Tidal technical potential is estimated based on a nonlinear function of the length of Israel coastline. Utility-scale PV plants technical potential is based on land area with at least the minimum acceptable solar insolation, which is a function of the total PV-system areal power density (areal power density of utility scale PV is estimated as a function of the module density (which increases over time) and a spacing factor (which is estimated based on a function of population density)). CSP technical potential is estimated by the land area with minimum exposure of 5 kWh/m^2/day.

Residential rooftop technical potential (also accounting for rooftop area of residential parking) is calculated by multiplying the product of the PV areal power density by rooftop area that is technically suitable for PVs. Rooftop area technically suitable is taken into account: average building height, average rooftop area, the percentage of rooftop area that is flat, and the average slope of pitched roofs. The potential also considers rooftop area of residential parking.

Calculation method for residential rooftop area suitable for PV is taken from Jacobson et al. (2016):

> The total residential rooftop area suitable for PV in each country in 2050 is calculated by extrapolating the fraction of 2050 population living in urban versus rural areas linearly but with upper limits from 2005-2014 urban fraction data (World Bank, 2015c). Projected 2050 population in each country is then divided between rural and urban population. Population in each case is then multiplied by floor area per capita by country (assumed the same for rural and urban homes) from Entranze Data Tool (2015) for European countries, IEA (2005) for a few additional countries, and IEA (2014a) for remaining regions of the world. The result is finally multiplied by the utilization factor (UF), which is the ratio of the usable rooftop area to ground floor area. For rural areas in each country, UF=0.2. Eiffert (2003) estimates UF=0.4 for rooftops and 0.15 for facades, but for single-family rural residential homes, shading is assumed here to reduce the UF to 0.2. For urban areas, UF=0.4 is assumed, but the urban area population is divided by the number of floors in each urban complex to account for the fact that urban buildings house more people per unit ground floor area. The number of floors is estimated by country in Europe from Entranze Data Tool (2015) as the number of dwellings per multi-family building divided by an estimated four dwellings on the bottom floor of a building. This gives the average number of floors in an urban area ranging from 2 to 5 for these countries. We assume 3 floors per urban dwelling in most other countries. Potential solar PV installed capacity is then calculated as the installed capacity of a Sunpower E20 435 W panel multiplied by the suitable rooftop area and divided by panel area. The total commercial rooftop area suitable for PV for European countries in 2050 is calculated as the product of the estimated 2050 country population, the average commercial ground floor area per capita (Entranze Data Tool, 2015), and a UF=0.4 (Eiffert, 2003). Scaling the European value to the GDP/capita of countries to that of European countries gives the average commercial ground floor area per capita in other countries. Potential solar PV installed capacity is then the installed capacity of a Sunpower E20 435 W panel multiplied by suitable rooftop area and divided by panel area. The potential rooftop or canopy area over parking spaces in each country is computed by multiplying the number of passenger cars per person (World Bank, 2014) by the average parking space per car (30 m^2, Dulac, 2013) in the country. Given that 1) some of these parking spaces will be in residential garages that have already been included in the residential rooftop PV calculation, and 2) some parking spaces will not necessarily have a roof (e.g. basement parking spaces), a utilization factor of 0.5 is applied to the estimate for parking area suitable for PV. With these assumptions, the PV capacity on parking-space rooftops is ~15% of the maximum capacity on residential rooftops and ~9% of the maximum capacity on residential-plus-commercial rooftops.

Jacobson's roadmap is unique since it is suggesting a long-term sustainable energy infrastructure that has the supplies 100% of Israel's energy in all sectors (electricity, transportation, heating/cooling, and industry) from Wind, Water, and Sunlight (WWS) power without fossil fuels, biofuels, or nuclear power. Thus this plan provides the largest possible reductions in air pollution and global-warming impacts. In this work, I have adopted Jacobson et al. (2016) proposal for a target WWS supply mix to address Israel's future energy demand projections in a 100% renewable energy manner.

4.3 The gap this project fills

As Israel is on one hand rich with renewable energy potential, and on the other currently have no single Israel-specific concrete actionable plan to transition into 100% renewable energy or close to it any time into the futures, relying on Jacobson's world plan for 139, and specifically the high-level plan for Israel is a very good starting point. Thus, this work starts with Israel's results from the World Plan aiming to build and present a long-term transition plan for Israel based on Jacobson's proposal. While the Jacobson's roadmap presents a cogent plan, the question remains about whether or not Israel has enough suitable area to develop the aforementioned WWS technologies in order to allow the country to generate the expected all-purpose end use power by 2050. Closing this gap is critical to implementing Jacobson's plan since if there is not enough suitable area available the plan's chance to succeed falls short. Beyond that, decisions makers would likely be very slow to adopt Jacobson's plan before it is validated for Israel, proved Israel has sufficient renewable energy potential, and suggested specific sites selection and specific implementation plan. Evaluation of areas suitable for renewable energy development has not been conducted yet for Israel and is conducted here for the first time.

The physical characteristics of the locations of renewable installations directly affect efficiency and cost-effectiveness of the installations (International Finance Corporation (IFC) 2012). To ensure a successful development, the environmental qualities in the planned area of the renewable installation should be carefully examined. For example, a successful wind farm should be in an area with sufficient wind speed for spinning the turbine and it will be more economical to generate wind power as the wind speed is greater (up to a certain limit, which above it may jeopardize the wind turbine). For the example of solar farms, a good location will include high radiation and long daylight hours. Israel has great potential for the generation of clean energy from solar and wind resources.

When evaluating suitable locations for various renewable-energy technologies, technical, economic, environmental, social and regulatory factors should be taken into account (Lopez et al. 2012; Brewer et al. 2015). Economic factors, for example, include distance to transmission lines and roads since the closer the wind turbines are to existing transmission lines and roads, the lower the construction and maintenance costs (Uyan 2013). Social factor include public attitudes, distance from structures, especially residential buildings due to physiological health effects that were found to be associated with the attitude to the noise emitted by wind turbines and their visual appearances. The scientific literature concludes that the health impacts on populations that live near wind turbines are primarily due to annoyance from the wind turbines and not from direct effects from the turbines. Annoyances from wind turbines could lead to sleep disturbances and psychological distress to the nearby population. Thus, in order to avoid such disturbances, a minimum setback distance has been established in different countries between residential buildings and wind turbines (Brewer et al. 2015;Knopper and Ollson 2011, Bakker et al. 2012).

This work focuses on assessing Israel's renewable energy technical and practical potential for wind and solar sources while considering environmental and regulatory factors. The technical potential represents Israel's renewable energy upper limit potential by taking into account topographic and land-use limitations for current renewable technologies system performances. The technical potential is based on feasibility from an engineering perspective, but does not take into account whether the potential is actually attainable as other constraints (i.e. social, environmental, and regulatory) must be considered. Hence, this work will also discuss practical potential, which, while based on technical potential, also takes into account these other considerations, including environmental and statutory regulations. The practical potential is a much more realistic indicator of Israel's "real" or "practical" renewable energy upper limit potential.

This work will rely on Jacobson's plan for Israel in the World Plan proposal- Jacobson et al. (2016), and will prove the plan is doable, and will further present specific site selection for implementing it.

5. Literature review

Jacobson et al. (2016) suggests Israel's 2050 energy mix to be comprised of 80.5% solar and 19.4% wind energy (with less than 0.1% for tidal and hydro). As wind and solar technologies comprise more than 99.97% of the WWS energy source mixture, and this thesis is based on Jacobson's et al (2016) proposed roadmap, this thesis will focus on exploring the technical and practical potential of wind and solar technologies (and not of geothermal, tidal and hydropower). This chapter first presents a literature review of criteria that will be used in the spatial analysis for onshore, offshore wind, CSP and utility PV. Following is a description of technical factors for rooftop development and previous work related to Israel's rooftop evaluation. Lastly, a review of other renewable energy sources is presented.

5.1 Spatial analysis criteria

Many different technical factors influence the feasibility of developing wind and solar technologies. Following is a short review of different factors used by different researchers for the primary technologies covered in this thesis.

In the literature different factors were used in order to find areas suitable for wind energy development. Miller & Li (2014) outlined modeling approaches and modeling factors used in studies to determine suitable areas for wind farm installation (Miller & Li 2014). Miller & Li (2014) demonstrate that there are no unified criteria used by researchers to determine suitable areas for wind farm installation but that each analysis relies on different criteria. For example, Aydin et al. (2010) used the following factors: distance to natural reserves, distance to large cities, distance from towns, distance from airports, noise, distance from lakes and wetlands, and wind power. Meanwhile, Baban, Parry (2001) used: slope, distance to water bodies, historical sites, urban areas, roads and railways, land use and the presence of important ecological area. van Hoesen and Letendre (2010) used wind potential, slopes and elevation.

For utility scale PV the following factors were used by Uyan (2013): distance from residential, land use, distance from roads, slope, distance from transmission lines, while Brewer et al. (2015) used slope, road and water proximity, land ownership and use, and grid connectivity. In International Finance Corporation (IFC) (2012) the following factors were mentioned: Solar resource (GHI), Local climate, Available area, Land use, Topography, Geotechnical (for example consideration of groundwater and seismic risk), Geopolitical (e.g. military zones), Accessibility (proximity to existing roads), Grid connection, Module soiling (e.g. local weather, environmental, human and wildlife factors), Water availability (required for module cleaning), and Financial incentives.

For CSP, Clifton, Boruff (2010) outlined modeling factors used in studies to determine suitable areas for wind farm installation. Their research shows that there while there exists a specific set of factors to determine suitable areas for CSP installation, each analysis used different criteria. For example, Anders et al. (2005) used: Solar radiation, slope, Minimum land area, protected and sensitive areas, and water bodies, while Gastli et al. (2010) used slope and minimum land area only, and Domínguez Bravo et al. (2007) used Solar radiation, slope, Minimum land area, protected and sensitive, Agricultural land use protected and sensitive area.

5.1.1 Technical criteria

As demonstrated by the brief literature review above, there are many criteria that can be taken into account for ensuring successful WWS project development and prior analyses have not adhered to a defined set of criteria to be used. The following section elaborates on the specific factors found most relevant for this thesis.

1.1.1.1 Criteria for wind development

5.1.1.1.1 Onshore wind

Final set of criteria selected for finding areas suitable for onshore wind installations:

Wind speed

Wind speed is the most important factor in the development of wind turbine. Wind speeds of 6 m/s at 100m elevation is the minimum speed necessary to make wind energy production possible (Miller & Li 2014).

Slope

At slope terrain percentages greater than 30%, wind turbine development is not feasible. Slopes greater than 10% limit the accessibility of the cranes needed to carry the heavy parts of the turbine (van Haaren & Fthenakis 2011, Miller & Li 2014). This technical limitation can be overcome at the expense of higher installation costs. The U.S. Department of Energy estimated the costs associated with installation as 25% of the capital cost. Furthermore, they assessed that the cost penalty for an increase of 2.5% of terrain slop leads to increases of one-fourth of the of the wind turbine capital installation costs (U.S. Department of Energy 2008, van Haaren & Fthenakis 2011). In many studies, areas with slope percentages greater than 20 percent were defined as unsuitable for wind farm installation. However, successful installations at 30% slope terrain in the Greek island of Crete and in Baoding Mountain in China have been documented (Tegou et al. 2010, Miller & Li 2014, Buist 2015). As successful installation at 30% were already made, and assuming technological advancement will make such inclined installations easier and cheaper, slope of 30% was chosen as threshold.

Land use

The land use of the area is important since wind farms cannot be developed on urban areas, archeological sites, airport or built structures like roads and parking lots, or if the area is water land. Meanwhile, wind turbines can be developed on areas with open space (Miller, Li 2014)

5.1.1.1.2 Offshore wind

Final set of criteria selected for finding areas suitable for offshore wind installations :

Wind speeds

Minimum wind speed is needed in order to make the development cost effective. Current development are locate in areas with at least average annual wind speeds of 7m/s at 90 m elevation but average annual wind speeds above of 6.4 m/s at 90 m height above surface is already considered suitable by NREL (Lopez et al. 2012; European Wind Energy Association 2013; Westgate, DeJong 2005)

Depths lower than 50 m

Currently, commercial installation is economical only up to 50 m depth. Installation at higher depths (over 50 m deep) could be done by floating turbines not yet commercialized or economical (European Wind Energy Association 2013).

Distance from shore

Distance to shore is usually another limitation that should be taken into consideration when planning offshore wind farms since as the distance from shore increases, costs also rise. World-wide offshore installation have reached distances from shore of over 100 km. The minimum distance from shore is meant to keep the turbines far enough from shore in order to avoid visual pollution and public annoyance (Jacobson et al. 2016; European Wind Energy Association 2013).

Other uses

The offshore area should not include archeological sites or previously assigned shipping lanes.

1.1.1.2 Criteria for Solar development

5.1.1.2.1 Utility-scale PV

Final set of criteria selected for finding areas suitable for utility-scale PV installations:

Irradiance

The most basic factor for developing a solar PV project is high average annual Global Horizontal Irradiation (GHI). The higher the solar insolation, the greater the energy yield per installed development (while there is no min GHI that is required, locations exceeding 5 kWh/m^2/day are considered with sufficient insolation) (Jacobson et al. 2016)

Land use

As with onshore wind turbine, PV cannot be constructed on urban areas, water land, archeological sites, or airports. PV also cannot be constructed on forests and agriculture land in order to prevent harm to the forest ecosystem due to the large land area needed as well as due to the competition between food and energy resources caused by agricultural development (Uyan 2013).

Topography

The solar farm should be on flat or south facing slopes to ensure greater solar radiation and power production due to the location of the sun installations (International Finance Corporation (IFC) 2012; McKinney 2014). Although PV farms can be constructed on steep slopes, construction on flat areas simplifies installation and reduces costs (International Finance Corporation (IFC) 2012)

5.1.1.2.2 CSP

*Final set of criteria selected for finding areas suitable for **CSP** installations:*

Land use

Same as for utility-scale PV

Irradiance

For CSP the most important factor is minimum annual average direct normal irradiance (DNI) of 5 KWh/m^2/day. This criterion is required in order to make the costs of generating electricity cost-effective. CSP electricity generation is linear to the amount of DNI. (Clifton and Boruff 2010, Lopez et al. 2012, Doris et al. 2013, Schmalensee et al. 2015).

Slope

CSP has to be constructed on relatively flat areas. The literature highlights different minimum slope percentages as criteria for CSP development. NREL and Uyan (2013) used a maximum of 3% slope while Clifton and Boruff (2010) used a maximum slope ranging from 1% to 7%.

Minimum contiguous area

Minimum contiguous area is needed to ensure an area size large enough to be considered a utility-scale project. Lopez et al. (2012) used a 0.18 km^2 minimum requirement while Clifton and Boruff (2010) used a range of 2 to 8 km^2.

5.1.2 Practical criteria

As development of wind turbine would not be feasible in areas with restricted regulatory limitation for development or in areas of environmental consequence, the following section presents information regarding regulations that affect renewable energy development in Israel.

Israel has created a statutory protection on open areas by declaring them nature reserves, national parks, or forest areas in order to prevent their development and preserve their ecosystem. The level of protection of open spaces depends on the statutory protection (Planning laws) granted to them by the law. For example, the National Outline Plan for Forests and Afforestation - NOP 22 - grants statutory protection to forest and afforestation formations. It presents guidelines for their preservation, cultivation, and integration into the overall planning of Israeli land. It was integrated with national and district outline plans as well as into the Integrated National Outline Plan for Building, Development and Conservation - NOP 35 (Kaplan and Abel 2011). NOP 35 defines 6 kinds of planning areas: Urban Texture, City Texture, Rural Texture, National Protected Texture, Combined Protected Texture, and Shore Texture. The textures differ from one another by the quantitative and spatial ratios designated to different land-uses. For example, urban texture contains more areas designated to urban developments while considering areas of environmental consequence such as ecological corridors. Whereas, most of the land-use for areas of Combined Protected Texture will be designated to preserve natural areas (State of Israel 2015).

Israel’s National Outline Plan for Wind Turbines - NOP 10/D/12 - bans the installation of wind turbines on greenhouses, preservations, and heritage, historic, or national sites. It also explicitly states that installation of wind turbines on shoreline areas requires the approval of a representative from the Ministry of Defense at the concerned regional committee.

The National Outline Plan for Photovoltaic Installations- NOP 10/D/10 bans small and moderate sized photovoltaic installations in shore texture (as defined in NOP35) and in areas with scenic, heritage, archeological, and ecological importance including Ecological Corridors. It also states that installation of photovoltaic on military ground requires the approval of the Ministry of Defense. Small and moderate sized photovoltaic installations are defined in the NOP as areas smaller than 750 Dunam (750,000 square meters). For large photovoltaic installations, each PV farm or CSP has to be assessed separately due to their individual large impacts on the environment (State of Israel 2015).

While development of renewable energy is beneficial for environmental conservation, it is important to ensure that wind turbine developments will not be located in areas with specific environmental importance such as those that harbor endangered species, bats caves and their lodging and breeding sites, or bird migration routes.

Ecological corridors should be taken into consideration when choosing a site to construct renewable energy technology. Ecological networks became a major tool world-wide in preserving biodiversity and natural habitats in order to mitigate fragmentation caused by humans (fragmentation of building roads, fences, rail tracks and buildings). Ecological corridor allows migration between two fragments that otherwise would have been separated, thus decreasing the risk of species extinction. Connecting between isolated natural reserves by a corridor such as natural land, woodland agriculture land and streams, is vital for species survival since it allows them to migrate and to colonize new areas when environmental conditions change. Thus, renewable energy development on ecological corridors should be avoided (Jongman et al. 2004, Ministry of Environmental Protection 2010).

Israel is a bottleneck for migratory birds due to its unique location between 3 continents (Figure 14). Israel's bird density and biodiversity is considered one of the richest in the world. Over 500 million birds migrate through Israel's sky from Europe and Asia to Africa during the migration season and over 530 different bird species permanently reside in Israel. The main harm from wind farms affects bats and birds if the wind farm is located on main migration routes. In 2008, The Society for Protection of Nature in Israel released a report on endangered birds which found that 46 birds species were in danger of extinction and 18 of them under severe danger of extinction (The Society for Protection of Nature in Israel 2008, Ben David and Avni 2013). Several Important Birds and Biodiversity Areas (IBA) have been recognized in Israel. IBA are sites of international significance for the conservation of birds and other biodiversity. These sites are part of a worldwide network considered essential to ensure bird survival. The sites are found by locally collected, ground-truthed data that are analyzed nationally. IBA are identified using criteria agreed upon internationally, such as the bird numbers and species' complements that they hold, and are selected in a way that they form a network throughout the species' biogeographic distributions. Thus, the consequences of preserving and protecting IBA sites are critical to preventing bird extinctions (BirdLife International 2014).

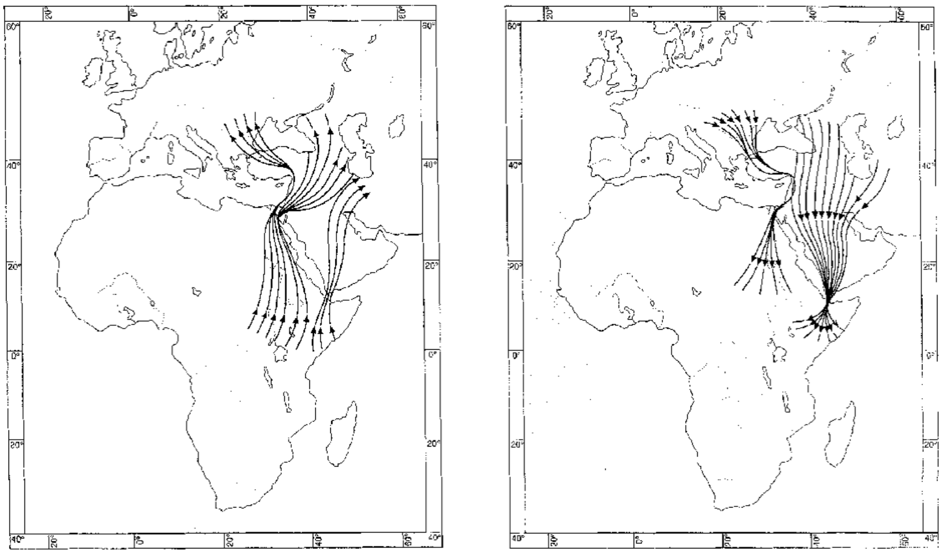

Figure 14. Migration routes of soaring birds in the Middle East at spring (left) and autum (right). Source: Yom-Tov 1988

For offshore wind development environmental factors such as protected marine environment or offshore birds migration route should be taken into consideration.

A more detailed explanation of which of the factors above were taken under consideration in this thesis and in what manner can be found later on in the Method chapter

5.2 Rooftop PV- technical background and previous work related to Israel's rooftop evaluation

The development of rooftop PV is limited to the fraction of roof area technically suitable. Factors considered when evaluating rooftop suitability are the roof portions directed to the south in the northern hemisphere countries, shading and occupying objects such as solar water heaters, AC units, antennas and satellite dishes that limit the area available for PV construction on the roof (Shofrony 2014; Jacobson et al. 2016). Melius et al. (2013) found that 10% to 60% of building rooftop area is suitable for PV development, with the higher end pertaining to commercial or large buildings, or buildings with flat roofs. Since commercial buildings usually have large flat roofs they usually have a larger portion of suitable area for PV than residential buildings (Melius et al. 2013; Jacobson et al. 2016).

Two studies were conducted in order to evaluate Israel's rooftops potential. Shofrony (2014) evaluated that in 2012, Israel residential rooftop was 170.4 km^2 and non-residential was 77.7 km^2 while Vardimon (2011) found that in 2007 Israel's residential rooftop was 188.7 km^{2}and non-residential was 62.7.7 km^2.

Table 5. Israel's rooftop area estimations for residential and non-residential structures from previous researches (Vardimon 2011, Shofrony 2014)

	Year of data source	Residential rooftop area (km^2)	Commercial and governmental rooftop area (km^2)	Total rooftop area (km^2)
Shofrony (2014)	2012	170.40	77.70	248.10
Vardimon (2011)	2007	188.70	62.70	251.40

5.3 Review of other sources

5.3.1 Geothermal

Sites suitable for conventional geothermal plants in Israel are very limited, at least with current technologies. Shalev et al. (2008) found that although Israel's average geothermal heat flux of 42 mW/m^2 is lower than the world average of 60 mW/m^2, the heat flux at the south end of the Golan Heights and in southern Israel is relatively high (larger than 10 bar) and accrue at relatively shallow depths (lower than 3000m). These measures would allow for the development of geothermal energy at these sites. Geothermal energy could be generated in most areas in Israel with Enhanced Geothermal Systems (EGS) technology. Shalev et al. (2008) also found that the ground temperatures in Israel are sufficient to produce geothermal energy with EGS, with temperatures higher than 150 Celsius at depths greater than 6 km and around 200 Celsius at depths of 8 km in most of Israel (Shalev et al. 2008). The technological immaturity, together with the lack of experience of developing the system at depths of 6 - 8 km, puts the feasibility of this technology in Israel in question.

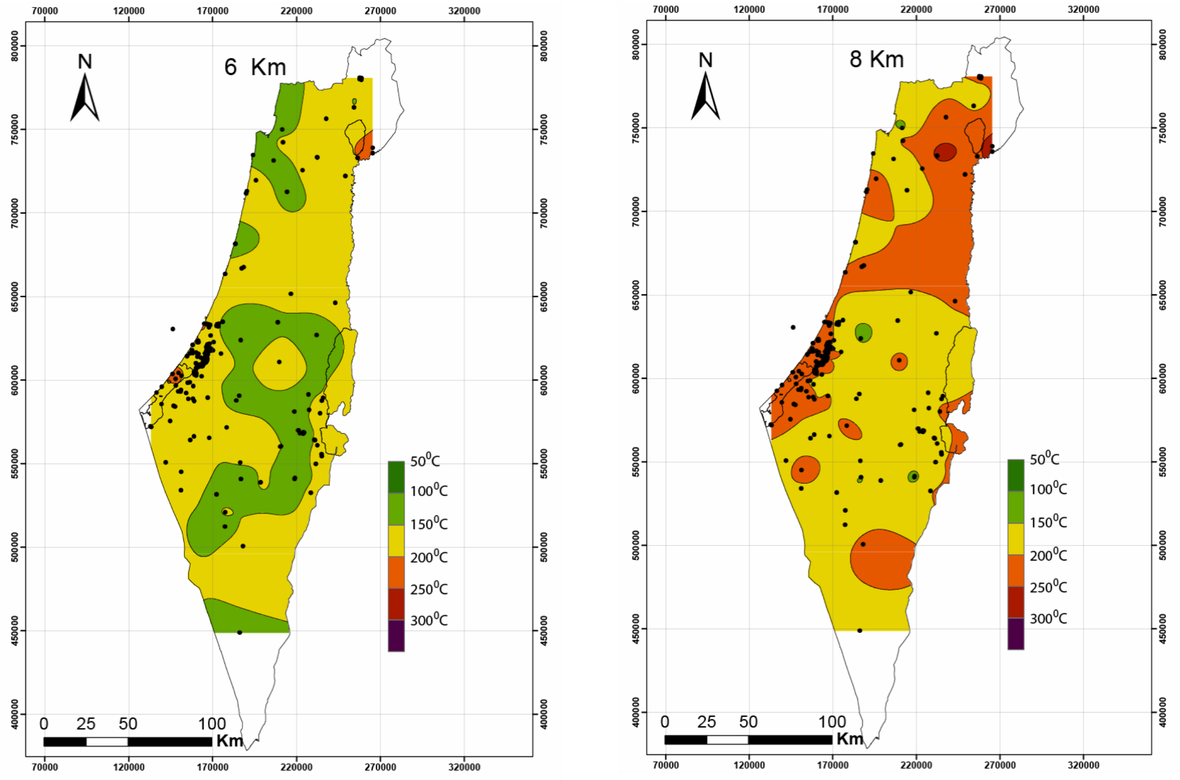

Figure 15. Average temperature at 6 km (on the left) and 8 km (on the right) underground. Source: Shalev et al. 2008

5.3.2 Hydropower

Hydropower is another renewable energy resource widely used to generate clean energy. As mentioned before, hydropower is classified into three categories: run-of-river, reservoir or storage, and pumped storage plants. Considering Israel's dry riverbeds, Israel does not have hydropower potential from run-of-river and reservoir or storage. However, Israel is developing pumped storage plants that can be used as storage (Willner 2014). Currently, Israel has a national plan for a total of 800 MW of pumped hydroelectric storage capacity by 2020. In 2014, Israel constructed its first PSH plant with a capacity of 300 MW on Mount Gilboa, and another PSH plant with a capacity of 340 MW is in the advanced planning stages at the Kochav ha-Yarden site (Public Utilities Authority Electricity 6/13/2012; Jacobson et al. 2014; Willner 2014).

