MASTER THESIS

THE ROLE OF VARYING FACTORS IN PREDICTIVE ENERGY SCENARIO MODELS: A META-ANALYSIS

---

by

ALEXANDER HOFFER, BSC.

student in

MSC. STRATEGY, INNOVATION AND MANAGEMENT CONTROL
at
VIENNA UNIVERSITY OF ECONOMICS AND BUSINESS (WU)
ADVISOR: DR. MICHAEL KÖNIG, MBA

and

MIM. MANAGEMENT
at
GRADUATE SCHOOL OF MANAGEMENT (GSOM), ST. PETERSBURG UNIVERSITY
ADVISOR: PROF. DMITRI KNATKO, PHD.

June 2020

АННОТАЦИЯ

Автор	Александр Хоффер
Название ВКР	Факторы в предиктивных сценарных моделях для энергетики: мета-анализ
Образовательная программа	Master in Management - MIM
Направление подготовки	Менеджмент
Год	2020
Научный руководитель	кандидат экономических наук Д.М. Кнатько
Описание цели, задач и основных результатов	Энергетические модели являются эффективным инструментом для создания вымышленных образов реальности с целью оценки будущего развития энергетических систем в определенном географическом месте. Это жизненно необходимо для энергетических компаний, государственных органов управления и других заинтересованных сторон по целому ряду причин, включая, но не ограничиваясь этим, инвестиционное планирование, развитие спроса на энергию, принятие решений о выходе на рынок и многое другое. В данной диссертации рассматривается типичная проблема несвязных и несопоставимых энергетических моделей для улучшения возможностей прогнозирования в энергетической сфере для лиц, принимающих решения. В контексте операционного исследования в рамках передового опыта стратегического управления, началось изучение энергетических моделей и лежащих в их основе входных переменных путем проведения мета-анализа различных сценарных энергетических моделей. Основным вкладом данной диссертации является исчерпывающий перечень 91 уникальной переменной энергетического сценария, который может быть использован менеджерами и исследователями как контрольный перечень и гарантия качества существующих моделей, а также как источник вдохновения для будущих энергетических моделей, чтобы избежать смещения вследствие пропущенных переменных. Другим выводом является кажущаяся чрезмерная представленность технических переменных по сравнению с другими типами. Это может привести к технически осуществимым прогнозам будущей энергетической системы региона, пренебрегая при этом нетехническими причинами, которые делают эти прогнозы бесполезными (например, атомная энергетика в Германии). Анализ множественных соответствий (MCA) представляет различные степени сходства между моделями энергетических сценариев, подчеркивая сильную потребность в стандартизации переменных в энергетическом моделировании. Кроме того, результаты указывают на значительные различия в использовании переменных в сценарных энергетических моделях и, особенно, в отраслевых отчетах и научных работах. Управленческие и практические выводы данной диссертации приводят к улучшению возможностей принятия стратегических решений руководителями и ключевыми лицами, принимающими решения в энергетической отрасли, а также правительствами для построения макроэкономических прогнозов устойчивого будущего.
Ключевые слова	энергетическая модель, энергетический сценарный анализ, стратегическое управление, принятие решений, операционное исследование, прогнозирование

ABSTRACT

Master Student's Name	Alexander Hoffer
Master Thesis Title	The Role of Varying Factors in Predictive Energy Scenario Models: A Meta-Analysis
Educational Program	Master in Management - MIM
Main field of study	Management
Year	2020
Academic Advisor's Name	Candidate of Economics D.M. Knatko
Description of the goal, tasks and main results	Energy models are an effective tool to create fictional images of reality in order to estimate future developments of energy systems in a certain geographic location. This is vital for energy companies, state governments and other stakeholders for a variety of reasons, including but not limited to investment planning, energy demand development, market entry decisions and many more. This thesis addresses the common issue of incoherent and incomparable energy models to improve decision makers' forecasting capabilities in the energy sphere. In the context of operational research as part of good practice strategic management an investigation into energy models and their underlying input variables is launched by conducting a meta-analysis of a variety of energy scenario models. One major contribution of this thesis is a comprehensive list of 91 unique energy scenario variables, which can be used by managers and researchers as a checklist and quality assurance of existing models, but also as inspiration for future energy models to avoid omitted variable bias. Another finding is the seeming overrepresentation of technical variables in comparison to other types. This can lead to technically feasible predictions of a region's future energy system, while neglecting non-technical reasons that render those predictions useless (e.g. nuclear energy in Germany). A Multiple Correspondence Analysis (MCA) presents varying degrees of similarities between energy scenario models, underlining the strong need for variable standardization in energy modelling. Furthermore, the results hint towards a strong variation of variable usage in energy scenario models and especially between industry reports and scientific papers. The managerial and practical implications of this thesis lead to the improvement of strategic decision-making capabilities of mangers and key decision-makers in the energy industry as well as governments to build macroeconomic predictions for a sustainable future.
Keywords	energy model, energy scenario analysis, strategic management, decision making, operational research, forecasting

Table of Content

Table of Figures

ABSTRACT

Energy models are an effective tool to create fictional images of reality in order to estimate future developments of energy systems in a certain geographic location. This is vital for energy companies, state governments and other stakeholders for a variety of reasons, including but not limited to investment planning, energy demand development, market entry decisions and many more. This thesis addresses the common issue of incoherent and incomparable energy models to improve decision makers' forecasting capabilities in the energy sphere. In the context of operational research as part of good practice strategic management an investigation into energy models and their underlying input variables is launched by conducting a meta-analysis of a variety of energy scenario models. One major contribution of this thesis is a comprehensive list of 91 unique energy scenario variables, which can be used by managers and researchers as a checklist and quality assurance of existing models, but also as inspiration for future energy models to avoid omitted variable bias. Another finding is the seeming overrepresentation of technical variables in comparison to other types. This can lead to technically feasible predictions of a region's future energy system, while neglecting non-technical reasons that render those predictions useless (e.g. nuclear energy in Germany). A Multiple Correspondence Analysis (MCA) presents varying degrees of similarities between energy scenario models, underlining the strong need for variable standardization in energy modelling. Furthermore, the results hint towards a strong variation of variable usage in energy scenario models and especially between industry reports and scientific papers. The managerial and practical implications of this thesis lead to the improvement of strategic decision-making capabilities of mangers and key decision-makers in the energy industry as well as governments to build macroeconomic predictions for a sustainable future.

INTRODUCTION

Energy models have the goal of supporting decision makers and stakeholders in making well-founded judgments by providing comprehensive forecasts. Yet, due to the rising number of energy simulations by the scientific community and international organizations, it can be increasingly challenging to keep up to date, identify potentially misleading models and transparently compare baseline assumptions. Especially due to rapidly developing technologies, balanced and exhaustive models are hard to find and demanding to recognize. Renewable energy for instance has been celebrated as well as ridiculed for many years. Some praise the wide array of clean energy sources as the saviour of all humanity, whereas others do not acknowledge renewables will have any significant share in the primary energy mix in the foreseeable future. Which position is more compelling and how do the underlying assumptions compare?

Besides speculations, it has become common practice to not just build one model, but rather create many different scenarios with varying baseline assumptions that yield different results. For instance, the International Energy Agency (IEA) offers three scenarios: the Stated Policy scenario – where planned regulations and near-term policies are considered; the Sustainable Development scenario – assuming a hard shift in public opinion, leading to a more sustainable approach towards energy; and Current Policies scenario – assuming no change in behaviour by humanity and the progression of the current path.

Even though this presents a greater variety of possible directions and is set out to increase the scope of included possible outcomes, it makes it almost impossible to compare models with each other across different resources, as granular differences in scenarios make them unparalleled. As a result, incomparable energy models can hinder the understanding of the whole energy industry and the identification of trends. To tackle this information gap and help improve future energy scenario models it is crucial to find a common baseline of comparison between energy scenario models and build a collection of deterministic variables that influence the outcome of the respective model.

For high-level managers and decision-makers in the energy industry it is imperative to improve forecasting capabilities in the energy field as long-term planning periods are common and can lead to huge sunk costs if developments in the energy market are misjudged. This is especially relevant in times of strong attention to greenhouse gas emissions and rapid shifts in policy and strategy. The viewing angle in the context of this thesis therefore has a macro orientation with a focus on the energy industry and related stakeholders. It builds on the concepts of Operations Research (OR), which involves the incorporation of mathematical methods to analyse problems and gain insights into a management problem (Merriam-Webster, 2020).

This thesis sets out to deliver a complete collection of used variables in energy scenario models and a statistical analysis that sheds light on usage patterns. Furthermore, a methodical analysis and description provide possibilities to recommend improvements for the future of energy modelling. It is argued that an expansion of the overall knowledge base in the context of energy systems and its deterministic variables ultimately leads to a better understanding and the ability to better forecast its future development.

In order to provide a contextual setting, a literature review of key energy technologies is carried out, discussing major advantages and shortcomings. It is essential to map the industry as well as its great variety of systems and technologies prior to diving into scenario models because several mechanisms or technologies might classify as novel or unintuitive. Ultimately, this thesis focuses not on the results and predictions of each scenario, but rather takes a close look at the considered factors and variables.

After all, this thesis presents 91 unique energy scenario variables, which can either be used as an inspiration to include in future models or to check for biases with regard to content coverage. This opportunity most certainly applies to managers in the energy industry, but also to developers of such energy models. Furthermore, the thesis offers an attempt to categorize unstandardized variables in this context and builds a base structure for potential further exploration of the topic.

Moreover, the statistical analysis carried out on top of the exploratory research provides an interesting insight into the inner works and apparent weightings of variable types in energy scenarios.

The thesis consists of the collection and analysis of papers and reports which present one or multiple long-term energy scenarios (to the year 2030 or further) and consider the complete energy mix of either regional, national or global scope. The methodology of the thesis is a meta-analysis.

CHAPTER 1: STATE OF THE ART OF ENERGY

In order to satisfy modern civilization a vast and ever-growing amount of energy is needed. Very broadly, energy sources are divided up in “renewable” and “non-renewable” or “conventional” energy sources, attesting to their nature of production. However, renewable energy (or also called sustainable energy) does not have a fixed definition but is rather defined differently and even contradictory at times. For instance, the German Umweltbundesamt (2016) says that “(…) The basic principle of renewable energies is that on the one hand processes taking place in nature are used. On the other hand, electricity, heat and fuels can also be generated from renewable raw materials.”, which puts a distinctive emphasize on the passive usage of natural occurrences. Twidell and Weir (2006, p. 6) describe renewable energy with “Energy obtained from natural and persistent flows of energy occurring in the immediate environment”, putting the main emphasis on a perpetual mechanism in a certain location. Sørensen (2004, p. 16) defines renewable energy resources as them being “(…) replenished at the same rate as they are ‘used’.” This definition looks at the in- and outflows of a certain energy system and classifies it by the “reservoir” being used up faster than it can regenerate (e.g. coal, natural gas, crude oil, uranium) versus energy sources with a virtually infinite “reservoir” (e.g. solar).

Especially solar energy radiating from the sun can either be directly used to generate energy or through secondary effects like wind energy, which are in turn caused by the sun’s radiation. Another virtually infinite power source is tidal energy caused by the moon’s gravitational field, which also counts as a pure renewable source of energy. Regarding biofuels the classification gets trickier as the reservoir is influenced by more than one factor.

The inflow into the biomass reservoir occurs due to the growth of biomass which can take place through natural growth or through afforestation (Regelous & Meyn, 2011). The effluent is either caused by natural death or by deforestation. As afforestation and deforestation are controlled by humans, biomass is the only energy source at which humans can influence inflow and outflow and thus control the lifespan. It is determined by the difference between afforestation and consumption. In most of the literature biofuels are considered a renewable energy, which is why in this thesis it will also be classified as such.

When it comes to geothermal energy there are two different classifications regarding the global or the local point of view. As for the global view, thermal energy in the core of our planet is an independent process disregarding human intervention or usage of the power generated by these complex processes. On the other hand, local geothermal energy does rely on the preservation of some heat in the energy pocket. This means, if the extraction of heat is being done at an unsustainable rate, the resource will only be available for a finite amount of time. (Regelous & Meyn, 2011)

The term energy can also lead to confusion at times as it can refer to energy production or consumption, electric energy or primary energy. Energy production and consumption are different because in every energy system losses occur when transforming, for instance fuel into heat or electric energy. Electric energy, as already stated, is not a primary but a secondary energy as it must be generated through other means first. The primary energy mix represents the initial stage of energy production, namely the fuel source, which is dominated by oil (31,8%), coal (27,1%) and natural gas (22,2%) (Figure 1).

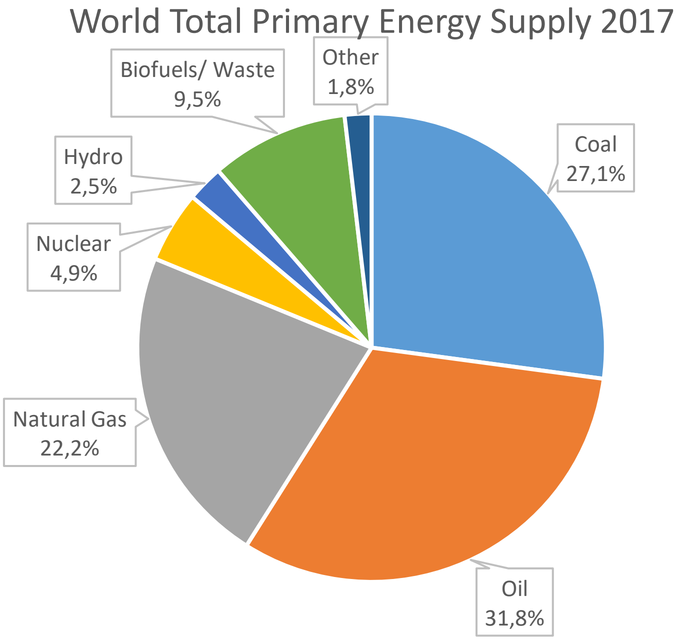


Figure 1, World Total Primary Energy Supply 2017, (Data from IEA (2019c))

In 2018, 38% of total electric energy has been generated through coal, a little over 25% through renewables, 23% through natural gas, 10% with nuclear energy and a mere 3% with oil (IEA, 2019d). However, electric energy only makes up around 19% of total consumption, whereas oil constitutes more than double, namely 40% of total global consumption in 2018 (IEA, 2019d). Subsequently, a shift towards a more renewable energy future usually goes hand in hand with a rising electrification especially of the sectors mobility and heat (IEA, 2019d). This, however, comes with its own set of issues as an infrastructure change of this magnitude requires a lot of effort, in particular in developing nations and rural areas (Lesperance et al., 2018; Zhang & Kumar, 2011).

1.1. ENERGY DEMAND STRUCTURE, STAKEHOLDERS AND RISK PROFILE

The energy sphere is arguable one of the most complex and impressive achievements of humanity as its reliability, strength and constant development requires high levels of creativeness and technological know-how. As a result, stakeholders are manifold and reach from private citizens, large production facilities and governments to energy producing companies, logistics providers, tech companies and many more.

This overreaching industry has generally been developing positively for many decades on a global level. Especially in Asian countries demand has been rising in an unprecedented scale (IEA, 2019a). Nevertheless, energy demand does not restrict itself to one singular commodity but rather spans across many different resource types, technologies and logistical routes. The electric energy grid for example must ensure a perfect balance of supply and demand every second, putting a lot of pressure on grid operators to make accurate predictions for the coming hours, weeks or months. Governments have to anticipate mid- to long-term developments and improve production capabilities or re-route to different areas. On the other hand, crude oil is being shipped all around the world and refined into different derivatives (gasoline, diesel, jet fuel, etc.), whereas gas is mostly transported via pipelines and is traded in separate hubs.

These technologies and types of energy do not just enrich the possibilities and diversity of the energy system but also significantly increase the level of complexity. Especially, apparently unforeseeable external influences can be powerful drivers of change that can lead to volatile and uncertain situations (IEA, 2018a).

A framework that precisely describes such situations is called VUCA, which stands for **v**olatility, **u**ncertainty, **c**omplexity and **a**mbiguity. It has originally been developed in the military sphere (Whiteman, 1998) but has recently been adopted in the world of business as well (Bennett & Lemoine, 2014). In “a VUCA world”, executives struggle to make educated decisions as external influences make foresight extremely challenging. This of course influences firm performance and can lead to bankruptcy or other severe setbacks.

The framework, however, pinpoints different kinds of challenges and provides the possibility to tackle them head on with appropriate measures. When faced with volatility the rate of change is fast and challenges are unexpected, nevertheless information about the issue is available. A possible mitigation strategy is to improve preparedness by spending more on stocks, human resources and essential goods. This provides the possible freedom to react fast.

Uncertainty is characterized by knowledge about the issue but a lack in predictability. Therefore, the effects are unknown and as a result it is not clear if active reaction is needed and if yes to which extent. Here information is key as an improved knowledge base can lower uncertainty and provide a clear path to success.

Complexity is made up by a low degree of knowledge about the situation as interconnected variables add layers to the problem set. To tackle the volume of complex problems it can help to task specialists to handle the situation and address the complexity.

Lastly, ambiguity is characterized by a total lack of knowledge and previous experience. The so-called “unknown unknowns” can be tackled by experimentation to gain experience and knowledge and subsequently find ways to mitigate the issue.

In the energy sphere all those types of issues are represented in a myriad of ways, which makes it ever more important to increase knowledge about the status quo, develop an understanding of potent influencers and factor them into predictive energy models.

It is imperative to stress the incredible complexity of energy systems and the energy business as a whole. In addition, cause and effect relationships within such a complex system is not always clear, leading to big uncertainty especially when estimating more than 30 years into the future (Sadorsky, 2011). Nevertheless, governments, energy companies and countless other stakeholders rely on such predictions to make strategic decisions, nurture growth or sustaining market share.

The following section examines main energy technologies within the renewable and non-renewable segment to provide a baseline understanding of the main factors to consider and main advantages and drawbacks of each respective technology. Furthermore, the segment will look at the status quo of energy scenario forecasts, discuss the research problem that arises from it and name the research statements that provide the main scientific baseline for this thesis.

1.2. BACKGROUND OF RENEWABLE ENERGY

To understand the future development of renewable energy and its progress estimations it is crucial to understand the past technological developments, changes in energy demand, energy trends, the issue of climate change as well as legislation and policy, first. The following section will give an overview of scientific literature in those fields to provide a baseline for the language and basic technological trends that still influence energy modelling and scenario building to this day.

The world of energy has been developing exponentially since the discovery of static energy in ancient Greece by Thales of Miletus at around 600 B.C. (Cork, 2015). Rubbing amber and fur together did not only statically charge the ancient scientists but sparked the development of technologies that would influence humanity in an unprecedented way. Since the Baghdad battery, the first ever electrical storage device, was invented in the Parthian or Sasanian empires at around 250 B.C. to 224 A.D. (Keyser, 1993), the human race has come a long way.

Even the very first source of artificial heat, namely controlled bonfires between 1.5 and 0.2 million years B.C. (James et al., 1989), was energy generation through biofuels as plant matter and biological waste (e.g. bones) was burned. Also, the usage of wind energy to power grain windmills in the middle ages or sail boats as early as the Mesopotamian empire in 5,500 B.C. can be considered energy usage of renewable sources (Carter, 2006). Therefore, it can be argued that the very beginnings of human exploration of energy had been through renewables. By simply "tapping into" an available renewable resource, humans were able to accelerate their overall development.

Before the first industrial revolution, the main primary energy source was wood. However, due to excessive forest clearings, which by far exceeded reforestation, it cannot be considered a renewable resource at this time anymore. As a result, when the first industrial revolution started in the middle of the 18th century, the main fuel source became coal and other fossil fuels. This led to a steadily increasing amount of generated emissions and unprecedented amounts of CO2 in the atmosphere. By the year 1960, global CO2 emissions had doubled from around 5 billion tons of CO2 in 1950 to 9.5 billion tons only 10 years later (Roser & Ritchie, 2017).

Around the same time the peak-oil theory by Hubbert (1956) was published, predicting peak oil production in the 1970s. This led to the first reoccurrence of renewable energy by means of initiatives pushing for more wind turbines. In that time, however, the overall energy output by renewables was negligible comparing to the overall amount generated by conventional methods. Photovoltaic panels were not yet feasible from neither a cost nor an efficiency perspective. Since the past 10 to 15 years, this has changed, and renewable energy has experienced tremendous growth ever since.

The following segment presents the most prominent renewable energy technologies, their functionality and use-cases. Geothermal and tidal energy generation are not covered in this segment, as their contribution to the global electricity production are just around 1% combined in 2018 (IEA, 2019d), and are not expected to grow to a significant production volume in the near future.

HYDROPOWER PLANTS

Hydropower plants have been the backbone of Europe’s renewable energy supply for many years and still hold a large share (10%) of the total amount of generated renewable energy (Eurostat, 2019b). Their advantages include very short response times and a high capacity while disadvantages include high cost of production, sometimes a great influence on the environment and a limited amount of appropriate locations to build a hydropower plant. This limits the potential output of hydropower in total. Regarding fluctuations hydropower can be considered a very stable and predictable source of energy, which highlights how valuable this renewable energy source is.

Hydropower makes up almost 16% of total global electricity generation and even though it represents the largest share at the moment, the growth rate of new installations has been declining for five consecutive years (IEA, 2019d), whereas other renewable sources experience exponential growth rates.

WIND POWER

One of those stellar rising energy sources is wind energy, only making up for 31 TWh of generated electricity in the year 2000. By the year 2018, total global production skyrocketed to 1265 TWh (IEA, 2019d), representing a more than 200% increase in production per year.

Wind power can be split into two groups, namely onshore and offshore. Onshore wind is among the least expensive sources of electricity in developed nations. For instance, most of the United States’ increase in renewable energy can be accounted to this technology. Offshore wind is still more expensive, however, due to the lack of space and unfavourable regulations it becomes a viable option in countries such as Germany. There the onshore wind sector has come under public scrutiny lately because of noise pollution and migrating birds falling trap to the spinning blades (Endt & Witzenberger, 2019). Furthermore, whereas there generally seems to be a positive attitude towards wind energy, research has shown that there is an element of “not in my backyard”

The European Environment Agency (2009) assess the EU’s technical wind energy potential in 2020 at around 17 to 20 times the size of the projected demand and even the economically competitive potential still at around three times the size of demand. This means that wind energy would have the technological as well as economic capacity to meet the EU’s energy demand with ease, making it one of the two major technological superstars in the renewable energy business alongside solar energy.

