SUSTAINABILITY ASPECTS ON NUCLEAR POWER

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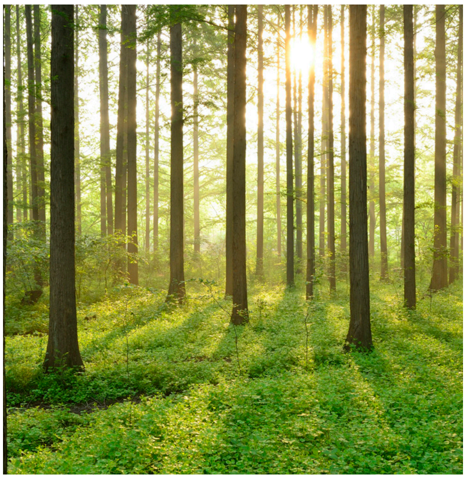

NUCLEAR

Energiforsk

Sustainability aspects on nuclear power

- A literature survey

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Preface

Sustainability can be considered from different aspects, like environmental, economic and social. To increase the complexity even further, different stakeholders add their own views and perceptions, when interpreting if nuclear is sustainable or not.

In the wake of increasing awareness of climate change, nuclear power has recently regained interest in the political debate and in the media as a potentially necessary means to mitigate climate change. But what does science say about that? Is there any scientific consensus on this topic and how do scientists view the possibilities of nuclear power to contribute to a sustainable energy system and to climate mitigation? Energiforsk Nuclear Portfolio initiated a literature survey and analysis to elaborate on the subject. The project was carried out by senior researchers from Profu during spring 2019, in collaboration with Energiforsk R&D program North European Power Perspectives, NEPP.

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Sammanfattning

I denna litteraturstudie har vi belyst frågan hur forskarvärlden idag ser på kopplingen mellan kärnkraft och hållbara energisystem. På samma sätt som i samhället i övrigt så visar det sig att synen på kärnkraft inom forskarkretsar är delad.

Det finns omkring 450 kärnkraftsreaktorer i drift i världen idag. Sedan den globala utbyggnadsboomen avstannade i slutet av 1980-talet har antalet reaktorer i drift ökat långsamt till dagens nivå. Ytterligare omkring 50 nya reaktorer är under byggnation, de allra flesta i Asien med Kina som framträdande exempel. I andra delar av världen, som exempelvis i Europa, har elproduktionen från kärnkraft istället långsamt minskat sedan tidigt 2000-tal. Några länder har även aviserat en fullständig avveckling med Tyskland som det kanske mest omtalade exemplet. Samtidigt har klimatfrågan stadigt ökat i betydelse och kärnkraft, såväl ny som livstidsförlängning av befintliga reaktorer, omnämns med ökad frekvens som en viktig pusselbit mot ett klimatneutralt energisystem i media och från vissa håll i den politiska debatten. Frågan är då vilken syn som forskarvärlden har på kärnkraft och dess plats inte bara i ett klimatneutralt energisystem utan även i utvecklingen mot ett hållbart energisystem. Hållbarhetsbegreppet är i sig komplext med olika definitioner, men generellt omfattar hållbarhet flera aspekter vid sidan om klimatneutralitet, såsom social och ekonomisk hållbarhet samt andra miljöaspekter.

I vår litteraturstudie, som omfattar främst forskningsartiklar från olika håll i världen, har vi inte funnit någon tydlig konsensus inom forskarkretsar med avseende på kärnkraftens roll i ett uthålligt (eller klimatneutralt) energisystem. På samma sätt som i debatten inom media, bland allmänheten och inom politiken så finns det ett polariserande element även inom forskarvärlden, vilket kanske inte är förvånande. Dels är frågeställningen med avseende på hållbara energisystem oerhört komplex, dels speglar forskarvärlden samhället i övrigt. Bland de mer tongivande forskarna har vi funnit ett relativt litet antal som tydligt tar ställning i frågan, såväl ”för” som ”emot”. Det stora flertalet av de forskningsartiklar som vi granskat och som tar upp frågeställningen väljer en mer balanserad och försiktigare hållning. Man berör därmed såväl de positiva egenskaperna och nyttorna som kärnkraft bidrar med men man diskuterar också de, ofta välkända, problembilder och utmaningar som är förknippade med kärnkraft. Generellt (men det finns undantag) betraktar forskarvärlden idag kärnkraft som ett potentiellt verkningsfullt energislag, på väg mot ett klimatneutralt energisystem. Samtidigt understryker dock flertalet forskare som intar en mer neutral ställning att kärnkraftindustrin måste komma till rätta med ett antal viktiga stötestenar om man fullt ut vill ta plats i ett hållbart energisystem. Sådana utmaningar berör bland annat acceptansfrågan, där allmänhetens förtroende för såväl kärnkraftbranschen som tillsynsmyndigheter pekas ut som särskilt viktig, samt de omfattande ekonomiska utmaningar som idag kännetecknar investeringar i kärnkraft i västvärlden.