5.3.3 Wave

Zodiatis et al. (2014) made an assessment of wave energy potential over the Eastern Mediterranean Levantine Basin conducted. In their research, a ten-year database (2001-2010) of wave energy potentials was produced using high resolution (1 arc minute), state-of-the-art wind-wave numerical models. Observational data by satellites and meteorological stations, such as measurements of buoy located in the shore of the Israeli city Hadera, have been integrated into the models, creating a hindcast platform. Zodiatis et al. found that Israel and other countries in the Levantine Basin enjoy relatively low stable wave energy potential (Zodiatis et al. 2014). The possibility of using this resource will be further touched on in the Discussion chapter.

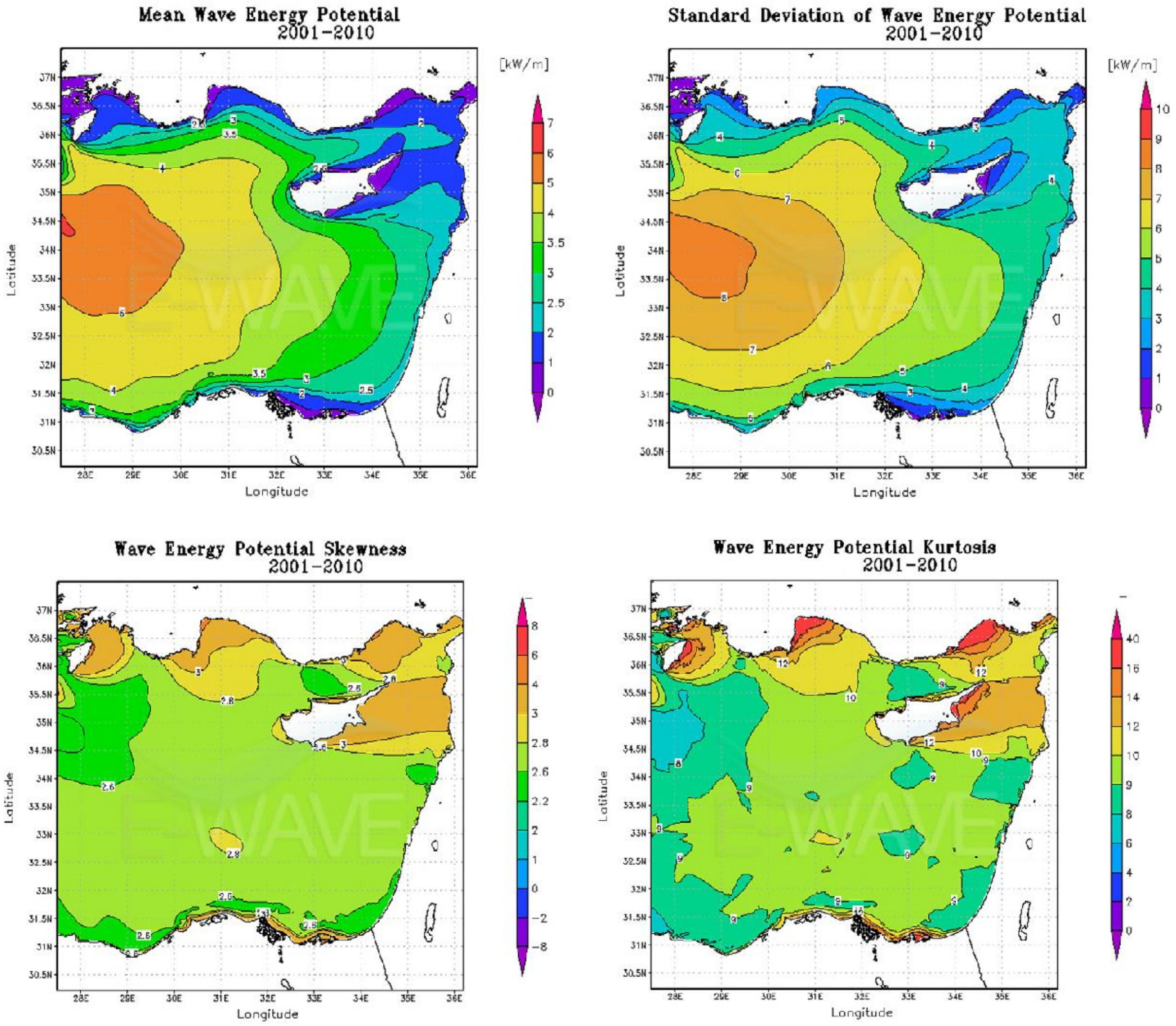

Figure 16. Ten years wave energy potential (kW/m) for the Eastern Mediterranean. a) Mean, b) Standard deviation, c) Skewness, d) Kurtosis values. Source: Zodiatis et al. 2014

6. Methods

This chapter presents the methods used to answer the main and sub research questions.

First, a literature review was conducted, surveying the latest state of the art knowledge with respect to the research questions. The literature review focuses on two main categories: data that will help construct the transition plan that will transform Israel energy resources to 100% WWS, and criteria for finding areas suitable for development of WWS technologies.

Jacobson et al. (2016) has created a World Plan to convert 139 countries which contains the most up to date data, including projections for Israel. Prof. Jacobson's proposal for a target WWS supply mix to address Israel's future energy demand projections in a 100% renewable energy manner was adopted in this thesis. The results and projections relevant to Israel's transition to renewable energy were derived from the World Plan roadmap (Jacobson et al. 2016) and spreadsheet (Jacobson & Delucchi 2016).

The following results and projections are presented in the 'Israel's results from the World Plan' chapter: Israel's projected future end-use power demand and a suggested energy mix to generate Israel's all-purpose energy demand in 2050 with only WWS technologies (onshore wind, offshore wind, utility-scale PV, residential PV, commercial/governmental PV, concentrated solar power (CSP), geothermal, wave, tidal, and hydropower). This thesis also presents Israel's expected energy demand in 2050 in Business As Usual (BAU) and in a scenario of converting its all-purpose energy infrastructures to one powered by wind, water, and sunlight (WWS)(Jacobson & Delucchi 2016). Furthermore, this work derives the number of WWS generators and corresponding footprint and spacing areas needed to meet demand in the WWS case and an energy mix that will allow Israel to convert its all-purpose energy infrastructure to WWS by 2050.

For the sake of consistency with prior roadmaps developed with the same methods as the World Plan used to study Israel, results are presented in the same format (similar tables) as previous roadmaps developed by Jacobson and Delucchi for individual U.S. state energy roadmaps for New York, California, Washington State, and the remaining United States (Jacobson et al. 2013; Jacobson et al. 2014; Jacobson et al. 2015a; Jacobson et al. 2015b respectively).

As Jacobson's et al. (2016) suggested energy mix is based on top-down modeling, and not on the actual bottom-up feasibility in Israel, considering its terrain, unique geography and WWS potential, etc., a site suitability map has been developed using the Geographic Information System (GIS). GIS is a geographical analysis tool used for solving complex geographic planning and management problems. GIS has become popular in recent years in the decision making process and specifically in assessing the most optimal sites for renewable energy installations (Brewer et al. 2015; Tegou et al. 2010; Uyan 2013). The GIS multi-criteria spatial analysis data layers of physical, regulatory and environmental variables were overlaid to create a map of locations most optimal for WWS installations.

Based on the criteria that were determined most relevant to help answer the main and sub questions of this thesis, GIS data sets required for analysis based on such criteria (e.g. land use data, slope and protected areas, etc) were collected for the study area from multiple sources, such as Israel Meteorology Center, Ministry of Interior, NASA, etc (full list of sources can be found in Annex 4).

Israel's GIS spatial analysis results reveal areas technically suitable for development of onshore wind, utility scale PV, and CSP technologies. It might be that the same areas prove to be suitable for several technologies. The results of the analysis were used to calculate the technical and practical potential (MW) for utility-scale photovoltaic (PV), concentrating solar power (CSP), and onshore wind power. These results help validate whether Israel has enough suitable area to develop the aforementioned WWS technologies in order to allow the country to generate the expected all-purpose end use power by 2050.

Additionally, this section analyzes Israel's rooftop PV technical potential that is based on previously published research. Estimates of Israel's technical potential for offshore wind, wave, geothermal, tidal, hydropower, and commercial rooftop PV system have not been calculated in this thesis but are taken from Jacobson et al. (2015) and integrated into the suggested WWS plan.

The outcome of both Jacobson's World Plan and the GIS analysis are compared and analyzed in the Discussion with the aim of providing technical and practical feasibility for Prof. Jacobson's World Plan model while taking into account Israel's unique geography, climate, environmental and regulation settings.

6.1 GIS analysis method

This section presents the methods used to estimate Israel's technical and practical potential. This chapter will first detail the multi-criteria spatial analysis, which was used to determine Israel's technical and practical potential for wind and solar technologies (onshore wind, utility scale PV and CSP). Secondly, this section outlines the methods used to estimate Israel's technical potential for residential rooftop PV. This thesis does not conduct spatial analysis of suitable areas for offshore wind as the data regarding Israel's offshore wind speed which is a critical factor for finding Israel's technical and practical potential for offshore wind turbines was unobtainable. Thus, the technical potential is taken from the World Plan estimation (Jacobson et al. 2016) and practical potential of offshore wind turbines is left unknown. Further, commercial rooftop PV system technical (and practical) potential was not estimated due to insufficient data with regards to the amount of floors in commercial buildings, a critical piece of data for a potential estimate. As the contribution of geothermal, tidal, and hydropower to WWS energy source mix is less than 0.03% (and there is little concern that this low energy supply can be achieved in Israel), geothermal, tidal, and hydropower technical potential have not been validated in this thesis but were taken from Jacobson et al. (2016) and later integrated into the suggested WWS plan.

In this work, a site suitability map has been developed using GIS multi-criteria analysis for onshore wind, utility scale PV and CSP technologies. With GIS multi-criteria analysis, data layers of raster or gridded values that represent different criteria are overlaid to create a suitability map that helps determine whether a given area is suitable for particular use (Tegou et al. 2010, Brewer et al. 2015). Spatial analysis aims to determine whether sufficient suitable area is available for the development of WWS technologies that will provide the needed capacity to meet Israel's energy demand in 2050 as proposed by Jacobson's et al. (2015).

A thorough literature review (presented in literature review chapter) led to the evaluation criteria for site suitability for each of the mentioned technologies. The ideal site for WWS development is a site with high-energy resources, low biological resources, and limited site regulations. The site-suitability analysis was conducted with these specifications in mind. First, areas found unsuitable for WWS installation due to topographic and land-use limitations were eliminated. Areas technically suitable for WWS installation remained. Next, out of the areas technically suitable for WWS installation, areas practically suitable for WWS installation were found by eliminating areas with burdensome environmental and statutory regulations. The spatial analysis has been conducted with a guideline that areas that are most suitable for WWS installations are the ones that have the lowest disruption to the existing land use and interfere the least with other limitations (environmental and regulation).

Here is a summary of the GIS analysis criteria:

Methods

Criteria for finding sites technically suitable for onshore wind farm development

- Annual wind speed greater than 6 m/s at a height of 100 m
- Slope less than than 30 percent
- Available Open Space areas that are not:
  - Archeological sites
  - Airports
  - Roads
  - Water bodies
  - Built structures

Criteria for finding sites practically suitable for onshore wind farm development

- Technically suitable
- Not part of shore texture
- Not ecologically sensitive
  - Nature reserves
  - National parks
  - Bird important areas

Criteria for finding sites technically suitable for PV farm development

- Available open space areas that are not:
  - Archeological sites
  - Airports
  - Roads
  - Forests
  - Water bodies
  - Built structures

Criteria for finding sites that are practically suitable for PV farm development

- Technically suitable
- Not part of shore texture
- Non-agricultural
- Not ecologically sensitive
  - Nature reserves
  - National parks
  - Bird important areas

Criteria for finding sites technically suitable for CSP development

- Available open space areas that are not:
  - Archeological sites
  - Airports
  - Roads
  - Forests
  - Water bodies
  - Built structures
- Slope less than or equal to 5 percent
- Continuous areas over 180,000 square meters
- Annual average DNI greater than than 5 $kWh/m^2/day$

Criteria for finding sites practically suitable for CSP development

- Technically suitable
- Not part of shore texture
- Non-agricultural
- Not ecologically sensitive
  - Nature reserves
  - National parks
  - Bird important areas

There may be an overlap between sites found technically and practically suitable for different WWS installations e.g. overlap between areas suitable for utility scale installations and onshore wind. However, per each WWS source (e.g. wind, solar, …), best-fit technology was found per site, without overlapping. E.g. sites suitable for CSP and utility scale PV do not overlap since areas suitable for CSP were eliminated from areas suitable for solar PV.

The spatial analysis does not account for social factors such as public attitudes towards WWS development on the suggested sites. In previous studies, public opinion was found to have a large role in the success of site development since it can slow or even completely halt a project deemed permissible by law and regulation. The spatial analysis also does not account for economic factors such as proximity to existing roads or grid transmission lines that affect the direct cost of WWS construction and development (Brewer et al. 2015). Those two aspects should be integrated in the final process of deciding site development.

6.1.1 Validation method

To validate Jacobson's et al. 2016 proposal, an analysis shall be conducted per each energy source to determine its technical and then practical potential and the results compared to Jacobson's proposed energy output for said source. The plan shall be considered invalid if Israel has insufficient energy output per one or more of the energy sources. In such a case, an alternative proposal shall be made.

Moreover, as there are many factors not taken into consideration by this evaluation (i.e. societal, political & cultural aspects), not to mention inaccurate data input and models for those factors - it may be that a certain calculated practical potentials are actually lower than estimated. Likewise, it may be that demand in 2050 is higher than projected (and therefore the proposed energy requirement per source should be higher, assuming same energy mix across sources per Jacobson's et al 2016 plan). Therefore the plan is not only evaluated as valid and invalid, but also as "safe" or "unsafe"/"uncertain". A "safe" plan shall be defined as a plan, where the found practical potential of each energy source is greater by at least 25% than the required energy capacity for that source. A "safe" plan has large enough error margins (at least 25%) implying high likelihood to implement the proposed plan. An "uncertain" plan, is one where at least one energy source doesn't have sufficient 25%+ margins. If a plan shall be found "uncertain," a safe alternative proposal shall be made.

6.1.1.1 Military Grounds

Out of Israel's total land of 21,640 km^2, 7,895 km^2 (or 36.5%) is currently defined as "military grounds". Military grounds are areas designated for army usage and include military sites, training areas, or other closed areas. While analyzing site suitability for renewable installations, some of the sites found suitable for site installation would inevitably overlap with military grounds. Israel does not need all of the currently allocated 36.5% of its area for military use, and this thesis assumes that Israel can repurpose up to 10% of its total area currently defined as military ground (789 km^2) as sites for allocated renewable energy installation. As such, in addition to meeting a 25% error margin per energy source, for the plan to be considered valid and safe, total area required to repurpose from military grounds should not exceed 10%.

The 10% military ground threshold will be calculated as follows: per each energy technology source the total (maximum) practical energy potential will be calculated P. Further the area required to achieve maximum potential production through installation will be calculated, A(P) - this is based on the GIS analysis conducted, summarizing all area of sites practically suitable per technology. Of that area, the sub-area that overlaps with military grounds will also be calculated, A(MP), again based on GIS analysis, intersecting the military grounds layer with the practical potential layer for each technology. Further, the area required to meet projected demand per that technology shall be calculated A(D). This can be calculated as follows: A(D)=D/P*A(P), relying on a nominal energy production to area ratio, which is a close enough approximation, considering the relatively uniform sun and wind distribution across Israel, and considering this calculation is done pre-specific site selection. It is further assumed that if there is enough available land that is not on military ground, then the renewable installation will be done on such land without requiring repurposing. Therefore, when accounting for military ground required for WWS installation, we want to consider per technology what is the minimal area that is absolutely required to be repurposed from military ground. This area is A(Repurpose)=Max(A(D)-(A(P)-A(MP)),0). Then, the requirement is Sum(A(Repurpose)i)/A(M)<10% where the A(Repurpose) is summed across all technologies (wind, PV, CSP) and then divided by entire military ground A(M) and should be less than 10% as defined.

Beyond the overall 10% repurposing threshold as described in detail above, per each specific technology, areas that were found practically suitable based on other considerations, and at the same time were overlapping with military grounds, were not excluded.

6.1.2 Wind turbine spatial analysis

Note: as explained previously, there is insufficient data to perform a meaningful analysis on offshore wind turbine energy potential, and therefore the focus here is solely on onshore wind turbine energy potential.

To find areas technically suitable for onshore wind farm development, the following criteria were considered in the spatial analysis: wind speed, land use, and slope. Regulatory and environmental criteria were also considered to estimate Israel's practical potential, and such regulatory and environmental datasets were overlaid using ESRI ArcGIS. Layers with coordinate systems different from the Israel TM Grid were projected onto it, raster datasets were converted into vector datasets and all data layers with world data were clipped to fit into Israel's border area. Figure 17 illustrates this spatial analysis.

Areas that were found unsuitable for installation due to technical constraints - an annual average wind speed lower than **6** m/s, slope greater than 30% or areas with unfit land-use – were excluded (explanation of the criteria can be found in the literature review chapter). Areas with unfit land-use are considered: urban areas, water land, archeological sites, and airports. Israel's onshore wind farm technical potential has been calculated by multiplying the technically suitable area (found by spatial analysis) by the wind turbine rated power of 5000 kW and dividing by the area for one turbine accounting for spacing of 0.78 km^2 as estimated by Jacobson and Delucchi (2016). Annex 3 provides a detailed explanation of the calculation.

The multi-layered analysis areas that were left were differentiated by their qualities - higher wind speeds, lower slope percentages, and the applicable restrictions (statutory or environmental). Areas practically suitable for wind farm installation were defined as areas that, in addition to being technically suitable for wind farm installation, also meet the following criteria: not on shore texture, and not located on nature reserves, national parks, or birds important areas (BIA). Israel's practical potential was calculated by multiplying the areas that were found in the spatial analysis as practically suitable by turbine rated power of 5000 kW and dividing by the area for one turbine accounting for spacing of 0.78 km^2 as estimated by Jacobson and Delucchi (2016).

Data of Israel's wind speed was provided by: Israel Meteorology Center. An annual average wind speed above 6 m/s was chosen as technical criteria for choosing a suitable site for wind turbines. Thus, areas with annual average wind speeds less than than 6 m/s at heights of 100 meters were excluded. As higher wind speeds generate more energy, three levels of wind speeds were defined, 6+m/s, 6.5+m/s and 7+m/s. Table 9, presented in the Results, summarizes the various areas with such energy speeds.

Slope percentage layer was derived from ASTER Global Digital Elevation Model Version 2 using ArcGIS slope tool. This thesis uses a slope threshold of 30% to eliminate areas from the technical analysis since a) this thesis presents a long-term plan where better future solutions to overcome slope limitations can be assumed, and b) installation at 30% slope terrain has already been constructed on the Greek island of Crete and in Baoding mountain in China (Tegou et al. 2010, Miller & Li 2014, Buist 2015).

Methods

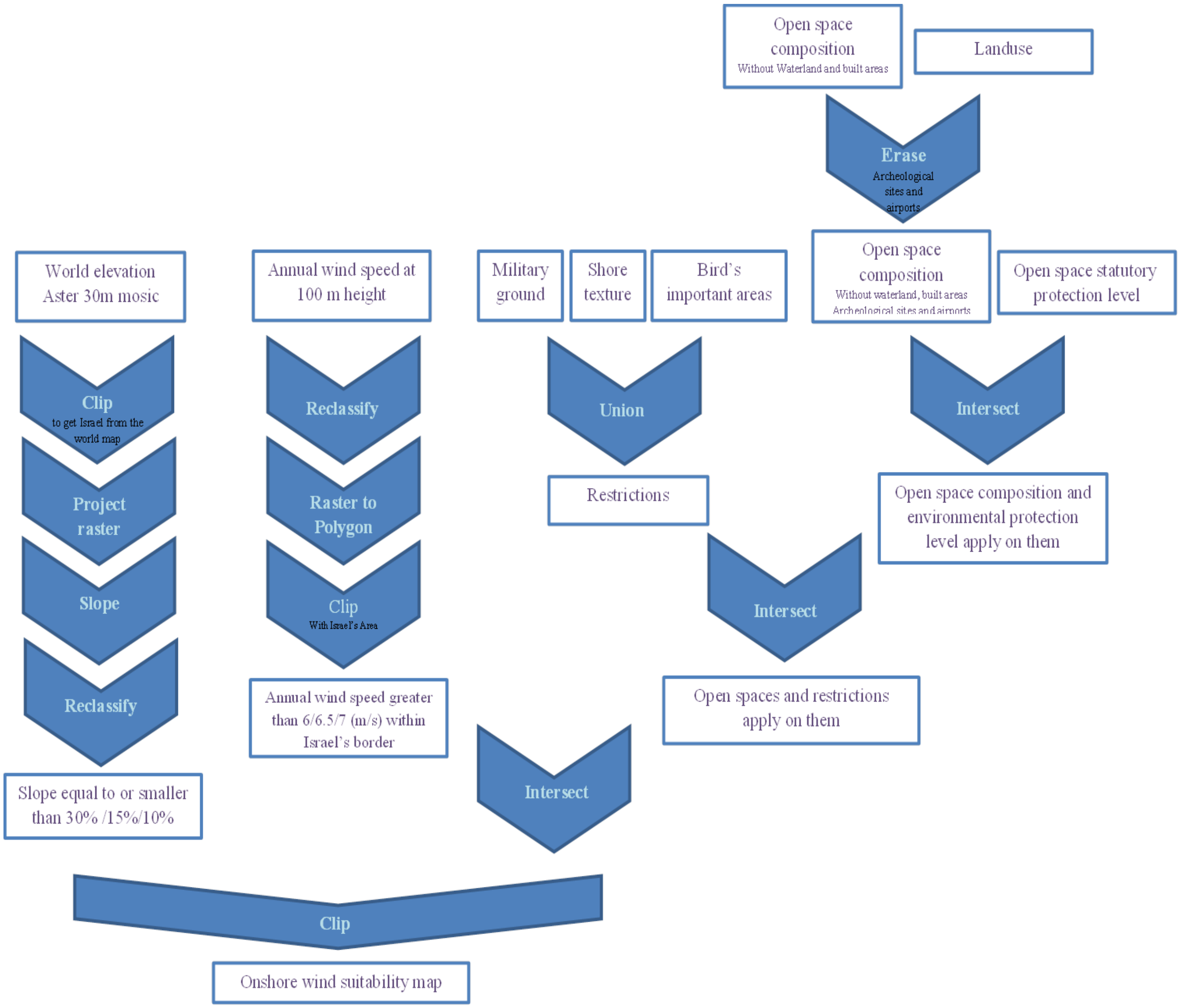

Figure 17. Flowchart for modeling suitability of wind farm

Methods

Data used to define locations of **open space** were derived from 'open space composition' polygon data retrieved from Israel's National Ecosystem Assessment Program called Hamarag . This data contains information on areas of shrub-steppe, Garrigue, forest and woodland, desert, field crops, plantations, water land and built structure (roads and parking lots were already excluded from the original data). All areas other than 'water land' and 'built structure' were extracted from this data layer in the process of creating a layer that contains only open space. Furthermore, 'airport' and 'archeological sites' were extracted from a 'land use' data layer that was provided by Central Bureau of Statistics. Those areas ('airport' or 'archeological sites') were further subtracted from the open space data layer and a data layer that contains only open space was received. Note, that the actual building of airports and archeological sites were already eliminated in the first phase of eliminating 'built structure' areas from the 'open space composition' layer. In the second phase, eliminating airports and archeological sites, the area surrounding the structures was also eliminated (as is appropriate for such installation due to proximity).

As explained, in order to eliminate protected areas, Hamaarag data source was used. Hamaarag defined three degrees of statutory protections in the State of Nature report 2015: 1. High protection for areas declared as Nature Reserves, National Parks or forests (including planted forests that were recognized by National Outline Plan for Forests and Afforestation-NOP 22). Those areas were found by the Nature and Parks Authority to be vital to preserving biodiversity; 2. Moderate protection for areas considered by the planning committees to become protected as Nature Reserves, National Parks or forest area that was not recognized by NOP22 to be protected. 3. No protection for areas that were not proposed to the planning committees but were offered to be recognized as protected by the Nature and Parks Authority and the Jewish National Fund (JNF) (Berg et al. 2015, Shkedi and Sadot 2000). When choosing areas practically suitable for wind turbine installation, areas with high protection and moderate protection were eliminated. Forests that are not part of the high or medium protection levels were not eliminated as wind turbines can be integrated into a forest's surroundings.

Israel's National Outline Plan for Wind Turbines - NOP 10/D/12 - bans installation of wind turbines on greenhouses, preservations, and heritage, historic, or national sites. Due to limited data on greenhouses, preservations, and heritage, historic, or national sites, these limitations were not part of the analysis but it can be assumed that most of these areas were eliminated as part of the elimination of built structures and archeological sites. In order to eliminate restricted locations of protected areas (national parks and forests), shore texture, and areas of high ecological sensitivity for birds (Birds Important Areas), a restriction layer was created by uniting data layers of those restrictions.

Since NOP 35 is dividing all of Israel into textures (Urban Texture, City Texture, Rural Texture, National Protected Texture, Combined Protected Texture, and Shore Texture) where the planning authority is required to approve any development, it was found unnecessary to add the textures as a regulation limitation. Nevertheless, this work considers shore texture as a practically unsuitable area for wind farm development since Israel's National Outline Plan for Wind Turbines- NOP 10/D/12 explicitly states that installation of wind turbines on shoreline areas requires the explicit approval of a representative from the Ministry of Defense at the concerned regional committee. Considering that these two areas were singled out, and considering the requirement for a committee representative to approach, it was deduced that such approvals would not come easy, and that it would be best to make a plan that works without relying on such approvals a-priori. The installation of [2]miniature wind turbines is allowed only in shoreline areas approved for construction while submission of a plan is required for installation of small[3], medium[4] and big[5] wind turbines in those areas.