In 2017, the highest wind energy production globally is found in the People’s Republic of China with 295 TWh, followed by the United States with 257 TWh and Germany with 106 TWh (IEA, 2019a).

SOLAR ENERGY

Solar power generation is made up of two technologies, namely photovoltaic (PV) energy generation and concentrated solar power (CSP). The former is by far the more significant technology in terms of installed capacity, making up almost 115.000 MW in 2018 of PV compared to only 2.300 MW of CSP in Europe (EurObserv’ER, 2019a, 2019b). The advantages of PV is its great variety and modularity of application, spanning from powering small objects like calculators to generating energy for whole cities by adding up modules to a large array. Another big advantage is the mode of production of PV panels. They can be produced on a large scale in production plants making use of economies of scale and steadily driving the cost per module down.

The big leap in solar energy adoption has been driven by precisely this steady decrease of PV panel cost, coming from around 10 EUR/Wp in the 1980s (Papaefthimiou et al., 2016) to as low as 0,4 EUR/Wp in 2019 (EurObserv’ER, 2019a). This reduction in cost has played a big role in making PV a viable source of energy from an economic point of view. This too has been aided by the vast production of PV modules in China, making it by far the sole leader in PV panel manufacturing. In 2017, 60% of solar panel production has been done in the People’s Republic while also achieving the same share in solar energy production globally (IEA, 2018b). This strong position in the industry has been good on the one hand for the rate of adoption of solar energy production, but on the other hand has been harmful to European panel producers because of the inability to produce at such low costs. This led to the European Union taking action by imposing anti-dumping tariffs in December 2013, only to abolish them again five years later in September 2018 (European Commission, 2018).

As already mentioned, this step has been taken primarily to lower cost of PV installation and reaching higher PV adoption rates in the EU. The technical term for a renewable energy source having the same cost per Watt as a traditional (non-renewable) source is “grid parity”. From a purely economic point of view, at gird parity energy sources become interchangeable. For ecologic reasons it could be decided to transition towards the respective renewable energy technology. Papaefthimiou et al. (2016) argue that for PV modules this point might happen very soon or has already happened in some parts of the world giving one possible explanation for its unprecedented growth of yearly installed capacity and increasing solar energy production with an average annual growth rate of 54% per year (2003-2017) (Eurostat, 2019).

Most of the solar energy in the EU has been generated in Germany with 46.164 TWh, followed by Italy with 22.654 TWh and the UK with 12.922 TWh in 2018. When looking at the installed capacity per capita, Germany is still on the first place (547 W/p), followed by Belgium (373 W/p) and Italy (332 W/p) (Eurostat, 2019).

Globally, China is again in the lead producing 131 TWh in 2017, followed by the United States with 67 TWh and Japan with 55 TWh. Total annual production in 2017 was 444 TWh. (IEA, 2019a)

BIOFUELS

As already mentioned, the somewhat split scientific opinion whether biofuels can be considered a true renewable energy source is highly dependent on the sourcing of raw materials that are used to produce the biofuel. The underlying discussion revolves around the fact that plants absorb CO_2 from the atmosphere over the course of their lifetime and the exact same amount gets released when using or burning this plant matter during the energy extraction process while using the fuel. The plant itself uses the energy of the sun to create a multitude of materials (Figure 2) that are essentially based on atmospheric CO_2, using the carbon in chemical processes like photosynthesis.

Thus, the argument of a “carbon cycle” can be made. However, this very simple depiction of the production process does not take into account the energy needed for land clearings and production of crops for especially first generation biofuels, which are made out of food crops (Skeer & Leme, 2018). Therefore, only locally and sustainably sourced biofuels can be classified as carbon neutral. The classification of first, second and third generation biofuels also is essential in the discussion around this topic. The first generation includes biofuels derived from agricultural feedstock like grain, sugar cane and oil crops (Twidell & Weir, 2006), which poses a whole other issue in itself as diverting resources away from food production would have an impact on food prices at the expense of fuel prices. The second-generation biofuel only includes the agricultural residue and the third-generation biofuels solely relies on algae as a source of plant material.

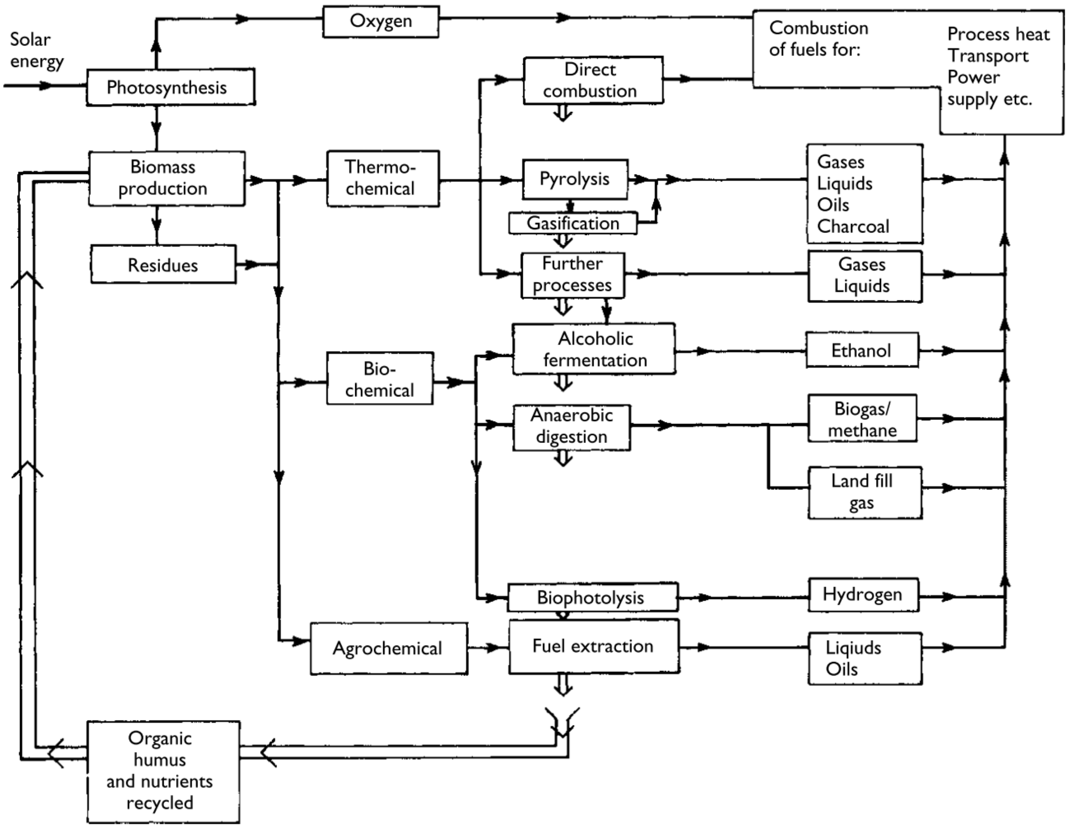


Figure 2, Biofuel production process (Twidell & Weir, 2006, p. 355)

From a global perspective, 6,1% of total primary energy supply has been met by biofuels and waste in 2017. This represents an uptrend comparing to 2,3% in 1973 (IEA, 2019a).

1.3. BACKGROUND OF NON-RENEWABLE ENERGY

To the contrary of renewable energy sources, non-renewable energy is generated using sources that do not get regenerated on a human timescale. Fossil fuels as well as nuclear fuels have been formed many thousands and even millions of years ago from organic material or geophysical processes.

OIL

In 2017, the largest portion of the world's primary energy supply is met by oil, namely 32% (IEA, 2019a). The annual production in 2018 was 4.482 Mt, of which 33% was produced in the Middle East and 26.8% in OECD countries. The largest net importers are China with 415 Mt, the United States with 349 Mt and India with 220 Mt (2017) (IEA, 2019a). Main uses of crude oil in 2018 include road transport (43,6%), industry and petrochemicals (18,9%), buildings and power (12,7%) and aviation and shipping (12,4%) (IEA, 2019d).

The price of crude oil and its derivatives has been extremely volatile since the big oil price crash in 1986 and in fact has been more unstable than 95% of other products. The reasons for such fluctuations include geopolitical conflicts in some of the major producing countries (e.g. Gulf War) (Regnier, 2007) and production decisions by influential producers, such as the Organization of the Petroleum Exporting Countries (OPEC) (Kaufmann et al., 2008). Additionally, the price is also influenced by cost of production, which is especially depending on whether local production is possible by conventional or unconventional means.

NATURAL GAS

Natural gas is closely connected to oil, as in most reserves both forms of fossil fuels are found. However, there are some key differences apart from the physical form. First, due to its gaseous form natural gas cannot be easily and cost efficiently be transported over long distances apart from pipelines. This in turn makes natural gas markets fairly separate and at times even fairly illiquid (Miriello & Polo, 2015). The three major import markets within the OECD are Europe, East Asia and North America (Economides & Wood, 2009). One major development in recent years has been the increased use of Liquified Natural Gas (LNG), which has the potential to connect for instance the North American with the European natural gas market despite the unfeasibility of a direct pipeline.

On a strategic front, natural gas, also due to its significantly lower CO2 emissions when burned, is being positioned as a transition fuel towards a more renewable energy landscape (IEA, 2019b). This means that highly emitting fossil fuels, such as coal, are being replaced by gas fired power plants to reduce emissions.

The largest natural gas producers in 2018 are the United States (862 bcm), the Russian Federation (715 bcm) and Iran (231 bcm), with a global total production of 3.937 bcm. Especially the United States' role as a producer has been amplified significantly since the past two decades because of the shale gas revolution, making cost effective extraction of tight gas feasible (Aruga, 2016). The largest net exporters are the Russian Federation (236 bcm), Qatar (121 bcm) and Norway (118 bcm) (IEA, 2019a).

COAL

The fossil fuel with the highest amounts of greenhouse gas emissions is coal, yet almost 16% of total primary energy production is met by this source (IEA, 2019a). The U.S. Department of the Interior (n.d.) classifies four different types of coal. Namely, from highest to lowest carbon concentration: Anthracite, Bituminous, Subbituminous and Lignite. Whereas the first is hard, glossy and fairly pure, the last (also known as brown coal) is fairly impure, moist but also cheaper in production. In the United States the most common type of coal for electricity generation is Bituminous (U.S. Department of the Interior, n.d.).

The largest producers in 2018 are China with more than 45% of total global production (3.550 Mt), India (771 Mt), the U.S. (685 Mt), Indonesia (549 Mt), Australia (483 Mt) and Russia (420 Mt) (IEA, 2019a). While China is consuming even more coal than its staggering production, countries like Indonesia and Australia export most of their coal abroad.

NUCLEAR ENERGY

Nuclear energy is also a very common but costly form of energy generation, which is one of the reasons annual investments have been the smallest among all primary energy types (IEA, 2019d). The technology makes use of nuclear fission and a nuclear chain reaction to heat up water and run steam engines to generate electrical power. Even though this mode of generation provides very stable and emission free energy, it cannot be classified as sustainable or clean because the radioactive fuel is used up and production of highly radioactive waste is still an unsolved problem.

In addition, the risk of nuclear fallout in the aftermath of an accident is a serious risk that cannot be overstated. Even though, the Fukushima nuclear accident in 2011 for example was found to be mostly caused by the operator’s negligence (Synolakis & Kânoğlu, 2015) accidents, even if very unlikely, have severe and lasting effects on the environment and global safety. A contributing factor is also the lack of international safety standards.

In 2017, most nuclear energy was produced in the United States (839 TWh), France (398 TWh) and China (248 TWh) with a total global production of 2.636 TWh. Nuclear energy makes up close to 5% of total global energy demand (IEA, 2019d).

1.4. LITERATURE REVIEW OF ENERGY SCENARIOS

Due to current uncertainties in the climate debate but also for economic or technical reasons it is invaluable to be able to anticipate future developments in the energy sector. Especially for energy companies (IEA, 2019d), governments (Gironès et al., 2015; Moret et al., 2016; Savio & Nikolopoulos, 2013) and industrial energy consumers (Cano et al., 2017) that rely heavily on energy prices, it is crucial to have good estimates on how the energy mix of the future is made up. Additionally, the energy sector contributes 72% of manmade greenhouse gas emissions in 2014 (World Resource Institute, n.d.), contributing heavily to the increasing levels of CO2 and Methane in the earth's atmosphere. This makes energy scenario models a central tool for raising sustainability issues and arguing for an environmental overhaul (Gironès et al., 2015).

The most important framework regarding energy modelling in the context of management theory is Operational Research (OR), signifying the value and influence of analytics, data and mathematical models on the decision making process (Merriam-Webster, 2020). Management Science has even been called the "business use of operations research" by Beer (1967). Specifically, it touches on the premise that management decisions are taken by applying models and concepts onto the real world, tackle management issues and reach organizational excellence. In the energy industry, energy models are a vital part of the entire strategic management effort as major decisions are taken based on forecasts derived from energy scenario models with the goal of sustained profit, increased market share, positive return on investment (ROI) or cost savings.

The trend of scientifically modelling energy systems on a large scale has been sparked by the 1973 oil crisis (Ormerod, 1980) disrupting the constant development and requiring more advanced risk management. Energy modelling has evolved since then into a complex data-driven sector of strategic decision-making tools. Today, it is most common in the scientific literature to create scenarios that include a variety of factors and make estimations on how those factors will develop in a set timeframe. The timeframe varies between scenarios that span until the year 2030 (IEA, 2019d; Sadorsky, 2011), 2050 (IEA/IRENA, 2017; IEA, 2019d; Sadorsky, 2011; Spiecker & Weber, 2014), 2060 (Sadorsky, 2011) and even until 2100 (Sadorsky, 2011) in very far reaching scenarios. Understandably, the accuracy of the predictions derived from very long-range scenarios are tied together with a larger degree of uncertainty, as unanticipated and/or unplanned developments in the environment can have a large effect on the end result.

Another central point of course is the development of total energy consumption as this influences the need for energy security and the capability of risking some of that stability for innovative technologies and concepts.

Due to the fact that well investigated, and precisely modelled energy scenarios are a very difficult and specific task, this kind of research is very time and resource intensive. The OSeMBE model for instance (Henke, 2018a), an open source modelling software based on the OSeMOSYS package, has been developed over the course of 42 months with almost 4 million EUR funding from the European Commission (REEEM, n.d.). It is capable of dynamically modelling energy scenarios for all 28 EU member states, Switzerland and Norway, minding capacity constraints, different fuel prices, seasons, fluctuating weather data, just to name a few. Even though this modelling approach is very technical and data based, the lead developer Henke (2018b) admits, that at first storage systems were not included in the system in their true form (charged up when production exceeds consumption and vice versa) due to the increased complexity. This, especially in times of an ever growing amount of installed storage capacity globally (World Energy Council, 2019), is at the least highly negligent. Furthermore, it has been stated that when checking the model against historical data it yielded lower gas consumption than in reality. The creators of the model subsequently manually increased gas consumption to bring the model closer to reality (Henke, 2018b, min. 25:50). This of course was necessary to correct for inaccuracies in the model; however, it also shows that even a very complex and sophisticated model such as OSeMBE does not accurately mimic reality.

Another issue with modelling and scenario creation in the energy sphere is background motivations of models' creators. The International Energy Agency (IEA) for instance, issues a yearly World Energy Outlook which has also been cited multiple times in this thesis already. Due to its large resources and multitude of member states, the primary data to evaluate the current status of the global energy landscape is advantageous for obvious reasons. Nevertheless, it has proven to underestimate renewable energies and in particular photovoltaic energy production in future scenarios for many years (Breyer et al., 2017; Creutzig et al., 2017). In turn, fossil fuels, and especially natural gas, have been overestimated and steadily corrected downwards. This stands to show that IEA forecasts seem to be biased towards a particular direction.

To get a better overview on how energy scenarios are built in scientific literature, a structured overview of four scenarios has been built (Appendix). The classifications (e.g. Low, Medium, High) represent qualitative interpretations of the relative level of effort in each scenario compared to all analysed reports. One apparent similarity is the creation of a highly optimistic case (e.g. “Sustainable Energy”; “66% 2°C Scenario”; “Clean and Secure”) and a reference or pessimistic case (e.g. “Business as usual”; “Conflict”; “Current Policies”). This approach does two very effective things, namely create a baseline scenario that gives the reader an idea where the energy market is heading and through that enables a comparison which effect particular changes would have. Essentially, an energy scenario is a “what if” question when tweaking certain variables. For instance, the IEA (2019d, pp. 35–36) scenarios consider installed energy storage capacity in their analysis as a vehicle to better integrate renewable energies into an existing energy system: “Available resources for this purpose double by 2040, with thermal and hydropower plants to the fore, and interconnections, battery storage and demand response all playing increasingly important roles”. Spiecker & Weber (2014) do not consider storage in this way at all, leaving out a potentially important variable to consider in forecasting the future development of energy systems.

Another variable considered in three of the four reports (IEA/IRENA, 2017; IEA, 2019d; Sadorsky, 2011) is the halt of deforestation. This measure, even though not directly impacting the energy mix, would be aimed to restore and increase the earth’s inherent capability to bind and conserve carbon dioxide through plant growth. Land-use change and forestry is considered to contribute 6.5% to total manmade greenhouse gas emissions (World Resource Institute, n.d.). This factor is not considered in Spiecker & Weber’s (2014) scenario analysis, although artificial carbon capture and sequestration technologies to reduce emissions are mentioned in two out of four scenarios within the report. In the narrow context of energy consumption modelling, a heterogeneous set of variables has already been established (Camarero et al., 2015). Overall, it is apparent that different reports and scenario analysis use different sets of variables and levers to create energy scenarios.

1.5. RESEARCH PROBLEM AND RESEARCH QUESTIONS

A major issue that comes to light when analysing existing energy models is the incoherency of used variables and a lack of standardization. Surely, it is possible to draw conclusions derived from a scenario that provides the basis for a mathematical model (Henke, 2018a), however, it is not always clear which aspects or variables are specifically considered and which might have been left without consideration inadvertently or on purpose (Breyer et al., 2017; Cochran et al., 2014; Creutzig et al., 2017; Henke, 2018b). Gironés et al. (2015) even describes large-scale energy models as „black-boxes“ to decision-makers, underpinning the troubling state of knowledge in this field.

This potential lack in information can prove problematic when strategic management decisions are taken as a direct result of such incomplete energy models as part of Operational Research. For example, the risk of bad investments can rise due to those faulty predictions. Furthermore, the question remains what a complete energy model in this context looks like as a collection of available variables has not been established yet. A complete assortment of energy models' baseline assumptions can therefore act as a quality checklist for end users of those models, but also inspire variable inclusion in future models.

Furthermore, it is unclear how specific models with the same scope and timeframe differ in terms of underlying assumptions. To enable well-founded strategic decision making it is therefore helpful to compare models with each other along their baseline assumptions to determine similarities and differences. Additionally, it is unclear which variables are commonly found together, potentially influencing and altering predictions.

Therefore, the two research questions for this thesis are as follows:

1. *Which variables and issues are considered in predictive energy scenario models?*
2. *Is there an inconsistency in variable usage among energy models and do correlated variables exist in this context?*

Through conducting this research, the author believes that he can contribute to the improvement of future energy modelling. He also raises the awareness of under-researched issues that might in fact have an important role to play in the energy mix of the future. Furthermore, this research is an important step to increase the sensibility on correlated and potentially biased assumptions made in energy models by researchers and model creators but also by manager when using and evaluating energy models for business use-cases. In a quest to make more precise and granular prediction on how the energy sphere is going to develop in future decades, it is crucial to know which factors are being used in predictive models. Only then, these models can be adapted according to new insights, environmental and social changes or technological advances. As this standardized and commonly agreed upon set of energy scenario variables has not yet been agreed upon between researchers, this thesis can be viewed as a first step in this direction. The collection and categorization of variables with their subsequent analysis provide great additional value to the level of precision of future energy models. This of course takes as a premise the intent of creating a balanced and unbiased prediction.

In all screened energy scenario models the authors explain and describe the basic assumptions for what things will or will not happen in the respective scenario. Some even go further and describe the overall sentiment towards politics and environmental targets (IEA, 2019d; Roinioti et al., 2012; Sadorsky, 2011), besides estimating technological developments. Therefore the methodology of a meta-analysis seems feasible and aligned with the aforementioned research questions.

Because of the aforementioned reasons it can be assumed that managers, especially in the energy industry but also in related industries, have a keen interest in factors that influence and affect the future development of energy systems, technologies, markets and consumption patterns. Such an analysis has not yet been conducted and therefore constitutes a research gap in this field.

1.6. SUMMARY OF CHAPTER 1

Chapter 1 has given a short recap of the historical background of energy use by human civilization and the transition from ancient energy generation through burning wood and organic waste, over the industrial revolution and the increasing popularity of fossil fuels to the present and a steep increase of renewable energy sources while still maintaining a high share of carbohydrates in the primary energy mix.

This has been followed by a description of different energy generation technologies, divided into renewable and non-renewable technologies. The distinction between the two terminologies, namely the consumption of a non-regenerating fuel to the contrary of tapping into an existing environmental process have been explained. The renewable energy sources described include solar, wind, hydro, and biofuels. The conventional energy sources described are oil, natural gas, coal and nuclear fuel.

The literature review regarding energy scenario analysis has shown that there is only very little consistency between different scenarios in terms of considered variables, scope and weighing of assumptions. It has been shown that certain issuers of scenario reports have consistently under- or overestimated certain kinds of technologies distorting the outcome in a certain direction. Even the very optimistic and sustainable scenarios are not consistent in which targets are met, which levers have an impact, and which do not (e.g. carbon capture and sequestration). Furthermore, decision-makers have been struggling with divergent and opaque energy models leading to unverifiable estimations. This leads to situations where energy models as a tool of operational research cannot be used as such because they are essentially “black boxes”.