För att ytterligare belysa frågeställningen har vi i vår litteraturstudie även granskat ett stort antal publikationer som inte publicerats i vetenskapliga tidskrifter. Det omfattar bland annat rapporter från olika mellanstatliga institutioner och organisationer (International Energy Agency (IEA), Intergovernmental Panel on Climate Change (IPCC), Nuclear Energy Agency (NEA), International Atomic Energy Agency (IAEA), EU-kommissionen med flera), från kärnkraftsbranschen (exempelvis World Nuclear Association, WNA), från icke-statliga organisationer (Naturskyddsföreningen (SNF), Greenpeace med flera) men även diverse tidskriftsartiklar i såväl dagspress som facktidskrifter. Baserat på flera av dessa källor har vi även valt att redogöra för ett urval av olika scenarioanalyser som beskriver utvecklingen för energisystemen mot typiskt 2050, och vilken roll kärnkraft får i dessa scenarier. Scenarioanalyserna omfattar såväl globala som regionala systemgränser. Även här är bilden mångfacetterad vilket inte minst beror på att scenarioanalyserna skiljer sig åt med avseende på viktiga beräkningsförutsättningar såsom energibehovsutveckling, tillgång till olika energiresurser, politik samt teknikutveckling för såväl kärnkraft som alternativa energislag. Även om det finns exempel på scenariostudier som pekar på möjligheten att nå klimatmålen globalt, helt utan kärnkraft eller med endast mycket marginellt bidrag från densamma, så finns det relativt många scenariostudier som indikerar att ett mål om att begränsa den globala uppvärmningen till ”klart under två grader” blir mycket svårt att möta utan en utbyggnad av kärnkraft. Gemensamt för alla dessa scenariostudier är dock att kärnkraft inte blir ett dominerade inslag i den framtida energimixen, globalt sett. Den överlägset största tillväxten antas istället ske inom förnybar energi.

Summary

In this literature review, we examine how the academic world views the link between nuclear power and sustainable energy systems. It turns out that researchers are divided on this issue, much like the society in general.

There are around 450 nuclear reactors in operation today, most of them built during the production boom of the 1980s. Another 50 reactors are under construction, primarily in Asia, with China leading the way. In other parts of the world, like Europe, electricity production from nuclear has instead slowly decreased since the early 2000s. Some countries have announced a complete phase-out of nuclear power, the most well-known example being Germany. As the issue of climate change gains more prominence, nuclear power (new construction as well as upgrade of old reactors) is increasingly mentioned in the media and by some politicians as having an important part to play in a future, sustainable energy system. The question is then how the academic world views nuclear power, not just as part of a climate-mitigation strategy but also as part of the transition towards a sustainable energy system. The term 'sustainable' is a complex term with varying definitions but generally encompasses several aspects besides climate mitigation, such as social and economic sustainability as well as other environmental aspects.

In our review of mainly scientific papers, we do not find a clear consensus among researchers regarding nuclear power's role in a sustainable energy system. There is polarization in the academic world, just as there is in the media, among the public and among politicians, which, perhaps, is not surprising. This polarization may be partly explained by the complexity of the issue of sustainable energy systems and partly due to the fact that the academic world reflects the society in general. We find that relatively few leading researchers take a clear stance 'for' or 'against' nuclear power. Most articles that we reviewed reflect instead a more balanced position on the matter of nuclear power and sustainability. Such views acknowledge the positive aspects and benefits of nuclear power but also consider the often-well-known issues and challenges. The overall view of researchers (with some exceptions) is that nuclear power is a potentially effective climate-mitigation measure. However, several researches point out that the nuclear industry must overcome important challenges in order to fully be part of a sustainable energy system. Such challenges include the issue of acceptance, including the public's trust in both the nuclear industry and in the regulation authorities, as well as the considerable economic challenges that characterize today's investments in nuclear power in the Western world.