[2] Horizontal or vertical wind turbine at maximum height of 4 m
[3] Horizontal or vertical wind turbine at maximum height of 18 m
[4] Horizontal or vertical wind turbine at maximum height of 40 m
[5] Horizontal or vertical wind turbine at height of at least 40 m.

Israel's onshore wind farm practical potential was evaluated by only accounting for areas with no limitations at all as such limitations were defined for wind installation (other than possibly overlapping with military designated grounds as explained above). Furthermore, agriculture areas were considered as practically suitable for wind farm installation since crop can still be grown on the same areas that wind farms are constructed

.

BIA were considered not practically suitable and were filtered out due to Israel's importance to bird migration population. Preserving and protecting BIA sites are critical to preventing bird extinctions (BirdLife International 2014).

Many other restrictions were not included in this estimate due to lack of data. These restrictions include areas such as those of endangered species, bird migration routes, bat caves and their lodging and breeding sites, buffer zones from the airport, and distance to populated areas and inhabited structures.

Ecological corridors should be taken into consideration when choosing a site to construct wind turbines. Nature and Parks Authority has identified areas of ecological corridor importance (Rotem et al. 2015). The ecological corridor data layer that was provided by the Nature and Parks Authority's presents almost all the areas that were not already used as an urban area or protected area (nature reserve/national park/forests) and designated these areas as ecological corridors. Ecological corridors are important for the mentioned reasons but they are also important to the understanding of the consequences of continued pollution on the ecosystem. Further research into understanding the benefits of preserving areas for ecological health versus the damage of continued fossil fuel usage need to be conducted and areas with a greater potential to be used as ecological corridors should be defined. A further understanding of which areas are really necessary and which could be used for wind turbines should be conducted.

6.1.3 Utility-scale solar power: PV and CSP

To find areas suitable for utility-scale photovoltaic (PV) and concentrated solar power (CSP), similar methods of GIS spatial analysis as were conducted for onshore wind turbine were used with a small adaptation (layers with coordinate system different than Israel TM Grid were projected onto it, raster datasets were converted into vector dataset, and all data layers with world data were clipped to fit into Israel's border area). Israel's solar technical potential was evaluated by taking into account topographic and land-use constraints. Areas unsuitable for installation due to land-use constraints such as urban areas, water land, archeological sites, airports and forests were excluded. Forest land was excluded since constructing CSP or PV solar farm will harm the forest ecosystem due to the large land area that both need.

Figure 18 presents a flow chart explaining the steps of the spatial analysis for finding areas suitable for CSP installation. In order to find CSP technical potential, areas with slopes larger than 5% were eliminated from the remaining areas. CSP has to be constructed on flat areas with low steepness slopes. While different maximum slope percentages were used in the literature, a maximum of 5% was chosen for this analysis. In order to ensure a large enough installation area, areas of minimum contiguous area of 180,000 m^2 were integrated into the analysis. Furthermore, a criterion of areas with minimum annual average direct normal irradiance (DNI) of 5 $KWh/m^2/day$ was integrated. (Schmalensee et al. 2015). Israel's DNI was derived from solar maps of 40 km resolution for Africa provided by the NREL online data repository. The data were developed from NREL's Climatological Solar Radiation (CSR) Model that uses the following parameters: cloud cover, atmospheric water vapor and trace gases, amount of aerosols in the atmosphere (OpenEI). The data reveals that Israel's annual average DNI is between 4.6

kWh/m^2/day to 6.5 KWh/m^2/day. Thus, areas with annual DNI smaller than 5 KWh/m^2/day were eliminated (Clifton and Boruff 2010, Lopez et al. 2012, Doris et al. 2013, Richter et al. 2009).

Lastly**, CSP technical potential** was **calculated** by multiplying the area found suitable for CSP storage by the weighted areal power density of 34.07 MW/km^2 (explanation of the calculation that led to this value can be found in the spreadsheet of Jacobson and Delucchi 2016). The storage is assumed to be with a maximum charge to discharge rate (storage size to generator size ratio) of 2.62:1 as assumed in Jacobson et al. (2015). For footprint calculation, a land area for one plant of typical size is assumed to be about 2.93 km^2 with CSP mirror sizes similar to those at Ivanpah.

Figure 19 presents a flow chart explaining the steps of the spatial analysis for finding areas suitable for utility scale PV. Israel's utility-scale **PV technical potential** has been **calculated** out of the sum of areas that were found in the spatial analysis to have a slope smaller or equal to 5% and that are not suitable for CSP installation (areas that were suitable for CSP were subtracted), together with half of the areas that were found to have slope percentages greater than 5%. Only half of the areas with slope percentages greater than 5 were used in the calculation since areas with slopes greater than 5% that are facing south have higher solar radiation due to the location of the sun (McKinney 2014). The limitation of minimum continuous area of 180,000 square meters was not applied on PV since small PV farms could be constructed in smaller areas and still serve as great sources of solar energy.

Israel has rich solar resource availability. Based on NREL's data of 40 km resolution for Africa (developed from NREL's Climatological Solar Radiation (CSR) Model), Israel's GHI is between 5.2 KWh/m^2/day and 5.9 KWh/m^2/day. This estimation was validated by comparing it to measurements conducted by Israel Meteorological Center[6] at four different stations (Beit Dagan, Haifa, Jerusalem, Bear Sheva) between the years 1994-2005. Solar irradiance was not integrated into the analysis as a criterion, since its annual average global horizontal irradiance (GHI) is sufficient and does not change much throughout Israel (although, generally speaking, the south GHI is higher than in the north of Israel) (Richter et al. 2009, Lopez et al. 2012).

Utility-scale PV technical potential was calculated by multiplying the suitable area found in the analysis by panel rated power output of 239 W/m^2 and dividing by spacing factor (total system area/panel area) of 1.8 m^2 that includes nominal "spacing" between panels in the plant footprint area. Detailed explanation of the calculations can be found in Annex 3.

From the results of the areas that were found technically suitable for PV and CSP installation, further GIS analysis was conducted by identifying areas with environmental statutory protection, areas important for bird conservation (BIA), and military ground. Explanations regarding the data sources, the reasoning behind the chosen criteria and the spatial analysis process are the same as the details outlined in the onshore wind part of this chapter. The National Outline Plan for Photovoltaic Installations- NOP 10/D/10 bans from installing small and moderate photovoltaic installations in shore texture (as defined in NOP35) and in areas with scenic, heritage, archeological, and ecological importance including Ecological Corridors. Due to limited data on heritage sites, this limitation was not part of the analysis but it can be assumed that most of those areas were eliminated as part of the elimination of built structures and archeological sites. It also states that installation of photovoltaic on military ground requires the approval of the Ministry of Defense. Small and moderate photovoltaic installations are defined in the NOP as areas smaller than 750 Donam (750,000 square meters). For large photovoltaic installations, each PV farm or CSP has to be assed separately due to their individual large impacts on the environment (State of Israel 2015). Constructing photovoltaic installations in protected areas will be more limited due to statutory

[6] Data source: https://ims.data.gov.il/he/ims/6 (In Hebrew)

limitations as described in the analysis of onshore wind farm. Further, agriculture areas were excluded in order to prevent competition between food resources and energy resources.

To evaluate **CSP practical potential** only areas with no limitations as described were considered as practically suitable areas. CSP practical potential was **calculated** by multiplying the area found suitable by CSP storage weighted areal power density of 34.07 MW/km^2.

From the results of this spatial analysis only areas with no limitations at all (possibly overlapping partially with areas designated to the military) on non-agricultural land were used to calculate the utility-scale PV practical potential. Although PV farm can be constructed on a steep slope, doing so would increase installation costs. To make sure no overlap exists between the CSP practical potential and utility-scale PV practical potential, areas suitable for CSP were subtracted since areas for CSP development are more restricted than to utility scale PV. The remaining area was multiplied by panel rated power output of 239 W/m^2 and divided by a spacing factor of 1.8 m^2.

For further steps towards implementation, economic limitations associated with solar construction and maintenance such as distance to transmission lines and roads, should also be taken into consideration as described in the onshore wind analysis.

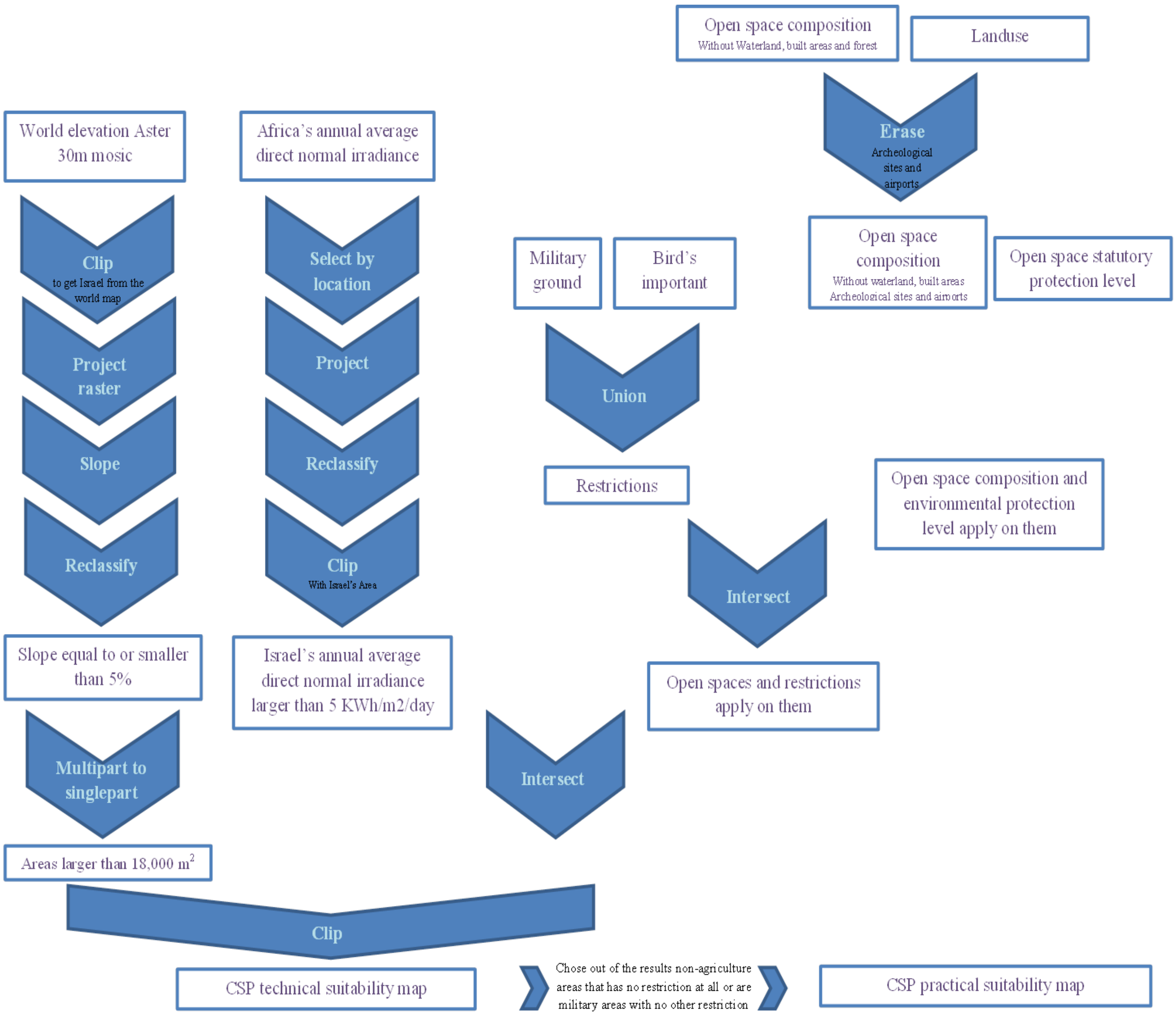

Figure 18. Flowchart for modeling suitability of CSP

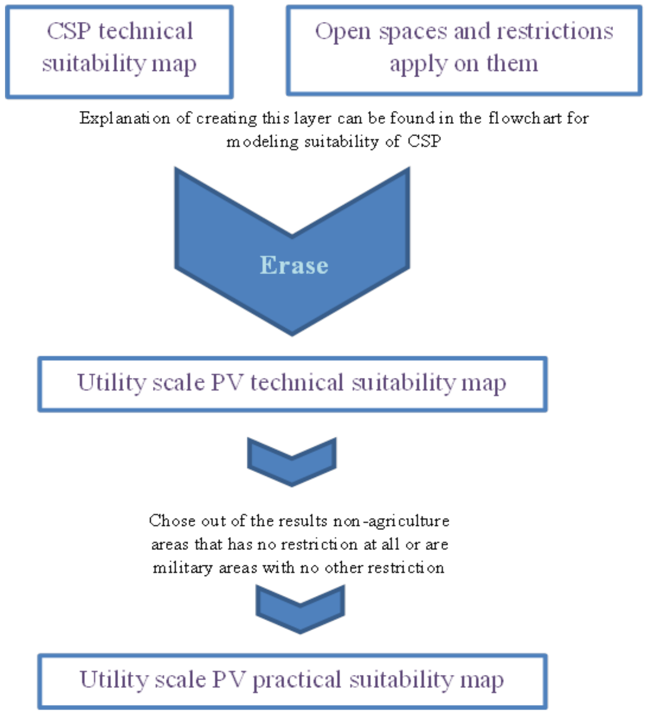

Figure 19. Flowchart for modeling suitability of utility scale PV

6.2 Rooftop analysis

To determine Israel's available residential rooftop space an analysis was conducted on data provided by Israel's Ministry of Environmental Protection from 2015. However, it was not possible to calculate the equivalent available commercial and governmental rooftop space since the necessary average number of stories in commercial and governmental building is nonexistent in Israel. The available area for PV in commercial rooftop in 2050 has been estimated by Jacobson at el. (2015) and its results are used as is without validation in the Discussion.

Israel's Ministry of Environmental Protection (MoEP) has provided results of an analysis the MoEP conducted on the uses of the structures in Israel. MoEP stated that the results for residential rooftop area and non-residential rooftop area such as leisure, services and commerce, religion, education, municipality and government and transportation, is inaccurate due to an inability of their analysis to correctly categorize the structures to the right usage.

In order to reveal the ratio between all of Israel's residential and non-residential structures an analysis was conducted using data of the amount of residential and non-residential structures that were built between the years 1995-2015 as previous data does not exist online by Israel Central Bureau of Statistics. From the ratio between the years 1995-2015 an extrapolation was made to estimate the ratio between all of Israel's residential and non-residential structures (also for the structures built previous to 1995). For verification purposes, the estimated ratio was compared to previous research of Vardimon (2011) and Shofrony (2014). Using the ratio Israel's rooftop area for residential and non-residential structures for 2015 was calculated.

Further verification has been conducted by comparing the results to the average floor area per capita of European countries based on data from [7]ENTRANZE from 2008. Israel's rooftop area was calculated based on number of residents that live in Israel, the number of averaged stories in residential buildings and the average floor area per capita for residential buildings. The average number of stories in residential building was calculated from data provided by Israel Central Bureau of Statistics (CBS) for the years for years 1995-2014 and later on was estimated for building that was built also before 1995.

The residential useable area of the rooftop was estimated by using Jacobson et al (2016) usability ratio for urban area and for non-urban area. Estimation of the percentage of urban population in 2050 are taken also from Jacobson and Delucchi (2016). The technical potential was calculated by multiplying the estimated usable area of residential rooftop by the solar panel rated power of solar PV panel SunPower E20.

The amount of area available for PV construction on residential rooftops in 2050 was calculated based on the fraction of rooftop areas suitable for PV installations in urban area and in non-urban areas in 2050, estimated residential floor area per capita in 2050, amount of population in 2050.
The technical potential was calculated by multiplying the estimated available residential rooftop by the estimated solar panel rated power in 2050. This rated power was calculated by Jacobson et al. (2015) by extrapolating from 2015 rated power assuming solar PV panel characteristics of SunPower E20.

Explanations to the calculation of available residential rooftops for PV construction can be found in Annex 3.

[7] Data source: http://www.entranze.enerdata.eu/

7. World plan results

This chapter presents Israel's results from Prof. Jacobson "World Plan" in the paper '100% Clean and Renewable Wind, Water, and Sunlight (WWS) All- Sector Energy Roadmaps for 139 Countries of the World' (Jacobson et al. 2016). This chapter will highlight Israel's expected energy demand in 2050 in Business As Usual (BAU) and in a scenario of converting its all-purpose energy infrastructures to one powered by wind, water, and sunlight (WWS). Furthermore, this chapter outlines the number of WWS generators and corresponding footprint and spacing areas needed to meet demand in the WWS case, and an energy mix that will allow Israel to convert its all-purpose energy infrastructure to WWS by 2050. Finally, this chapter presents a timeline to transform 139 countries that can also be suitable for Israel to rely only on WWS technologies by 2050.

As mentioned before, in this work I have adopted Prof. Jacobson's proposal for a target WWS supply mix to address Israel's future energy demand projections in a 100% renewable energy manner. The results presented here will be discussed in context of the results of the GIS analysis.

7.1 Demand projection

Jacobson et al. (2016) estimate that Israel's total end-use power demand in 2050 will be 27.2 GW (104.5 TWh/year) in a "business as usual" (BAU) fossil-fuel based scenario, and 15.8 GW (139.1 TWh/year) in a 100% WWS scenario. Replacing fossil fuels with WWS technologies is expected to generate total reduction of end-use demand by 42% relative to a BAU scenario. These projections are based on expected Israel's population growth by 36.5% between 2015-2050.
Jacobson et al. projects that Israel's population will grow from 8.4 million in 2015 to 9.4 million in 2030 and 10.8 million in 2050.

Israel's reduction of end-use demand in 2050 is projected to be 24.4% due to electrification of end uses, 8.4% due to changes in upstream energy use, and 8.9% due to additional efficiency measures (Jacobson et al. 2016, Jacobson & Delucchi 2016). Israel's efficiency gain due to electrification of end-uses in the WWS scenario is projected to be influenced mainly by efficiency in the transportation and industrial sectors (69% and 50%, respectively).

Table 6. Israel's end-use power demand for all-purposes by sector in 2012 and estimated demand in 2050 in case of (1) "business as usual" (BAU) where fossil-fuel, nuclear, and biofuel will continue to be consumed or in case of (2) converting Israel's all-purpose energy resources to 100% WWS by 2050. Also presented is the reduction of end-use demand in 2050 due to conversion to WWS.

Energy Sector	BAU- Conventional fossil fuels, nuclear and biofuel (GW)		WWS- Replacing fossil fuels, nuclear and biofuel with WWS (GW)		Energy end-use demand reduction due to conversion to WWS in 2050 (%)
	2012	2050	2012	2050	
Residential	4.30	6.02	3.15	4.45	26%
Commercial	2.07	4.00	1.61	3.10	22%
Industrial	4.19	5.90	2.13	2.96	50%
Transportation	7.35	7.81	2.24	2.38	69%
Agriculture/forestry/fishing	0.22	0.24	0.22	0.24	0%
Other	3.10	3.28	2.58	2.74	17%
Total	**21.22**	**27.26**	**11.93**	**15.88**	**42%**

Data derived from Jacobson and Delucchi (2016) calculations for 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World. The calculations use the method of Jacobson and Delucchi (2011) with IEA (2015) end-use demand data.

7.2 Suggested 2050 WWS energy mix

Table 7 presents Prof. Jacobson's proposed energy mix and the amount of new plants or devices that are needed for providing Israel's total projected end-use energy demand from Table 6. According to Prof. Jacobson's proposal, 80.5% of Israel's energy will be generated by solar and 19.4% by wind turbines. Intuitively, this energy mix makes sense considering Israel's high solar resource accessibility while wind has lower availability since sufficient wind speed for generating electricity is limited to specific areas. Solar and wind are the only two resources capable to power Israel on their own, and a mix of both is required to ensure grid reliability. Furthermore, in 2050 with WWS world, the grid will be more flexible than today due to integration of technologies such as BEV charging and hydrogen production that will allow better matching load with peak WWS availability (Jacobson et al. 2014).

According to estimates of Table 7, replacing Israel's all-purpose energy infrastructure with WWS by 2050 will require 2.3% of Israel land area (of which 13% of land is already in-use (primarily roof-tops), and 87% (or 2% of Israel's total land area) is the additional land required footprint for new devices/plants). "This does not account for the decrease in footprint from eliminating the current energy infrastructure, which includes the footprint for mining, transporting, and refining fossil fuels and uranium and for growing, transporting, and refining biofuels and bioenergy" Jacobson et al. (2016). Spacing area on new land is 1.6% of Israel's land area and is needed only for wind turbines. Spacing on Israel's offshore area is 3.2% of Israel's offshore area and is needed only for wind turbines. Furthermore, Table 7 demonstrates that in 2015 only 1.6% of the total nameplate capacity necessary for converting Israel to 100% of its all-purpose energy infrastructure to one derived entirely from renewable energy by 2050 was already installed (Jacobson et al. 2016).

Table 7. Presented are the rated power and average capacity factors in 2050 for WWS technologies, as well as the number and capacities of WWS power plants or devices needed to provide Israel's total annually-averaged end-use power demand for all-purposes in 2050, accounting for transmission, distribution, forced and unforced maintenance, and array losses. Also shown are currently installed nameplate capacity and the footprint areas and spacing areas in Kilometer Squared and percentage of Israel's land area.

	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)
Energy Technology	Rated power of one unit (MW)	Average capacity factor in 2050	Percent of 2050 power demand met by technology	Technical potential capacity (MW)	End use power delivered (MW)	Total nameplate capacity needed (MW)	Installed nameplate capacity for 2015 (MW)	Percent of nameplate capacity already installed 2015	Number of new units needed	Footprint area for new units (km^2)	Spacing for new units (km^2)	Footprint area for new units (% of Israel)	Spacing area for new units (% of Israel's land)	Spacing area for new units (% of Israel's offshore area)
Onshore wind	5	40.51%	6.84%	2,682	1,087	2,682	31	1.16%	530	0.01	353.55	0.00%	1.63%	-
Offshore wind	5	32.49%	12.60%	6,155	2,000	6,155	0	0%	1,231	0.02	820.86	0.00%	-	3.16%
Wave device	0.75	9.49%	0.00%	0	0	0	0	100%	0	-	-	-	-	-
Geothermal electric plant	100	85.44%	0.00%	0	0	0	0	100%	0	-	-	-	-	-
Hydroelectric plant	1300	47.45%	0.02%	7	3	7	7	100%	0	-	-	-	-	-
Tidal turbine	1	23.36%	0.01%	9	2	9	0	0%	9	0.00	0.03	0.00%	-	0.00%
Res. roof PV	0.005	23.44%	17.48%	19,162	2,775	11,838	239	2.02%	2,319,806	50.95	-	0.24%	-	-
Com/gov roof PV	0.1	22.22%	9.03%	8,827	1,434	6,452	298	4.62%	61,540	27.03	-	0.12%	-	-
Solar PV plant	50	23.70%	41.29%	1,905,180	6,555	27,656	344	1.25%	546	333.82	-	1.54%	-	-
CSP plant	100	61.24%	12.73%	488,561	2,021	3,301	6	0.18%	33	96.69	-	0.45%	-	-
Total			**100.0%**	**2,430,583**	**15,877**	**58,099**	**925**	**1.59%**	**2,383,695**	**508.50**	**1174.44**	**2.35%**	**1.63%**	**3.16%**
Total new land												**1.99%**	**1.63%**	**3.16%**
For peaking power / storage														
CSP plant	100		7.6%		1,213	1,980.40	0	0.00%	20	58.12	-	0.27%	-	-
Solar thermal for heat	50					7,227.29	3,501	48.44%	75	5.32	-	0.02%	-	-
Geothermal heat plant	50					82.40	82	100%	0	0	-	0.00%	-	-
Total for storage						**9,290**	**3,583**	**38.57%**	**94**	**63**	**0**	**0.29%**	**-**	**-**
Total new land												**0.29%**	**-**	**-**
Annual power + storage												**2.64%**	**1.63%**	**3.16%**
*New land												**2.28%**	**1.63%**	**3.16%**

Data derived from Jacobson and Delucchi (2016) Spreadsheets of calculations for 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World. The source of the footnotes of the table is Jacobson et al. (2016). *New land= New land for annual power + storage

a. Rated powers[8] are based on existing reliable technologies.
b. The capacity factors[9] for 2050 for residential PV, commercial/government rooftop PV, utility scale PV, and CSP are calculated for Israel from the 3-D global model. The onshore and offshore wind capacity factors in 2050 are calculated

[8] Defined in Terms
[9] Defined in Terms

for Israel at 100-m hub height out of global model simulations of wind power that account for competition between wind turbines for available kinetic energy based on the estimated number of wind turbines needed for Israel and after subtracting transmission, distribution, maintenance, and array losses (Jacobson et al. 2016).

c. Percent of annually all-purpose end-use power demand in a WWS scenario (from Table 6) to be met by each of the WWS technologies, according to Prof. Jacobson proposal. The percent of power demand met by technology in 2050 assumes that wind and solar are the only two resources that Israel can rely on.

d. Israel's technical potential for onshore wind is based on onshore wind areal power density and total onshore land area minimum acceptable capacity factor. The technical potential for offshore wind was estimated as the product of the areal power density for offshore wind systems and Israel's coastal length. Wave technical potential capacity was estimated as a function of the wave power available per unit of coastline, the fraction of the coastline that can be exploited for wave power, the efficiency of the wave-energy converter (WEC), and the capacity factor without consideration of the availability of the WEC. Tidal technical potential is estimated based on a nonlinear function of the length of Israel coastline. Utility-scale PV plants technical potential is based on land area with at least the minimum acceptable solar insolation which is a function of the total PV-system areal power density (areal power density of utility scale PV is estimated as a function of the module density (which increases over time) and a spacing factor (which is estimated based on a function of population density)). CSP technical potential is estimated by the land area with minimum DNI exposure of 5 kWh/m^2/day.

e. Israel's end-use power delivered in 2050 for each of the technologies was calculated by multiplying the fraction of load fulfilled by each WWS technology (as proposed) by the total end-use power delivered in 2050.

f. Total nameplate capacity[10] needed to be installed in 2050 for onshore wind, offshore wind, geothermal, tidal, and wave power is limited to Israel technical potentials. For hydropower, the nameplate capacity is assumed to be the same as in 2015. For rooftops, utility scale PV, and CSP, the total nameplate capacity needed to be installed in 2050 is calculated by dividing the end-use power delivered in 2050 by the product of 2050 capacity factors and the overall transmission and distribution efficiency in 2050.

g. Nameplate capacity already installed in 2015

h. Percent of nameplate capacity already installed in 2015 out of the total nameplate capacity needed in 2050 to provide 100% of Israel's all-purpose energy demand.

i. The number of new devices needed in 2050 is calculated by dividing the total of the nameplate capacity needed in 2050 minus the already installed capacity in 2015 by the rated power of device or plant.

j. For utility PV plants, nominal "spacing" area between panels is counted in the plant footprint area. For CSP plant the mirror sizes characteristics are the same as the mirror used at Ivanpah Solar Power Facility in California Mojave Desert.

k. Spacing area for onshore and offshore wind is calculated as 42D2, where D is rotor diameter of the wind turbine of 126 m (same as Senvion's RePower 5M wind turbine).

l. Israel's land area is 21,640 km^2.