Overall, in the sphere of energy scenario analysis and modelling there has not yet been established a collection of variables which can be used for standardization and quality assurance to improve decision-making capabilities within strategic management. The existence of such a unique and comprehensive collection can improve future scenario models in the energy field and sharpen the understanding of the status quo within the field of energy modelling.

CHAPTER 2: METHODOLOGY

In the following chapter, the methodology of a meta-analysis in the context of energy scenario modelling will be explained. It will be used to tackle both research statements and provide a clear path to understand the issues regarding used variables in energy scenario analysis. The research mode will be exploratory in nature with an overreaching goal of improving the understanding and refining of energy models.

2.1. META-ANALYSIS APPROACH WITH ENERGY SCENARIOS

A meta-analysis is an empirical research technique that combines a multitude of previous scientific works as the foundation of the research (Baumgarth et al., 2009). It generally consists of three phases: (1) the data collection in form of scientific literature and reports, (2) the classification, encoding and structuring of data and (3) the analysis through various statistical methods. The data collected during this thesis and the results are unique and constitute a valuable insight into the scenario creation methodology in the energy modelling sphere.

DATA COLLECTION

The first phase, data collection, is done with the help of SCOPUS, which is one of the largest scientific databases having included more than 22.800 serial titles and 70 million individual items (Elsevier, n.d.). To narrow down the pool of literature, a combination of search terms was used to select an initial batch of papers. Those search terms include “energy scenario”, “scenario analysis” and “energy system”, limiting the search to the titles and abstracts. The results of these searches are then skimmed through manually to filter for either regional, national or supranational energy forecasts that make use of different scenarios to model the future of the entire energy mix of a certain region or globally. This manual approach of research pool creation has been used as there is no complete list of energy scenario models to date.

The publication period of the selected articles has been limited to the past 13 years until (including) 2007. The reason for this decision is that since then the growth rate of renewable energy in installed capacity as well as yearly production has picked up significantly (IEA, 2019a) and has proven to be an emergent new trend. This cut has been made to account for analysis that include all factors after this tangible shift has become apparent and also to keep the number of resources manageable.

Additionally, a certain kind of grey literature is included in the analysis as some of the most extensive scenario models have been conducted by organizations like the International Energy Agency (IEA), which are recognized to have a certain bias as described earlier. Their research still constitutes an important part of the conversation regarding energy transition and the measures that have to be taken into account. In recognition of the different quality standards and the potentially lacking peer review, a marker is placed during the data collection to easily distinguish peer reviewed scientific papers from industry reports. The selection of these pieces of grey literature has been created by collecting strongly cited non-scientific references from scientific energy models. It should also be added that as this thesis does not focus on the results and predictions of said papers but only analyses the factors included in the scenario building, the wider and more diverse the spectrum the better. Furthermore, including certain forms of grey literature also gives the opportunity to research potential differences in variable consideration when building energy scenarios.

DATA CLASSIFICATION

After the collection of 29 relevant documents a random selection for the reading order aims to ensure an unbiased starting point while identifying the first factors and variables. The papers are then read through by the author while all scenario variables are noted, making use of five rough classifications, namely governance (G), technological (T), economic (E), social (S) and environmental (V) as proposed in previous literature (Michalena & Hills, 2012). The identified variables are then numbered in chronological order within their respective category (S1, S2, S3, …). During the data collection new variables are then recorded, and whenever an already recorded variable is found, it is registered with the initial classifier.

This way during the data collection a wide range of datapoints are generated. Besides the author, title, year of publication and scenario variables also the publication type (scientific paper or industry report) as well as scenario scope are being recorded (e.g. Italy, Europe, Global).

The data collection and classification continue until the number of new variables found per new analysed article drops over a sustained number of articles. This helps to reveal the point in research, where the number of uncovered scenario variables in energy scenarios is striving towards its maximum. To manage the workload in relation to the expected reward in form of additional data, the flattening reward curve will point to the number of papers of maximum marginal return.

Subsequently, all of the identified variables will be screened and combined to merge similar or closely related variables in order to enhance comparability and clarity of the results. They will be named with double letters of the respective category and numbered again in chronological order (EE1, EE2, …).

DATA ANALYSIS

The recorded data is subsequently analysed by variables frequencies, giving an insight into the most common but also rare types of variables. This analysis will also be extended to the section level and the resource level to showcase differences and possible outliers. For this part Microsoft Excel is used to record and analyse the datapoints.

Additionally, a Multiple Correspondence Analysis (MCA) will be performed to discover patterns in the recorded data. The MCA is related to the Principle Components Analysis (PCA), with the crucial difference of being factor based and not value based. This is important, as the recording of the data will be performed using X for the first variable entry, O for every subsequent variable mentioning and an empty cell for not mentioned. To perform the MCA dummy variables are then put in place, replacing the X and O with a Y (yes) and the empty cells with a N (no). This gives the algorithm two factors to compute correspondences, with the resources as instances and the scenario variables as statistical variables (with either Y or N as a factor).

The MCA is performed using the statistical language R and the developing environment RStudio after converting the datapoints into the right format in Excel and exporting it into a csv-file. The R program code can be found in the Appendix.

2.2. LIMITATIONS

This mode of research of course involves a certain amount of selection bias especially when selecting suitable papers to be included in the analysis. This has been counteracted by the author's randomized order of reading and striving to extract variables until the marginal amount flattens, assuming that a maximum of uncovered variables is reached.

Another limitation might be intrinsic assumptions that were made to create models which are not expressed directly in the respective paper, but only used in the modelling software behind the scenes. This most likely applies to transmission losses, efficiency, and other technical hard facts and less to qualitative factors, such as public opinion towards renewable energy sources.

2.3. SUMMARY OF CHAPTER 2

This chapter has explained how the meta-analysis of energy scenarios is carried out, using SCOPUS as a tool to find and select appropriate scientific papers and grey literature, such as reports. The selection focuses on content with energy scenario analysis for the complete energy mix of either a specific region (local, country or continent) or globally. Technology or industry specific content is not considered. As for the information extraction, the order of reading is determined randomly to counteract selection bias. Every article is then read by the author and all used variables in the scenario analysis extracted and codified in a category-based system. If a previously identified variable is found in a new article, it is noted as such.

After the marginal number of new variables per article drops over a sustained number of articles, the search for new variables is halted and all found ones are consolidated into super categories to enhance comparability and clarity.

After this step, the data is analysed by simple frequency statistics and a Multiple Correspondence Analysis (MCA) to determine linkages and patterns in the data using the discovered variables as factors.

CHAPTER 3: EMPIRICAL STUDY OF VARIABLES IN ENERGY SCENARIO MODELS

The overreaching goal of this thesis is to identify and classify variables used in energy scenario models in order to point out possible shortcomings and possibly hint towards ways to improve future energy scenarios. The first step is data collection, where a multitude of papers and reports is selected to be included in the research pool.

3.1. DATA COLLECTION

The selection of the initial pool of papers and reports has been done with the help of the largest scientific database SCOPUS (Elsevier, n.d.) as well as references to important industry reports. This yielded 29 documents that fit the pre-set requirements (refer to the Appendix for the full list). The general topic of all can be summarized to be about energy system modelling in a wider sense, without a tight restriction on technology or industry. This was done to avoid very specialized papers which would make a direct content comparison unbalanced. Surely, some resources are naturally more specific in a certain sector (D. Connolly et al., 2016; Krewitt et al., 2009; Roinioti et al., 2012) than others (IEA, 2019d; Winkler et al., 2009) either due to the geographical scope or natural conditions, however, all consider the overall energy system of the respective region for the energy scenario model.

In this context the phrase “energy system” means electric energy as well as other forms of energy generation, such as fossil fuels and heat generation through natural gas.

During the resource pool selection it turned out to be surprisingly challenging to find papers that consider the “big picture” instead of focusing on a narrow sub-categories of the energy system, such as bioenergy (Szarka et al., 2017), energy transmission (Wang et al., 2016) or power-to-gas (Bellocchi et al., 2019).

Upon completion of building the initial research pool of 29 papers (26) and industry reports (3) the extraction of variables was initiated by randomly selecting one document at a time and reading it. The data collection was facilitated through an Excel spreadsheet, where additional variables were added in columns and recorded with an “X” in the row of the initial paper. Every subsequent finding of the same variable is noted with and “O” in the respective row of the resource. (An example for the notation can be found in the Appendix).

This enabled the author to not only track the accumulating total amount of variables and the variables per paper but also the share of new variables per paper in percent, and the absolute number of new variables per paper.

The two latter were used and implemented to keep track of the progress of the research and also determine the point where marginal returns in the form of additional variables per paper reached zero. After the tenth document this point has been reached. To make sure this was not just a statistical outlier, three additional papers were screened, which confirmed that marginal returns have reached zero (Figure 3).

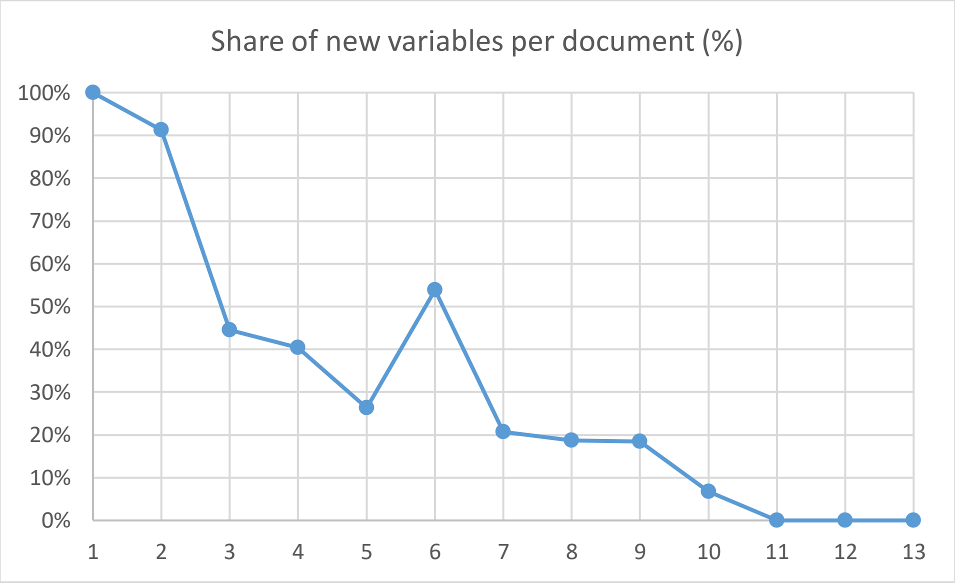


Figure 3, Share of new scenario variables per additional analysed document

This indicator leads to the conclusion that with a high degree of confidence a representative number of variables within scenario-based energy models has been recorded. At this stage, a cumulative amount of 97 scenario variables have been collected.

Upon review, some of these 97 variables, however, have been combined due to contextual similarities. For instance, the two variables in the section Governmental “G6 Reluctance to change” and “G7 Short sighted policies” have been combined to “GG6 Short sighted policies and reluctance to deviate from current path”. Likewise, the variable “T31 Material production efficiency (steel, concrete, plastics, etc.)” has been included into “TT3 Efficiency improvement in energy, buildings and material production” due to the low representative value when contrasted against a general push for better technological efficiency.

The resulting variables, classified with double-section letters (e.g. GG, TT, EE, etc.), amount to 91 final individual variables (full list in Appendix).

SCREENED DOCUMENTS

The thirteen randomly selected papers out of the predetermined research pool are a diverse set of twelve scientific papers and one industrial report, which were published between 2009 and 2019. Whereas two documents have a global and one has a European scope, most documents are focused on a single nation, such as Ireland, Greece, Taiwan, South Korea and South Africa. One has a regional focus, namely Scotland.

Resource	Name	Author(s)	Scope	Type	Year
15	Renewable Energy in French Guiana: Prospects towards a Sustainable Development Scenario	Lesperance, et al-	French Guiana	Scientific Paper	2018
3	Renewable energy scenarios for major oil-producing nations: The case of Saudi Arabia	Al-Saleh, Yasser	Saudi Arabia	Scientific Paper	2009
2	Technology learning for renewable energy: Implications for South Africa's long-term mitigation scenarios	Winkler, Harald Hughes, Alison Haw, Mary	South Africa	Scientific Paper	2009
7	Some future scenarios for renewable energy	Sadorsky, Perry	Global	Scientific Paper	2011
16	Scenarios for sustainable energy in Scotland	Child et al.	Scotland	Scientific Paper	2019
17	Investigating 100% renewable energy supply at regional level using scenario analysis	Waenn, Annicka Connolly, David Gallachóir, Brian	Ireland	Scientific Paper	2014
20	The future of the european electricity system and the impact of fluctuating renewable energy - A scenario analysis	Spiecker, Stephan Weber, Christoph	Europe	Scientific Paper	2014
11	Future scenarios and trends in energy generation in Brazil: Supply and demand and mitigation forecasts	De Andrade et al.	Brazil	Scientific Paper	2015
1	World Energy Outlook 2019	IEA	Global (Part A)	Industry Report	2019
19	Sustainable energy futures: Methodological challenges in combining scenarios and participatory multi-criteria analysis	Kowalski et al.	Austria	Scientific Paper	2009
28	The long-term forecast of Taiwan's energy supply and demand: LEAP model application	Huang et al.	Taiwan	Scientific Paper	2011
27	Modeling the Greek energy system: Scenarios of clean energy use and their implications	Roinioti et al.	Greece	Scientific Paper	2012
23	Long-term energy strategy scenarios for South Korea: Transition to a sustainable energy system	Hong et al.	South Korea	Scientific Paper	2019

Figure 4, List of analysed resources

The timely distribution is relatively even between 2009 and 2019 with the most articles included in the analysis per year are 2009 and 2019 with three documents each. The years 2011 and 2014 are represented with two documents each and finally the years 2012, 2015 and 2018 with one document each.

On a linguistic level, the variety is quite diverse. This posed as a challenge in some areas due to very specific terms, that either can be classified as synonymous or are a very different set of things. An example for the former are the formulations "(…) variable generation of wind (…)" by Child et al. (2019, p. 680) and "Wind power initiatives are criticized for intermittent supply (…)" by Sadorsky (2011, p. 1097). However, two very different pieces of information that might mistakenly be combined are Demand Side Response (DSR) (Huang et al., 2011; IEA, 2019d) and energy demand development (Al-Saleh, 2009; Child et al., 2019; Sadorsky, 2011; Winkler et al., 2009). (Further detailed in Section 3.2)

Regarding structure of the scenario models, already during the selection for the research pool an emphasis was put on clear scenario outlines, as this was important in identifying underlying premises. Nevertheless, some authors were very structured in outlining the "storyline" of each scenario included in the respective paper, whereas others described it in a more integrated style. Sadorsky (2011) for instance puts a lot of effort in designing and outlining all premises important for the model, giving the reader not just an idea of which technologies might be put to use or abandoned, but even goes as far as describing the overall sentiment towards certain measures and policies: "In this scenario, discussions on the greater usage of renewable energy get bogged down in criticism and comments surrounding what cannot be done rather than focusing on what has been done and the more that could be done." (Sadorsky, 2011, p. 1097). This, among other reasons, could be an explanation for the high number of variables found in this article (45).

Huang et al. (2011) on the other hand is an example for a paper that presents scenario variables according to topic and not integrated in a distinct storyline. Additionally, it can be classified as much more technical and focused on mathematical modelling in comparison to the previous example.

Even though the style of documents is different, assumptions are made in every resource in order to enable predictions of the future development of the energy mix.

VARIABLE NOTATION AND VARIETY

The variable collection was carried out as explained above in the section Data Classification. While reading through a document, passages classifying as a deterministic scenario variable were noted as a new column in an Excel sheet following the notation format as follows: section letter, number and name of variable. This enabled not only a structured way of notation but also gave every variable a unique identifier before its description. The order of variables, due to the nature of the procedure, is chronological and follows the order of reading. This in turn means that the variable E4 has been discovered before E5. On the other hand, by simply looking at variable identification numbers it cannot be determined in which order cross-sectional variables where discovered. To put it in practical terms: the variable T4 has in fact been discovered before variable G4, which can be checked by looking at the resources the variables have been discovered in.

Apart from the classification and numbering, the most important part in the variable notation is the descriptive naming scheme. Here the variable itself is described in a precise manner that explains the underlying assumptions. In contrast to Michalena & Hills (2012), who had to explain specific measures in EU member states which required longer and spelled out explanations, in this thesis solely the consideration of a topic or determinant has been declared the subject of analysis.

3.2. VARIABLE DESCRIPTION

The following section will provide an in-detail description of the identified variables within energy scenario models including references to the source papers. The variables are structured along the predetermined sections Governance, Technical, Economic, Social and Environmental to present similarities but also showcase conflicting considerations between different resources. As a baseline for this description the 91 variables after re-classification are being used.

GOVERNANCE VARIABLES

The section governance is characterized by energy model determinants that influence or are determined by policymakers, governments, politics or regulators of some sort. In the final iteration of variables there are seventeen in this category.

A fairly common statement in resources has been the striving for energy independence and self-sufficiency of supply. This notion has been mentioned in documents of varying scope including global, European, South Korean, Irish and several more. The variable GG1 is characterized by the government striving to ensure a non-dependence in the level of energy in order to be able to tap into abundant domestic resources as the example of French Guiana shows: “Due to its favourable location, French Guiana has abundant RE resources available offering various ways to accelerate the energy transition towards a self-sufficient department.” (Lesperance et al., 2018, p. 135). In South Korea the emphasis is put on “(…) easing … imbalances between imported and self-supplied primary energy sources (…)” (Hong et al., 2019, pp. 431–432).

Similarly, GG2 considers national support mechanisms and localization pushed by policy makers to counteract the current economic status quo, as described by Sadorsky (2011, p. 1102):

“In many cases economic activity needs to shift from globalization to localization (…)”. This statement clearly shows an anticipated shift in political mindset in a specific scenario. In a paper about Greece (Roinioti et al., 2012, p. 722) it is anticipated that “RES investments will yield benefits for local communities through fees”. Thich showcases an alignment with national and local financial needs.

Governance Variables
GG1 Strive for energy independence and self-sufficiency
GG2 Implementation of national support mechanisms (Localization)
GG3 Financial incentives towards RE
GG4 Existing energy infrastructure
GG5 Focus on energy security
GG6 Short sighted policies and reluctance to deviate from current path
GG7 Global consensus on climate change
GG8 Binding emission target for developed nations
GG9 Fund Renewable Energy R&D
GG10 Opposition against nuclear power
GG11 Homogenous regulatory framework
GG12 Viable solution for nuclear waste available
GG13 Switch from domestic gas heat pumps to electric or hydrogen
GG14 Infrastructure change dictated by longevity of existing
GG15 Early retirement/ reduction of coal-fired power-plants
GG16 Better and more extensive recycling of materials
GG17 Push technologies to develop technological leadership

Figure 5, Governance variables

GG3 broadly describes financial incentives towards renewable energy generation in a variety of ways. In Spiecker and Weber’s (2014, p. 196) paper it says that “The scenarios particularly indicate that incentive measures for renewables tend to lower the price of conventional power (…)”. On the other hand in the case of Saudi Arabia it is acknowledged that the “(…) relative absence of any financial incentives … could enhance the potential of renewables.” (Al-Saleh, 2009, p. 654).

An important and very commonly mentioned variable is GG4 considering the existing energy infrastructure. This seems natural, however, is still not the most common variable uncovered in energy models in this analysis. It is best showcased by Child et al.’s (2019, p. 680) paper about Scotland’s energy model, evaluating if one or another infrastructure development measure is preferable: “(...) synthetic liquid fuels that could be “dropped in” to existing technologies and infrastructure without the possibly expensive need for technology and infrastructure replacement, or renewable-based gaseous fuels that could be used with newly developed technologies."

GG5 is similar to GG1 and GG2, but touches more broadly on the context of energy security as a goal itself while neglecting other fallout effects, such as rising carbon emissions.

The short-sighted nature of politics and policymakers is expressed in GG6 and describes the sometimes-difficult split between what is required to make a difference and what is actually done. The reluctance to make big and radical decisions that shift the status quo and tackle problems head on is best described in the World Energy Outlook 2019: "Reactions to this market and technological uncertainty have included a systematic preference for shorter cycle investments: in many parts of the world, committing to any project with a long lead time or extended payback period is seen as risky." (IEA, 2019d, pp. 77–78)

GG7 describes the global consensus regarding climate change and recognizes the lack of it as a major issue for overcoming it. This of course also impacts the subsequent design and estimation of energy models.

GG8 is a policy suggestion by Sadorsky (2011) evaluating and discussing binding emissions targets for developed nations. He argues that "The developed countries need to demonstrate that low-carbon economic growth is possible, and this would involve implementing many of the carbon stabilization wedges proposed under the Carbon Mitigation Initiative." (p. 1099).

Surprisingly, only three documents include the consideration of funding renewable energy research and development projects which is expressed in variable GG9. The IEA (2019d, p. 121) suggests that "(…) governments may wish to consider the scope for redirecting revenues from pollution charges to clean energy research grants (…)". For obvious reasons, increased research grants improve the possibility for renewable energy technologies to surpass traditional and non-renewable energy sources in efficiency and cost.

Another variable to consider is GG11, which is related to GG3 but more tailored towards micro-producers. This variable describes feed-in-tariffs which are specially subsidized compensation tariffs for private households or businesses to "sell" overproduction of PV panels (or similar decentralized energy production technologies) to the grid (Sadorsky, 2011).

GG12 is the political attitude towards nuclear power plants, which most prominently in Germany leads to the planned closure of all nuclear power plants. Spiecker and Weber (2014) among others also include this as a possible path in the future of energy systems and in their energy model as a variable.

Another wide-reaching policy decision is GG13, which discusses the switch away from domestic non-renewable heating systems and a switch to electric or hydrogen in people's homes. This includes heat pumps for water as well as space heating and cooking.