The following values were used for Israel as for the rest of the countries in the world plan: "Short- and moderate distance transmission, distribution, and maintenance losses for all energy sources treated here, except rooftop PV, are assumed to be 5-10%. Rooftop PV losses are assumed to be 1-2%. The plans assume 38 (30-45)% of onshore wind and solar power and 20 (15-25)% of offshore wind power is subject to long-distance transmission loss with line lengths of 1400 (1200-1600) km and 120 (80-160) km, respectively. Line losses are 4 (3-5)% per 1000 km plus 1.5 (1.3- 1.8)% of power in the station equipment " (Jacobson et al. 2016).

Offshore energy sources or rooftops PV do not require new land for spacing. Thus, the new land area required is smaller than the total footprint area and equals the sum of the footprint areas for new onshore wind, geothermal, hydropower, and utility solar PV. Offshore wind, wave and tidal generators are in water and thus do not require new land; likewise for rooftop PV that can be installed on existing rooftops, parking lots or other structures. Note that only onshore wind requires new land for spacing. The additional needed CSP power or storage in addition to the necessary annual power generation for insuring the grid reliability is presented.

Table 8 presents suitable rooftop areas and technical potentials for PV installation for residential, commercial, government and industrial buildings in 2050 as estimated by Prof. Jacobson. Furthermore, the proposed installed capacities and fractions out of technical potential in 2050 are presented. The calculations account for rooftops of residential, commercial, and governmental buildings. Garages, parking lots and structures associated with these buildings were accounted for. Commercial and governmental buildings include any non-residential buildings (including schools) excluding manufacturing, industrial, and military buildings (Jacobson et al. 2016).

[10] Defined in Terms

Table 8. Suitable rooftop areas and technical potential for PV installation for residential, commercial, government and industrial buildings in 2050. Also shown are proposed installed capacities and fractions out of technical potential in 2050

	Suitable rooftop area 2050 (km2)	Technical potential 2050 (MW)	Installed generation capacity to meet electricity demand in 2050 (MW)	Percent of installed capacity relative to technical potential in 2050
Residential buildings, including residential parking	80	19,162	11,838	62%
Commercial government and industrial buildings	37	8,827	6,452	73%

Data derived from Jacobson and Delucchi (2016) Spreadsheets of calculations for 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World.

Jacobson et al. (2016) estimates that Israel's technical potential for residential rooftops in 2050 to be 19,162 MW and suggests using 62% of Israel's technical potential for PV installed on residential rooftops. For commercial/government rooftop areas, Israel's technical potential is estimated to be 8,827 MW and Jacobson et al. (2016) suggests using 73% of the potential.

Jacobson et al. (2016) propose the following timeline to transform 139 countries of the world to rely only on WWS technologies by 2050:

- As soon as possible- Development of super grids and smart grids that will allow better manage energy demand and supply.
- by 2020, all new power plants will be WWS. Existing conventional power plants will be phased out gradually by 2050. Also, heating/cooling, drying, and cooking devices in the residential and commercial sectors will be powered by electricity.
- by 2025, all new ships should be electrified and/or use electrolytic hydrogen. All new port operations, new rail and bus transport should be electrified and powered by WWS electricity.
- by 2030 all new off-road transport, small-scale marine, light-duty on-road transport, heavy-duty truck transport, and industrial processes should be electrified.
- by 2035, all new short-haul aircraft should be powered by battery or electrolytic hydrogen.
- by 2040, all new long-haul aircraft should be powered by electrolytic cryogenic hydrogen.

Jacobson et al. (2016) roadmap presents the projected end-use power demand and suggests energy mix that will fulfill this demand without accounting for environmental and site regulations. In the next chapter an analysis for site suitability will be presented.

8. Results

8.1 GIS spatial analysis

8.1.1 Onshore wind

Table 9 presents areas found by spatial analysis to be technically suitable for onshore wind farms. Israel has an area of 2153 km^2 with onshore annual average wind speeds at 100 m height greater than 6 m/s. With wind turbine same as Senvion's RePower 5M at 100 m height, Israel has a total potential of 13.8 GW of installed capacity. Multi-layered analysis found 1211 km^2 of Israel's onshore area to be technically suitable for onshore wind farm installation (Those areas stand in the criteria of being in open space (areas that are not urban areas, water land archeological sites and airports), slope percentage less than or equal to 30, wind speed equal to or greater than 6 m/s. Israel's total technical potential for wind farms is 7.8 GW of installed capacity. Out of the areas found technically suitable, further criteria, as detailed in the Methods, were used in order to find areas practically suitable for wind farm installation. After accounting for such criteria, spatial analysis found 448 km^2 of Israel's onshore area practically suitable for wind farm installation. Spatial analysis also found that 137 km^2 of the area practically suitable area for onshore wind development has annual average wind speeds greater or equal to 6.5 m/s at heights of 100 meters and 23 km^2 have annual average wind speeds greater or equal to 7 m/s at 100 meters. Israel has 633.45 km^2 of area technically suitable for wind farm development with slope percentages less than or equal to 15 and 386.19 km^2 of area with slope percentages less than or equal to 10. It's noteworthy to mention that out of the 448 km^2 of area practically suitable, 249 km^2 overlaps with military grounds, which is roughly 3% of Israel's total military ground (7,895 km^2). An analysis of energy sources overlap with military grounds can be found at the end of the Results chapter, and further a discussion of such finding can be found at the Discussion chapter.

Figure 20 presents Israel's technical suitability map for wind energy development. The map uses color coding to distinguish between different areas that are technically suitable, based on the practical limitations applied to them. Gradations of red indicate the more severe limitations, while the less severe limitations are highlighted by green gradations. About 6% of Israel's land area is technically suitable for wind energy development. As can be seen in the map, these areas are primarily located in the northern and southern parts of Israel - the Galilee and Negev areas. As the map illustrates (Figure 20), a large area in the southern part of Israel close to the city of Eilat was found technically suitable for wind farm installation but subject to environmental protection regulations and high ecological sensitivity for birds (Birds Important Areas). Figure 21 presents Israel's practical suitability map for the wind energy development where only areas with no limitations at all or military land areas are marked. Areas practically suitable for wind farm installation are also located mainly at the northern and southern parts of Israel- Galilee and Negev areas.

Results

Table 9. Spatial analysis results for areas suitable for wind farm installation (km^2)

Slope precentage	Area's limitations*	Total area [Km^2] for average wind speed greater than		
		6 (m/s)	6.5 (m/s)	7 (m/s)
Any slope	No limitation. Including not open space areas	2153.57	952.51	292.49
	No limitation (& areas on Open Space)	1978.71	875.98	278.58
	No Limitation	198.63	64.52	12.88
	Military Ground	249.37	72.56	10.53
	BIA	87.93	62.07	10.59
	Shore Texture	0.24	0.08	0.04
	Military Ground &BIA	4.31	1.07	0.05
	BIA & Shore Texture	---	---	---
	Military Ground &Shore Texture	---	---	---
	Military Ground & BIA & Shore Texture	---	---	---
	Medium Env. Protection	10.94	2.63	0.64
	Medium Env. Protection & Military Ground	0.19	0.06	0.04
	Medium Env. Protection & BIA	0.64	0.18	0.01
	Medium Env. Protection & Shore Texture	---	---	---
Slope=<30%	Medium Env. Protection & Military Ground &BIA	0.07	0.00	0.00
	Medium Env. Protection& BIA & Shore Texture	---	---	---
	Medium Env. Protection & Military Ground &Shore Texture	---	---	---
	Medium Env. Protection & Military Ground & BIA & Shore Texture	---	---	---
	High Env. Protection	243.11	107.79	35.28
	High Env. Protection & Military Ground	233.71	75.36	17.50
	High Env. Protection & BIA	176.01	117.72	57.66
	High Env. Protection & Shore Texture	0.20	0.13	0.07
	High Env. Protection & Military Ground &BIA	5.67	0.93	0.16
	High Env. Protection& BIA & Shore Texture	---	---	---
	High Env. Protection & Military Ground &Shore Texture	---	---	---
	High Env. Protection & Military Ground & BIA & Shore Texture	---	---	---
	Total slope =< 30	**1211.01**	**505.10**	**145.43**
	No Limitation	112.04	36.79	7.47
	Military Ground	136.83	36.60	5.28
	BIA	71.56	54.11	8.40
	Shore Texture	0.06	0.01	0.01
	Military Ground &BIA	1.88	0.40	0.03
	BIA & Shore Texture	---	---	---
	Military Ground &Shore Texture	---	---	---
	Military Ground & BIA & Shore Texture			
	Medium Env. Protection	5.41	1.17	0.24
	Medium Env. Protection & Military Ground	0.09	0.02	0.01
	Medium Env. Protection & BIA	0.32	0.14	0.00
	Medium Env. Protection & Shore Texture	---	---	---
Slope =<15%	Medium Env. Protection & Military Ground &BIA	0.01	0.00	---
	Medium Env. Protection& BIA & Shore Texture	---	---	---
	Medium Env. Protection & Military Ground &Shore Texture	---	---	---
	Medium Env. Protection & Military Ground & BIA & Shore Texture	---	---	---
	High Env. Protection	111.86	46.14	14.42
	High Env. Protection & Military Ground	104.24	32.87	7.68
	High Env. Protection & BIA	86.72	56.79	22.56
	High Env. Protection & Shore Texture	0.05	0.04	0.02
	High Env. Protection & Military Ground &BIA	2.37	0.32	0.07
	High Env. Protection& BIA & Shore Texture	---	---	---
	High Env. Protection & Military Ground &Shore Texture	---	---	---
	High Env. Protection & Military Ground & BIA & Shore Texture	---	---	---
	Total slope=< 15%	**633.45**	**265.41**	**66.20**
	No Limitation	67.83	22.15	4.44
	Military Ground	81.09	20.66	2.96
	BIA	58.82	45.77	6.57
	Shore Texture	0.03	0.01	0.01
	Military Ground &BIA	1.03	0.21	0.01
	BIA & Shore Texture	---	---	---
	Military Ground &Shore Texture	---	---	---
	Military Ground & BIA & Shore Texture	---	---	---
	Medium Env. Protection	3.22	0.66	0.14
	Medium Env. Protection & Military Ground	0.05	0.01	0.00
	Medium Env. Protection & BIA	0.25	0.13	0.00
	Medium Env. Protection & Shore Texture	---	---	---
Slope= < 10%	Medium Env. Protection & Military Ground &BIA	0.01	0.00	0.00
	Medium Env. Protection& BIA & Shore Texture	---	---	---
	Medium Env. Protection & Military Ground &Shore Texture	---	---	
	Medium Env. Protection & Military Ground & BIA & Shore Texture	---	---	---
	High Env. Protection	62.28	24.57	7.58
	High Env. Protection & Military Ground	56.64	17.67	4.10
	High Env. Protection & BIA	53.66	35.37	12.11
	High Env. Protection & Shore Texture	0.02	0.02	0.01
	High Env. Protection & Military Ground &BIA	1.27	0.16	0.04
	High Env. Protection& BIA & Shore Texture	---	---	---
	High Env. Protection & Military Ground &Shore Texture	---	---	---
	High Env. Protection & Military Ground & BIA & Shore Texture	---	---	---
	Total slope=< 10%	**386.19**	**167.39**	**37.98**

All the areas are within Israeli territory. If not mentioned otherwise all areas are on open space. Open space is the area left after eliminating areas unsuitable for installation due to land-use constraints such as urban areas, water land, roads archeological sites and airports. When a limitation is mentioned the other limitations are excluded. For example- if military ground limitation is mentioned it means the area excludes BIA, Shore Texture & Low/Mid/High Environmental Protection. Values that are marked in light purple are the values used to calculate Israel's technical potential while the light green values were used to calculate the practical potential

Although the plan area of the roadmap is only within Israeli territory, the possibility to collaborate with West Bank on wind energy will be briefly discussed in the Discussion chapter. As such, Table 10 presents areas with onshore wind speeds greater than 6, 6.5 and 7 m/s side by side for Israel and the West Bank.

Table 10. Comparison between areas with suitable wind speed at the West Bank territory and within Israel border (km^2)

Wind speed greater than (m/s)	West Bank area (km^2)	Israel area (km^2)
6	892.61	2153.57
6.5	441.62	952.51
7	166.45	292.49

Note: the values are before elimination of areas not suitable for wind farm installation due to land use, environmental and statutory limitations.

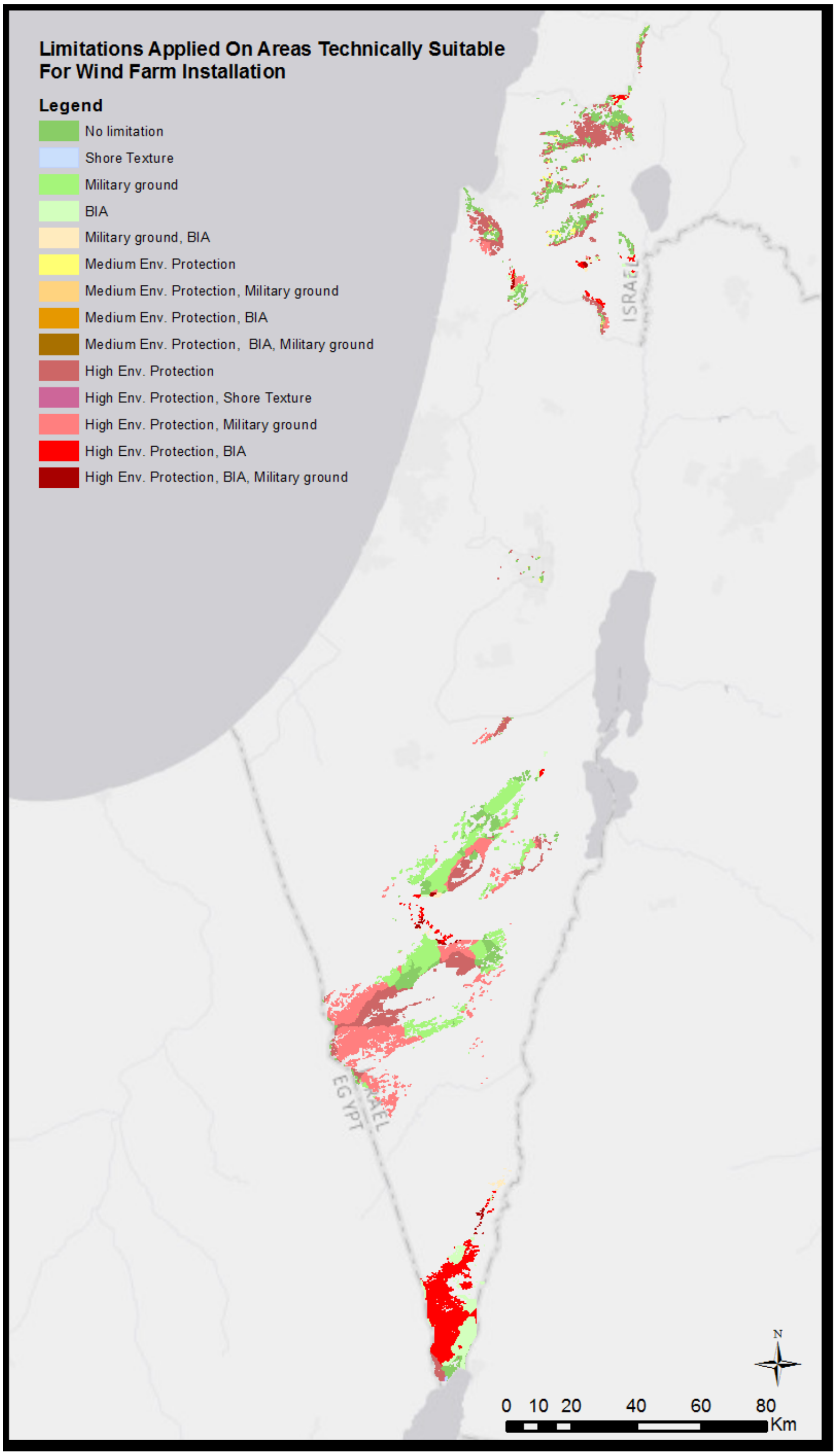

Figure 20. Areas suitable for wind farm installation differentiated by their limitations

Note: The areas marked in the map are technically suitable for onshore wind farm installation. Those areas follow the criteria of being in open space (areas that are not urban areas, water land archeological sites and airports), slope percentage less than or equal to 30, wind speed equal or greater than 6 m/s. The areas marked in green are areas considered most suitable since they are with the least limitations, medium suitability is marked in yellow and the least suitable areas marked in red. Those areas could overlap with areas suitable for CSP and utility scale PV installation.

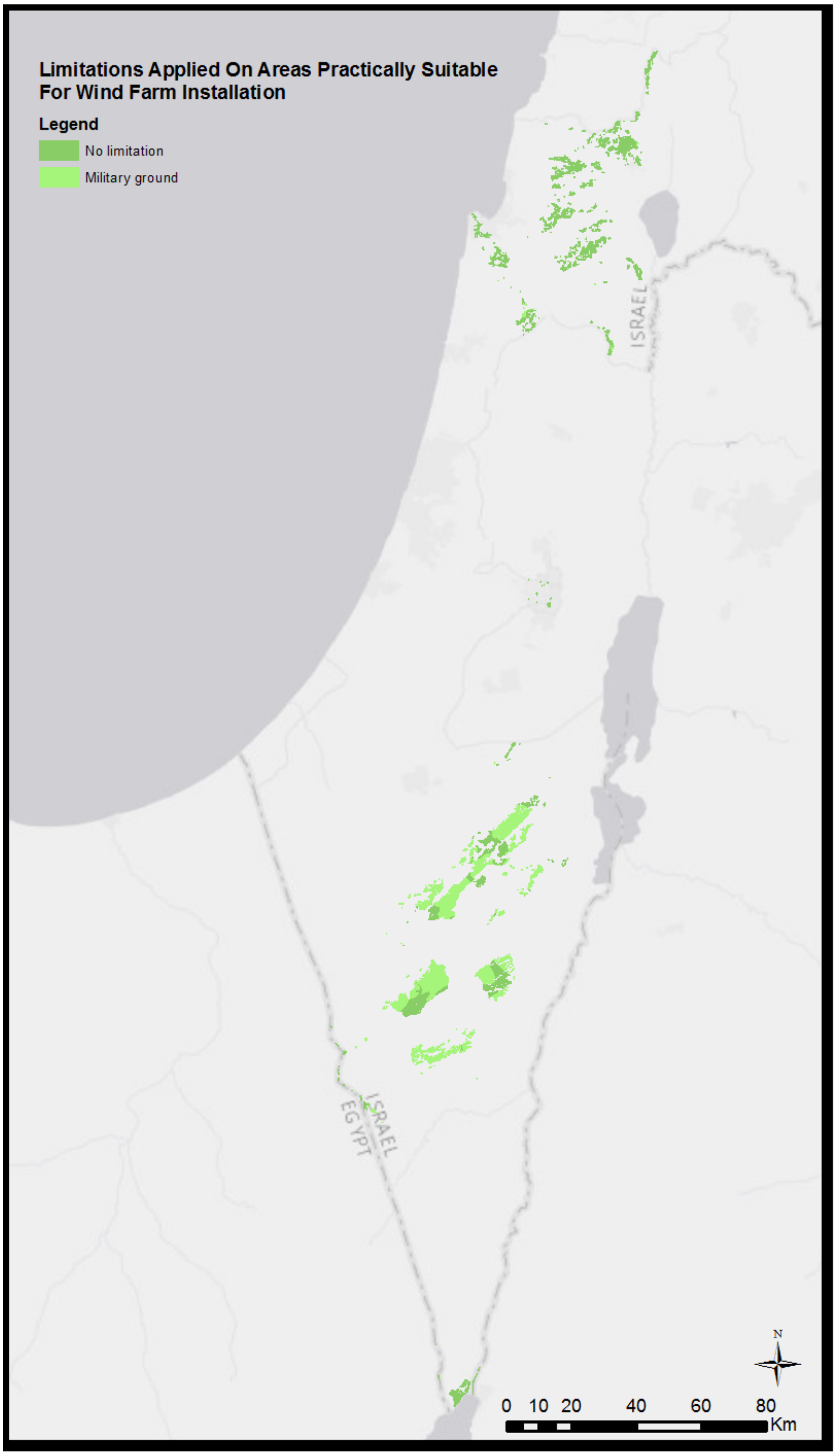

Figure 21. Areas practically suitable for wind farm installation

Note: The areas marked in the map are practically suitable for onshore wind farm installation. Those areas follow the criteria of being in open space (areas that are not urban areas, water land archeological sites and airports), slope percentage less than or equal to 30, wind speed equal or larger than 6 m/s, have no limitation at all or are military ground with no other limitation. Those areas could overlap with areas suitable for CSP and utility scale PV installation.

8.1.2 Solar

8.1.2.1 CSP plant

Table 11 presents areas suitable for utility scale PV and CSP (km^2) as found by spatial analysis. About 1139 km^2 of land are technically suitable for CSP installation. These areas fall into the criteria of being in open space (areas that are not urban areas, water land, archeological sites, airports and forests), having a slope percentage less than or equal to 5, continuous area larger or equal to 18,000 m^2, and DNI greater than or equal to 5 kwh/m^2/day. The technical potential for electricity generation from CSP installation is about 39 GW. It was found that about 266 km^2 are practically suitable for CSP installation. Those areas include areas found in the spatial analysis with no limitations (civilian or military grounds). The practical potential for electricity generation from CSP installation was found to be about 9 GW.

Figure 22 presents Israel's technical suitability map for CSP. The areas found technically suitable were differentiated by the limitations applied to them. Similarly to onshore wind, the map is color coded - areas with less limitations or limitations that were found less destructive to the environment were marked in green while areas with a greater amount of limitations or areas more destructive to the environment were marked in red. Areas technically suitable for CSP were found in limited locations spread all over Israel whereas areas with more environmental protection regulations and high ecological sensitivity for birds (BIA) are located mainly in south Israel (Negev). Figure 23 presents Israel's practical suitability map for the CSP development where only areas with no limitations at all or military ground areas are marked. The practical suitability map illustrates that areas practically suitable for CSP development are spread all over Israel with high concentrations in the southeastern parts of Israel.

Table 11. Spatial analysis results for areas suitable for utility scale PV and CSP (km^2)

	Open Areas				**Area with Slope=<5**				**Area with Slope=<5 & Continuous size=>18,000 m2 & DNI=>5 kwh/m2/day**			
Limitations applied on area	Agri & Non Agri		Non Agri		Agri & Non Agri		Non Agri		Agri & Non Agri		Non Agri	
No Limitation	4,500.85		1,906.71		1,019.83		377.27		326.76		144.83	
Military Ground	2,855.31		2,777.56		420.43		408.15		125.32		121.23	
BIA	3,238.73		1,453.50		668.10		276.79		239.07		124.77	
Military Ground &BIA	1,943.84		1,802.83		390.91		376.77		166.48		163.33	
Medium Env. Protection	101.82		60.78		16.26		8.89		3.03		1.57	
Medium Env. Protection & Military Ground	106.87		105.84		24.31		24.02		14.59		14.50	
Medium Env. Protection & BIA	63.05		39.90		9.73		5.44		1.91		0.81	
Medium Env. Protection & BIA & Military Ground	55.93		52.61		13.66		12.99		4.18		4.04	
High Env. Protection	1,246.89		1,124.72		128.79		111.85		29.82		25.56	
High Env. Protection & Military Ground	2,175.16		2,159.96		243.62		242.30		63.80		63.73	
High Env. Protection & BIA	1,433.91		1,371.20		201.90		194.75		91.26		89.86	
High Env. Protection & BIA & Military Ground	531.28		525.79		130.64		130.22		72.39		72.38	
Total	18,253.64	Z3	13,381.38		3,268.18	Z4	2,169.45		**1,138.63**	Z1	826.59	
Areas used to calculate practical potential (No Limitation + Military Ground)			4,684.27				785.42	Z8			**266.05**	Z7

Note: Open area is the area left after eliminating areas unsuitable for installation due to land-use constraints such as urban areas, water land, archeological sites, airports and forests.

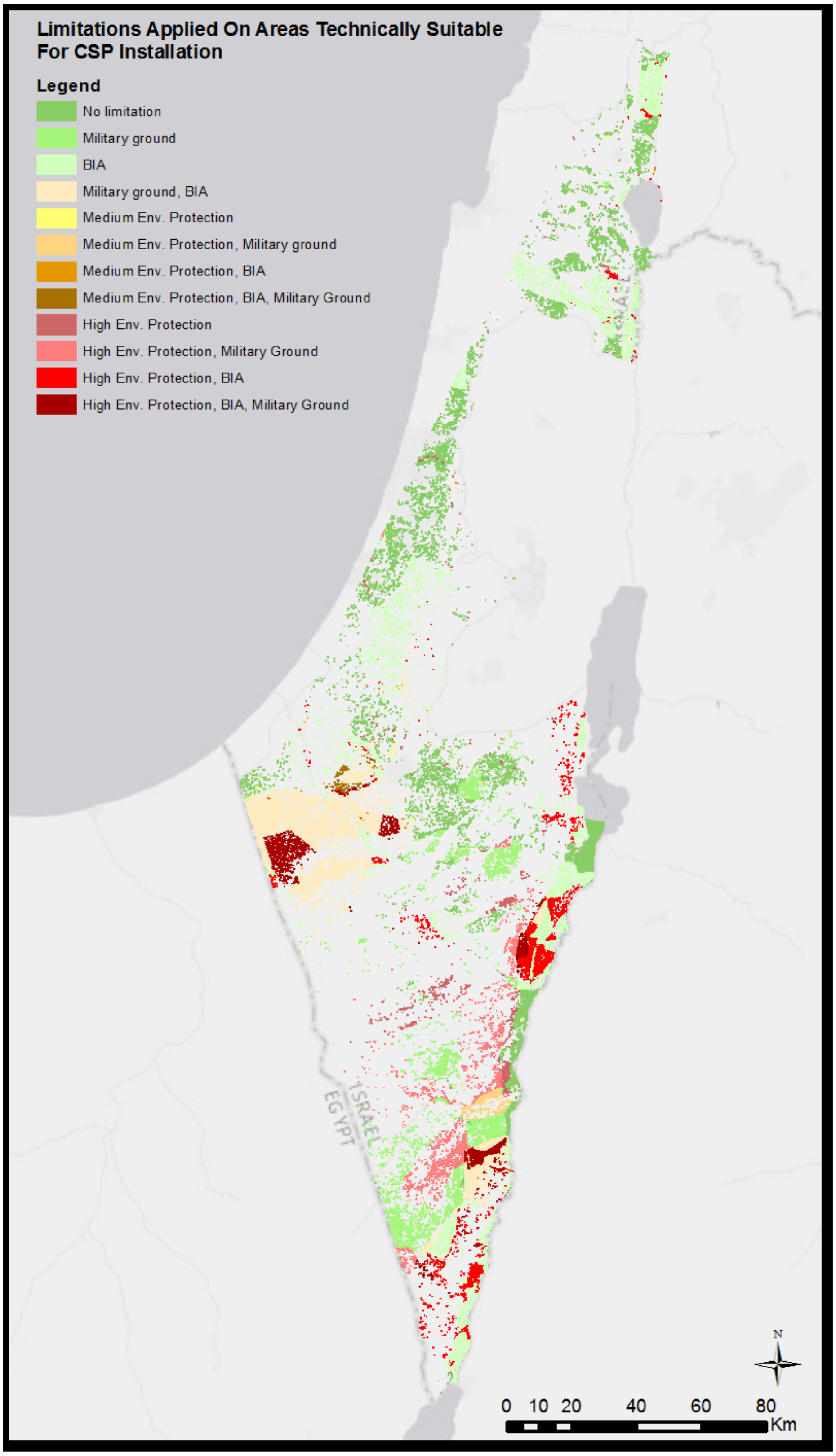

Figure 22. Areas technically suitable for CSP installation differentiated by their limitations

Limitations applied on areas suitable for CSP Installation where open area, slope smaller or equal to 5 percent, continues areas over 180,000 square meters and annual average DNI larger than 5 kWh/m^2/day.

Results

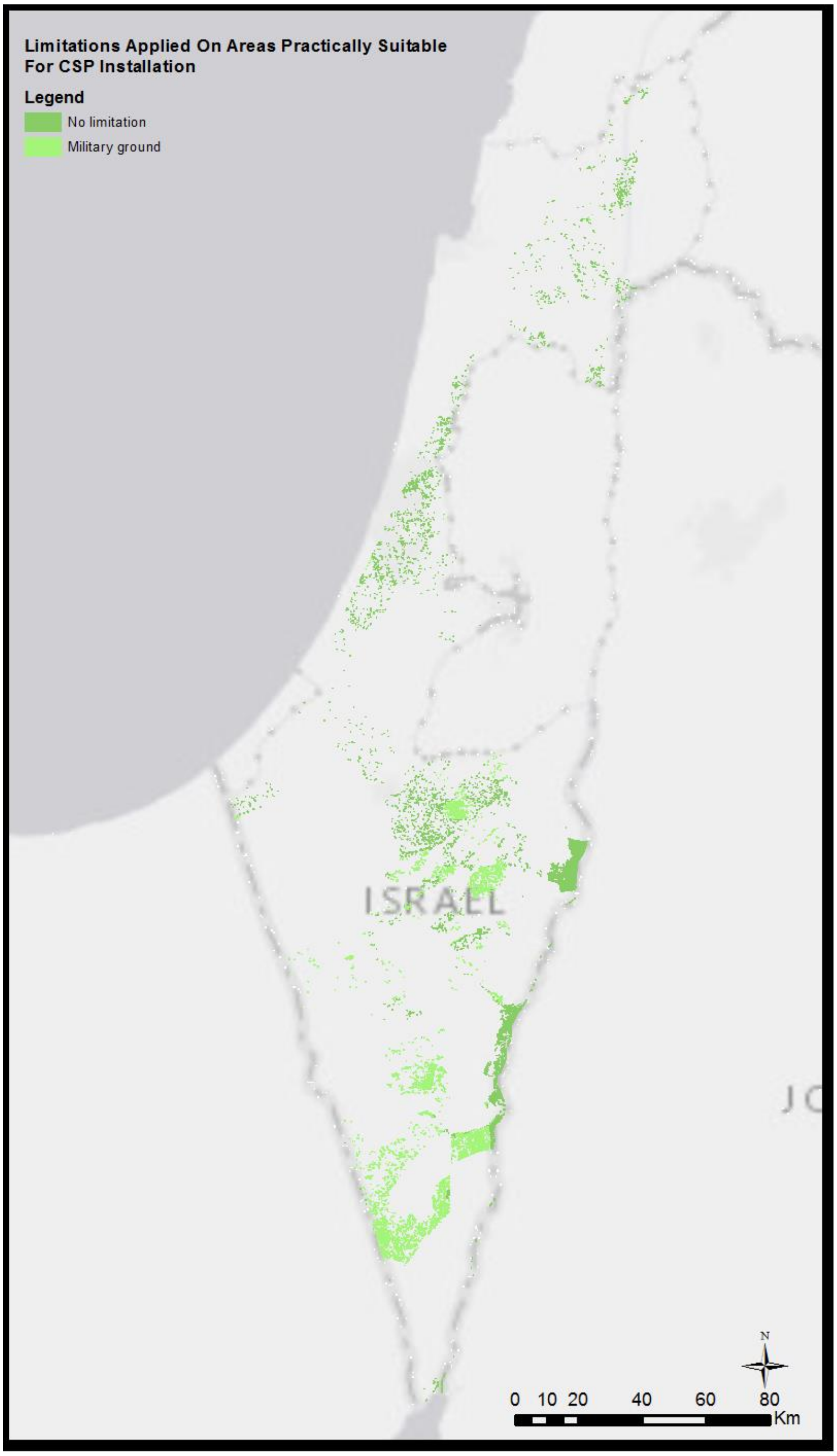

Figure 23. Areas practically suitable for CSP installation with differentiated limitations applied.

Areas that are practically suitable for CSP installation are areas that are defined as open areas with slopes less than or equal to 5 percent, continues size of over 180,000 m2 and annual average DNI larger than 5 kWh/m^2/day, on non-agriculture land, and are not on ecologically sensitive land such as Nature Reserves, National parks and BIA. Those areas were extracted out of areas technically suitable for CSP installation.

8.1.2.2 Utility-scale PV plant

The spatial analysis found 9622 km^2 of area technically suitable for utility scale PV (table 3). Those areas are the sum of areas that were found in the spatial analysis to have slopes less than or equal to 5% and that are not suitable for CSP installation (areas found suitable for CSP were subtracted in order to make sure there will be no overlap), together with half of the areas found to have slope percentages greater than 5. The utility scale PV technical potential was found to be about 1,277,778 MW. Areas practically suitable for utility scale PV installation were found to be about 519 km^2. As mentioned in the Methods, in addition to the mentioned criteria for areas found technically suitable, the following criteria were applied in the spatial analysis to find the practical potential: slope less than or equal to 5%, areas with no limitations at all or military ground with no other environmental or statutory limitation and on non-agricultural land. The practical potential for electricity generation from Utility scale PV is about 9 GW. The final results of this analysis are summarized in Table 12.

Figure 24 presents Israel's technical suitability map for utility scale PV. Areas found technically suitable were differentiated by the limitations applied on them. The same criteria used for the suitability map for onshore wind turbine and CSP were used here. Areas technically suitable for utility scale PV were found all over Israel whereas areas with many environmental protection regulations and high ecological sensitivity for birds (BIA) are located mainly in southern Israel (Negev) and some in the north (Golan Heights). Areas with all three limitations- environmental protection regulations, high ecological sensitivity for birds (BIA), and military ground - were found in several limited locations in southern Israel. Figure 25 displays Figure 24 without areas found technically suitable for CSP. Figure 26 presents Israel's practical suitability map for the utility scale PV development after eliminating areas found practically suitable for CSP. Only areas with no limitations at all or military ground areas are marked. The practical suitability map illustrates that areas practically suitable for utility scale PV development are spread all over Israel with higher concentrations in the southeastern parts of Israel.

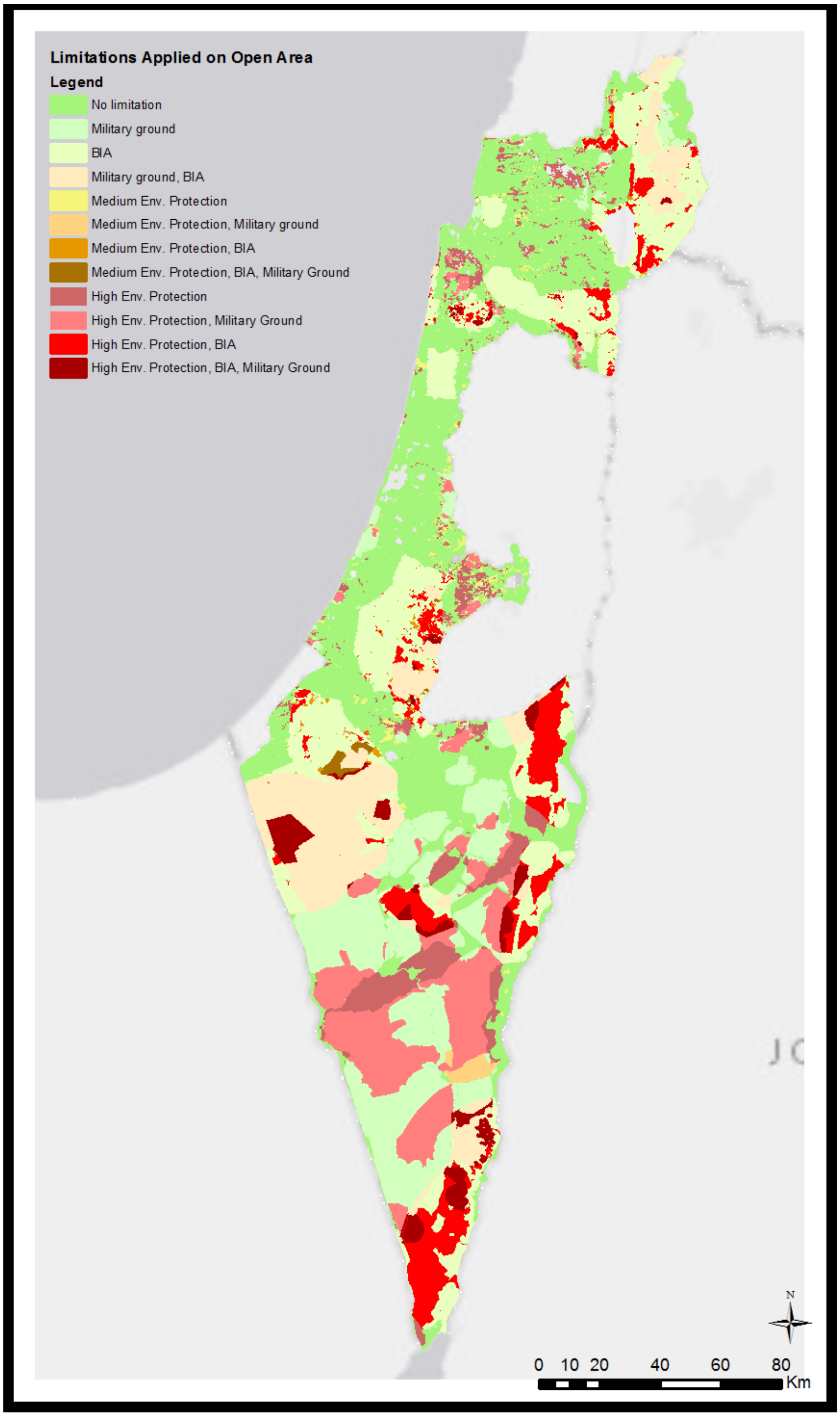

Figure 24. Areas suitable for utility scale PV differentiated by their limitations

Note: The areas marked in green are the most technically suitable for utility scale PV installation (green), medium suitability (yellow), and least suitable (red). These areas overlap with areas suitable for CSP installation. The areas marked in the map are available open space areas that are defined as areas without built structures, water bodies, archeological sites, airports, roads, or forests.

Results

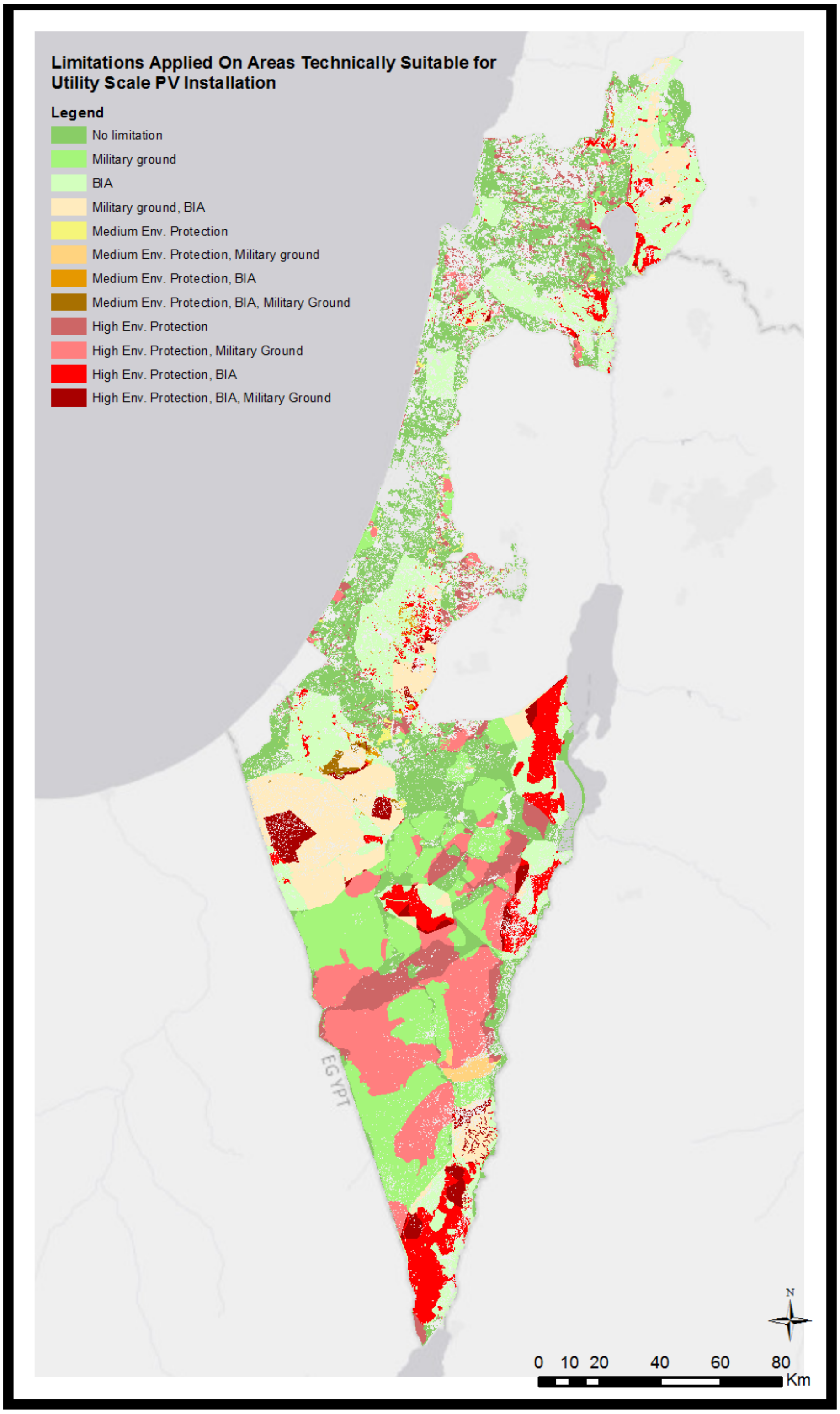

Figure 25. Areas technically suitable for utility scale PV after eliminating areas suitable for CSP

Note: The areas marked on the map are areas most technically suitable (green) for utility scale PV installation, medium suitability (yellow), and least suitable (red). These areas are not built structures, water bodies, archeological sites, airports, roads, or forests. Those areas are ***not*** *overlapping with areas suitable for CSP installation.*

Results

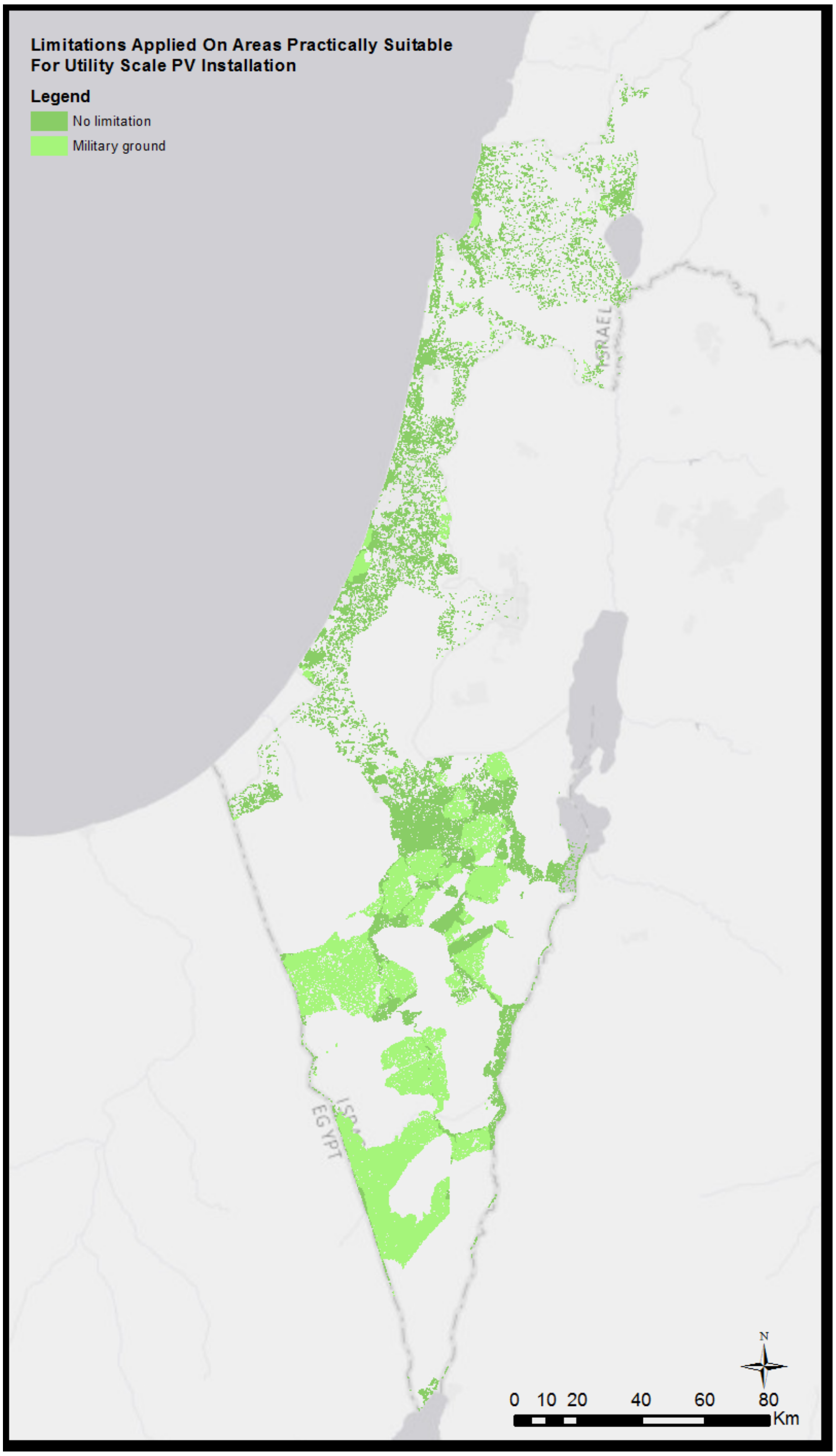

Figure 26. Areas practically suitable for utility scale PV after eliminating areas suitable for CSP

Note: The areas marked on the map are areas that were found practically suitable for utility scale PV installation by the following criteria: they are open areas with slopes less than or equal to 5 percent, on non-agriculture land, and are not on ecologically sensitive land such as Nature Reserves, National parks and BIA. Those areas were extracted out of areas technically suitable for utility scale PV installation and are not overlapping with areas suitable for CSP installation.

Table 12. Summary table of the results of the spatial analysis for technical and practical potential of utility scale solar installation.

	CSP	Utility scale PV
Area suitable techniclly (km^2)	1,138.63	9,622.28
Technical potential (MW)	38,797.90	1,277,778.52
Area suitable practiclly (km^2)	266.05	2,468.79
Practical potential (MW)	9,065.61	327,840.24

8.1.3 Military grounds

Table 13. Summary of results of calculation with regards to the required military grounds repurposing

Energy Technology	A(P) = Area Practically Suitable (km^2)	A(D) = Area required to meet proposed energy output (km^2)	A(MP) = Area Practically Suitable Overlapping With Military Grounds (km^2)	A(P)-A(MP) = Area Practically Suitable Not Overlapping With Military Grounds (km^2)	A(repurpose) = Area to be developed that is overlapping with military (km^2)	% of total area currently defined as military ground
Onshore wind	448	417	249	199	218	2.8%
Solar PV plant	2,469	208	1,471	998	0	0%
CSP plant	266	97	121	145	0	0%

8.2 Rooftop PV

It was found that in 2015 the maximum residential rooftop area suitable for PV installation is 85 km^2, with a technical potential of 17 GW. In 2050 the amount of useable area is estimated to be 91 km^2 with a technical potential of 21.6 GW. Summary of the results can be found in Table 14.

Table 14.Suitable rooftop area for PV installation and technical potential of residential buildings in 2015 and 2050

Year	Suitable residential rooftop area (km^2)	Technical potential (MW)
2015	85	17,035
2050	91	21,661

9. Discussion

This chapter discusses, in combination, Prof Jacobson's results for Israel from the World Plan and the results of this thesis' analyses in an attempt to answer the primary and secondary research question.

Primary research question:
What practical transition plan can convert Israel to 100% all-sector renewable energy by 2050?

Secondary research question:
When accounting for technical, environmental, and regulatory limitations, does Israel have sufficient area for development of wind and solar installations that will allow Israel to fulfill its all-purpose energy demands by 2050?

As Prof. Jacobson's proposal for Israel (Jacobson et al (2016)) was adopted as base plan, to answer the research questions the discussion would focus on the validation of Jacobson's proposal across the different WWS energy sources, and overall, per the proposal. Such validation directly answers the secondary research question. Then, following such validation, a clear practical transition plan to convert Israel to 100% all-sector renewable energy by 2050 will be presented.

To elaborate further on the validation of Jacobson's proposal, the results of the GIS analysis will be discussed in order to conclude whether Israel has sufficient area for development of onshore wind, utility scale PV and CSP plants when accounting for site technical, environmental and regulatory limitations that will allow Israel to meet all-purpose energy demand by 2050. Likewise, the results of the analysis for residential rooftop will be discussed, to see if Israel has sufficient available rooftop area, whether residential or commercial, to meet Jacobson's plan.

Table 15 displays the combined results from Jacobson et al. (2016) and the results of the analyses conducted in this thesis. Table 15 presents the percent of power demand met by each of WWS technologies in 2050 with WWS system per Jacobson's proposal, the end use power delivered by each technology, the total nameplated capacity needed by each technology, and the percentage of currently installed nameplated capacity relative to need in 2050 as estimated by Jacobson et al. (2016). It also presents Israel's technical and practical potential as was found in this thesis for onshore wind, utility scale PV and CSP (marked in blue) and the rest of the WWS technologies estimations as was found by Jacobson et al. And lastly, Table 15 presents the ratio between nameplated capacity needed by each technology and the practical potential in 2050.

Discussion

Table 15. Presented is the percent of 2050 demand met by each WWS technology as suggested by Jacobson et al. (2016), the end-use power delivered, and capacity needed to meet Israel's total annually-averaged end-use power demand for all-purposes in 2050 (marked in black). Also shown are the amount of areas found technically and practically suitable for each of the WWS technologies and their technical and practical nameplate capacity (marked in blue).

Energy Technology	Percent of 2050 power demand met by technology	End use power delivered (MWe)	Total nameplate capacity needed (MW)	Percent of nameplate capacity already installed 2015	Areas found technically suitable (km^2)	Areas found practically suitable (km^2)	Technical potential nameplate capacity (MW)	Practical potential nameplate capacity (MW)	Ratio: practical potential capacity relative to nameplate capacity needed
Onshore wind	6.8%	1,087	2,682	1%	1211.01	448.00	7,784	2,879	1.07
Offshore wind	12.6%	2,000	6,155	0%	---------	---------	6,155	---------	---------
Wave device	0%	0	0	100%	---------	---------	782	---------	---------
Geothermal plant	0%	0	0	100%	---------	---------	0	---------	---------
Hydroelectric plant	0.02%	0	7	100%	---------	---------	7	---------	---------
Tidal turbine	0.01%	2	9	0%	---------	---------	9	---------	---------
Res. roof PV system	17.5%	2,775	11,838	2%	---------	90.62	21,661	21,661	1.83
Com/gov roof PV system	9.0%	1,434	6,452	5%	---------	---------	8,827	8,827	1.37
Solar PV plant	41.3%	6,555	27,656	1%	9622.28	2468.79	1,277,779	327,840	11.85
CSP plant	12.7%	2,021	3,301	0%	1138.63	266.05	38,798	9,066	2.75
Total	**100%**	**15,874**	**58,099**	**1.6%**	---------	---------	**1,361,801**	**370,273**	**6.37**

Based on the estimated 2050 power demand, the total nameplate capacity and the number of units of each of the WWS technologies was calculated after all sectors have been electrified but before considering grid reliability. Values in blue are the results of the analysis conducted in this thesis. Values in black are derived from Jacobson and Delucchi (2016) Spreadsheets of calculations for 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World.