Another more far-reaching policy style variable is GG14, stating that the infrastructure development is dominated by the longevity of the existing. This in turn is related to GG6 and the time perspective of policy making. The IEA (2019d, p. 27) explains that "If the world is to turn today's emissions trend around, it will need to focus not only on new infrastructure but also on the emissions that are 'locked in' to existing systems. That means addressing emissions from existing power plants, factories, cargo ships and other capital-intensive infrastructure already in use." This stands to show that reaching low emissions targets may require large investments and radical change in policy making, infrastructure design and also decision-making processes.

The variable GG15 is related to GG12 and the early reduction or shutdown of coal fired power plants due to their unpopularity and severe impact on greenhouse gas emissions but also the air quality in general. In the South Korean example it is stated as follows: "For energy supply, the scenarios vary depending on the level of electrification and the degree of renewable energy replacing the centralized generation facilities such as coal-fired and nuclear power plants." (Hong et al., 2019, p. 428).

GG16 has only been mentioned once and calls for more efficient recycling of materials, especially in the sector of metal works and building materials. According to the IEA (2019d) this can lead to substantial reductions in energy usage in these areas.

The last variable in the sector governmental is GG17 which talks about the goal of creating a technological leadership position by a certain country through promoting the production and usage of said energy technology locally. The examples brought by Kowalski et al. (2009) are to promote small scale hydropower, individual biomass systems, solar thermal, wind power and passive house components. On a large scale this policy has already been adopted by China several years ago in the sector of photovoltaic panels. This lead to 60% of global PV panels production in 2017 being attributed to the People's Republic (IEA, 2018b) with cost of production being way below European or US.

TECHNOLOGICAL VARIABLES

The second category is called technological variables and combines all technical energy related variables which include special technological developments and adoption of technologies. This category is the largest of five with 30 unique variables (Figure 6).

Technological Variables
TT1 Push for electrification
TT2 Electrical storage installations and storage cost
TT3 Efficiency improvement in energy, buildings and material production
TT4 Shifting from thermal to electric energy
TT5 Intermittency of RE and network stability
TT6 Carbon Capture and Storage (CCS)
TT7 Next generation fuel cells
TT8 Hydrogen economy
TT9 Unconventional O&G technology becoming feasible
TT10 Hydrogen or Biofuels widely used as transport fuel
TT11 Technological learning
TT12 Increase coal efficiency
TT13 Increase biofuel production
TT14 Existing or close to existing RE tech needs to be put to work
TT15 Investment into new breakthrough technology (algae, advanced solar, etc)
TT16 Natural gas as transition fuel
TT17 Wind energy expansion
TT18 Importance of hydroelectric power (conventional and pumped)
TT19 Vehicle to grid charging
TT20 Electrification of mobility
TT21 Energy from waste (MSW, used cooking oil, etc.)
TT22 Solar thermal installation on home rooftops
TT23 Use of grass and rape seeds as energy crop
TT24 Cogeneration Heat and Power (CHP) units
TT25 Distributed energy storage systems
TT26 Retrofitting buildings for efficiency
TT27 Redesign of mobility systems
TT28 Liquified Natural Gas (LNG)
TT29 Development of digitalization trend
TT30 Demand Side Response (DSR)

Figure 6, Technological variables

The scenario variable TT1 has been mentioned five times and covers a push for electrification across industries and appliances. This is especially important in the context of emissions reduction as a large percentage comes from the mobility sector. Apart from mobility, as already mentioned before in GG13, domestic heating is also included here.

TT2 is one of the big wildcards brought up in the discussion of renewable energy solution in the context of being feasible cost wise but also when looking at production stability. Currently the overwhelming amount, namely 98% of global storage capacity (Mongird et al., 2019), is met by hydropower plants; however, due to the lacking scalability, the centralized and localized nature, as well as the ever growing need for storage capacity, new technologies are on the verge. Most prominently Lithium batteries have been meeting the rising demand, Tesla and Panasonic being mostly responsible for a surge in production output at up to 54 GWh per year in one factory alone (Electrek, 2019). The increasing supply leads to steadily dropping cost (Mongird et al., 2019), in turn making renewable energy production more feasible.

TT3 is one of the most commonly mentioned variables, stating efficiency improvements in energy, buildings and material production. In some reports (IEA, 2019d, p. 25) it is described as most crucial: “A sharp pick-up in efficiency improvements is the single most important element that brings the world towards the Sustainable Development Scenario”. Also Sadorsky (2011, p. 1102) states that “(…) energy has to be used more efficiently in buildings, transportation, industry, power generation, and agriculture”. Due to this variable’s broad spectrum of meaning it seemed as if many researchers use the phrase “efficiency” to cover many hazily described improvements, without going much into detail about the associated cost, performance improvements and other associated issues. In general it can be said though, that in the context of this variable in energy models it is to be seen as a reduction of losses.

The variable TT4 describes the switch from thermal to electric energy on the production side. In the case of French Guiana it is stated that “(…) the thermal share will represent only 16% compared to 45% in 2016” (Lesperance et al., 2018, p. 135).

The instability of supply and network stability when increasing the share of renewable energy sources in an energy system is described by TT5. Due to the unpredictability of weather, differing wind production rates and sun hours (e.g. due to clouds) renewable energy production is not as stable as large power plants. This variable is often mentioned as one of the main points of criticism, such as “(…) the integration of intermittent energy (photovoltaics and wind power) raises key questions about network stability” (Lesperance et al., 2018, p. 135).

TT6 is also a highly controversial variable, describing Carbon Capture and Storage (CCS) which is a strain of technologies that aim to limit or eliminate carbon emissions by capturing them during production. Subsequently, the carbon is then stored long-term underground in depleted oil or gas reservoirs. In Spiecker and Weber's (2014, p. 189) paper the twofold perspective on this matter gets showcased well as in one scenario it is rejected, "carbon capture and sequestration technologies are not put into practice due to low public acceptance", while in another it is attributed great potential, "(…) the carbon capture and sequestration (CCS) technology is also envisaged to achieve a low CO2 power generation."

The next variable is TT7 which again is mentioned fairly often without giving much in-detail explanation of what to expect. It describes "next generation fuel cells", mostly going into hydrogen fuels cells being adopted as a middle-ground technology between combustion engines and electric batteries. According to Huang et al. (2011) this sector is for instance one of eight major investment pillars in Taiwan.

A closely related topic is the development of an end-to-end hydrogen economy, classified as TT8. This long-term vision is the connection point of many different technologies: namely producing energy through renewable sources of which some percentage is used to produce low-carbon hydrogen which then can be stored or used as fuel. The main reason in favour of such a system is that the only by-product is clear water. Additionally, existing gas pipelines can be used as an infrastructure backbone (IEA, 2019d). Nevertheless, this is one of the more far-reaching variables, being described as more of a long-term goal.

TT9 is an entirely different kind of variable, describing the possibility of today's unconventional oil and gas technologies as well as reserves becoming feasible. This undoubtedly would have a great effect on non-renewable energy production and shape the future's energy landscape significantly. Even though it is expensive, Sadorsky (2011, p. 1101) argues for instance that "it might be possible to eventually produce up to 5 million barrels of oil per day by 2030 from the tar sands".

TT10 is connected to TT8 as it describes alternative fuels being used in the transport sector as it is stated by Al-Saleh (2009, p. 658) that "(...) hydrogen and biofuels would become widely used as transport fuels" in Saudi-Arabia in his environmental scenario. In the World Energy Outlook 2019 this variable is a major contributor for a potential sharp decline in transport oil demand apart from electrification of mobility: "(…) it is accompanied by additional improvements in fuel efficiency, as well as by the use of other alternative transport fuels, such as advanced biofuels and hydrogen." (IEA, 2019d, p. 58)

Technological learning (TT11) is a variable and a concept that is not simply an improvment in production capacity but rather a reduction of cost, induced by a learning experience (Winkler et al., 2009), which can also be applied to the energy sector. One result of this line of thought is the anticipated drop in price of energy storage systems, which has already been mentioned in TT2.

In the context of environmental protection and technological improvements to fight climate change there is usually one number one enemy called out most frequently: coal-fired power plants. This kind of energy generation is by far the largest producer in emissions and aerosol pollutants so variable TT12 is the prospect of making this kind of power generation more efficient. In Sadorsky's (2011, p. 1098) scenario model the goal is to "increase coal-fired power plant efficiency from 40% to 60%" as one of 15 stabilization wedges, each of which has the power to reduce carbon emissions by 1 billion metric tons.

TT13 is a call for an increase in biofuel production, however, it is not specified which kind of sourcing strategy is used. This potentially rises another set of problems, as already described in the section Biofuels. Kowalski et al. (2009, p. 1070) even dedicated one scenario to a biofuel centred scenario where "the main focus is on renewable heat generation from biomass resources". In this scenario biofuels include biomass combustion and gasification as well as imported biogas. In the Greek scenario model an increase use of biofuels, especially in the transport sector is being evaluated (Roinioti et al., 2012).

Variable TT14 is a call for putting renewable energy technologies that are close to market readiness to work as quickly as possible. It is argued that by holding back for the right moment, valuable adoption time and potential technological learning is missed out on. "Multiple approaches and technologies – including much greater efficiency – are required across all parts of the energy system, alongside a clear-eyed appreciation of where emissions occur and what the abatement options are in each area." (IEA, 2019d, p. 77)

A step further is the strong investment into breakthrough technologies like third generation biofuel through algae and high efficiency solar panels, codified as TT15. In combination with TT14 this creates a well-rounded short- and mid-range plan for the future development of the energy system, which could also be classified as "future-proofing".

On the other hand, natural gas can be positioned as a transition fuel towards renewable energy, as it is the carbohydrate with the lowest emissions profile when used. TT16 is a suggested approach that combines the stability and reliability of natural gas power plants and the renewable profile of photovoltaic and wind to create a low carbon but functional energy system. In Sadorsky's (2011, p. 1100) "focus on energy security"-scenario it is characterized as follows: "Proponents of low carbon energy sources see natural gas as a transition fuel until hydrogen (the cleanest of all of these fuels) becomes dominant (somewhere around the year 2100)".

Surely, this can be seen as a deflective measure to avoid going all-in on renewable energy and has also major political implications.

One very common variable in scenarios was TT17, the expansion of wind energy. It can be seen that on- as well as offshore wind energy has the greatest potential for delivering large amounts of energy in renewable energy scenarios, besides photovoltaic panels. The Scottish energy model describes it as follows: “Onshore and offshore wind are the technologies with the highest generation in future scenarios (…)” (Child et al., 2019, p. 677).

TT18 is the mentioning of the importance of hydroelectric power in the future which includes conventional hydro power generation but also pumped hydro power plants. The latter, as already previously mentioned, are vital as an energy storage backbone and are capable of transferring energy even between seasons without suffering much loss. One of the Greek energy models for instance even “(…) assumes a remarkable small hydro exploitation (…)” (Roinioti et al., 2012, p. 721) complementing large hydropower stations in the near future.

A fairly complex and also ambitious technological leap concerning infrastructure is vehicle to grid (V2G) charging TT19, essentially making every compatible electric car an energy provider. The great advantage with this kind of technology would be to make use of the large battery packs in electric vehicles and smoothen out peaks in energy demand. It is estimated that with the help of these cars as well as dynamic domestic thermal storage 50-60% of the total European energy system can be shouldered with fluctuating renewable energy sources (David Connolly et al., 2015). The IEA (2019d, p. 68) also mentions potential shortcomings in development and lacking legislature regarding “(...) the interface between electric vehicles and the grid (…)”.

Related to this topic of course is the overreaching topic of electrification of the mobility sector, classified as TT20. This ongoing trend is being continued when following this variable, leading to the majority of vehicles being electric in the future. This includes public transport, personal vehicles as well as goods traffic. “Rising electric vehicles sales, together with a potential shift in consumer preferences away from personal ownership of vehicles, raise profound questions about the future of conventional cars.”, is noted by the IEA (2019d, p. 57)

TT21 is the increased and more efficient usage of waste for energy production. This includes the biodegradable portion of municipal solid waste (MSW), wood waste, agricultural waste, cooking oil, slaughter waste as well as garden and food waste. Biodegradable waste facilitates the production of bio methane which is composed of more than 97% methane (CH4). This makes it possible to utilize the new resource exactly as the natural one for heating, cooking or for electricity production in gas-fired power plants (Waenn et al., 2014).

Variable TT22 is the widespread installation of solar thermal installation on domestic rooftops in order to reduce heating expenses and decentralize heat energy generation. In this sense it is related to the preceding GG1 and TT14. In the case of the energy scenario by Waenn et al. (2014, p. 28) “It is estimated that 50% of housing stock is south facing and that 50% of all south facing roof tops will use solar thermal for heating (…)” in the Republic of Ireland. This scenario shows that there are also different approaches towards transitioning to a more renewable energy system which is not solely reliant on electrifying all sectors.

Variable TT23, the use of grass and rape seeds as an energy crop, is very closely related to the general production increase in biofuels TT13, however, it is set apparat by making increased use of untapped resources that do not necessarily require much more input. Waenn et al. (2014) have shown future scenarios that source more than 80% of Ireland’s energy needs from grass that gets transformed into natural gas quality bio methane. For a country that is covered in grassland to the amount of 60%, this is a very viable option for carbon neutral energy generation (CSO, n.d.).

T24 is the use of cogeneration heat and power (CHP) units, of which the main value comes from the omitted need for conversion from heat energy to electric or vice versa. Depending on the overall implemented strategy (majority electric or mixed) in a given energy system those kinds of units can increase efficiency overall.

TT25 covers the topic of distributed energy systems, specifically looking at storage. As it has been already mentioned, large percentages of renewable energy sources potentially can create fluctuations in the energy supply which has to be evened out. Similar to the V2G technique in TT19, distributed storage can even out these issues with the main advantage of not having to rethink the entire existing energy system but rather installing storage solutions right where they are needed. This means that by installing storage solutions in a modular fashion at variable suppliers (like wind farms) or on the demand side (in industrial factories) can help balance the power system better and integrate innovative technologies effectively.

TT26 is the retrofitting of existing buildings for efficiency, which is a further pursuit of variable TT3. In the IEA’s Sustainable Development Scenario it is best explained as follows: “(…) a large portion of the buildings stock undergoes deep retrofitting in an effort to improve the energy efficiency of building envelopes, thereby creating an incentive to continue using the building for longer in order to realise savings and reducing the need to construct new buildings." (IEA, 2019d, p. 314)

Furthermore, the (IEA, 2019d) is also considering an entire overhaul of mobility systems (TT27) including micro-mobility, rethinking of car ownerships and digital ride-sourcing solutions (e.g. Uber).

Another far reaching development (TT28) within the energy industry is the wide-spread adoption of liquified natural gas (LNG) and its role in connecting previously isolated natural gas markets. Especially the U.S. has been increasing its capabilities in this sector and are selling its liquified gas worldwide. This for instance has an effect on natural gas price development in Europe, which traditionally has mostly been dependent on Russia in this context.

Digitalization, as already mentioned in TT27 through digital ride sourcing solutions, has had and will have growing influence on the energy profile of the world (TT29). Small scale devices like smartphones and laptops but also electric cars might be one of the reasons for an ever increasing energy demand over the past decade (IEA, 2019d). "Moreover, the confluence of digitalisation and electrification, if not managed well, could make systems more vulnerable to cyber-attacks and also lead to significant privacy concerns" (IEA, 2019d, p. 68). On the flipside, digital tools can also help streamline energy systems through detailed monitoring, predictive modelling or advanced power management systems.

One of those advanced management systems is called Demand Side Response (DSR) and is classified with TT30. This variable describes the wide-spread adoption of a technology that lets the grid provider shut down non-critical energy consumers either at a moment's notice or with several hours of lead time. This technique makes it possible to not just avoid voltage drops in the grid in peak demand times, but also to steer the energy consumption and avoid supplemental switch on of large-scale power plants. The benefits of having such a system in place can be increased by the number of participants that are willing to trade flexibility in their energy consumption against lower energy prices. In combination with volatile renewable energy sources, this can drastically decrease CO2 emissions (IEA, 2019d).

ECONOMIC VARIABLES

The following section covers economic variables discovered in the thirteen analysed papers and reports. They are related to the financial perspective as well as macroeconomic theories and processes. The total number of variables in this section is sixteen (Figure 7).

The first variable EE1 covers the impact of deregulation in energy markets on the renewable energy sector. The result is a high level of competitiveness on the cost side as well as the efficiency. To overcome these difficulties and give renewable energy technologies a chance in the market financial support can be issued (Variable GG3) to support. The fact is, that especially photovoltaic and wind energy generation has been growing tremendously every year since 2009 and consistently show the highest growth rates in the energy sector (IEA, 2018b).

EE2 also ties into exactly this issue, as it covers high investment costs of renewable energy. This variable, however, only looks at the raw initial investment cost which would be due today, if a new solar or wind farm was constructed against an already existing gas-fired power plant. This angle is not very objective as every large investment has to be looked at over its expected lifespan and also taking other cost factors into account. Sadorsky (2011) for instance notes that after the financial crisis in 2009 the US government spent a massive US$ 787 billion on an economic recovery package. In comparison "(…) a US government investment of $400 billion would be enough to construct giant solar plants in the American southwest and high-efficiency transmission lines to carry the generated electricity nationwide." (p. 1100). Such an initiative would be able to cover 66% of the nation's demand in electric energy.

Economic Variables
EE1 High competitiveness in RE due to de-regulation
EE2 High investment costs of RE
EE3 High cost of electricity production
EE4 Lack of economic dynamism
EE5 Availability of fossil fuels
EE6 Peak Oil Theory
EE7 Oil production increase
EE8 Reform of carbon trading systems
EE9 Economic liberalization
EE10 High oil price
EE11 Decreasing RE cost
EE12 GDP Growth
EE13 Carbon Pricing
EE14 Aviation industry escaping fossil fuels
EE15 Transportation cost of fossil fuels
EE16 Interest rates

Figure 7, Economic Variables

Related to high cost of renewables is the high cost of electricity production as a whole, represented by EE3. This variable covers the idea that high energy prices using traditional (non-renewable) energy sources induce financial motivation to develop renewable sources in order to increase financial independence and decrease energy cost.

The lack of economic dynamism, represented by variable EE4, has only been mentioned in the paper about the French Guiana energy system (Lesperance et al., 2018) and is formulated as a point of criticism and disconnect between the economy as well as the growing population and number of young people, aged between 15 and 24 years.

A large point of uncertainty for the future of energy systems is the future availability of fossil fuels, represented by variable EE5. It can be stated that all scenarios that cover this point explicitly have at least one scenario that includes low availability of fossil fuels. While the availability of coal seems to be secured for even the long-term future, other fossil fuels like oil and gas seem to be effectively depleted or financially unfeasible by the second half of the 21st century. In the paper by Al-Saleh (2009, p. 653) it is even stated that "(…) the factor of 'availability of fossil fuels' [is] (…) one of the most significant and uncertain factors when considering the prospects of renewables (…)", which is especially interesting coming from a paper that covers Saudi Arabia's energy future. According to the author, the kingdom might not be capable to go beyond 12 million barrels per day (mbd) and even less likely to the 15 mbd. This doubt holds even though Saudi Arabia controls around one quarter of the world's oil reserves. This increase in oil production is covered by variable EE7, which due to the increased supply would lead to lower crude oil prices. As a result at a later point this would lead to decreasing prices in downstream resources, effectively making renewable energy sources less competitive.

Another variable which is related to the depletion of natural resources and the production of crude oil is variable EE6, the peak oil theory. The initial theory has been published decades ago by Hubbert (1956) and has been heavily discussed ever since. According to the theory, oil production levels over time resemble a bell shape and would reach a peak around the year 2000. It is common knowledge that this has not occurred, however, due to crude oil's non-renewable nature there is only a finite amount available. Therefore the "modified" peak oil theory represented by the variable expects a peak in production at some point and a steady decrease over the course of the next decades. Nevertheless, it is very uncertain if the peak has already occurred or if it lies in the future, even for major producers like Saudi Arabia (Al-Saleh, 2009).

Variable EE8 is the call for a reform in carbon emissions trading system, which among other places has been in use in the European Union and manages around 40% of its carbon emissions (Spiecker & Weber, 2014). This approach manages to “internalize externalities for emissions” (p. 185), making it a powerful tool to maintain and ultimately reduce carbon emissions. However, after China has put an emissions trading system in place in 2020, still only 13% of global emissions are covered in such a system, making a reform necessary.

More generally speaking, some sort of carbon pricing has also been included in several scenarios, codified by the variable EE13. This more broadly formulated variable covers a dedicated carbon tax but also all ways that increase the price for carbon emissions in general and subsequently discourage the usage of those legacy technologies. The ultimate goal here is to substitute greenhouse gas emitting sources, most prominently power generation technologies with ones that do not emit any greenhouse gases.

As a result of such a policy, technological learning (TT11) or some other unspecified reason variable EE11 broadly covers decreasing renewable energy cost. This of course makes it more competitive on a price level and at some point can lead to grid parity. This is the point where the price for renewable energy and for conventional electricity production is equal (Papaefthimiou et al., 2016).

Increasing oil costs, represented by variable EE10, would undoubtedly aid in a decarbonization of the economy. This can have multiple reasons, among which are the aforementioned depletion of the resource, political conflicts and costly unconventional oil production (IEA, 2019d).

EE9 economic liberalization is essentially the counterpart of GG2 and GG3, giving every player an equal chance on the market. The major player in the energy sector Saudi Arabia for example has a heavily subsidized carbohydrate and water industry, creating an unfair advantage towards other players on the market, such as renewable energy producers. An actual liberalization would favour those novel technologies, but would also lead to compliance with WTO commitments (Al-Saleh, 2009).

GDP growth is represented by variable EE12, which has been closely correlated to energy consumption in the past (IEA, 2019d). This is one reason why some energy models have assumed rising energy consumption in the case of rising GDP for the baseline or energy security scenarios. “In line with economic growth, demand is also increasing.” (Spiecker & Weber, 2014, p. 189)

One of the harshest industries to compete in with renewable energy in mind is the aviation industry. The variable EE14 covers the question whether the aviation industry manages to move away from fossil fuels, as it makes up around 12% of global oil demand in 2018 (IEA, 2019d).