Israel's 2050 energy mix as suggested by Jacobson et al (2016)) is: 80.5% solar, 19.4% wind, and less than 0.03% hydro and geothermal. When broken down into specific technologies the energy mix is as follows: residential rooftop PV system 17.5%, commercial and governmental rooftop PV 9%, utility scale PV 41.3%, CSP plant 12.7%, onshore wind 6.8%, and offshore wind 12.6% (Figure 27). As Table 15 demonstrates, Israel has validated sufficiently higher technical potential for each of the wind and solar technologies than the nameplate capacity needed in order to provide the energy demand projected for 2050 as estimated by Jacobson et al. (2016), per Jacboson's energy mix proposal. Thus, technically, Jacobson et al (2016) suggested energy mix can be applied. However, the practical potential found for onshore wind has a margin of only 7% more than the planned energy supply for onshore wind according to Jacobson. As 7% is lower than the defined threshold of 25% for "safe" validation, then onshore wind is validated with "uncertainty". All other technologies are "safely" validated with margins greater than 25% (+37% for commercial rooftop, +83% for residential roof top and +175% for CSP, and +1085% solar PV).

As onshore wind wasn't "safely" validated, it is therefore recommended to consider an alternative proposal, in case site area for onshore wind is physically found to be insufficient. The alternative proposal ("proposal B") shall be based on the minimal changed required on top of Jacobson's proposal, where suggested power from each source is safely validated. Moreover, between the fact that offshore wind farms practical potential wasn't validated (due to lack of offshore wind speed data) and Israel's offshore attributes, namely that it reaches depth of 50m+ very rapidly (in some areas reaching 50m depth already at 4 km from shore), proposal B shall also be more conservative with its reliance on offshore wind.

To summarize: proposal B will be based on minimum alternation to Jacobson's proposal while meeting the following criteria:

(1) 25% margin per each energy source (that can be validated)
(2) Offshore wind end use power delivery plan that does not exceed its onshore equivalent
(3) Minimum footprint

Discussion

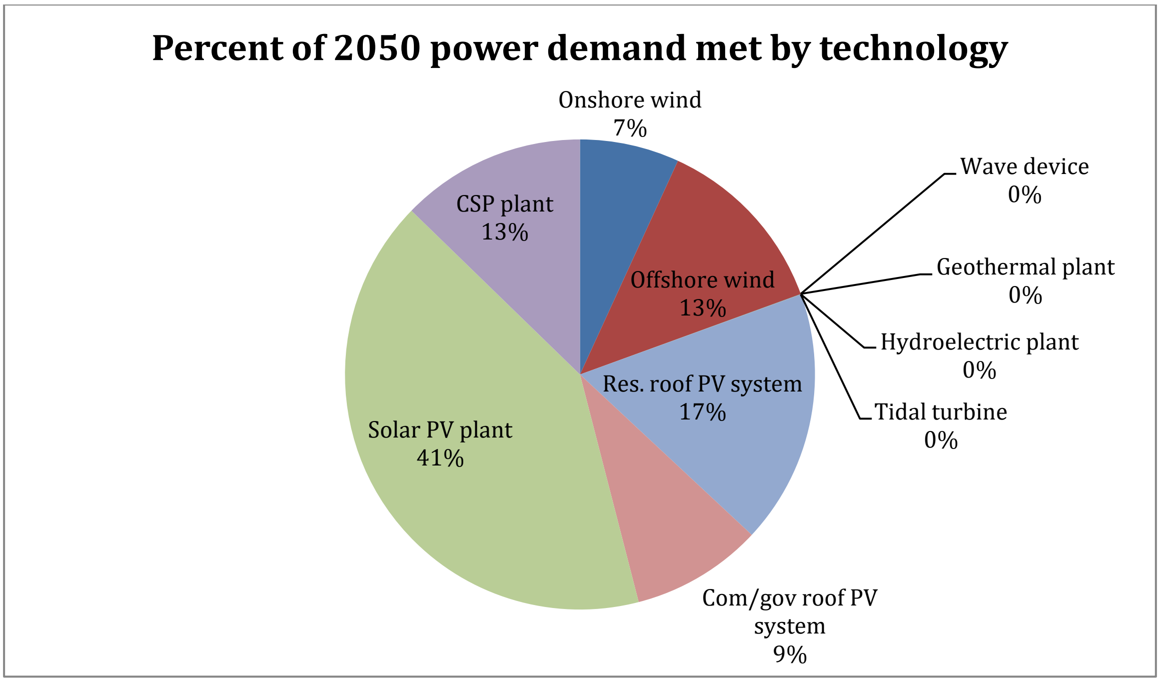

Figure 27: Israel’s proposed 2050 energy mix by Jacobson et al. (2016)

Based on the above criteria, proposal B to meet Israel’s energy requirement in 2050 is therefore:

Table 16. Presented is the percent of 2050 demand met by each WWS technology for the alternative proposal (“proposal B”), the end-use power delivered and capacity needed to meet Israel's total annually-averaged end-use power demand for all-purposes in 2050. Also shown are the amount of areas found technically and practically suitable for each of the WWS technologies and their technical and practical nameplate capacities

Energy Technology	Percent of 2050 power demand met by technology	End use power delivered (MWe)	Total nameplate capacity needed (MW)	Percent of nameplate capacity already installed 2015	Areas found technically suitable (km^2)	Areas found practically suitable (km^2)	Technical potential nameplate capacity (MW)	Practical potential nameplate capacity (MW)	Ratio: practical potential capacity relative to nameplate capacity needed
Onshore wind	5.9%	933	2,304	1%	1,211.01	448.00	7,784	2,879	1.25
Offshore wind	5.9%	933	2,872	0%	---------	---------	6,155	---------	---------
Wave device	0%	0	0	100%	---------	---------	782	---------	---------
Geothermal plant	0%	0	0	100%	---------	---------	0	---------	---------
Hydroelectric plant	0%	0	7	100%	---------	---------	7	---------	---------
Tidal turbine	0%	2	9	0%	---------	---------	9	---------	---------
Res. roof PV system	25.2%	3,995	17,043	2%	---------	90.62	21,661	21,661	1.27
Com/gov roof PV system	9.0%	1,434	6,452	5%	---------	---------	8,827	8,827	1.37
Solar PV plant	41.3%	6,555	27,656	1%	9,622.28	2,468.79	1,277,779	327,840	11.85
CSP plant	12.7%	2,021	3,301	0%	1,138.63	266.05	38,798	9,066	2.75
Total	**100.00%**	**15,874**	**59,642**	**1.6%**	---------	---------	**1,361,801**	**370,273**	**6.21**

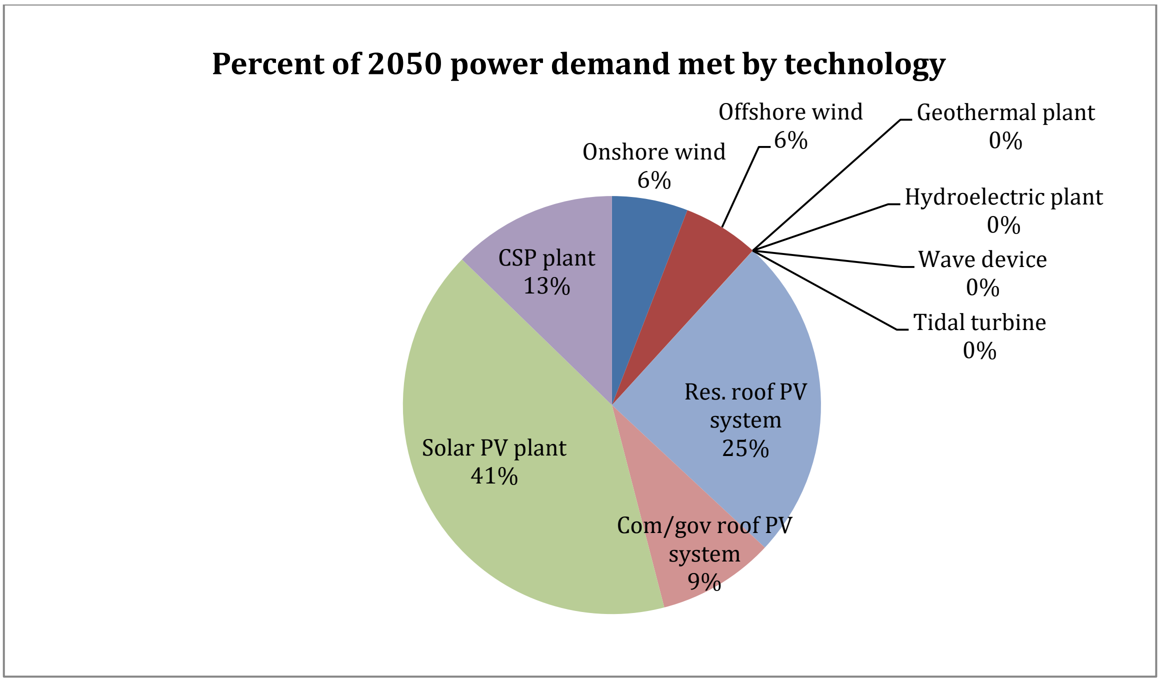

Figure 28. Proposal B for 2050 energy mix

Note that in proposal B both onshore wind and offshore wind end use power delivered were reduced to 933 MWe (or 5.9% of total energy required, each), which leaves onshore wind with a desired 25% error margin. Residential rooftop PV absorbed the additional energy requirement and now provides nearly 4 GWe, instead of 2.77 GWe per Jacobson's original proposal. Even with this heavier reliance on residential rooftop PV, there is still more than 25% margin for residential rooftop PV, so this new plan meets all desired criteria. As residential rooftop PV absorbed 100% of the additional energy required, we have successfully met the "minimum footprint" criteria for the alternative proposal, with zero footprint (as additional PVs are to be installed on then existing structures).

Overlap with military ground

As can be seen in table 15, all sources other than onshore wind has sufficient area practically suitable not on military ground, and therefore can be constructed entirely on non-military grounds. Onshore wind has less area practically suitable, and therefore out of its 417 km^2 required, only 198.6 km^2 can be built non-military ground, meaning 218.7 km^2 must be built on military ground. As this is the only source that must be built on military ground, and as 218.7 km^2 is less than 3% of total military ground, far less than set threshold of 10%, then such land repurposing is reasonable and from this perspective the plan is validated. As proposal B requires even less onshore wind land, proposal B is similarly also validated from the military grounds aspect.

9.1 Discussion of the results wind and solar

Following the high-level discussion presented in the section above, in this section, the GIS multi-criteria spatial analysis and its results are discussed in greater detail.

9.1.1 Onshore wind

Although Israel has an area of 2153 km^2 with onshore annual wind speeds greater than 6 m/s at 100 m height, the spatial analysis reveals that only 1211 km^2 of Israel's onshore area are technically suitable for onshore wind farm installation and 448 km^2 are practically suitable for wind farm installation. I.e., only 20.8% of the total onshore area with high wind speed is practically suitable for wind farm installation. This surprisingly poor 1:5 ratio between total area with sufficient annual onshore wind speed and the actual practically available area may explain the narrow 7.4% margins between Israel's validated practical potential and proposed energy generated from onshore wind in Jacobson's plan.

According to the plan proposed by Prof. Jacobson, 6.8% of Israel's WWS 2050 all-purpose energy demand is generated with onshore wind. To achieve that, 93.1% of the area found practically suitable for onshore wind needs to be developed with wind turbines. Such tight implementation plan with margins smaller than the target 25% threshold is considered validated with uncertainty. To name a few factors that may contribute to insufficient suitable area with such tight margins: social or political objection to certain sites, overlap with bird migration paths not taken into account, slower technological progress than expected (resulting in lower MW/km^2 ratio, requiring more land-use), overlap with specific military area that cannot be repurposed (e.g. military facility that cannot be relocated) and overall errors in data or modeling that can accumulate. For this reason an alternative proposal B was made, where onshore wind is expected to produce only 5.9% of Israel's WWS 2050 all-purpose energy demand. In such a case practical potential was safely validated (margins great than 25%).

The 448 km^2 found practically suitable for onshore wind farm installation meet all the criteria specified in methods: slopes less than or equal to 30%, wind speeds equal to or greater than 6 m/s, compliance with Israel's regulations (not located on shore texture nor on Nature Reserves and National Parks), and not located on areas of importance for birds conservation.

Geographically, areas technically and practically suitable for wind farm installation are located mainly at the northern and southern parts of Israel in the Galilee and Negev areas. With wind turbines similar to Senvion's RePower 5M at 100 m, Israel has a technical potential of 7.8 GW and practical potential of 2.8 GW of installed capacity.

About 50% of the area found practically suitable for onshore wind is overlapping with military ground. From total military grounds perspective this means areas found practically suitable for wind farm installations overlaps with only 3% of the total area designated to military use. Still, it may be that certain specific locations must remain in military use for strategic reasons. Considering that about 50% of the area found practically suitable for onshore wind is overlapping with military ground, this leaves room for high volatility, and is actually a reason for concern, especially considering onshore wind has a very slim margin of 7.4% to begin with.

Implementation notes

137 km^2 of the area practically suitable area for onshore wind development has annual average wind speeds greater or equal to 6.5 m/s and 23 km^2 of the area has annual average wind speeds greater or equal to 7 m/s. Since areas with higher wind speeds should be preferred for development over those with lesser wind speeds due to better efficacy and cost-effectiveness, these 137 km^2 should be prioritized for wind development. To decrease wind turbine capital installation costs, areas practically suitable with smaller slope percentages should be preferred. Areas that were found in the spatial analysis practically suitable with slope percentages less than or equal to 10 should be preferred to those with slope percentages of 15, also for reasons of increased cost effectiveness. The same can be said for areas with slopes of 15% versus 30%.

Although this roadmap does not include the West Bank territory it may be beneficial to consider obtaining a share of onshore wind from the West Bank. Cooperation between Israel and the West Bank could multiply the amount of available area suitable for wind turbine installations by a factor of up to 3X, as the West Bank territory has 900 km^2 of area with wind speeds greater than 6 m/s (Table 10 in Results chapter). Assuming a similar 4:1 ratio of 6 m/s areas to areas practically suitable for onshore wind installation, 225 km^2 would increase area available for onshore wind turbine by nearly 50%. This may be a possibility worth exploring.

9.1.2 Utility scale PV

The GIS multi-criteria spatial analysis found that about 9,622 km^2 are technically suitable for utility scale PV installation and 2,469 km^2 are practically suitable for utility scale PV. Since area suitable for utility scale PV is also suitable for CSP but not the other way around, areas that are suitable for both were subtracted and the mentioned results do not overlap with areas suitable for CSP. The suitability map illustrates that areas technically and practically suitable for utility scale PV installation are located all over Israel. It was found that assuming PV installation of Sunpower E20 435 W panel Israel has a technical potential of 1,277.8 GW and practical potential of 327.8 GW of installed capacity. Both capacities, technical and practical, greatly (nearly 12X) exceed the 27.6 GW of total nameplate capacity needed to provide 41.3% of Israel's 2050 all-purpose energy demand by utility scale PV in a WWS case as proposed by Jacobson et al. (2016). Since the practical potential that was found in the analysis is about 10 times greater it can be concluded that even after taking into account further environmental factors such as endangered species or ecological corridors or social and economic factors (distance to transmission lines and roads) enough area will be left that will allow for the development of utility scale PV that will meet 41.3% of Israel's 2050 all-purpose energy demand. Further research of the mentioned factors is needed.

Thus, Israel has enough area that complies with technical limitations for utility scale PV, which include area with sufficient GHI (5.2-5.9 KWh/m^2/day), slopes less than or equal to 5% or areas with slope percentages greater than 5 that are facing south to ensure greater solar radiation due to the location of the sun, has no other land use (including no archeological sites, airports and forests), practically suitable when considering Israel's regulations (not located on shore texture, Nature Reserves, National Parks as stated in the National Outline Plan for Photovoltaic Installations-NOP35), and are not located on areas of importance for birds conservation nor on agriculture land in order to prevent competition between food resources and energy resources.

8.4% of the area found practically suitable for utility scale PV needs to be developed in order to generate 41.3% of Israel's 2050 all-purpose energy demand by utility scale PV in a WWS case as proposed by Jacobson et al. (2016). Since about a half of the area found practically suitable for utility scale PV development is designated for military usage, that means that even if using military grounds for PV installation is entirely avoided, the land area required to reach 41.3% of all energy would take just about 15%-20% of the non-military area practically suitable for PV installation. Undoubtedly, enough area is practically suitable for PV installation.

Implementation notes

Although PV farms can be constructed on steep slopes, doing so would increase installation costs. Thus, construction on areas with slopes equal to or less than 5% will increase the cost-effectiveness of the project. It was found that Israel has 519 km^2 of practical area that also has slope percentage less than or equal to 5% while the necessary area for utility scale PV that will comply with WWS 2050 utility scale PVs needed energy demand is only 338 km^2 - about two thirds. Thus, development of utility scale PV can be made only on areas that are more cost-effective (sufficient margin error of +50%). Moreover, of the 519 km^2 practical area that also has slope percentage less than or equal to 5%, 287 km^2 is on military ground, meaning even if constraining PV installations to slopes less than 5%, only 51 km^2 would overlap with military ground, which is less than 0.65% of total military ground, so unless there is a specific strategic importance of this particular area, it is very likely that it can be allocated for PV installation, thus allowing 100% of installation to take place on cost-effective sites with less than 5% slope. And in any case, even if PV were to be installed entirely on military grounds, the PV sites will take less than 4.3% of total military area).

9.1.3 CSP

The spatial analysis found that Israel has an area of 1139 km^2 technically suitable for CSP and 266 km^2 practically suitable for CSP. Areas practically suitable for CSP development are spread all over Israel with higher concentrations in the southeastern parts of Israel. Israel has a technical potential of about 39 GW and practical potential of 9 GW of installed capacity. Both capacities, technical and practical, exceed the 3.3 GW of total nameplate capacity needed to provide 12.6 % of Israel's 2050 all-purpose energy demand by CSP in a WWS case as found by Jacobson et al. (2016). Since the practical potential that was found in the analysis is more than twice greater than the total nameplate capacity needed it can be concluded that even after taking into account further environmental, social and economic factors, enough area will be left that will allow for the development of CSP that will meet 12.6 % of Israel's 2050 all-purpose energy demand. Further research of the mentioned factors is needed.

Thus, Israel has enough area that complies with CSP technical limitations of areas with no other land-use (including no archeological sites, airports and forests), slope less than or equal to 5% since CSP has to be constructed on flat areas, continuously greater or equal to 18,000 m^2 to ensure large enough installation area, and with DNI greater than or equal to 5 $kwh/m^2/day$ to make the costs of generating electricity cost-effective and also comply with Israel's regulations (not located on Nature Reserves, National Parks) and not located on areas of importance for birds conservation nor on agriculture land.

As 36.4% of the area found practically suitable for CSP installation is needed to generate 12.7% of Israel's 2050 all-purpose energy demand by CSP in a WWS case and less than a half of the area that was found practically suitable for CSP development is designated for military usage, it means that there is enough area for CSP development that is not on military ground, thus saving further coordination with the Ministry of Defense. Regardless, the total onshore ground that was found practically suitable for CSP development and overlaps with military grounds is only 2% of the total onshore army ground to begin with. So also from military perspective, CSP is safely validated.

9.1.4 Offshore wind

As explained, data on Israel's offshore wind speed critical for determining Israel's offshore wind technical and practical potential isn't available. Therefore this thesis doesn't provide validation for Israel's offshore wind practical potential. The technical potential is taken as is from the World Plan estimation. Jacobson et al. 2016 estimated the technical potential based on Israel's costal water length and areal power density for offshore wind systems.
When applying all the different factors needed for the development of offshore wind turbine (minimum average annual wind speeds of 5.7 m/s at 100 m heights above surface, depths lower than 50 m, do not carry any environmental importance etc), limited amount of areas are left for offshore wind development.

Considering that above constraints and concerns, along with Israel's offshore attributes, reaching depth of 50m+ very rapidly, proposal B is also conservative with its reliance on offsore wind, aiming for 5.9% instead of 12.6% per Jacobson's original proposal.

As a side note, as it has been demonstrated that Israel has +1085% more area suitable for PV installation than required by Prof. Jacobson's proposed plan for PV, the excess area can be used for further PV installation to account for some missing offshore wind suitable area, if such were found in deeper inspection.

9.1.5 Residential rooftop PV

Table 16 indicates that for residential rooftop PV the proposed installed generation capacity to meet electricity demand in 2050 (as was estimated by Jacobson and Delucchi (2016)) is a bit more than half (55%) of Israel's technical and practical potential.

Both Jacobson and this project's rooftop PV estimations took into consideration 'usability fraction' that stands for different practical reasons such as shading on the rooftop or reasonable orientation to the south. In addition, since installation of PV on existing residential rooftops does not interfere with any environmental or regulation limitations, the technical potential in this case is actually also the practical potential. Thus, Israel has almost twice more residential rooftop area than is needed in order to generate 17.5% of Israel's energy demand in 2050. In cases of greater energy demand than estimated by Jacobson et al. (2016) or in case other WWS resources will not be available as expected, development of further residential rooftop PV is available.

Table 17 compares the results of the residential rooftop analysis conducted in this thesis and the results from Jacobson et al (2016). The analyses conducted in this thesis estimates suitable rooftop area in 2050 of 91 km^2 which is close to the estimate of 80 km^2 by Jacobson et al. (2016). The difference between the two estimates (+13.7%) is reasonable and could be the result from multiple variance in models or parameters used, such as an inaccuracy in the number of stories or the estimated rooftop area per capita. Both residential rooftop technical potential estimations (calculated here as 21.6 GW and Prof. Jacobson's as 19.1 GW) in 2050 are significantly (almost twice) greater than 11.8 GW which is the total nameplate capacity needed in 2050 to provide 17.5% of Israel's all-purpose energy demand by residential rooftop PV in a WWS case as found by Jacobson et al. (2016). PV is safely validated.

Table 17. Suitable rooftop areas for PV installation and technical potential of residential buildings in 2050 as found by analysis and Jacobson et al. (2016). Also shown are proposed installed capacities of residential buildings of rooftop PV and its fraction out of technical potential in 2050

	Suitable rooftop area 2050 (km2)	Technical potential 2050 (MW)	Installed generation capacity to meet electricity demand in 2050 (MW)	Percent of installed capacity relative to technical potential in 2050
Residential buildings, including residential parking	80	19,162	11,838	62%
Commercial government and industrial buildings	37	8,827	6,452	73%

Accordingly to proposal B, residential rooftop are planned to produce nearly 4GW instead of 2.775GW per Jacobson's original plan, replacing some of the energy originally planned for onshore and offshore wind that could not be safely validated. Even with this increase reliance on residential rooftop, their practical potential is safely validated (27% margin).

9.1.6 Commercial rooftop PV

Jacobson et al. (2016) estimate that the maximum installed PV capacity in 2050 for commercial/government rooftops, including carports, garages, parking structures, and parking lots, is about 8.8 GW. This capacity is greater by a "safe margin" of 37.5% than the total nameplate capacity of 6.4 GW which is sufficient to provide 9% of Israel's all-purpose energy demand by commercial/government rooftops PV in a WWS case as was found by Jacobson et al. (2016). As only

73.1% of Israel's technical potential for commercial and governmental rooftop PV is suggested to be used to generate 9% of Israel energy demand in 2050, this resource could be seen as a resource that could be further developed in case of need.

9.1.7 Summary of solar and Wind Analysis

Table 16 indicates that Israel's technical potential for each of the wind and solar technologies is greater or similar to the total nameplate capacity needed to provide Israel's 2050 all-purpose energy demand. The practical potential for onshore wind, utility-scale PV and CSP, and residential and commercial rooftop PV was validated to be greater than or similar to the total nameplate capacity needed to provide Israel's 2050 all-purpose energy demand according to Jacobson's proposal, while the practical potential for offshore wind remains unknown. A slightly modified proposal B was introduced which "safely" validates the practical potential of onshore wind, utility scale PV and CSP, and residential and commercial rooftop PV as at least 25% higher than total nameplate capacity needed per resource, with significantly lower reliance on onshore and offshore wind. This demonstrates that Israel has enough available wind and solar resources to supply its energy demand in 2050 when taking technical limitations into account and also when accounting for environmental and regulatory limitations

9.2 Alternative renewable energy resources

Tidal energy is required to supply total nameplate capacity of 9 MW in order to fulfill 0.01% of Israel's expected total energy demand in 2050 in a WWS scenario. **Wave** energy in the proposed roadmap is not required. The literature review highlighted that Israel enjoys relatively low stable wave energy potential since the costs of wave energy in 2050 are expected to stay relatively high versus other WWS technologies. Additionally, due to wave energy's technological immaturity, it is not integrated into this energy mix. Nevertheless, **wave energy** should be remembered as an option since its development doesn't require new land area, which is especially beneficial in a country like Israel where land is a scarce resource. In the potential case of technological improvement and cost-competiveness with other WWS technologies this resource might be beneficial to use.
Although **geothermal** energy could be generated in most areas in Israel at depths of 6 - 8 km with Enhanced Geothermal Systems (EGS) technology, geothermal is not suggested as part of Israel's 2050 WWS energy mix due to technological immaturity as well as due to a lack of experience in developing the system at the mentioned depths. Nevertheless, the potential of developing conventional geothermal system at the south end of the Golan Heights and in southern Israel, sites that were found suitable by Shalev et al. (2008), should be further assessed. In case the development of conventional geothermal system in Israel is found possible, it should be considered to be integrated in the final energy mix due to the system's relatively low cost and reliable production of base-load power.

Hydropower capacity in the end use energy mix is kept the same as the capacity already existing in 2015 (with installed capacity of 7 MW) as Israel does not have resource availability for additional hydropower implementation. Nevertheless, pumped-storage hydroelectricity (PSH) method can help manage and stabilize Israel's grid at times when other main energy resources of solar and wind do not work. It is also a cheaper storage method than CSP. This it is an option that should be preferred over CSP. It is interesting to note that Israel aims to build 800 MW capacity of PSH by 2020 (of which about 600 MW are already in the construction process).

9.3 Suggested transformation plan

Transforming Israel to 100% WWS system as suggested by Jacobson et al (2016) will reduce the end-use demand in 2050 to 15.8 GW versus 27.2 GW in BAU case. This difference can be attributed to conversion of fossil fuel combustions to a more efficient electrified system. All sectors will be electrified as suggested by Jacobson et al. (2016): Short distance ground transportation will electrified with battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (HFCVs) (hydrogen will be produced by electrolysis from WWS electricity), long distance ground transportation will use BEVs with fast charging or battery swapping, heavy-duty ground transportation will use BEV-HFCV hybrids and ships, aircraft, and long-distance freights will use hydrogen-energy storage. Furthermore, in 2050, WWS case heating or cooling will be powered primarily by electric heat pumps and high-temperature industrial applications will be powered by electric arc furnaces, induction furnaces, dielectric heaters, and resistance heaters.