EE15 takes into account the cost of transportation of fossil fuels itself, which of course is correlated with the price of fossil fuels as cargo ships, planes, pumps and generators also run on fossil fuels. Generally, it can be said that the lower the transportation costs are, the lower the price for fossil fuels becomes – assuming all other factors stay constant. Oil pipelines for instance are a very cost-effective way of transportation but are much less flexible in routing than cargo ships. In the case of coal "(…) the transportation costs depend on the access to the sea. Countries with direct access thus have lower transport costs than countries without direct access, while countries with access to the North Sea have the lowest transport costs." (Spiecker & Weber, 2014, p. 189)

The last variable in this category concern interest rates (EE16), as cheaper capital enables the possibility for larger investment projects and can fund larger shifts in the energy landscape. According to the IEA (2019d), especially renewable energy projects have gained from low interest rates, halving debt financing for offshore wind projects and giving banks confidence to fund Indian PV energy projects (IEA, 2019d). Additionally, oil producers have benefited in the past from having access to cheap capital in order to fund tight oil exploration and extraction projects.

SOCIAL VARIABLES

This section of variables covers issues which are related to socio-cultural developments, public opinion, human behaviour and habits. It consists of 15 unique variables and is therefore on the smaller end of the spectrum (Figure 8).

The first variable SS1 covers the lack of local structures to implement reforms. This variable in particular applies to regions with a lower level of development, which makes the communication between decision makers difficult and ineffective. In the case of French Guiana, it was stated by Lesperance et al. (2018) that even though there is an abundance of renewable energy resources, they do not get used up to their full potential at least in part due to the lacking social structures.

Another variable that is primarily an issue in underdeveloped regions is the lack in professional workforce and unemployment (SS2), which of course is necessary to build, operate and implement advanced energy technologies. This lack in know-how can be either overcome with knowledge import, which is rather expensive and potentially short-lived, or by building up know-how at the respective location through public education. The need-oriented education of the population in turn can help mitigate unemployment. On the other hand, knowledge-import can lead to leaps in development, which would not be possible without outside help as an example in Pakistan has shown. In August of 2015, the Chinese government agreed to export its own nuclear technology abroad for the first time (World Nuclear Association, 2020). This unique approach made it possible to extend the Karachi Nuclear Power Complex with a second reactor. The ACP1000 nuclear reactor is a combination of China’s long experience in nuclear energy development and extensive research in the matter. Influences like this have a lasting effect on a region’s energy system.

Variable SS3 is the perception towards renewable energy. In a scenario a positive perception can lead to higher renewable energy targets and shape policy decisions and the overall vision, whereas a low or negative perception can have the opposite effect. This of course is highly subjective and is simply a tool to factor in “public opinion” towards the technology. A prominent example is the aftermath of the Fukushima nuclear accident which sparked a shift in public opinion and ultimately had several EU member states shift their power strategy away from nuclear energy (European Commission, 2011).

Population growth (SS4) is a variable similar to GDP growth (EE12), as it ultimately is a proxy variable for the development of energy demand as a whole (SS5), which is one of the most commonly included variables in this analysis. The reason for this is that a higher population leads to higher energy usage, given the premise that all other factors stay the same.

SS6 is a variable that explores the possibility of travel distance reduction. Sadorsky (2011) mentions a reduction of average miles travelled by half as one wedge to reduce carbon emissions by one billion tons annually. Especially in the business world, some travels could be substituted by video- or teleconference calls making it much less energy demanding and also cheaper.

One factor for retaining conventional energy sources is the strong lock-in effect regarding jobs. A way to mitigate this shortcoming is to introduce job retraining programs (SS7) to educate professionals in new technologies and make a switch to renewables easier. This is especially relevant for the coal sector as current trends show a decreasing amount of coal fired power plants, which could have substantial negative consequences on regional economies and employment numbers (IEA, 2019d).

Public transport (SS8) changes the energy usage profile of any given region. Increased use decreases energy consumption per capita but also changes the primary energy source away from oil and more towards electricity. In Ireland for instance the status quo is that 64% travel to work by car, whereas only 1% commute to work by public transport. An efficient public transport system and its increased usage are a great tool to decrease energy demand and potentially make it more sustainable at the same time.

Social Variables
SS1 Lack of local structures to implement reforms
SS2 Lack of qualified workers and high unemployment
SS3 Perception with regard to RES
SS4 Population growth
SS5 Energy demand development
SS6 Reduce travel distances
SS7 Job retraining programs
SS8 Use of public transport
SS9 Use of cooling devices
SS10 Public acceptance of a lifestyle change
SS11 Number of passenger cars increase
SS12 Rising ownership of personal electronics
SS13 Access to clean cooking
SS14 Emission related health issues/deaths
SS15 Popularity of SUV cars

Figure 8, Social Variables

Electric air conditioning systems are very power-hungry devices and make up a large share of power consumption in regions with high ambient temperatures or in hot seasons. A change in their usage (SS9) can have a great influence on the overall energy consumption. The same of course applies to using higher efficiency devices. The IEA (2019d) states that in India due to increasing wealth and population, cooling already makes up 30% of the country's demand growth in electricity.

A variable related to the perception of renewables (SS3) is the public acceptance towards lifestyle changes (SS10) in favour of higher efficiency, sustainability and eco-friendliness in general. Past examples include waste separation, energy saving lamps and consciousness of energy consumption in the own household. A trend that clearly undermines this factor is the rising popularity of SUV style vehicles, which are generally heavier and have a higher resource consumption. “The rise of the SUV is significant because larger, heavier cars are more difficult to electrify fully, and because a conventional SUV consumes about 25% more fuel to travel a given distance than a medium-size car.” (IEA, 2019d, p. 57)

Apart from larger SUV style cars, the total number of passenger cars (SS11) is also highly relevant for the energy mix as personal mobility is one of the main power consumption sectors. Authors like Roinioti et al. (2012) also include the changing energy intensity per car in comparison to just the change in number. This takes into account improvements in vehicle energy efficiency.

A variable that has only been mentioned by the IEA (2019d) is the raising ownership of personal electronic devices and appliances which contribute to a rising amount among energy consumption. Additionally, many electronic devices are produced with petrochemical ingredients, increasing the demand for oil production.

Another variable (SS14) that surprisingly has only been mentioned by the IEA (2019d) covers emission related health issues and deaths. This potentially has a large effect on public opinion, makes clean energy sources much more attractive and can lead to a sense of urgency in changing an energy system.

ENVIRONMENTAL VARIABLES

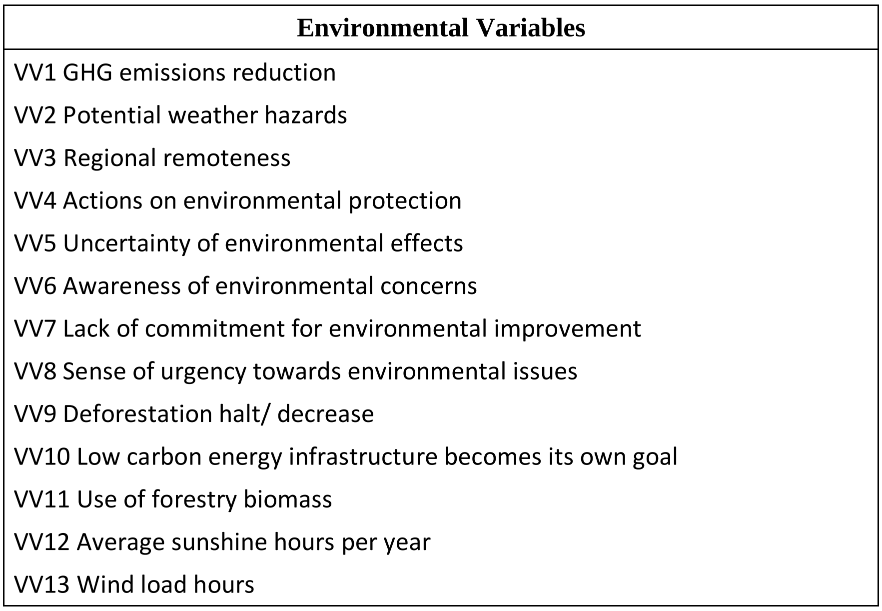
This section covers all variables that have a connection to environmental influences, weather conditions and environmental planning. It has the lowest count of unique variables, namely 13, but also consists of the single most frequently named variable.

The first variable VV1 is the most common variable in this whole analysis and it covers the topic of greenhouse gas emissions reduction as an explicit goal or factor to consider in energy planning. Man-made climate change has been recognized by at least 97% of the scientific community as a central threat to society (Anderegg et al., 2010). Due to the vast implications artificial climate change can have on the environment, economy and life on earth as a whole, this motivator has increased in relevance in the past. In the analysed energy scenario models climate change has been recognized as a threat and the measure of reducing carbon emissions is chosen to avoid even higher levels of atmospheric concentration. The level of greenhouse gasses in the atmosphere are measured parts per million (ppm) of CO2 equivalent and it is predicted that limiting emissions to 450 ppm will cap the raise in global temperatures to 2-3°C until the year 2100 (Sadorsky, 2011). The only way to keep concentrations bellow this point is by decreasing emissions globally. As two thirds originate in the energy production and consumption, it is the single most influential pressure point in the effort of reducing GHG emissions (Skeer & Leme, 2018).

Even though scientific evidence seems unquestionable, there is still uncertainty involved in the impact of GHG emissions on the environment, which is addressed in variable VV5.

The variable VV2 covers potential weather hazards that have the potential of damaging hydropower plants (Lesperance et al., 2018) or other critical infrastructure. It is also argued that climate change can increase the risk for severe weather events, such as heat waves, floods, droughts and crop failure potentially inflicting extreme destruction on certain regions (IEA, 2018a).

Regional remoteness is covered by variable VV3 which is characterized by energy need in geographically remote areas that are difficult to access. In the course of this analysis the main focus is on availability of energy in such areas and the logistics behind it. In the case of French Guiana (Lesperance et al., 2018), the country's energy grid is structured like an island and functions fairly independent. To this date, however, this is only possible with large imports of fossil fuels to bring energy into remote areas. To mitigate this dependency, sustainable energy programs are on the verge, even though 100% energy from renewables is excepted a far reach.



Environmental Variables
VV1 GHG emissions reduction
VV2 Potential weather hazards
VV3 Regional remoteness
VV4 Actions on environmental protection
VV5 Uncertainty of environmental effects
VV6 Awareness of environmental concerns
VV7 Lack of commitment for environmental improvement
VV8 Sense of urgency towards environmental issues
VV9 Deforestation halt/ decrease
VV10 Low carbon energy infrastructure becomes its own goal
VV11 Use of forestry biomass
VV12 Average sunshine hours per year
VV13 Wind load hours

Figure 9, Environmental Variables

VV4 is concerned with actions and measures that are aimed at environmental protection. Even though the primary focus in the context of environmental impact of fossil fuels is climate change, there exist several other unanticipated and harmful externalities that are addressed in the models. Air and ground water pollution, oceanic pollution and acid rain are only a few of the potential issues. Especially coal fired power plants are heavy polluters, not only with CO2 but also with heavy metals like mercury (EPA, 2016), Sulfur Dioxide (EPA, n.d.-b) and Nitrogen Dioxide (EPA, n.d.-a) which can be a severe burden on a society's health. In China for instance, coal fired power plants and the resulting air pollution are the single most severe burden on public health (Health Effects Institute, 2016).

The awareness in the public and the direct correlation of environmental pollution and their negative effects are covered by VV6. In models, this variable acts as an additional motivator to adopt "clean" energy sources instead of conventional ones which are based on carbohydrate fuel.

Variable VV7 is the lacking commitment and failure to take on responsibility for the improvement of environmental conditions. Al-Saleh (2009, p. 658) paints the picture as follows in one of the variables concerning Saudi Arabia: "There is an apparent lack of adequate commitment to reducing CO2 with only a few residual emission trading schemes. Consequently, there is an increase in climate change migrations and natural disasters such as flooding."

Most of the above-mentioned variables, but especially the increased awareness (VV6) and most prominently greenhouse gas emissions (VV1) create a sense of urgency (VV8) that is modelled as strong motivational force in favour of renewable energy sources. "(…) there is a position that focuses not on the pace of change that we can see today, but on the urgency to move much faster towards carbon neutrality given the increasingly visible threat of climate change." (IEA, 2019d, p. 54)

Another radical variable that concerns forestry is VV9, which plays with the possibility of a decrease or complete halt of deforestation. The reasoning behind this is the time-gap between deforestation and reforestation of many decades as the trees have to regrow. Additionally, reforestation and a simultaneous halt in deforestation can act as a natural carbon dioxide extraction mechanism. On the contrary VV11 includes forestry biomass in the energy generation mix.

Variable VV10 is the strongest resulting form of environmental behaviour and planning, where the low carbon infrastructure becomes its own goal, instead of a way to achieve lower emissions. "This opens up the possibility of a 'green-tech' feedback loop where technological development brings about improvements in supplying renewable energy and widespread adoption of renewable energy leads to further technological breakthroughs." (Sadorsky, 2011, p. 1101)

The last two variables are average sunshine hours per year VV12 and wind load hours VV13, which are the baseline metrics for renewable energy generation planning in the context of solar and wind.

3.3. STATISTICAL DATA ANALYSIS AND DISCUSSION

The previous chapter has described all 91 variables on a content basis, whereas the following part will go over basic frequencies and findings. The analysis is structured along three levels, namely the classification by section, by resource and by variable. The aim of this descriptive analysis is to give a good overview of the created dataset and its insights.

DESCRIPTIVE STATISTICS

A fact that has already been established is that the five different sections, which constitute a rough classification of variable types, are not represented by an equal number of variables. That is true for individual unique variables but also for the total variable count, as can be seen in Figure 10. The total variable count is the sum of all mentioned variables in all of the analysed papers. As a result, if a single variable is mentioned in three papers, all three occurrences are counted. The unique variable count on the other hand is the sum of all unique variables which have been recorded.

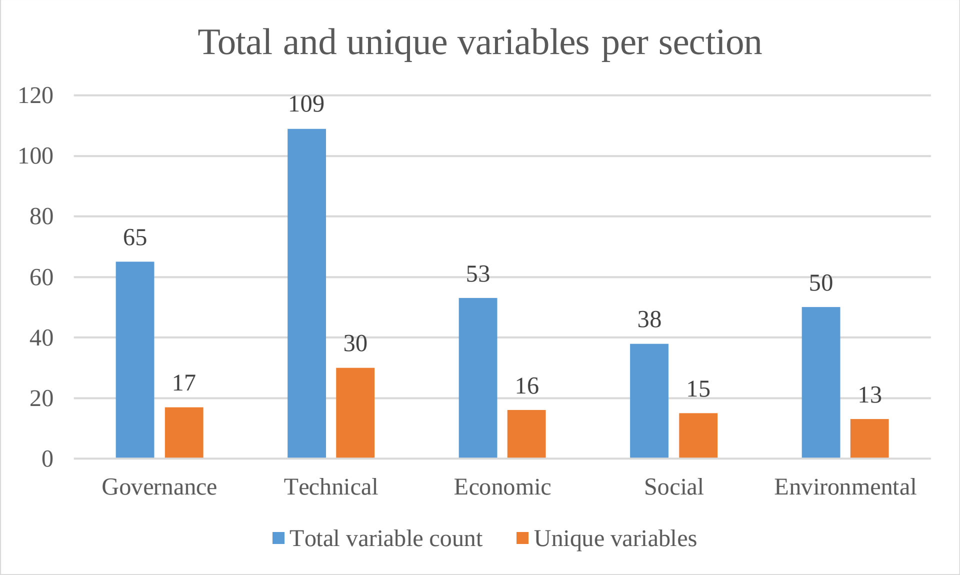


Figure 10, Total and unique variable count per variable section

This already presents an interesting insight, as it shows that technical variables are much more commonly referenced in energy scenario models than all the other sections. On average technical variables are mentioned more than twice as often as economic and environmental variables and almost three times as often as social variables. Governance variables are mentioned 40% less often than technical ones, but 22% more often than economic variables. Environmental variables are mentioned almost as often as economic variables.

Looking at the unique variable count the special status of technical variables is clear as in the four other sections there are 13 to 17 unique variables, whereas technical variables are roughly twice as many at 30 unique variables. This difference raises the question on why technical variables are so much more common in energy scenario models than any other type of variable. One explanation is that technical variables and their underlying assumptions are fairly straightforward to handle in calculations whereas qualitative variables like the public support for renewable energy are much more difficult to quantify and as a result to work with.

Another explanation could be the increasing focus on renewable energy, which inherently raises questions on network stability and technical feasibility. These questions can of course be tackled best by creating mathematical models that optimize with a given set of input factors. However, this has already been shown to be just one side to a multifaceted problem as for instance the very expensive and complex European OSEmBE model had to be manually corrected for increased gas consumption (Henke, 2018b, min. 25:50), because the model does not factor in political will and only focuses on technical optimization. Furthermore, the frequently mentioned improvements for (technical) optimizations and efficiency improvements have been attributed to the technical section in this analysis, making it a prominent factor.

Section	**Total variable count**	**Unique variables**	**Average count per variable**	**Std. Dev.**
Governance	65	17	3,82	3,03
Technical	109	30	3,63	2,14
Economic	53	16	3,31	1,49
Social	38	15	2,53	2,26
Environmental	50	13	3,85	3,05
Total	**315**	**91**	**3,46**	**2,39**

Figure 11, Basic statistics of scenario variable sections

Looking at the average variable count per document (Figure 11), it is unsurprising to see the lowest value at the section Social, as it also has the lowest overall number of variables and the second lowest number of unique variables. The highest number of variables per document on average can be found in sections Governance (3,82) and Environmental (3,85), which both also have the two highest standard deviations, 3,03 and 3,05 respectively. This is a hint towards some singular highly mentioned and a multitude of low count variables. The lowest standard deviation can be found in the section Economic with only 1,49. The average count of variables across all sections is 3,46 and the standard deviation 2,39 making it a fairly volatile dataset.

Resource	**Total variable count**	Deviation from ø
15	16	*-8,23*
3	22	*-2,23*
2	9	*-15,23*
7	45	*20,77*
16	18	*-6,23*
17	13	*-11,23*
20	28	*3,77*
11	16	*-8,23*
1	73	*48,77*
19	15	*-9,23*
28	21	*-3,23*
27	17	*-7,23*
23	22	*-2,23*
Average	**24,23**	
Std. Dev.	**17,11**	
Minimum	**9**	
Maximum	**73**	

Figure 12, Analysis statistics per paper (Resource ID following Figure 4)

On the level of single papers (Figure 12), the average number of variables is 24,23 with a standard deviation of 17,11. A curious outlier here is the maximum, which lies at 73 variables (Resource 1) with the IEA's (2019d) World Energy Outlook 2019, whereas the minimum is at only 9 variables (Winkler et al., 2009). The large stylistic differences in approach, aim and depth might be the cause for such deviances. Nevertheless, the World Energy Outlook arguably acts as one of the most important energy industry reports and as a result covers a lot of ground on the content side. In terms of document length, it is also by far the longest with 810 pages in total and more than 300 pages for part A (global analysis), making it the single most important variable contributor of this analysis.

The most commonly referred variable of the analysis, which has been mentioned in all thirteen resources, is “VV1 Greenhouse Gas Emissions Reduction” (Figure 13). It is understandable that this topic, which is often linked to human made climate change, is the most frequently mentioned variable of the analysis. Among others Antonio Guterres, the UN General Secretary, has described climate change as “the most systematic threat to humankind” (Sengupta, 2018) and as a result calls for the UN members to reduce GHG emissions. This powerful motivator functions as a reason to act in all of the papers and at least in most of the energy scenarios.

The two runners-up (Figure 13), with ten counts each, are “GG4 Existing energy infrastructure” and “TT3 Efficiency improvement in energy, buildings and material production”. This supports the previous assumption that most energy scenario models utilize a deductive approach while creating scenario models for the future. Both variables are not particularly radical, but rather incremental changes to the existing system. One covers the question on how to utilize the existing infrastructure best and match it for the new needs, the other trying to improve wasted energy in existing energy demanding areas. Especially the “improvements in efficiency” have been mentioned repeatedly in many papers without explanations, essentially making it a wildcard for all sorts of beneficial developments.

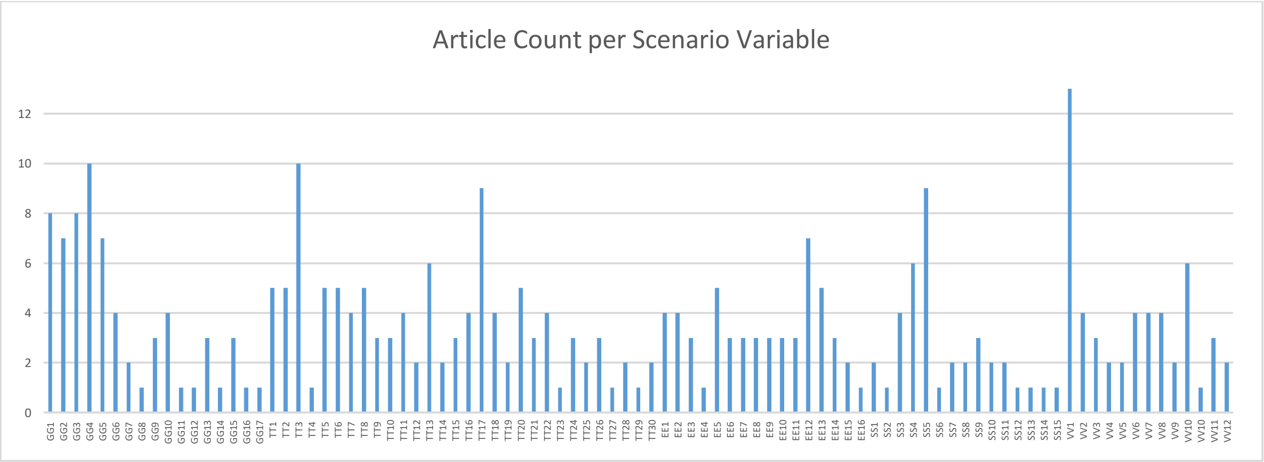


Figure 13, Article Count per Scenario Variable

TT17 the wind energy expansion as well as SS5 the development of energy demand has been mentioned in nine resources making both also frontrunners in the race for most popular energy scenario variables. As for an explanation, wind energy has sparked an increasing amount of interest in recent years as it experiences vast growth rates in energy production and investments. It seems to follow the trend of photovoltaic, with the main difference of not being primarily focused on distributed installations (such as residential and corporate rooftops) but rather in specific locations on- and offshore. Even though costs for off-shore wind farms are still high in comparison to on-shore wind farms, the requirement to move onto sea is facilitated greatly due to unfavourable regulations for the land (IEA, 2019d). Also, the development of energy demand is understandably one of the most important factors when considering the future development of the energy system and has been found in both highly technical but also very qualitative resources.

GG1 and GG3 have both been mentioned in 8 resources, which cover the goal for more energy independence and financial incentives towards renewable energy technology, respectively. Coincidentally, those two factors can have underlying motivations in common as it has been mentioned in several papers (Lesperance et al., 2018) that renewable energy sources can lead to more energy independence as the dependence on imports decrease. Financial incentives towards renewable energy sources of course have been a prominent reason for the initial boost in adoption, however, increasingly fall into the background as price of production decreases (IEA, 2019d).

From there frequencies per number of mentioned papers increase, with three variables being mentioned seven times (GG2, GG5, EE12) and six times (TT13, SS4, VV10), 8 variables being mentioned five times and so on. The complete list can either be found as a bar chart in Figure 13 or in the Appendix as an aggregated list.

MULTIPLE CORRESPONDENCE ANALYSIS

The multiple correspondence analysis paints an interesting picture of the relationship of all analysed resources to each other, using the scenario variables as statistical variables. This multi-dimensional approach using dummy variables for included (Y) and not included (N) variables shows a cluster (Figure 14) of some of the analysed papers suggesting similarities in the context of used variables across scenario models.

This is also supported by the fact that the marginal number of uncovered energy scenario variables has reached zero after ten analysed resources. Following this result it can be argued that most scientific papers focus on a very limited set of variables when anticipating the future development of energy systems.

One prominent outlier is the World Energy Outlook 2019 by the IEA (2019d) (Nr. 1) in the top right corner of Figure 14. It is the most different resource of the pool providing the most in-depth analysis on a very wide scale. In its analysis, it includes aspects in its energy model that have not been included in any other analysis such as the rising ownership of personal electronics (SS12) and the rising popularity of SUV type cars (SS15), while including a big share of the cumulative number of variables. The style of the resource is also fairly different, not just because it counts as an industry report rather than a scientific paper but also because the in-depth analysis of certain industry sectors and topics make the World Energy Outlook a rather extensive reference book for present energy data and potential future developments.

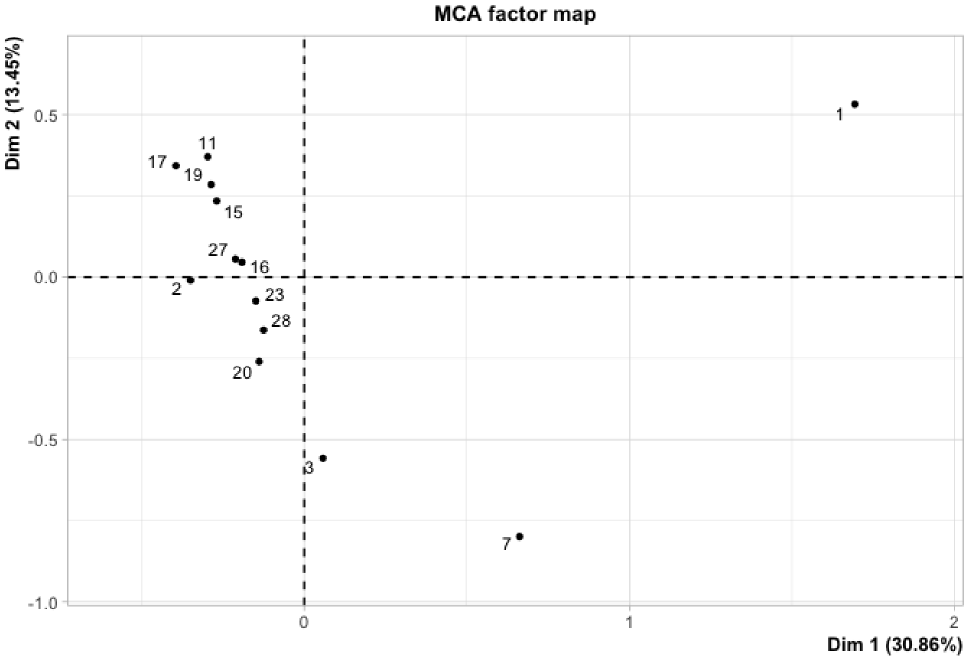


Figure 14, Multiple Correspondence Analysis (MCA) on resource relationship

Another outlier in the MCA is the paper by Sadorsky (2011) (Nr. 7), which includes the second highest number of variables (45) after the World Energy Outlook 2019 (73). It is characterized by a very detailed description of the mapped-out scenarios, focusing on the qualitative inclusion of many diverse factors in contrast to few very technical factors. This paper is much more argumentative in style than for instance the paper by Lesperance et al. (2018) starting from a status quo analysis of French Guiana and deriving possible developments for the future given a limited set of already existing variables. The second approach might technically be more deterministic, nevertheless, there is the risk of missing important non-quantitative variables as they can be difficult to include in a data-driven analysis.

Al-Saleh's (2009) energy scenario model about Saudi Arabia (Nr. 3) also finds itself separated from the majority of the papers, hinting towards another type of variables used in the model. The reason for this could be again the qualitative orientation of the paper, including interviews with thirty-five individuals of varying backgrounds. According to the author, at least half of which are industry representatives, possibly creating at least some bias for conventional energy generation sources.

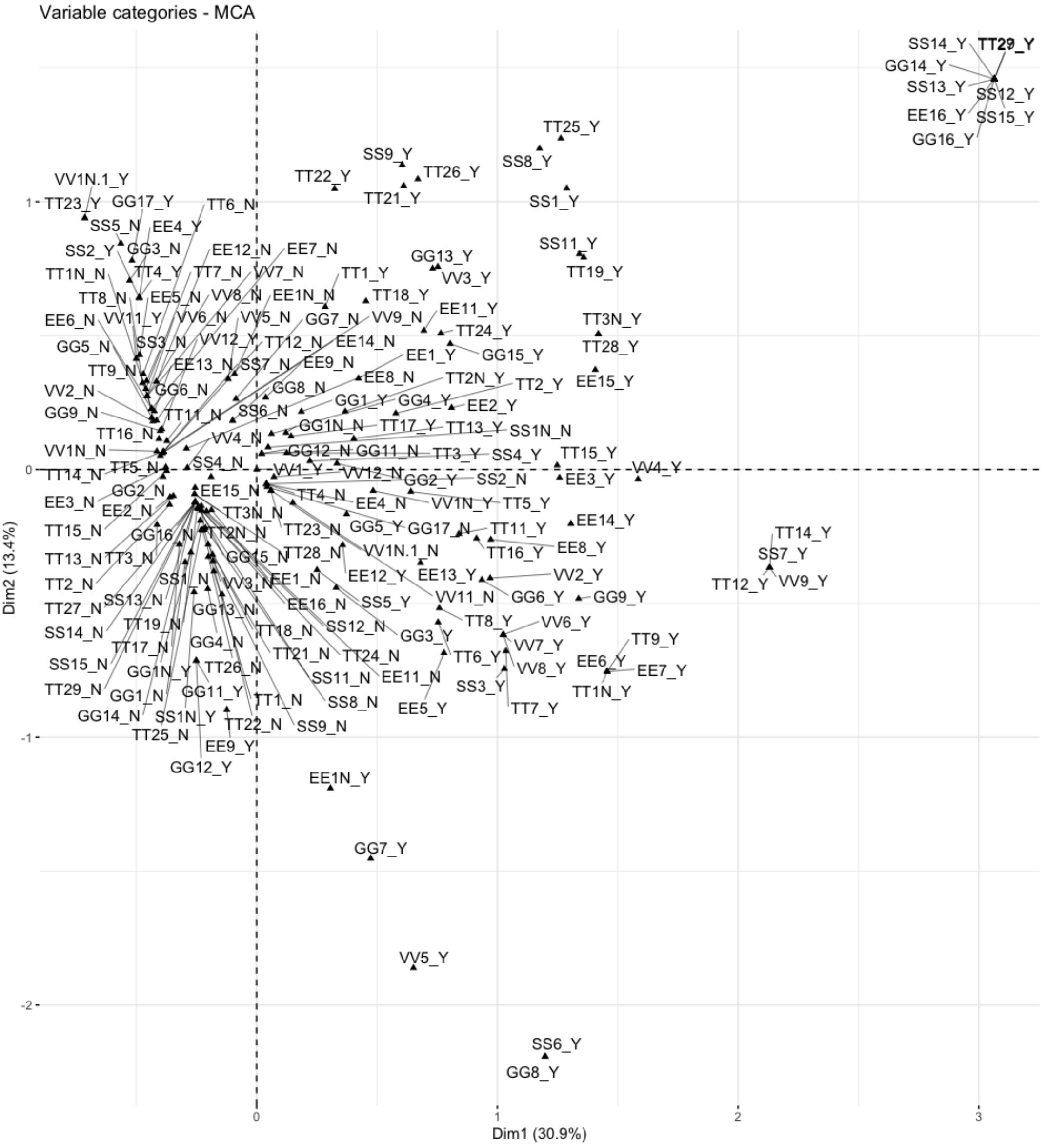


Figure 15, Multiple Correspondence Analysis (MCA) on variable relationship

The MCA shows that the arguably single most influential contributor (Resource 1)(IEA, 2019d) to the energy scenario modelling sphere and another very extensive piece of research in terms of variable volume (Resource 7)(Sadorsky, 2011) seem to be the “most different” from all analysed papers. Admittedly, increasing the amount of data involved in an analysis is not always the right way to go, however, in a sphere as complex as energy it can be argued that including more and diverse factors might sharpen estimations and give a better predictions of future developments.

Furthermore, regarding the linkages between variables and their correlated appearance in resources, Figure 15 presents the complex relationship of variable correlation. It is apparent that the majority of variables is clustered in one part, which corresponds with Figure 14, revealing a certain degree of similarity between the papers and their variable usage. Notable in this graph is again the top right cluster, representing variables that are exclusive to Resource 1, the World Energy Outlook 2019. This is also the reason why they are aggregated on one dot, which displays perfect correlation. The closer variables are in this graph, the more papers they have in common.

3.4. SUMMARY OF CHAPTER 3

Chapter 3 covers the main research outcome of this thesis, detailing the procedure and operational particularities. Descriptions for the uncovered variables are given by further explanation, clarification and referencing of the source documents. This reveals similarities between different variables but also shows important differences and contradictions among the collection. The detailed description is structured along the five sections governance, technological, economic, social, and ecological.

The descriptive analysis reveals interesting details about the collected dataset, which among other things uncovers an apparent overrepresentation of technical variables compared to other variables. This can be explained by the easily computable nature of technical assumptions, whereas qualitative variables are much more difficult to integrate into a model. The Multiple Correspondence Analysis (MCA) reveals a clustering of some analysed resources, which hints towards some similar use of variables. One industry report, however, is the largest outlier, coincidently also being one of the most influential energy scenario publishers. This suggests a high potential benefit of using more scenario variables.

CHAPTER 4: SCIENTIFIC CONTRIBUTION AND MANAGERIAL IMPLICATIONS

This chapter is dedicated to the resulting theoretical contributions of this thesis as well as practical implications for managers.

4.1. SCIENTIFIC CONTRIBUTION

The literature review has revealed among other things the high level of complexity of energy systems as a whole and the resulting difficulty of applying Operational Research in the context of strategic management. One crucial tool of decision making in the energy industry is predicative energy modelling, providing a set of tools to anticipate and plan energy systems on a macro level all around the globe. These models are mostly constructed in several different scenarios, making a multitude of "what-if" situations possible and computable. Nevertheless, it has been unclear whether the underlying assumptions and variables included in the energy scenario models are comparable and which variables even exist.

This thesis has shown that energy scenario models in fact show some similarity in variable usage, but overall are not comparable because of a divergent use of underlying assumptions and included variables. This is best exemplified by the average variable count per resource being 24, whereas the overall number of unique variables being 91. Furthermore, the Multiple Correspondence Analysis scatterplot visualizes key differences in variable usage across energy scenario models. This differences in model creation makes a comparative analysis of predictions very challenging as two models might be built upon entirely different premises.

In order to improve the transparency of energy scenario modelling, the comprehensive list of 91 energy scenario variables presented in this thesis can serve as a first step towards standardization. A standardized variable pool for energy scenario modelling would have the advantage of making the cause effect relationship between input variable and output prediction clearer and giving researchers the opportunity to compare different approaches in a more effective manner. However, even on its own the list of 91 variables constitutes a contribution to the body of knowledge as until now a collection like this has not been created before.

Another major finding of this thesis is the overrepresentation of technical variables in comparison to other categories. There have been identified roughly twice as many technical variables (30) than any other type of variable (13 – Environmental, 15 – Social, 16 – Economic, 17 – Governance). Also, the total variable count is higher at a factor between 2,8 and 1,7 in favour of technical variables (Figure 11). Even though the root cause for this is unknown, it can be speculated that technical variables are simply much easier to put into numbers that in turn can be more easily integrated into a mathematical energy model. On the other hand, effects of qualitative variables such as “VV6 Awareness of environmental concerns” are much more difficult to predict and model. Nevertheless, it has been shown that especially those non-technical factors can have large effects on the development of energy markets (GHG emissions movement, fear of nuclear energy, etc.).

A scientific continuation of this thesis could therefore include the cause and effect of an overrepresentation of technical variables as well as a comparison of energy model predictions and their underlying input variables.

4.2. MANAGERIAL IMPLICATIONS

The energy sector is one of the most important branches of global economy. It provides employment, investment and most importantly energy resources to the benefit of society. Without doubt it is crucial for every business operating in the energy sector to have available accurate predictions of the future development in the industry in order to plan new investments, make strategic decisions, hire new employees or expand production in a certain region.

Most decisions like this are made based on some sort of model and research predicting energy demand, competition, grid stability and externalities like CO2 emissions. The question, which is most important in this context is how accurate the respective model or prediction is and how it can be improved. Situations where energy models are described as “black boxes” by decision-makers must be avoided (Gironès et al., 2015). Therefore, a more accurate and transparent energy model has the potential of giving managers in the energy sector, policymakers and other important stakeholders an increased chance of making sound strategic management decisions and leverage the competitive advantage of having the best quality information available. Making better and informed strategic decisions in the energy industry can increase the chance of success in many different aspects. Those include but are not limited to a market expansion, deciding on the focus of innovation efforts, infrastructure development, cost saving efforts and customer acquisition attempts.

In this sense, the main use case for managers in the energy sector, is the possibility of adding previously unexplored or unknown variables to future energy scenario models and cover as many developments in the future of the energy industry as possible. Especially the large and arguably overrepresented emphasis of technological capabilities in comparison to social, economic, governance or environmental factors can lead to predictions that might technically be possible but fall short because of other overlooked factors.

The leading example here is the German “Energiewende”, which is the ambitious plan of the strongest economy in Europe to revolutionize its energy system to become more sustainable, eco-friendly and low-carbon oriented. The initial plan was to position nuclear energy as a central transition technology (BMWi, 2010), due to its zero-carbon footprint and its reliability and predictability in the rate of production. This is required in order to sustain a baseload which is a major prerequisite for a functioning energy grid. However, few months after the announcement, the Fukushima nuclear disaster happened and after a public outcry, mass protests and political leaders expressing reservations against nuclear energy a 180 degree shift took place, amending the initial plan that “(…) the role assigned to nuclear power in the energy concept was reassessed (…)” (BMWi, 2011, p. 1) which ultimately led to the progressive phase-out of nuclear power plants all together in the following years.

Fukushima in this sense did not necessarily uncover new technical details about nuclear power plants and their potential risk but rather emotionalized the discussion and brought about a result which was mostly unpredicted.

Taking this sequence of events as a real-life example, before 2011 it was very difficult to predict an energy system with no nuclear energy in Germany. Governmental policy, industry and technological orientation seemed very much aligned towards this new and revolutionary plan. Nevertheless, scepticism towards nuclear energy is not a new phenomenon and has led to a stop of power plant construction before (Weish, 1988). The aforementioned disaster in Japan might have been a spark in an already sceptical public mindset which escalated after the Fukushima incident. As a result, the antipathy against nuclear power could have been factored into energy models at that time, which opens up the risk for omitted variable bias. This bias occurs in statistical models when a deterministic variable is not included in the respective model and as a result its effect is attributed to a different variable. Besides statistics, common sense also dictates that leaving out important factors from a model lead to inaccurate results.

As the change in plans in Germany was not due to any technical issue, a purely technical or quantitative energy scenario model could not have predicted this development. In practical terms, energy models of the future can explicitly take into consideration some or all of the variables presented in this thesis, such as “GG10 Opposition against nuclear power”, “GG12 Viable solution for nuclear waste available”, “VV2 Potential weather hazards” and “VV6

Awareness of environmental concerns” to actively include this specific risk profile in the respective energy model. Omitted variable bias is reduced, leading to a more precise and higher quality energy forecasting model. As for the case of Germany, nuclear energy producers have been tied up in legal disputes with the German government since 2011 over multiple billion Euros restitution claims (Spiegel, 2016) apart from the fact that it is unclear who pays for the deconstruction of the soon to be inactive power plants.

Apart from more effective risk management, the inclusion of a vetting process for energy scenarios in large international corporations can prove valuable in terms of company ethics and the way how decision-making processes are implemented. As it has been shown before, some estimations have continuously been misleading in favour of non-renewable energy sources (Breyer et al., 2017; Creutzig et al., 2017), which can act as a motivation to retain the status quo of the energy mix as long as possible. In return, an investing company using a comprehensive list of energy variables to check whether a certain prediction seems valid, can change evaluations and as a result can change decisions that reduce cost. This can have an effect on investment behaviour but also influence stakeholder management by checking for the inclusion of a wide range of different aspects in contrast to only looking at technical feasibility and profit potential. Furthermore, decisions on increased sustainability and energy security on long time-scales can be aided by better performing and clearer energy models (Moret et al., 2016).

To sum up, managers can improve the prediction accuracy of an energy model by designing energy scenarios in a way, so they cover a lot of ground. Following the results of this thesis, this directly translates to the inclusion of more cross-sectional and unique variables, such as the ones presented as a result of this thesis. Likewise, second-guessing one-sided predictions by cross-checking included variables can help making better decision on a strategic level. This increases transparency and understanding of the underlying model and gets rid of “black box” situations with decision makers. External risks and opportunities can be accounted for better to maintain a competitive advantage and improve energy related strategic decision making.

CONCLUSION

In conclusion, it can be said that the sphere of energy scenario models is highly diverse and covers many different aspects of the possible future development of energy markets all around the world. On a quest to improve the understanding of this complex industry and its future development this thesis gives an overview of the scientific background of several energy technologies. Furthermore, it has covered the methodology of energy models and in particular scenario models, which add an additional layer of complexity in the context of comparability.

The main goal of this thesis is to uncover *"which variables and issues are considered in predictive energy scenario models"*, which has been done by conducting a meta-analysis of relevant documents covering this topic. By way of this methodology, it was possible to collect a pool of 29 resources out of which ultimately 13 were randomly chosen for the analysis. After the tenth document, marginal returns in form of additional variables have reached zero. Three additional resources were analysed to make sure a maximum has been reached.

The final number of uncovered scenario variables is 91, with 17 in the section governance, 30 in technical, 16 in economic, 15 in social and 13 in environmental (Figure 10). The total variable count across all resources is 315 with an average of 3,45 mentions per variable. This stands to show that technical variables seem to be much more common in energy scenario models than any other type of variable. An explanation could be that technical estimates are much easier to implement in a model as they might be considered more rigid in a scientific sense. Nevertheless, it can be argued that this overrepresentation of technical variables creates a bias for the "rational" or "economically most sensible" solution, whereas it has been shown that decisions do not necessarily follow pure logic but rather are influenced by many softer factors (BMWi, 2010, 2011).

By pointing this out, it enables future creators of energy models to attempt and include more deterministic variables or at least consider their possible effects. This way, the additionally considered pieces of information have the power of influencing and most crucially improving forecasts and in turn give decision-makers better tools to make strategic management decisions. To do this, the main implication for the scientific community is to put a special focus on effects the variables have on energy models and their results, as well as the unequal distribution of types of variables. A possible continuation for this line of research can be the inclusion of energy model results into the analysis, giving a more detailed look into cause-effect relationships within energy models. The research can also be expanded in a vertical scale, including a larger number of energy models written in languages other than English.

Another finding of the research is the detection of multiple different styles of energy scenario models. The variety spanned from strongly numbers and data driven analysis to qualitative argumentative models. Nevertheless, the most distinct scenario model in the context of variables is the World Energy Outlook 2019 by the IEA (2019d) as it includes more than 80% of the uncovered variables and represents an unmatched curiosity.

The complex relationship between variables has been visualized with a Multiple Correspondence Analysis, providing a clear outline of variables which are commonly found together, and others which are fairly unrelated. This shows that there are in fact inconsistencies in variable usage among energy scenario models. In practical terms this means that a better understanding of correlated variables also reduces the risk of energy models becoming impenetrable “black-boxes” for decision-makers.

In conclusion, it has been revealed that there is in fact some heterogeneity among energy scenario models that can become an issue when looking for a clear understanding how the future of an energy system might look like. To tackle this, it is recommended to standardize a complete set of deterministic energy scenario variables so researchers can better find, evaluate and integrate those into future models and give decision-makers the power to plan a strong, sustainable and healthy globe energy system.