Jacobson's et al. (2016) suggested timeline offers a conversion of 20% of Israel's all-purpose energy by 2020, 50% by 2025, 80% by 2030, 95% by 2040, and 100% by 2050 (Figure 29). In order to achieve the goal of 100% WWS by 2050 and its mid goal of 80% by 2030, better policies to incentivize the market are needed (Jacobson et al. 2016).

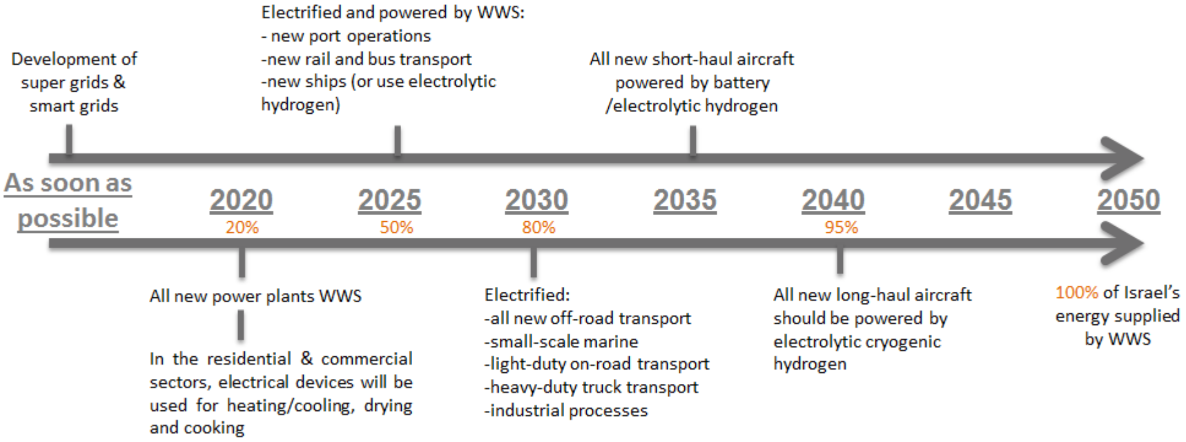

Figure 29: Proposed timeline for necessary actions needed to transform Israel's all-purpose energy to 100% WWS by 2050. Timeline is similar to the one proposed to 139 countries of the world (Jacobson et al. (2016)). The percentage next to the years in the time axis indicates the percent energy supplied by WWS sources by that year.

In the first years of the transition to WWS system, WWS devices will be produced by conventional fuels but as the proportion of WWS power increases, a larger portion of clean energy will be used to power WWS devices until all new WWS devices will be produced with WWS electricity and the usage of conventional fuels will be stopped. Figure 30 presents the transition plan from an end-use power demand perspective. The figure displays the projected end-use power demand and its supply by conventional fuels and WWS technologies from 2015 to 2050 with BAU scenario and WWS scenario. It illustrates the reduction in end-use demand with WWS (21.2 GW) scenario versus BAU (27.2 GW) due to conversion from fossil fuel combustions to an electrified system that has better efficiency (Jacobson et al. 2016).

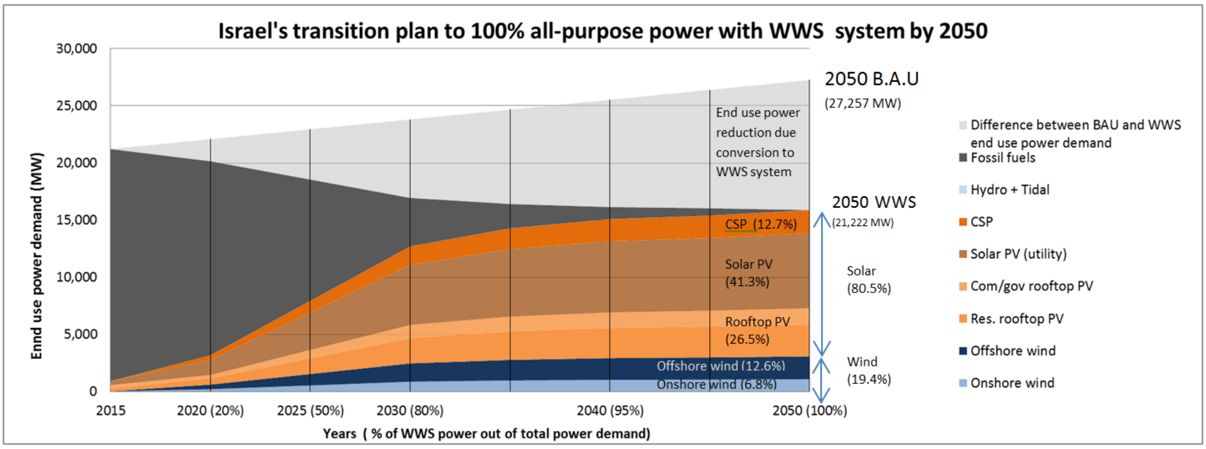

Figure 30. Israel's mean change of all-purpose end-use power demand and its supply of conventional fuels (fossil fuels, Bio-fuels, and nuclear) and WWS technologies over time. Next to each WWS technology is the percent of end-use power provided by WWS in 2050. The percentage next to the years in the time axis indicates the percent energy supplied by WWS sources by that year. Data derived from Jacobson and Delucchi (2016) Spreadsheets of calculations for 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World. The table format is similar to previous state roadmaps and the 139 countries of the world roadmap (Jacobson et al. 2014; Jacobson et al. 2015a; Jacobson et al. 2016)

Specific sites were selected for installation per technology, and specific energy goals were set per every 5 years. Decision makers still need to choose per each 5 years which specific sub-set of sites to develop over those 5 years to achieve the 5-year goal, across each WWS energy source.

As wind farm is most limited in space, areas found suitable for wind farms should get first priority for wind farms and not developed with any other WWS technology. Figure 31 bellow presents final locations chosen for onshore wind farm installation. Both military and non-military grounds are needed (light and dark shades of green on map), and overall 93.1% of the land marked practically suitable for onshore wind should be developed by 2050.

Discussion

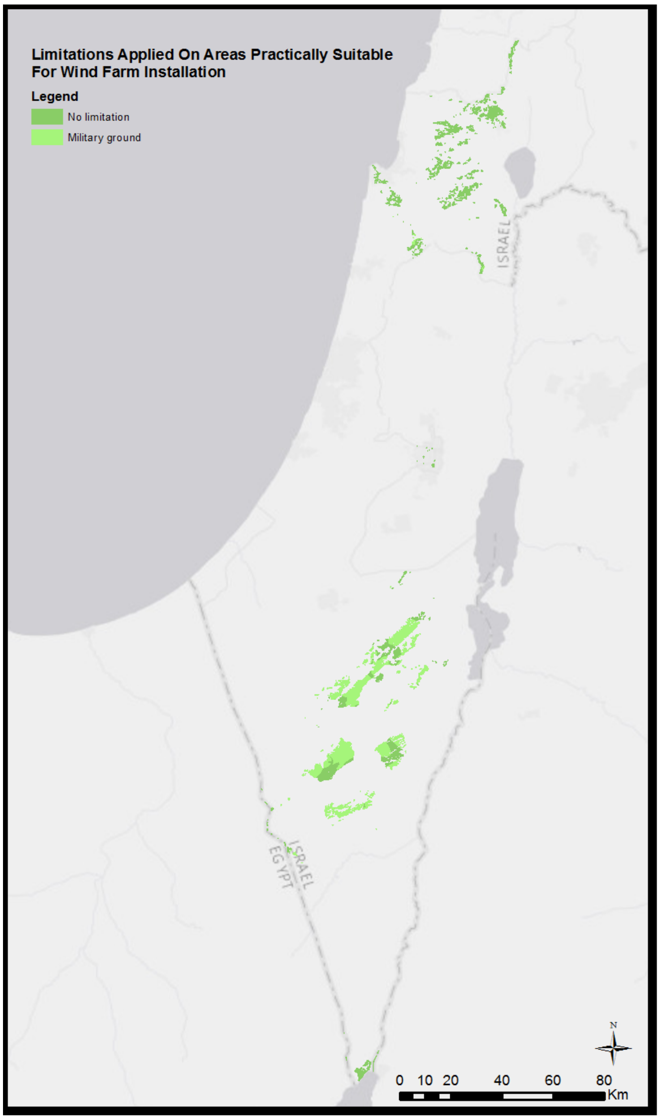

Figure 31. Map of area practically suitable in Israel for onshore wind development.

Discussion

CSP should be developed according to Figure 32, focused only on non-military ground (areas colored in dark green on map). 36.4% of the total green area should be developed with CSP by 2050.

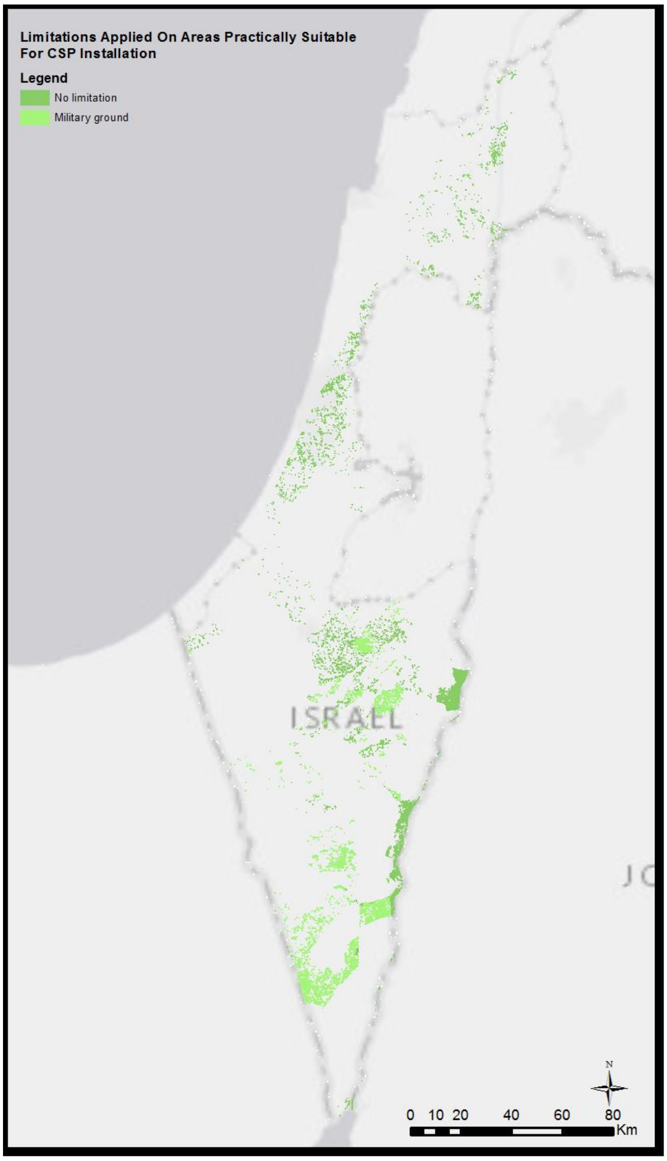

Figure 32. Map of area practically suitable in Israel for CSP development.

PV plants should be developed according to Figure 33 bellow, solely on non-military ground areas (darker shades of green). Construction should focus on areas with slopes equal to or less than 5% to keep costs to minimum. About 15%-20% of the non-military area should be developed by 2050.

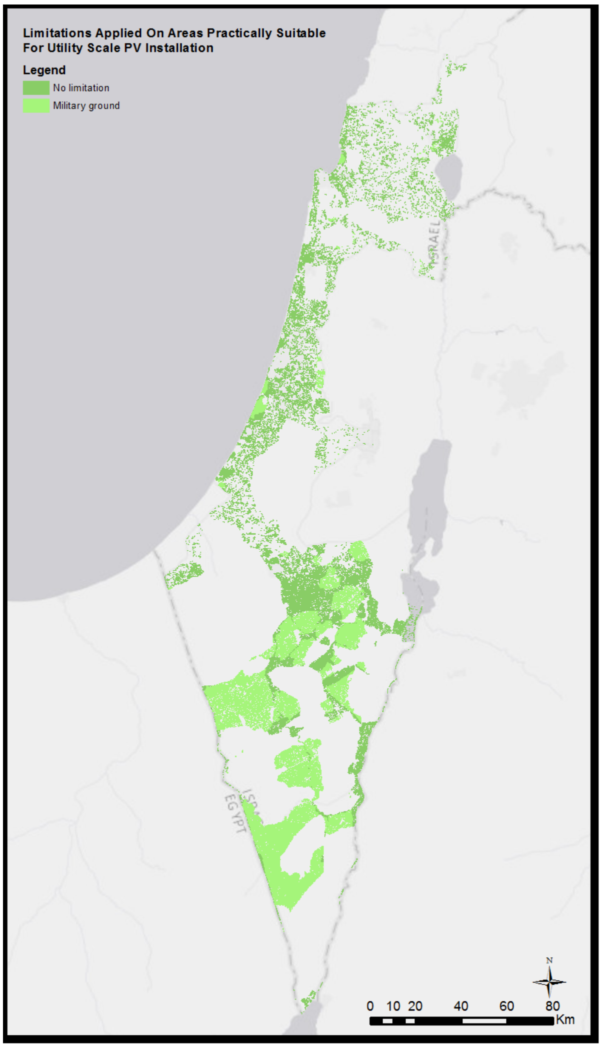

Figure 33. Map of area practically suitable in Israel for utility scale-PV wind development

And rooftop area, residential and commercial, should be developed to hit 2050 goals of 55% of all practically suitable residential rooftop area and 73.1% all practically suitable commercial rooftop area.

Last, offshore wind should also be developed until hitting set goals of 6,155 MW total nameplate capacity in 2050. Specific sites are not selected for offshore wind as such could not be determined without offshore wind data as explained.

9.3.1 Footprint of implementing the plan

Replacing Israel's all-purpose energy infrastructure with the WWS mix suggested by Jacobson et al. (2016) will require 2.3% of Israel's land area, while the footprint of new land area will be 2%. These values do not account for the decrease in footprint from eliminating the current energy infrastructure. Spacing area on new land is 1.6% of Israel's land area and is needed only for wind turbines. Spacing on Israel's footprint of offshore area was found to be 3.2% and is needed almost entirely for the development of offshore wind turbines. This evaluation does not take into account eliminating the current energy infrastructure. Thus, the footprint from converting to WWS could practically be smaller. Considering the small footprint percentage this aspect should not serve as a roadblock for the implementation of this roadmap (Jacobson et al. 2016).

Replacing Israel's all-purpose energy infrastructure with the 'alternative' WWS mix suggested in this thesis will require a slightly greater footprint area (2.5%) than Jacobson's original proposal (2.3%) but development on new land will require same 2% percent as all additional installations are done on rooftops of then existing residential buildings. Spacing area for onshore wind is decreased to 1.4% of Israel's land area and the pacing footprint for offshore wind turbines is decreased to 1.5% of Israel's offshore area in the alternative proposal B.

Furthermore, as can be seen in Table 16 that in 2015 only 1.6% of the total nameplate capacity necessary to convert Israel to 100% of its all-purpose energy infrastructure to one derived entirely from renewable energy by 2050 was already installed. Thus, in order to reach the 100% WWS system by 2050 significant development is needed.

9.4 Benefits from transforming to WWS

9.4.1 Financial benefits

Figure 34 presents 2050 LCOE of WWS and coal in cases of further fossil fuel usage (BAU) as was estimated by Jacobson et al. (2016) (presented in Table 2) The figure illustrates whether WWS technology is more or less expensive compared to coal, which represents the least expensive fossil fuel. While usually the decision of energy project development is based on a least-cost analysis it reveals that only solar thermal, hydropower, utility PV, and CSP with storage are competitive energy resources in 2050 when compared to coal. The cost estimates take into account generation, short and long distance transmission, distribution and storage, but they do not include external costs. Thus, WWS technologies become more competitive compared with conventional sources of energy if the comparison is not limited exclusively to strict financial/cash criteria, but also accounts for external costs. When accounting for external costs such as air pollution health costs and climate change damage costs, such as loss of coastline, fishery and agricultural, heat stress mortality and morbidity, food scarcity, drought, wildfires, and severe weather, the total cost of electricity generation for each of the WWS technologies is less than conventional fuels in 2050. Jacobson et al. (2016) estimates that in 2050 Israel's averaged LCOEs for WWS technologies WWS scenario will be lower than in a BAU scenario, with weighted LCOEs among all generators of 9.91 ¢/kWh for WWS and 10.5 ¢/kWh for BAU (The LCOE accounts for transmission and distribution, but not externalities).

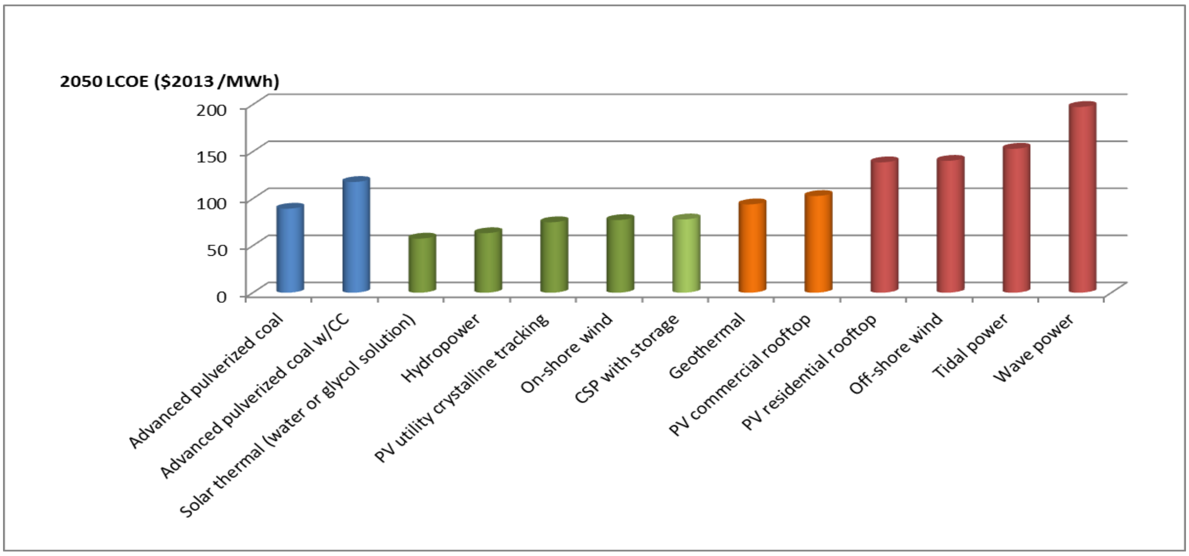

Figure 34. 2050 average estimates of fully annualized levelized business costs of electricity (LCOE) to end users in 100% BAU scenario. The costs include generation, short and long distance transmission, distribution and storage, but they do not

include external costs. The figure presents the predicted WWS power prices vs the cheapest fossil fuel option- coal in 2050. Dark green represent technologies that there energy generation is cheaper than coal already today and in 2050, light green represent technologies that in 2050 there energy generation will be cheaper than coal, yellow for technologies with has similar price to coal and red for technologies more expensive than coal. Values are extracted from Table 2.

9.4.2 Health and health cost saving benefits

Converting Israel to a WWS system by 2050 will not only contribute to the prevention of climate change but also **benefit** Israel directly by preventing health issues caused by air pollution. The fossil fuel emissions of particulate matter ($PM_{2.5}$) and ozone (O_3) were found by to have a relative risk in causing premature deaths due to cardiovascular disease, respiratory disease, and complications from asthma. Converting Israel's all-purpose energy infrastructure to WWS by 2050 will prevent 2,674 premature deaths per year on average due to the reduction of air pollution as estimated by Jacobson et al. (2016).

Converting to WWS will create on average a total cost savings of 65 billion dollars (2013 USD) per year and 6,029 dollars (2013 USD) per person a year due to damage prevention of air pollution, climate change and energy saving due to better efficiency. The damage prevention costs for air pollution are estimated to be on average 27 billion dollars (2013 USD) per year and account for mortality, morbidity, and non-health costs. The damage prevention costs for air greenhouse gas (GHG) emissions created by burning fossil fuels in BAU scenario is 36 billion dollars (2013 USD) per year and 3,300 dollars (2013 USD) per person a year. Thus, the upfront investment due to conversion to a WWS system is expected to be returned on average after 2 years when accounting for the sum of the aforementioned cost-savings. Furthermore, due to switching from BAU electricity to WWS electricity the average electricity cost saving in 2050 is expected to be 2.46 billion dollars (2013 USD) per year and 227 dollars per person a year (2013 USD). **Thus, converting Israel to rely only on WWS resources will be more economical than continuing to burn fossil fuels in a BAU scenario.** (Jacobson et al. 2016; Jacobson & Delucchi 2016).

9.4.3 Labor benefits

Furthermore, converting Israel to 100% WWS system will create 62,408 new jobs from 2015 to 2050. Those new jobs account for both short term construction jobs and long-term operation and maintenance jobs and discounts for jobs lost due to lack of further development of fossil-fuel infrastructures. Moreover, additional job creation due to conversion to WWS system for research and development of WWS technologies and storage can also be accounted for but is not included in Jacobson's calculations (Jacobson et al. 2016).

9.4.4. Energy security benefits

Deployment of energy resources with WWS technologies over many locations instead of the current situation of several specific locations of conventional power plants, will contribute to Israel's energy immunity to potential terrorist attacks or weather hazards, an aspect that should also be taken under consideration when evaluating the benefits from implementing this roadmap.

In this roadmap, Israel is assumed to generate all of its annually averaged power independently to meet energy demand by 2050. This is the ideal scenario considering Israel's political conflicts with its neighboring countries. Converting to WWS system will contribute to energy resource diversification and energy independency, which are acute factors in increasing Israel's energy security leading to stronger economic and national security. Also, Israel's energy independency will help ensure that expected rising and fluctuating fossil fuels fluctuation prices would not affect Israel.

9.5 Further work

As this plan only focuses on the technical and practical limitations, before wind turbine development it is essential to conduct further analysis that will also account for areas with endangered species, ecological corridors, bats caves and their lodging and breeding sites, bird migration routes, buffer zones from the airport, distance to transmission lines and roads, and distance to populated areas and inhabited structures. Further research into understanding the benefits of preserving areas for ecological health versus the damage of continued fossil fuel usage need to be conducted and areas more likely to be used as ecological corridors should be defined.

As mentioned before, the spatial analysis does not account for social factors such as public attitudes, which can play a large role in the success of site development since they can slow or stop a project that should be permissible by law and regulation. Also, the spatial analysis does not account for economic factors such as proximity to existing roads or grid transmission lines that affect the direct cost of WWS construction and development. Since those factors are important in the success of development of WWS and the transition of Israel to renewable energy further research with those factors should be done.

Moreover, as offshore wind turbine practical potential wasn't validated due to lack of offshore winds peed data, such data should be gathered, and based on offshore wind practical potential should be validated.

As grid reliability and energy exchanges among countries were not considered but are critical factors for the success of converting Israel to rely only on renewable energy, further research on those issues is needed. While grid reliability was not part of the calculations, the number of additional generators needed to ensure reliable electric power grid was estimated by Jacobson et al. (2016)).

In order to achieve the goal of 100% WWS by 2050 and its mid goals, policies to incentivize the market are needed. The government has the ability to ensure the implementation of this roadmap by improving its renewable energy policies. Financial incentives can make WWS technologies that are more expensive in generating electricity relative to conventional fossil fuels economically feasible on the short term, and ensure long-term economic and social benefits for Israel. Thus further research on policies and incentives with regard to development of renewable energy is needed.

9.6 Bottom line

This thesis highlights the significant practical potential of onshore wind, utility scale PV, and CSP as well as rooftop PV technologies to be used in the future to generate clean energy. Although this study does not cover all possible limitations regarding WWS development and there are various aspects that still need to be assessed, this thesis allows developers and decision makers to estimate Israel's WWS energy potential and help determine the best locations for onshore wind, utility scale PV, and CSP when taking into account Israel's technical, environmental, and regulatory limitations.

While the economic factors were not taken into account, the thesis does demonstrate that the transition path to 100% renewable energy laid out in this work is indeed cheaper in the long-term than the continued burning of fossil fuels. Meaning, the plan presented here is not only ecological and feasible, but also more economical compared to business as usual alternatives. Although this roadmap does not attempt to present the least-cost future energy mix or satisfy grid reliability constraints, the number of additional generators needed to ensure reliable electric power grid was estimated. Further research would be needed to ensure grid reliability.

The negative externalities of the use of fossil fuels, such as air pollution and the contribution to climate change, together with the mentioned additional benefits of energy security, more independent and stable energy, and job creation, provide strong reasons for Israel to convert its all-purpose energy infrastructure to 100% WWS system by 2050.

10. Conclusion

In order to answer the main research question of 'What practical transition plan can convert Israel to 100% all-sector renewable energy by 2050?' this thesis adopted Jacobson's et al. (2016) "world plan",'100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World'. The World Plan offers a long-term transition plan to supply 100% of Israel's energy in all sectors (electricity, transportation, heating/cooling, industry, etc.) from Wind, Water, and Sunlight (WWS) power. Jacobson's et al. (2016) roadmap was validated by evaluating Israel's WWS technical and practical potential per technology, while taking into account Israel's unique geography, climate, environmental, and regulation settings. This roadmap answers the sub research question of 'When accounting for technical, environmental, and regulatory limitations, does Israel has sufficient area for development of wind and solar installations that will allow Israel to fulfill its all-purpose energy demands by 2050?'

In order to validate Jacobson's et al. (2016) plan the following steps were taken:

I. Literature review, to learn about the different factors to be considered for each technology in Jacobson's proposed energy sources mix
II. Deciding on clear criteria for the technical potential and practical potential per technology
III. Obtaining data from multiple sources to use in analysis against criteria
IV. Perform analysis using data, compared against criteria. The primary tool here was the multi-factor GIS analysis
V. Analyze results, answer the research questions, and present a clear transition plan

Validation of Jacobson's et al. (2016) proposed plan is based on evaluating the availability of sites suitable for WWS development per each energy resource, and comparing the total energy each resource can produce (practical potential) with the total nameplate capacity needed by that resource according to Jacobson's et al. (2016) proposed energy mix. Under the assumption that both data and its analysis in this thesis are not 100% comprehensive nor 100% accurate, a "safe" validation was defined as one that included an "acceptable error margin" of 25% between found practical potential per technology and the required nameplate capacity per Jacobson's plan.