SOURCES

Al-Saleh, Y. (2009). Renewable energy scenarios for major oil-producing nations: The case of Saudi Arabia. *Futures*, *41*(9), 650–662. https://doi.org/10.1016/j.futures.2009.04.005

Anderegg, W. R. L., Prall, J. W., Harold, J., & Schneider, S. H. (2010). Expert credibility in climate change. *Proceedings of the National Academy of Sciences*, *107*(27), 12107–12109. https://doi.org/10.1073/pnas.1003187107

Aruga, K. (2016). The U.S. shale gas revolution and its effect on international gas markets. *Journal of Unconventional Oil and Gas Resources*, *14*, 1–5. https://doi.org/10.1016/j.juogr.2015.11.002

Baumgarth, C., Eisend, M., & Evanschitzky, H. (2009). Empirische Mastertechniken: eine anwendungsorientierte Einführung für die Marketing-und Managementforschung. In *Empirische Mastertechniken: eine anwendungsorientierte Einführung für die Marketing- und Managementforschung* (1st ed.).

Beer, S. (1967). *Management science: The business use of operations research*. Doubleday.

Bellocchi, S., De Falco, M., Gambini, M., Manno, M., Stilo, T., & Vellini, M. (2019). Opportunities for power-to-Gas and Power-to-liquid in CO2-reduced energy scenarios: The Italian case. *Energy*, *175*, 847–861. https://doi.org/10.1016/j.energy.2019.03.116

Bennett, N., & Lemoine, G. J. (2014). What a difference a word makes: Understanding threats to performance in a VUCA world. *Business Horizons*, *57*(3), 311–317. https://doi.org/10.1016/j.bushor.2014.01.001

BMWi. (2010). *Energy Concept for an Environmentally Sound, Reliable and Affordable Energy Supply*. https://web.archive.org/web/20161006040920/http://www.bmwi.de/English/Redaktion/Pdf/energy-concept%2Cproperty%3Dpdf%2Cbereich%3Dbmwi%2Csprache%3Den%2Crwb%3Dtrue.pdf

BMWi. (2011). *The Federal Government's energy concept of 2010 and the transformation of the energy system of 2011*. https://web.archive.org/web/20161006040646/http://www.germany.info/contentblob/3043402/Daten/3903429/BMUBMWi_Energy_Concept_DD.pdf

Breyer, C., Bogdanov, D., Gulagi, A., Aghahosseini, A., Barbosa, L. S. N. S., Koskinen, O., Barasa, M., Caldera, U., Afanasyeva, S., Child, M., Farfan, J., & Vainikka, P. (2017). On the role of solar photovoltaics in global energy transition scenarios. *Progress in Photovoltaics: Research and Applications*, *25*(8), 727–745. https://doi.org/10.1002/pip.2885

Camarero, M., Forte, A., Garcia-Donato, G., Mendoza, Y., & Ordoñez, J. (2015). Variable selection in the analysis of energy consumption-growth nexus. *Energy Economics*, *52*, 207–216. https://doi.org/10.1016/j.eneco.2015.10.012

Cano, E. L., Moguerza, J. M., Ermolieva, T., & Yermoliev, Y. (2017). A strategic decision support system framework for energy-efficient technology investments. *Top*, *25*(2), 249–270. https://doi.org/10.1007/s11750-016-0429-9

Carter, R. (2006). Boat remains and maritime trade in the Persian Gulf during the sixth and fifth millennia BC. *Antiquity*, *80*(307), 52–63. https://doi.org/10.1017/S0003598X0009325X

Child, M., Ilonen, R., Vavilov, M., Kolehmainen, M., & Breyer, C. (2019). Scenarios for sustainable energy in Scotland. *Wind Energy*, *22*(5), 666–684. https://doi.org/10.1002/we.2314

Cochran, J., Mai, T., & Bazilian, M. (2014). Meta-analysis of high penetration renewable energy scenarios. *Renewable and Sustainable Energy Reviews*, *29*, 246–253. https://doi.org/10.1016/j.rser.2013.08.089

Connolly, D., Lund, H., & Mathiesen, B. V. (2016). Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. *Renewable and Sustainable Energy Reviews*, *60*, 1634–1653. https://doi.org/10.1016/j.rser.2016.02.025

Connolly, David, Mathiesen, B. V., & Lund, H. (2015). Smart Energy Europe: From a Heat Roadmap to an Energy System Roadmap. In *Aalborg Universitet*. https://vbn.aau.dk/en/publications/smart-energy-europe-from-a-heat-roadmap-to-an-energy-system-roadm

Cork, C. R. (2015). Conductive fibres for electronic textiles. In *Electronic Textiles* (pp. 3–20). Elsevier. https://doi.org/10.1016/B978-0-08-100201-8.00002-3

Creutzig, F., Agoston, P., Goldschmidt, J. C., Luderer, G., Nemet, G., & Pietzcker, R. C. (2017). The underestimated potential of solar energy to mitigate climate change. *Nature Energy*, *2*(9). https://doi.org/10.1038/nenergy.2017.140

CSO. (n.d.). *Land Use - CSO - Central Statistics Office*. Retrieved April 10, 2020, from https://www.cso.ie/en/releasesandpublications/ep/p-eii/eii2016/lu/

Economides, M. J., & Wood, D. A. (2009). The state of natural gas. *Journal of Natural Gas Science and Engineering*, *1*(1–2), 1–13. https://doi.org/10.1016/j.jngse.2009.03.005

Electrek. (2019, December 30). *Tesla Gigafactory 1: Panasonic ready to ramp up battery production to 54 GWh - Electrek*. https://electrek.co/2019/12/30/tesla-gigafactory-1-panasonic-ready-ramp-up-battery-cell-production/

Elsevier. (n.d.). *Content - How Scopus Works - Scopus - | Elsevier solutions*. Retrieved February 8, 2020, from https://www.elsevier.com/solutions/scopus/how-scopus-works/content

Endt, C., & Witzenberger, B. (2019). Energiewende: Wo noch Raum für die Windkraft bleibt. *Süddeutsche Zeitung*. https://www.sueddeutsche.de/wirtschaft/energiewende-windenergie-abstandsregeln-1.4691305

EPA. (n.d.-a). *Basic Information about NO2 | Nitrogen Dioxide (NO2) Pollution | US EPA*. Retrieved April 16, 2020, from https://www.epa.gov/no2-pollution/basic-information-about-no2#Effects

EPA. (n.d.-b). *Sulfur Dioxide Basics | Sulfur Dioxide (SO2) Pollution | US EPA*. Retrieved April 16, 2020, from https://www.epa.gov/so2-pollution/sulfur-dioxide-basics#effects

EPA. (2016). *2014 National Emissions Inventory, version 1 Technical Support Document*.

EurObserv'ER. (2019a). *Photovoltaic Barometer* (Issue April 2019). https://www.eurobserv-er.org/pdf/photovoltaic-barometer-2019-en/

EurObserv'ER. (2019b). *Solar Thermal And Concentrated Solar Power Barometers* (Issue June 2019). https://www.eurobserv-er.org/pdf/solar-thermal-and-csp-barometer-2019-en/

European Commission. (2011). *Energy Roadmap 2050* (COM(2011) 885). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52011DC0885&from=EN

European Commission. (2018). *Commission decides not to extend trade defence measures on solar panels from China - Trade - European Commission*. http://trade.ec.europa.eu/doclib/press/index.cfm?id=1904

European Environment Agency. (2009). *Europe's onshore and offshore wind energy potential* (Issue 6). https://doi.org/10.2800/11373

Eurostat. (2019). *Complete energy balances*. Eurostat - Your Key to European Statistics.

https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_bal_c&lang=en

Gironès, V. C., Moret, S., Maréchal, F., & Favrat, D. (2015). Strategic energy planning for large-scale energy systems: A modelling framework to aid decision-making. *Energy*, *90*(PA1), 173–186. https://doi.org/10.1016/j.energy.2015.06.008

Health Effects Institute. (2016). *Burden of Disease Attributable to Coal-Burning and Other Major Sources of Air Pollution in China*. www.healtheffects.org

Henke, H. (2018a). *OSeMBE - An open-source engagement model*. http://www.osemosys.org/uploads/1/8/5/0/18504136/osembe_documentation.pdf

Henke, H. (2018b). *OSeMBE Webinar [YouTube]*. https://www.youtube.com/watch?v=7-GnZ-Xhars

Hong, J. H., Kim, J., Son, W., Shin, H., Kim, N., Lee, W. K., & Kim, J. (2019). Long-term energy strategy scenarios for South Korea: Transition to a sustainable energy system. *Energy Policy*, *127*(July 2018), 425–437. https://doi.org/10.1016/j.enpol.2018.11.055

Huang, Y., Bor, Y. J., & Peng, C. Y. (2011). The long-term forecast of Taiwan's energy supply and demand: LEAP model application. *Energy Policy*, *39*(11), 6790–6803. https://doi.org/10.1016/j.enpol.2010.10.023

Hubbert, M. K. (1956). Nuclear energy and the fossil fuels. *Drilling and Production Practice 1956*, *1956-Janua*, 7–25.

IEA/IRENA. (2017). *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Mar/Perspectives_for_the_Energy_Transition_2017.pdf?la=en&hash=56436956B74DBD22A9C6309ED76E3924A879D0C7

IEA. (2018a). *World Energy Outlook 2018*. https://www.iea.org/workshops/world-energy-outlook-2018-the-future-is-electrifying.html

IEA. (2018b). *Renewables 2018* (Market Report Series: Renewables). OECD. https://doi.org/10.1787/re_mar-2018-en

IEA. (2019a). *Key World Energy Statistics 2019*. https://webstore.iea.org/key-world-energy-statistics-2019

IEA. (2019b). *The Role of Gas in Today's Energy Transitions*. https://webstore.iea.org/download/direct/2819?fileName=TheRoleofGas.pdf

IEA. (2019c). *World Energy Balances 2019*. https://webstore.iea.org/world-energy-balances-2019

IEA. (2019d). *World Energy Outlook 2019*. https://webstore.iea.org/world-energy-outlook-2019

James, S. R., Dennell, R. W., Gilbert, A. S., Lewis, H. T., Gowlett, J. A. J., Lynch, T. F., McGrew, W. C., Peters, C. R., Pope, G. G., Stahl, A. B., & James, S. R. (1989). Hominid Use of Fire in the Lower and Middle Pleistocene: A Review of the Evidence [and Comments and Replies]. *Current Anthropology*, *30*(1), 1–26. https://doi.org/10.1086/203705

Kaufmann, R. K., Bradford, A., Belanger, L. H., Mclaughlin, J. P., & Miki, Y. (2008). Determinants of OPEC production: Implications for OPEC behavior. *Energy Economics*, *30*(2), 333–351. https://doi.org/10.1016/j.eneco.2007.04.003

Keyser, P. T. (1993). The Purpose of the Parthian Galvanic Cells: A First-Century A. D. Electric Battery Used for Analgesia. *Journal of Near Eastern Studies*, *52*(2), 81–98. https://doi.org/10.1086/373610

Kowalski, K., Stagl, S., Madlener, R., & Omann, I. (2009). Sustainable energy futures: Methodological challenges in combining scenarios and participatory multi-criteria analysis. *European Journal of Operational Research*, *197*(3), 1063–1074. https://doi.org/10.1016/j.ejor.2007.12.049

Krewitt, W., Teske, S., Simon, S., Pregger, T., Graus, W., Blomen, E., Schmid, S., & Schäfer, O. (2009). Energy [R]evolution 2008-a sustainable world energy perspective. *Energy Policy*, *37*(12), 5764–5775. https://doi.org/10.1016/j.enpol.2009.08.042

Lesperance, W., Kamdem, J. S., Linguet, L., & Albarelo, T. (2018). Renewable Energy in French Guiana: Prospects towards a Sustainable Development Scenario. *2nd International Conference on Smart Grid and Smart Cities, ICSGSC 2018*, 133–136. https://doi.org/10.1109/ICSGSC.2018.8541267

Merriam-Webster. (2020). *Operations Research | Definition of Operations Research by Merriam-Webster*. https://www.merriam-webster.com/dictionary/operations research

Michalena, E., & Hills, J. M. (2012). Renewable energy issues and implementation of European energy policy: The missing generation? *Energy Policy*, *45*, 201–216. https://doi.org/10.1016/j.enpol.2012.02.021

Miriello, C., & Polo, M. (2015). The development of gas hubs in Europe. *Energy Policy*, *84*, 177–190. https://doi.org/10.1016/j.enpol.2015.05.003

Mongird, K., Fotedar, V., Viswanathan, V., Koritarov, V., Balducci, P., Hadjerioua, B., & Alam, J. (2019). Energy Storage Technology and Cost Characterization Report. *Pnnl*, *July*. https://www.energy.gov/sites/prod/files/2019/07/f65/Storage Cost and Performance Characterization Report_Final.pdf

Moret, S., Bierlaire, M., & Maréchal, F. (2016). Strategic Energy Planning under Uncertainty: a Mixed-Integer Linear Programming Modeling Framework for Large-Scale Energy Systems. *Computer Aided Chemical Engineering*, *38*(2003), 1899–1904. https://doi.org/10.1016/B978-0-444-63428-3.50321-0

Ormerod, R. J. (1980). Energy models for decision making. *European Journal of Operational Research*, *5*(6), 366–377. https://doi.org/10.1016/0377-2217(80)90123-X

Papaefthimiou, S., Souliotis, M., & Andriosopoulos, K. (2016). Grid parity of solar energy: Imminent fact or future’s fiction? *Energy Journal*, *37*(Special Issue 2), 263–276. https://doi.org/10.5547/01956574.37.SI2.spap

REEEM. (n.d.). *Home | REEEM*. Retrieved January 22, 2020, from https://www.reeem.org/

Regelous, A., & Meyn, J. (2011). Erneuerbare Energien - eine physikalische Betrachtung. In *Physikalisches Institut - Didaktik der Physik, FAU Erlangen-Nürnberg* (pp. 1–5). http://www.phydid.de/index.php/phydid-b/article/viewArticle/251

Regnier, E. (2007). Oil and energy price volatility. *Energy Economics*, *29*(3), 405–427. https://doi.org/10.1016/j.eneco.2005.11.003

Roinioti, A., Koroneos, C., & Wangensteen, I. (2012). Modeling the Greek energy system: Scenarios of clean energy use and their implications. *Energy Policy*, *50*(2012), 711–722. https://doi.org/10.1016/j.enpol.2012.08.017

Roser, M., & Ritchie, H. (2017). *CO_2 and Greenhouse Gas Emissions*. Our World in Data. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions#per-capita-co2-emissions

Sadorsky, P. (2011). Some future scenarios for renewable energy. *Futures*, *43*(10), 1091–1104. https://doi.org/10.1016/j.futures.2011.07.008

Savio, N. D., & Nikolopoulos, K. (2013). A strategic forecasting framework for governmental decision-making and planning. *International Journal of Forecasting*, *29*(2), 311–321.

https://doi.org/10.1016/j.ijforecast.2011.08.002

Sengupta, S. (2018). *Biggest Threat to Humanity? Climate Change, U.N. Chief Says - The New York Times*. New York Times. https://www.nytimes.com/2018/03/29/climate/united-nations-climate-change.html

Skeer, J., & Leme, R. (2018). *Renewable Energy in the Energy Future* (pp. 473–502). https://doi.org/10.1142/9789813278356_0014

Sørensen, B. (2004). Renewable Energy: Its physics, engineering, use, environmental impacts, economy and planning aspects. In *Elsevier Academic Press* (Third).

Spiecker, S., & Weber, C. (2014). The future of the european electricity system and the impact of fluctuating renewable energy - A scenario analysis. *Energy Policy*, *65*, 185–197. https://doi.org/10.1016/j.enpol.2013.10.032

Spiegel. (2016). *Regierung muss Energiekonzerne entschädigen*. https://www.spiegel.de/wirtschaft/soziales/bundesverfassungsgericht-zum-atomausstieg-energie-konzerne-haben-anspruch-auf-entschaedigung-a-1124612.html

Synolakis, C., & Kânoğlu, U. (2015). The Fukushima accident was preventable. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *373*(2053), 20140379. https://doi.org/10.1098/rsta.2014.0379

Szarka, N., Eichhorn, M., Kittler, R., Bezama, A., & Thrän, D. (2017). Interpreting long-term energy scenarios and the role of bioenergy in Germany. *Renewable and Sustainable Energy Reviews*, *68*, 1222–1233. https://doi.org/10.1016/j.rser.2016.02.016

Twidell, J., & Weir, T. (2006). *Renewable Energy Resources* (Second). Taylor & Francis.

U.S. Department of the Interior. (n.d.). *What are the types of coal?* Retrieved January 19, 2020, from https://www.usgs.gov/faqs/what-are-types-coal?qt-news_science_products=0#qt-news_science_products

Umweltbundesamt. (2016). *Erneuerbare Energien | Umweltbundesamt*. https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien

Waenn, A., Connolly, D., & Gallachóir, B. (2014). Investigating 100% renewable energy supply at regional level using scenario analysis. *International Journal of Sustainable Energy Planning and Management*, *3*, 31–32. https://doi.org/10.5278/ijsepm.2014.3.3

Wang, G., Zhang, Q., Mclellan, B. C., & Li, H. (2016). Multi-region optimal deployment of renewable energy considering different interregional transmission scenarios. *Energy*, *108*, 108–118. https://doi.org/10.1016/j.energy.2015.08.060

Weish, P. (1988). *Austria's no to nuclear power*. *April*, 1–6.

Whiteman, W. E. (1998). *Training and Educating Army Officers for the 21st Century: Implications for the United States Military Academy*. https://apps.dtic.mil/dtic/tr/fulltext/u2/a345812.pdf

Winkler, H., Hughes, A., & Haw, M. (2009). Technology learning for renewable energy: Implications for South Africa's long-term mitigation scenarios. *Energy Policy*, *37*(11), 4987–4996. https://doi.org/10.1016/j.enpol.2009.06.062

World Energy Council. (2019). *Energy Storage Monitor 2019*. https://www.worldenergy.org/assets/downloads/ESM_Final_Report_05-Nov-2019.pdf

World Nuclear Association. (2020). *Nuclear Power in Pakistan*. https://www.world-nuclear.org/information-library/country-profiles/countries-o-s/pakistan.aspx

World Resource Institute. (n.d.). *CAIT Historical - Explore Historic Greenhouse Gas Emissions*. Retrieved January 26, 2020, from http://cait.wri.org/historical/Country GHG Emissions?indicator[]=Energy&indicator[]=Industrial Processes&indicator[]=Agriculture&indicator[]=Waste&indicator[]=Land-Use Change and Forestry&indicator[]=Bunker Fuels&year[]=2014&sortIdx=NaN&regions=true&chart

Zhang, X., & Kumar, A. (2011). Evaluating renewable energy-based rural electrification program in western China: Emerging problems and possible scenarios. *Renewable and Sustainable Energy Reviews*, *15*(1), 773–779. https://doi.org/10.1016/j.rser.2010.08.023

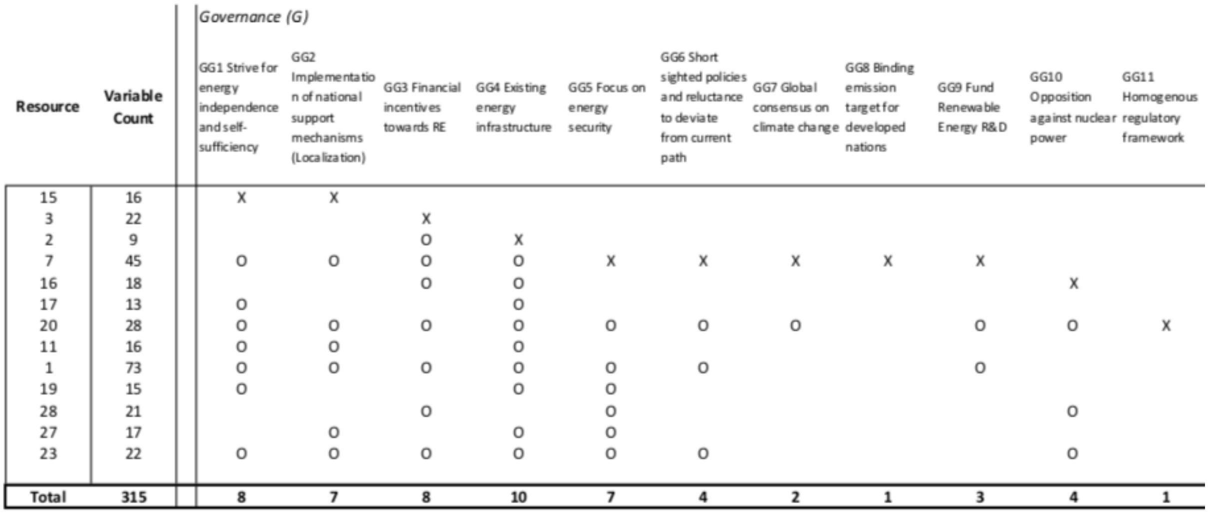
APPENDIX

RESEARCH POOL

ID	Title	Author	Year	Scope	Type
1	World Energy Outlook 2019	IEA	2019	Global	Industry Report
2	Technology learning for renewable energy: Implications for South Africa's long-term mitigation scenarios	Winkler, Harald Hughes, Alison Haw, Mary	2009	South Africa	Scientific Paper
3	Renewable energy scenarios for major oil-producing nations: The case of Saudi Arabia	Al-Saleh, Yasser	2009	Saudi Arabia	Scientific Paper
4	The future of Russia's renewable energy sector: Trends, scenarios and policies	Proskuryakova, Liliana N. Ermolenko, Georgy V.	2019	Russia	Scientific Paper
5	Energy [R]evolution 2008-a sustainable world energy perspective	Krewitt, Wolfram Teske, Sven Simon, Sonja Pregger, Thomas Graus, Wina Blomen, Eliane Schmid, Stephan Schäfer, Oliver	2009	Global	Scientific Paper
6	Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union	Connolly, D. Lund, H. Mathiesen, B. V.	2016	EU	Scientific Paper
7	Some future scenarios for renewable energy	Sadorsky, Perry	2011	Global	Scientific Paper
8	The European renewable energy target for 2030 - An impact assessment of the electricity sector	Knopf, Brigitte Nahmmacher, Paul Schmid, Eva	2015	Europe	Scientific Paper
9	Multi-region optimal deployment of renewable energy considering different interregional transmission scenarios	Wang, Ge Zhang, Qi Mclellan, Benjamin C. Li, Hailong	2016	Japan	Scientific Paper
10	A sustainable energy future: Construction of demand and renewable energy supply scenarios	Sørensen, Bent	2008	Northern Europe	Scientific Paper
11	Future scenarios and trends in energy generation in Brazil: Supply and demand and mitigation forecasts	De Andrade Guerra, José Baltazar Salgueirinho Osório Dutra, Luciano Schwinden, Norma Beatriz Camisão Andrade, Suely Ferraz De	2015	Brazil	Scientific Paper
12	Future energy scenarios with distributed technology options for residential city blocks in three climate regions of the United States	Yuan, Shengxi Stainsby, Wendell Li, Mo Xu, Kewei Waite, Michael Zimmerle, Dan Feiock, Richard Ramaswami, Anu Modi, Vijay	2019	USA	Scientific Paper
13	Interactions and implications of renewable and climate change policy on UK energy scenarios	Anandarajah, Gabrial Strachan, Neil	2010	United Kingdome	Scientific Paper
14	National energy scenario of Pakistan – Current status, future alternatives, and institutional infrastructure: An overview	Rafique, M. Mujahid Rehman, S.	2017	Pakistan	Scientific Paper
15	Renewable Energy in French Guiana: Prospects towards a Sustainable Development Scenario	Lesperance, Wilna Kamdem, Jules Sadefo Linguet, Laurent Albarelo, Tommy	2018	French Guiana	Scientific Paper