Based on the results of the GIS multi-criteria spatial analysis, when taking into account Israel's technical, environmental and regulatory limitations, utility scale PV, CSP, and rooftop PV commercial and residential were safely validated with margins greater than 25% (+37% for commercial rooftop, +83% for residential roof top, +175% for CSP, and +1085% solar PV).

Offshore wind could not be validated because offshore wind speed data, one of the most critical data required for offshore wind siting and potential evaluation could not be obtained. Another marker that was obtained and analyzed for offshore wind - offshore depth as distance from the shoreline - was analyzed and found to be steeper than expected, implying less offshore potential probably exists than previously estimated.

Moreover, the practical potential found for onshore wind was validated but with a slim margin of only 7% more than the required nameplate capacity for onshore wind per Jacobson's et al. (2016) plan. As onshore wind was not "safely" validated, it was recommended to consider an alternative proposal ("proposal B"), in case site area for onshore wind is physically found to be insufficient. Proposal B is based on the minimal changes required as a supplement to Jacobson's proposal, where suggested power from each source is safely validated, offshore wind end use power delivery plan does not exceed its onshore equivalent, while keeping footprint to minimum.

Conclusion

Jacobson's et al. (2016) roadmap suggests the following energy mix for 2050: 80.5% solar (residential rooftop PV system 17.5%, commercial and governmental rooftop PV 9%, utility scale PV 41.3%, CSP plant 12.7%) and 19.4% wind (6.8% onshore wind & offshore wind 12.6%).

Proposal B suggests the following energy mix: 88.2% solar (residential rooftop PV system 25.2%, commercial and governmental rooftop PV 9%, utility scale PV 41.3%, CSP plant 12.7%) and 11.8% wind (5.9% onshore wind & offshore wind 5.9%).

As the above proposals validate the practical potential of converting Israel into 100% renewable by 2050, a clear actionable plan was presented.

First, in terms of timeline, and with 5-year goals increments, as can be seen in following graph:

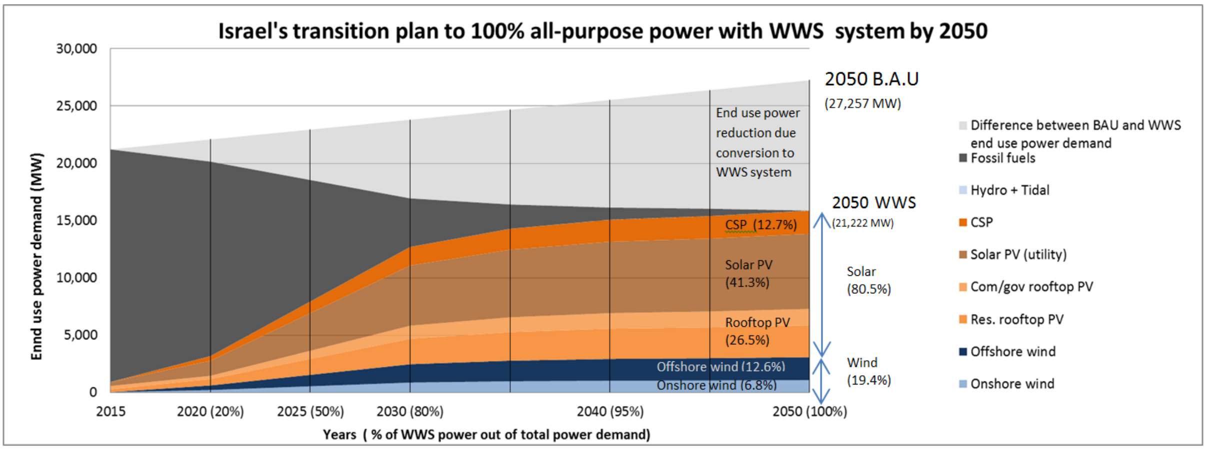

Figure 35. Israel's mean change of all-purpose end-use power demand and its supply of conventional fuels (fossil fuels, Bio-fuels, and nuclear) and WWS technologies over time. Next to each WWS technology is the percent of end-use power provided by WWS in 2050. The percentage next to the years in the time axis indicates the percent energy supplied by WWS sources by that year.

Second, in terms of siting, as specified through siting maps and suggested implementation details per each technology, this thesis presented sites that were found suitable for WWS installation per technology and detailed the guidelines necessary to follow during implementation.

Further, footprint impact of implementing the plan was calculated. Replacing Israel's all-purpose energy infrastructure with the WWS mix suggested by Jacobson et al. (2016) will require 2.3% of Israel's land area, while the footprint of new land area will be 2%. These values do not account for the decrease in footprint from eliminating the current energy infrastructure. Spacing area on new land is 1.6% of Israel's land area and is needed only for wind turbines. Spacing on Israel's footprint of offshore area was found to be 3.2%.

Last, benefits from adopting Jacobson et al. (2016) and transitioning Israel's all-purpose energy infrastructure to one derived entirely from WWS by 2050 were presented, and includes: direct savings of 2.46 billion dollar (2013 USD) per year on energy costs, and additional 63 billion dollar (2013 USD) annual savings when accounting for avoided health and air pollution costs. Beyond economics benefits, 2,674 premature deaths per year would be saved and 62,408 new jobs will be created between 2015 to 2050. Moreover, Israel will achieve greater energy security through decentralization of its energy production.

Conclusion

The following follow up work on this thesis is recommended:

- Gather offshore wind speed data and validate offshore wind practical potential
- Evaluate social factors such as public attitudes and include them in practical potential evaluations
- Evaluate and include economic factors such as proximity to existing roads or grid transmission lines
- Conduct further analysis on areas with high ecological sensitivity such as areas endangered species, ecological corridors, bats caves and their lodging and breeding sites, bird migration routes, so such ecological factors can take into account when validating wind or solar farm practical potential
- Take into account issues beyond energy supply that are essential for reliance on alternative energy sources, namely: grid reliability, storage, and handling peak-hours
- Research on policies and governmental incentives that encourage the development of renewables as well as facilitate transition to fully electrified consumption, especially at earlier stages of implementing the plan, where economics are less clearly in favor of the renewable alternative

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Appendix

Appendix 1

The following values are relevant characteristics of wind and solar technologies used by Jacobson et al. (2016) and in the calculations of this thesis. Data source is: Jacobson, M.Z & Delucchi, M.A., 2016.

Wind turbine characteristics		Low case	High case	AVERAGE
D1(S8)	Mean annual wind speed (m/s)	8.50E+00	7.00E+00	
D2 (S9)	Turbine rated power (kW)	5.00E+03	5.00E+03	5.00E+03
D3 (S9)	Turbine rotor diameter (m)	1.26E+02	1.26E+02	
D4=(0.087*D1-D2/D3^2) (S10)	Turbine capacity factor	4.25E-01	2.94E-01	
D5	Hours per year (hrs)	8.76E+03	8.76E+03	8.76E+03
D6=D2*D4*D5	Turbine energy output without losses (kWh/yr)	1.86E+07	1.29E+07	
D7	Turbine effic. (transmission,conversion, array losses)	9.00E-01	8.50E-01	
D8=D6*D7	Turbine energy output with losses (kWh/yr)	1.67E+07	1.09E+07	
D9=(4*D3)*(14*D3)/10^6 (S10)	Area for one turbine accounting for spacing (km2)	6.67E-01	8.89E-01	7.78E-01
D10	Diameter of turbine tubular tower (m)	4.00E+00	5.00E+00	
D11=PI*(D10/2)^2/10^6	Area of turbine tower touching ground (km^2)	1.26E-05	1.96E-05	
D12	Lifetime of wind turbine (yr)	3.00E+01	3.00E+01	
D13 (S11)	Energy to manufacture one turbine (kWh/MW)	1.37E+06	1.37E+06	
D14=D13*D2/(D12*1000)	Energy to manufacture one turbine (kWh/yr)	2.28E+05	2.28E+05	
D15=0.5*(D6a+D6b)	Avg turbine energy output before transmission (kWh/yr)	1.86E+07	1.29E+07	
D16=D13*D2/D15	Energy payback time (yr) for given turbine and winds	3.68E-01	5.31E-01	
D17=D14*C4	Single-turbine CO2 emissions (g-CO2e/yr)	1.39E+08	1.39E+08	
D18=D17/D15	Single-turbine CO2 emissions (g-CO2e/kWh)	7.47E+00	1.08E+01	
D19	Time lag (yr) between planning and operation	2.00E+00	5.00E+00	
D20	Time (yr) to refurbish after first lifetime	1.00E+00	2.00E+00	
D21=C4*(D19+D20*(100yr/D12))/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	3.25E+01	7.10E+01	
D22=D21-D21	Wind minus wind time lag CO2 (g-CO2e/kWh)	0.00E+00	0.00E+00	
D23 (Ni, 2002)	Grassland soil organic carbon (kg-C/m^2)	1.32E+01	1.32E+01	
D25 (Ni, 2002)	Grassland above-ground carbon (kg-C/m^2)	1.15E+00	1.15E+00	
D26=D22*0.66 (34% loss Table 6 of Pouyat et al.,2006	Impervious surface soil organic carbon (kg-C/m^2)	8.71E+00	8.71E+00	
D27=(D23+D24-D25)*44.01/12.01	CO2 loss due to impervious surface (kg-CO2/m^2)	5.26E+01	5.26E+01	
D28=D27*D47*1e9(m2-g/km2-kg)/(D8*100yr)	CO2 emissions due to loss of soil+surface carbon g-CO2e/kWh)	3.95E-04	9.43E-04	

Solar PV panel characteristics	SunPower E20	Low-cost case	High-cost case	AVERAGE
G21	Panel rated power in base year (W)	3.27E+02	3.27E+02	3.27E+02
G19	Area of panel itself (m2)	1.63E+00	1.63E+00	1.63E+00
	Panel efficiency in base year	2.04E-01	2.04E-01	2.04E-01
G22	Annual rate of change in efficiency	4.00E-03	6.00E-03	5.00E-03
	Base year of panel data	2.02E+03	2.02E+03	2.02E+03
G1 (S16)= G21*EXP(G22*(Target_year-E156))	Panel rated power in 2050, at constant area	3.76E+02	4.03E+02	3.90E+02
	Panel efficiency in 2050	2.35E-01	2.52E-01	2.43E-01
G2 (S16)	Mean capacity factor accounting for sunlight, PVs, inverter	2.40E-01	2.00E-01	2.20E-01
G4	Transmission efficiency	9.50E-01	9.00E-01	9.25E-01
G18=G1/G19	Panel rated power output (W/m2) in 2050	2.31E+02	2.48E+02	2.39E+02
	Total footprint/panel area, utility PV	2.34E+00	2.57E+00	2.45E+00
	Total footprint/panel area, rooftop systems	1.00E+00	1.10E+00	1.05E+00
G3=G1*G2*D5/1000	Single-panel energy output before transmis. loss (kWh/yr)	7.91E+02	7.07E+02	7.51E+02
G5=G3*G4	Single-panel output w/ transmis. loss (kWh/yr)	7.51E+02	6.36E+02	6.94E+02
G6 (S16)	Solar panel area (m2) plus walking and other non-panel space	3.81E+00	4.18E+00	4.00E+00
G7 (S17)	Lifetime of solar panel (yr)	3.00E+01	3.00E+01	3.00E+01
G8 (S17)	Single-panel CO2 emissions (g-CO2e/kWh)	1.90E+01	5.90E+01	3.90E+01
G9=G8*G3	Single-panel CO2 emissions (g-CO2e/yr)	1.50E+04	4.17E+04	2.93E+04
G10	Time lag (yr) between planning and operation	2.00E+00	5.00E+00	3.50E+00
G11	Time (yr) to refurbish after first lifetime	1.00E+00	2.00E+00	1.50E+00
G12=C4*(G10+G11*100yr/G7)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	3.25E+01	7.10E+01	0.00E+00
G13=G12-D21	Solar PV minus wind time lag CO2 (g-CO2e/kWh)	0.00E+00	0.00E+00	0.00E+00
G14	Ratio of carbon lost from desert to that from grassland (include only the 70% of PV on land)	7.00E-02	7.00E-02	7.00E-02
G15=G14*D27*G6*1e3(g/kg)/(G5*100yr)	CO2 emissions due to loss of soil+surface carbon g-CO2e/kWh)	1.87E-01	2.42E-01	0.00E+00
G16=G8*G3/G5+G13+G15	Total g-CO2e/kWh	2.02E+01	6.58E+01	4.22E+01
G17=G8*G3+(G13+G15)*G5	Total CO2 emissions per panel (g-CO2e/yr)	1.52E+04	4.19E+04	2.93E+04
G20	Spacing factor (m2) (total system area/panel area)			1.80E+00
G23	Panel rated power output (W/m2) in 2015	2.01E+02	2.01E+02	2.01E+02
G24= G6/G21	Footprint utility PV (km^2/MW)	1.17E-02	1.28E-02	1.22E-02

Concentrated solar power with no storage characteristics		Low-cost case	High-cost case	WEIGHTED AVERAGE
M1	Typical plant size (MW)	1.00E+02	1.00E+02	1.00E+02
M2 (S39)	Capacity factor (no storage)	2.50E-01	1.80E-01	
M3=M1*M2*1000*D5	Energy per plant before transmission (kWh/yr)	2.19E+08	1.58E+08	
M4=G4	Transmission efficiency	9.50E-01	9.00E-01	
M5=M3*M4	Energy per plant after transmission (kWh/yr)	2.08E+08	1.42E+08	
M6=E2/M5	Number of 100 MW CSP plants to run U.S. CSP-BEV	5.87E+03	1.11E+04	8.49E+03
M7 (S40)	Lifetime of CSP plant (yr)	3.00E+01	3.00E+01	
M8 (S40, S41)	Energy payback time (yr)	4.17E-01	5.58E-01	
M9=0.5*(M3a+M3b)	Avg energy per plant before transmission (kWh/yr)	1.88E+08	1.88E+08	
M10=M9*M8/M7	Energy to manufacture one CSP plant (kWh/yr)	2.62E+06	3.51E+06	
M11=M10*C4	Single-CSP plant CO2 emissions (g-CO2e/yr)	1.59E+09	2.13E+09	
M12=M11/M9	Single-CSP plant CO2 emissions (g-CO2e/kWh)	8.45E+00	1.13E+01	
M13 (S42)	H2O consumption wet-cool parabolic trough (gal/kWh)	7.77E-01	7.77E-01	
M14=M13*M3*M6	Gal-H2O/yr required to run U.S. CSP-BEV	9.99E+11	1.36E+12	
M15=M14/I32	Fraction of U.S. water demand for wet-cool CSP BEV	6.71E-03	9.13E-03	
M16=M14*F15/E2	Fraction of U.S. water demand for wet-cool CSP HFCV	2.11E-02	2.72E-02	
				WEIGHTED AVERAGE
M34	CSP (no storage) installation areal density (MW/km2-land occupied)	5.26E+01	4.12E+01	
M35	CSP (with storage) installation areal density (MW/km2-land occupied)	3.09E+01	3.13E+01	
M36=1/(M37/M35+(1-M37)/M34)	CSP storage weighted areal power density (MW/km2-land occupied)	3.47E+01	3.34E+01	3.41E+01
M37	CSP storage share, the ratio of capacity with storage to total capacity			7.33E-01
M18=M17*M1	Land area required (km^2) for one plant of typical size	2.88E+00	2.99E+00	2.93E+00
M19=M18*M6	Land area (km^2) required to run U.S. CSP-BEV	1.69E+04	3.32E+04	2.49E+04
M20=M19/E7	Fraction of U.S. land for CSP-BEV	1.85E-03	3.62E-03	
M21=M19/E10	Fraction of California land for CSP-BEV	4.19E-02	8.22E-02	
M22=M19/E12	Ratio of CSP to wind footprint area for BEV	1.84E+04	1.17E+04	
M23=M19/E4	Ratio of CSP to wind spacing area for BEV	3.47E-01	2.59E-01	
M24 (see text)	Time lag (yr) between planning and operation	2.00E+00	5.00E+00	
M25	Time (yr) to refurbish after first lifetime	1.00E+00	2.00E+00	
M26=C4*(M24+M25*100yr/M7)/100yr	CO2 emissions due to time lag (g-CO2e/kWh)	3.25E+01	7.10E+01	
M27=M26-D20	CSP minus wind time lag CO2 (g-CO2e/kWh)	0.00E+00	0.00E+00	
M28	Ratio of carbon lost from desert to that from grassland	1.00E-01	1.00E-01	
M29=M28*D27*M18*1e9(m2-g/km2-kg)/(M5*100yr)	CO2 emissions due to loss of soil+surface carbon g-CO2e/kW	7.28E-01	1.11E+00	
M30=M12+M27+M29	Total g-CO2e/kWh	9.18E+00	1.24E+01	
M31=M30*E2/10^12	CSP-BEV CO2 emissions (MT-CO2e/yr)	1.12E+01	1.96E+01	

Appendix 2

Presented are the values used in the calculation of the thesis in order to make it easier for the reader to follow the calculation method.

Israel's population and energy demand		
Z1	Population in 2015 (Not including residents in the west bank)	8.09E+06
Z2	Population in 2050 (Not including residents in the west bank)	1.08E+07
Z3	Percentage of urban population in 2050	9.33E-01
Z4	Percentage of Non-urban population in 2050	6.65E-02
Z5	Israel energy demand in 2050 (TWh/yr)	1.39E+02
Z6	FACSHT=factor to multiply total solar PV by to get size of heat collectors for grid integration study	1.90E-01
Z7	integration model to ensure collector size no larger than max power collected.	8.28E-01
Z8=Z6*Z7	FACSHT*SHEATFAC	1.57E-01
Z9	Installed nameplate capacity for storadge in 2013 for utility scale PV (MW)	0.00E+00
Z10	Israel land area (km2)	2.16E+04
Z11	Israel water area= EEZ+costal (km2)	2.60E+04
Z12	Costal length (km)	2.73E+02
	Israel's EEZ	2.20E+04
	Total on shore militaty ground km^2	7.89E+03
	Military area practically suitable for wind turbine installation	2.49E+02
	Military area practically suitable for CSP	1.21E+02
	Military area practically suitable for PV	1.47E+03
Values used for rooftop calculation		
W1	Estimated number of stories of urban area residences assuming higher residential buildins will be constructed in 2050 (based on analysis on data from Central Bureau of Statistics)	2.30E+00
W2	Estimated residential m^2/capita in 2015 and 2050 (Assuming it will stay the same as 2015)	5.00E+01
W3	Fraction of rooftop area suitable for PVs in urban area and commertial use	4.25E-01
W4	Fraction of rooftop area suitable for PVs in Non-urban area in 2050	2.00E-01
W5	Estimated number of stories of Commercial buildings in 2050	3.00E+00
W6	Avarage number of stories of residential buildigs constructed by 2015	1.80E+00
W7	Estimation of percentage of urban population 2015 (based on data of urban precentage in 2014)	9.12E-01
W8	Estimation of percentage of non-urban population 2015 (based on data of urban precentage in 2014)	8.75E-02
W9	Estimation of percentage of urban population in 2050. Assumed to be higher than 2015	9.30E-01
W10	Percentage of Non-urban population in 2050. Assumed to be lower than 2015	7.00E-02
W11 (Y1)	Onshore wind rated power of one unit (MW)	5
W12 (Y2)	Offshore wind rated power of one unit (MW)	5
W13 (Y3)	Wave device rated power of one unit (MW)	0.75
W14	Geothermal plant rated power of one unit (MW)	100
W15	Hydroelectric plant rated power of one unit (MW)	1300
W16	Tidal turbine rated power of one unit (MW)	1
W17	Res. roof PV system rated power of one unit (MW)	0.005
W18	Com/gov roof PV system rated power of one unit (MW)	0.1
W19	Solar PV plant rated power of one unit (MW)	50
W20	CSP plant rated power of one unit (MW)	100

Appendix 3

Explanations of calculations

Calulation of available residential rooftops for PV installation in 2050		
W1	Estimated number of stories of urban area residences assuming higher residential buildins will be constructed in 2050 (see number stories in residential building built 2010-2014 (Red Building story tab))	2.30E+00
W2	Estimated residential Floor area m^2/capita in 2015 and 2050 (assuming that will stay the same as 2050)	4.50E+01
W6	Avarage number of stories of residential buildigs constructed by 2015	1.80E+00
W7	Estimation of percentage of urban population 2015 (based on data of urban precentage in 2014)	9.12E-01
W8	Estimation of percentage of non-urban population 2015 (based on data of urban precentage in 2014)	8.75E-02
W9	Estimation of percentage of urban population in 2050. Source: Jacobson et al (2015)	9.33E-01
W10	Percentage of Non-urban population in 2050. Source: Jacobson et al (2015)	6.65E-02
X1=W2*W3/W1	Suitable PV m^2 roof/capita in Urban area in 2050	8.32E+00
X2=W2*W4	Suitable PV m^2 roof/capita in Non-Urban area in 2015 and 2050	9.00E+00
X3=Z2*W9*X1	Suitable PV area in Urban area in 2050 (m^2)	8.41E+07
X4=Z2*W10*X2	Suitable PV area in Non-Urban area in 2050 (m^2)	6.48E+06
X5=(X3+X4)/10^6	Suitable Area in 2050 (km^2)	9.06E+01
X6=X5*G18	Technical potential in 2050 (MW)	2.17E+04
X7=W2*W3/W6	Suitable PV m^2 roof/capita in Urban area in 2015	1.06E+01
X8=Z1*W7*X7	m^2 suitable PV area in Urban area in 2015	7.85E+07
X9=Z1*W8*X2	m^2 suitable PV area in Non-Urban area in 2015	6.37E+06
X10=(X8+X9)/10^6	km^2 Useable Area in 2015	8.49E+01
X11=X10*G23	Technical potential in 2015 (MW)	1.70E+04
Onshore wind		
	Israel's onshore wind capcity from areas where wind speed is greater than 6 m/s at 100m hight (MW)	1.38E+04
X12	Area available at Wind speed bigger than 6 m/s Slope 30 and in open space (Urban areas, water land archeological sites and airports were exluded)	1.21E+03
X13=X12*D2*10^-3/ D9	Onshore technical potential (MW)	7.78E+03
X14	Area practiclly suitable: available in open space (Urban areas, water land archeological sites and airports were exluded) at wind speed bigger than 6 m/s slope equal or smaller than 30% and with no environmental or on military ground	4.48E+02
X15= X14*D2*10^-3/ D9	Onshore wind practical Potential (MW)	2.88E+03
Calculating technical potential capcity for Solar PV		
X16 (Z6)	Areas technically suitable for utility scale PV (Open areas that are not suitable for CSP installation)	9.62E+09
X17=10^-6*G18*X16/G20	Technical Potential for PV farm (MW)	1.28E+06
Calculating Practical potential capcity for Solar PV		
X18 (Z9)	Area with Slope=<5 with no limitation at all or areas defined as military ground, on non agricultural land that is not suitable for CSP due to continious size<18,000 m2 DNI<5 kwh/m2/day (since this area is flat it the solar farm doesn't need to face only on south mountain edge and not need to split the area to half)	2.47E+09
X19=10^-6*G18*X18/G20	Practical Potential for PV farm (MW)	3.28E+05
Calculating technical MW for CSP		
X20 (Z1)	Available area for CSP (km2) with Slope=<5 continious size=>18,000 m2 DNI=>5 kwh/m2/day	1.14E+03
X21=X20*M36	Technical Potential for CSP (MW)	3.88E+04
Calculating Practical MW for CSP		
X22 (Z7)	Available area for CSP (km2) Slope=<5 continious size=>18,000 m2 DNI=>5 kwh/m2/day with no limitation or only fire, on non agricultural land:	2.66E+02
X23=X22*M36	Practical Potential for CSP (MW)	9.07E+03

Appendix 4. . The following table presents the data sources that were used to create the criteria layers for finding areas suitable for WWS development.

Layer	Original dataset type	Data source	Original Resolution / Data type	Data from	Description	Criteria the data was used for	Used as part of the special analysis is of
Annual wind speed at a height of 100 m	Raster	Israel Meteorology Center	100 m	2015	Annual wind speeds at a height of 100 m created by using regional model (COSMO) and micro model (WAsP)	Wind layer Areas with wind speeds less than 6/6.5/7 (m/s) were excluded. Areas in the West Bank were excluded.	Onshore wind PV farm CSP
ASTER Global Digital Elevation Model Version 2	Raster	NASA	30 m	2011		slope	Onshore wind CSP
Textures	Vector	Ministry of Interior. NOP 35	Polygon	2015		Within Israel border AND Shore texture	Onshore wind
Land use	Raster	Central Bureau of Statistics	100 m	2013		Open space Areas defined in the Landuse layer as 'airport' or 'archiological sites' were erased from the open area layer	Onshore wind PV farm CSP
Open space composition	Vector	Hamaarag, The State of Nature 2015 report	Polygon	2015	The layer divides Israel's area into eight categories: Shrub-steppe, Garrigue, Forest and woodland, Desert open space, 'other' open space, Field crops, Plantations, waterland, built areas. (This layer already doesn't contain areas of roads). The data is based on Survey of Israel landuse data, Kaplan's built areas data together with remote sensing analysis.	Open space Waterland and built areas were excluded from the open areas composition data since theywere found as unsuitable for wind installation.	Onshore wind PV farm CSP
Open space statutory protection level	Vector	Hamaarag. The State of Nature 2015 report	Polygon	2015	The layer aggregates plans of the Jewish National Fund Nature and Parks Authority and National Outline Plan 22 The layer describes the Environmental statutory protection level of open space areas (High, median and low)	Open space	Onshore wind PV farm CSP
Bird Important Areas	Vector	Nature and Parks Authority	Polygon	2016		Environmental importance: Birds Important Areas	Onshore wind PV farm CSP
Military areas	Vector	Ministry of Interior. National Outline Plan 35	Polygon	2015		Military areas	Onshore wind PV farm CSP
Solar radiation of Africa	Vector	NREL	Polygon	2014	Monthly and annual average direct normal (DNI), global horizontal (GHI), latitude tilt, and diffuse data and GIS data at 40 km resolution for Africa developed from NREL's Climatological Solar Radiation (CSR) Model.	DNI larger than 5 $KWh/m^2/day$ annually.	CSP