16	Scenarios for sustainable energy in Scotland	Child, Michael Ilonen, Roope Vavilov, Mihail Kolehmainen, Mikko Breyer, Christian	2019	Scotland	Scientific Paper
17	Investigating 100% renewable energy supply at regional level using scenario analysis	Waenn, Annicka Connolly, David Gallachóir, Brian	2014	Ireland	Scientific Paper
18	Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System	IEA/IRENA	2017	Global	Industry Report
19	Sustainable energy futures: Methodological challenges in combining scenarios and participatory multi-criteria analysis	Kowalski, Katharina Stagl, Sigrid Madlener, Reinhard Omann, Ines	2009	Austria	Scientific Paper
20	The future of the european electricity system and the impact of fluctuating renewable energy - A scenario analysis	Spiecker, Stephan Weber, Christoph	2014	Europe	Scientific Paper
21	A nonparametric approach for evaluating long-term energy policy scenarios: an application to the Greek energy system	Halkos, George Tzeremes, Nickolaos G. Tzeremes, Panayiotis G.	2015	Greece	Scientific Paper
22	Deciding the Future: Energy Policy Scenarios to 2050	WEC	2007	Global	Industry Report
23	Long-term energy strategy scenarios for South Korea: Transition to a sustainable energy system	Hong, Jong Ho Kim, Jitae Son, Wonik Shin, Heeyoung Kim, Nahyun Lee, Woong Ki Kim, Jintae	2019	South Korea	Scientific Paper
24	Long-term scenarios and strategies for the deployment of renewable energies in Germany	Pregger, Thomas Nitsch, Joachim Naegler, Tobias	2013	Germany	Scientific Paper
25	ENERGY SECURITY of CHINA, INDIA, the E.U. And the U.S. And LONG-TERM SCENARIOS: RESULTS from SIX IAMs	Jewell, Jessica Cherp, Aleh Vinichenko, Vadim Bauer, Nico Kober, T. O.M. McCollum, David Van Vuuren, Detlef P. Van Der Zwaan, B. O.B.	2013	China, India, EU, USA	Scientific Paper
26	Analysis of Japan's long-term energy outlook considering massive deployment of variable renewable energy under nuclear energy scenario	Komiyama, Ryoichi Fujii, Yasumasa	2015	Japan	Scientific Paper
27	Modeling the Greek energy system: Scenarios of clean energy use and their implications	Roinioti, Argiro Koroneos, Christopher Wangensteen, Ivar	2012	Greece	Scientific Paper
28	The long-term forecast of Taiwan's energy supply and demand: LEAP model application	Huang, Yophy Bor, Yunchang Jeffrey Peng, Chieh Yu	2011	Taiwan	Scientific Paper
29	Development a scenario-based model for Iran's energy future	Bahrami, Mohsen Abbaszadeh, Payam	2016	Iran	Scientific Paper

VARIABLE NOTATION IN EXCEL (EXEMPLARY)



Resource	Variable Count	*Governance (G)*										
		GG1 Strive for energy independence and self-sufficiency	GG2 Implementation of national support mechanisms (Localization)	GG3 Financial incentives towards RE	GG4 Existing energy infrastructure	GG5 Focus on energy security	GG6 Short sighted policies and reluctance to deviate from current path	GG7 Global consensus on climate change	GG8 Binding emission target for developed nations	GG9 Fund Renewable Energy R&D	GG10 Opposition against nuclear power	GG11 Homogenous regulatory framework
15	16	X	X									
3	22			X								
2	9			O	X							
7	45	O	O	O	O	X	X	X	X	X		
16	18			O	O						X	
17	13	O			O							
20	28	O	O	O	O	O	O	O		O	O	X
11	16	O	O		O							
1	73	O	O	O	O	O	O			O		
19	15	O			O	O						
28	21			O		O					O	
27	17		O		O	O						
23	22	O	O	O	O	O	O				O	
Total	**315**	**8**	**7**	**8**	**10**	**7**	**4**	**2**	**1**	**3**	**4**	**1**

R SCRIPT TO CALCULATE MULTIPLE CORRESPONDENCE ANALYSIS (MCA) PLOT

```r
require("FactoMineR")
require("factoextra")

data <- read.csv(file.path("~/Downloads", "en_variables.csv"),
                 sep = ";", stringsAsFactors = FALSE)
rownames(data) <- c("15", "3", "2", "7", "16", "17", "20",
                    "11", "1", "19", "28", "27", "23")

res <- MCA(data)
print(res)
fviz_mca_var(res, repel = TRUE, col.var = "black")
```

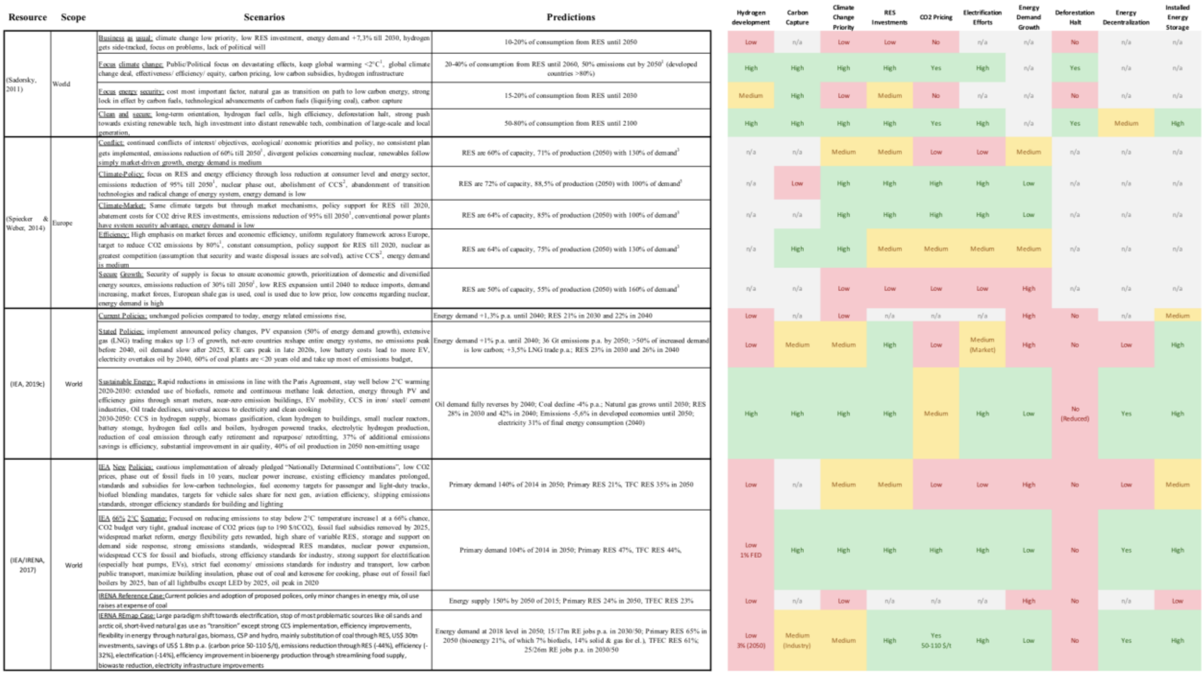
AGGREGATED LIST OF VARIABLES AND THEIR FREQUENCIES

Governance	GG1 Strive for energy independence and self-sufficiency	8
	GG2 Implementation of national support mechanisms (Localization)	7
	GG3 Financial incentives towards RE	8
	GG4 Existing energy infrastructure	10
	GG5 Focus on energy security	7
	GG6 Short sighted policies and reluctance to deviate from current path	4
	GG7 Global consensus on climate change	2
	GG8 Binding emission target for developed nations	1
	GG9 Fund Renewable Energy R&D	3
	GG10 Opposition against nuclear power	4
	GG11 Homogenous regulatory framework	1
	GG12 Viable solution for nuclear waste available	1
	GG13 Switch from domestic gas heat pumps to electric or hydrogen	3
	GG14 Infrastructure change dictated by longevity of existing	1
	GG15 Early retirement/ reduction of coal-fired power-plants	3
	GG16 Better and more extensive recycling of materials	1
	GG17 Push technologies to develop technological leadership	1
Technical	TT1 Push for electrification	5
	TT2 Electrical storage installations and storage cost	5
	TT3 Efficiency improvement in energy, buildings and material production	10
	TT4 Shifting from thermal to electric energy	1
	TT5 Intermittency of RE and network stability	5
	TT6 Carbon Capture and Storage (CCS)	5
	TT7 Next generation fuel cells	4

	TT8 Hydrogen economy	5
	TT9 Unconventional O&G technology becoming feasible	3
	TT10 Hydrogen or Biofuels widely used as transport fuel	3
	TT11 Technological learning	4
	TT12 Increase coal efficiency	2
	TT13 Increase biofuel production	6
	TT14 Existing or close to existing RE tech needs to be put to work	2
	TT15 Investment into new breakthrough technology (algae, advanced solar, etc)	3
	TT16 Natural gas as transition fuel	4
	TT17 Wind energy expansion	9
	TT18 Importance of hydroelectric power (conventional and pumped)	4
	TT19 Vehicle to grid charging	2
	TT20 Electrification of mobility	5
	TT21 Energy from waste (MSW, used cooking oil, etc)	3
	TT22 Solar thermal installation on home rooftops	4
	TT23 Use of grass and rape seed as energy crop	1
	TT24 Cogeneration Heat and Power (CHP) units	3
	TT25 Distributed energy storage systems	2
	TT26 Retrofitting buildings for efficiency	3
	TT27 Redesign of mobility systems	1
	TT28 Liquified Natural Gas (LNG)	2
	TT29 Development of digitalization trend	1
	TT30 Demand Side Response (DSR)	2
Economic	EE1 High competitiveness in RE due to de-regulation	4
	EE2 High investment costs of RE	4
	EE3 High cost of electricity production	3
	EE4 Lack of economic dynamism	1
	EE5 Availability of fossil fuels	5
	EE6 Peak Oil Theory	3
	EE7 Oil production increase	3
	EE8 Reform of carbon trading systems	3
	EE9 Economic liberalization	3
	EE10 High oil price	3
	EE11 Decreasing RE cost	3
	EE12 GDP Growth	7
	EE13 Carbon Pricing	5
	EE14 Aviation industry escaping fossil fuels	3
	EE15 Transportation cost of fossil fuels	2
	EE16 Interest rates	1
Social	SS1 Lack of local structures to implement reforms	2
	SS2 Lack of qualified workers and high unemployment	1
	SS3 Perception with regard to RES	4
	SS4 Population growth	6
	SS5 Energy demand development	9
	SS6 Reduce travel distances	1
	SS7 Job retraining programs	2
	SS8 Use of public transport	2
	SS9 Use of cooling devices	3
	SS10 Public acceptance of a lifestyle change	2
	SS11 Number of passenger cars increase	2
	SS12 Rising ownership of personal electronics	1
	SS13 Access to clean cooking	1
	SS14 Emission related health issues/ deaths	1
	SS15 Popularity of SUV cars	1
Environmental	VV1 GHG emissions reduction	13
	VV2 Potential weather hazards	4
	VV3 Regional remoteness	3
	VV4 Actions on environmental protection	2
	VV5 Uncertainty of environmental effects	2
	VV6 Awareness of environmental concerns	4
	VV7 Lack of commitment for environmental improvement	4
	VV8 Sense of urgency towards environmental issues	4
	VV9 Deforestation halt/ decrease	2

	VV10 Low carbon energy infrastructure becomes its own goal	6
	VV11 Use of forestry biomass	1
	VV12 Average sunshine hours per year	3
	VV13 Wind load hours	2

INITIAL RESEARCH



Resource	Scope	Scenarios	Predictions	Hydrogen development	Carbon Capture	Climate Change Priority	RES Investments	CO2 Pricing	Electrification Efforts	Energy Demand Growth	Deforestation Halt	Energy Decentralization	Installed Energy Storage
(Sadorsky, 2011)	World	Business as usual: climate change low priority, low RES investment, energy demand +7,3% till 2030, hydrogen gets side-tracked, focus on problems, lack of political will	10-20% of consumption from RES until 2050	Low	n/a	Low	Low	No	n/a	n/a	No	n/a	n/a
		Focus climate change: Public/Political focus on devastating effects, keep global warming <2°C[1], global climate change deal, effectiveness/ efficiency/ equity, carbon pricing, low carbon subsidies, hydrogen infrastructure	20-40% of consumption from RES until 2060, 50% emissions cut by 2050[1] (developed countries >80%)	High	High	High	High	Yes	High	n/a	Yes	n/a	n/a
		Focus energy security: cost most important factor, natural gas as transition on path to low carbon energy, strong lock in effect by carbon fuels, technological advancements of carbon fuels (liquifying coal), carbon capture	15-20% of consumption from RES until 2030	Medium	High	Low	Medium	No	n/a	n/a	No	n/a	n/a
		Clean and secure: long-term orientation, hydrogen fuel cells, high efficiency, deforestation halt, strong push towards existing renewable tech, high investment into distant renewable tech, combination of large-scale and local generation,	50-80% of consumption from RES until 2100	High	High	High	High	Yes	High	n/a	Yes	Medium	High
(Spiecker & Weber, 2014)	Europe	Conflict: continued conflicts of interest/ objectives, ecological/ economic priorities and policy, no consistent plan gets implemented, emissions reduction of 60% till 2050[1], divergent policies concerning nuclear, renewables follow simply market-driven growth, energy demand is medium	RES are 60% of capacity, 71% of production (2050) with 130% of demand[3]	n/a	n/a	Medium	Medium	Low	Low	Medium	n/a	n/a	n/a
		Climate-Policy: focus on RES and energy efficiency through loss reduction at consumer level and energy sector, emissions reduction of 95% till 2050[1], nuclear phase out, abolishment of CCS[2], abandonment of transition technologies and radical change of energy system, energy demand is low	RES are 72% of capacity, 88,5% of production (2050) with 100% of demand[3]	n/a	Low	High	High	High	High	Low	n/a	n/a	n/a
		Climate-Market: Same climate targets but through market mechanisms, policy support for RES till 2020, abatement costs for CO2 drive RES investments, emissions reduction of 95% till 2050[1], conventional power plants have system security advantage, energy demand is low	RES are 64% of capacity, 85% of production (2050) with 100% of demand[3]	n/a	n/a	High	High	High	High	Low	n/a	n/a	n/a
		Efficiency: High emphasis on market forces and economic efficiency, uniform regulatory framework across Europe, target to reduce CO2 emissions by 80%[1], constant consumption, policy support for RES till 2020, nuclear as greatest competition (assumption that security and waste disposal issues are solved), active CCS[2], energy demand is medium	RES are 64% of capacity, 75% of production (2050) with 130% of demand[3]	n/a	High	High	Medium	Medium	Medium	Medium	n/a	n/a	n/a
		Secure Growth: Security of supply is focus to ensure economic growth, prioritization of domestic and diversified energy sources, emissions reduction of 30% till 2050[1], low RES expansion until 2040 to reduce imports, demand increasing, market forces, European shale gas is used, coal is used due to low price, low concerns regarding nuclear, energy demand is high	RES are 50% of capacity, 55% of production (2050) with 160% of demand[3]	n/a	n/a	Low	Low	Low	Low	High	n/a	n/a	n/a
(IEA, 2019c)	World	Current Policies: unchanged policies compared to today, energy related emissions rise,	Energy demand +1,3% p.a. until 2040; RES 21% in 2030 and 22% in 2040	Low	n/a	Low	n/a	n/a	n/a	High	No	n/a	Medium
		Stated Policies: implement announced policy changes, PV expansion (50% of energy demand growth), extensive gas (LNG) trading makes up 1/3 of growth, net-zero countries reshape entire energy systems, no emissions peak before 2040, oil demand slow after 2025, ICE cars peak in late 2020s, low battery costs lead to more EV, electricity overtakes oil by 2040, 60% of coal plants are <20 years old and take up most of emissions budget,	Energy demand +1% p.a. until 2040; 36 Gt emissions p.a. by 2050; >50% of increased demand is low carbon; +3,5% LNG trade p.a.; RES 23% in 2030 and 26% in 2040	Low	Medium	Medium	High	Low	Medium (Market)	High	No	Low	High
		Sustainable Energy: Rapid reductions in emissions in line with the Paris Agreement, stay well below 2°C warming 2020-2030: extended use of biofuels, remote and continuous methane leak detection, energy through PV and efficiency gains through smart meters, near-zero emission buildings, EV mobility, CCS in iron/ steel/ cement industries, Oil trade declines, universal access to electricity and clean cooking 2030-2050: CCS in hydrogen supply, biomass gasification, clean hydrogen to buildings, small nuclear reactors, battery storage, hydrogen fuel cells and boilers, hydrogen powered trucks, electrolytic hydrogen production, reduction of coal emission through early retirement and repurpose/ retrofitting, 37% of additional emissions savings is efficiency, substantial improvement in air quality, 40% of oil production in 2050 non-emitting usage	Oil demand fully reverses by 2040; Coal decline -4% p.a.; Natural gas grows until 2030; RES 28% in 2030 and 42% in 2040; Emissions -5,6% in developed economies until 2050; electricity 31% of final energy consumption (2040)	High	High	High	High	Medium	High	Low	No (Reduced)	Yes	High
(IEA/IRENA, 2017)	World	IEA New Policies: cautious implementation of already pledged "Nationally Determined Contributions", low CO2 prices, phase out of fossil fuels in 10 years, nuclear power increase, existing efficiency mandates prolonged, standards and subsidies for low-carbon technologies, fuel economy targets for passenger and light-duty trucks, biofuel blending mandates, targets for vehicle sales share for next gen, aviation efficiency, shipping emissions standards, stronger efficiency standards for building and lighting	Primary demand 140% of 2014 in 2050; Primary RES 21%, TFC RES 35% in 2050	Low	n/a	Medium	Medium	Low	Low	High	No	Low	Medium
		IEA 66% 2°C Scenario: Focused on reducing emissions to stay below 2°C temperature increase1 at a 66% chance, CO2 budget very tight, gradual increase of CO2 prices (up to 190 \$/tCO2), fossil fuel subsidies removed by 2025, widespread market reform, energy flexibility gets rewarded, high share of variable RES, storage and support on demand side response, strong emissions standards, widespread RES mandates, nuclear power expansion, widespread CCS for fossil and biofuels, strong efficiency standards for industry, strong support for electrification (especially heat pumps, EVs), strict fuel economy/ emissions standards for industry and transport, low carbon public transport, maximize building insulation, phase out of coal and kerosene for cooking, phase out of fossil fuel boilers by 2025, ban of all lightbulbs except LED by 2025, oil peak in 2020	Primary demand 104% of 2014 in 2050; Primary RES 47%, TFC RES 44%,	Low 1% FED	High	High	High	High	High	Low	No	Yes	High
		IRENA Reference Case: Current policies and adoption of proposed polices, only minor changes in energy mix, oil use raises at expense of coal	Energy supply 150% by 2050 of 2015; Primary RES 24% in 2050, TFEC RES 23%	Low	n/a	Low	n/a	n/a	n/a	High	No	n/a	Low
		IERNA REmap Case: Large paradigm shift towards electrification, stop of most problematic sources like oil sands and arctic oil, short-lived natural gas use as "transition" except strong CCS implementation, efficiency improvements, flexibility in energy through natural gas, biomass, CSP and hydro, mainly substitution of coal through RES, US\$ 30tn investments, savings of US\$ 1.8tn p.a. (carbon price 50-110 \$/t), emissions reduction through RES (-44%), efficiency (-32%), electrification (-14%), efficiency improvement in bioenergy production through streamlining food supply, biowaste reduction, electricity infrastructure improvements	Energy demand at 2018 level in 2050; 15/17m RE jobs p.a. in 2030/50; Primary RES 65% in 2050 (bioenergy 21%, of which 7% biofuels, 14% solid & gas for el.), TFEC RES 61%; 25/26m RE jobs p.a. in 2030/50	Low 3% (2050)	Medium (Industry)	Medium	High	Yes 50-110 \$/t	High	Low	No	Yes	High

[1] Compared with 1990 levels

[2] Carbon Capture and Sequestration

[3] Compared to 2010

[4] Includes nuclear, hydro, bioenergy, other renewables and fossil fuel use with CCS

TFC = Total Final Consumption