To broaden the view on these issues, we have also reviewed publications that have not been published in peer-reviewed journals. These include reports published by intergovernmental institutions (International Energy Agency (IEA), Intergovernmental Panel on Climate Change (IPCC), Nuclear Energy Agency (NEA), International Atomic Energy Agency (IAEA), the EU-commission and others), the nuclear industry (World Nuclear Association, WNA), NGOs (Swedish

Society for Nature Conservation (SNF), Greenpeace and others) and articles published in professional magazines and in the daily press. We highlight several scenarios based on these sources that show how the energy system might develop typically by year 2050 and what the role of nuclear power might be. The scenarios include both global and regional system boundaries. The possible outcomes vary significantly, depending on some important assumptions, such as the development of energy demand, availability of different resources, technical development for both nuclear and other energy sources as well as the influence of different policies. While there are some scenarios that show that climate goals can be reached with little or no contribution from nuclear power, a significant number of scenarios indicate that reaching a ‘well below two degrees’ goal will be very difficult without the contribution from nuclear power. Common to all scenarios that we have looked into is, however, that nuclear power will not dominate the future global energy mix. The greatest growth is instead expected to take place in renewable energy.

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1 Introduction

This report presents a meta study of the literature regarding the link between nuclear power, sustainable energy systems and climate change-mitigation. The rationale for this study is the (perceived) recent increase in interest in nuclear power as a potential key to climate change-mitigation policy. As we will see in this report, the views on this matter are widely divergent. The call for a nuclear dawn or a "nuclear renaissance" has been recently presented (again) in the media and in the public debate, as concern for climate change is growing across the world (see e.g. TIME Magazine, 2019; The National Interest, 2018; DN, 2018; ars TECHNICA, 2018). A core question for this study has been to evaluate whether such "renewed" interest also applies to the scientific community and whether scientific findings on this subject have been impacted by the increasing concern for climate change. The term "nuclear renaissance" emerged around the turn of the millennium when nuclear power gained interest as a climate-change mitigation option and as a means of increased security of energy supply (Diaz-Maurin & Kvacic, 2015).

Nuclear power has been around as an energy source for approximately 70 years and has been subject to controversy during most of that time. As aptly pointed out by Kermisch & Taebi (2017), "*There is probably no other energy technology that could give rise to controversy as much and for as long as nuclear technology*". *Or as Cottrell (2017) puts it: "the development of nuclear power has the potential both to enhance and to threaten national and global security. This paradox is reflected in policy debates surrounding nuclear security and climate change*".

1.1 OBJECTIVE

The objective of this study is to assess and report on the different views and arguments presented by a large number of authors, scientists and others, relating to the topic on nuclear power, sustainable energy systems and climate change-mitigation. We aim to present a broad perspective and an updated view on how nuclear power and its position in a sustainable energy system is presented in the literature. In our literature survey, we have included peer-reviewed papers, conference papers, positions papers, scientific reports, books and articles in science magazines and newspapers written by scientists, NGOs, authorities, international organisations and institutes and the nuclear industry. We have also included several well-known scenario analyses of the development of the energy systems at different regional levels in order to reflect what such studies reveal about the future role of nuclear power.

1.2 IMPORTANT CONSIDERATIONS

We wish to emphasize that we in this report reflect what other authors and sources have found, believe, or seem to believe on the topic of nuclear power and sustainability. In doing so, we have included many key issues, which are typically discussed in relation to nuclear power. For each key issue, we have presented how different authors and sources position themselves and their corresponding arguments. Since our aim is to present a broad picture, we have included sources that express clear anti-nuclear views as well as those expressing clear pro-nuclear views. It is a fact that nuclear power polarizes not only the public, politicians and media but also the scientific community. This means that some of the findings and claims mentioned in our report might be rejected by certain readers, depending on what position the reader has in relation to the polarized world of nuclear power. But these claims, or findings, are nevertheless reported on in either peer-reviewed scientific papers or other well-known and widespread channels which is why we have chosen to include them in this report. Our task is not to judge or to criticize the authors mentioned in this report but instead to present the great variety of (recent) arguments and beliefs that are present in the scientific community. Consequently, we have not checked if any errors, mistakes or deliberately biased reporting has occurred. Such scrutiny is beyond the scope of this report. Even though the subject is polarized, most of the (scientific) literature included in our survey seems to aim at objective and well-balanced discussions and assessments.

Furthermore, in terms of climate change, we only look at the issue of climate change-*mitigation* and not at climate change-*adaptation*, i.e. how nuclear power (and other sources of useful energy) is itself affected by climate change and what that may say about the robustness of different electricity-generation technologies. Adapting nuclear power and other supply means to climate change may also become a crucial issue as part of a final assessment (see e.g. Kopytko & Perkins, 2011) but is not dealt with in our study. This subject may, however, be subject to further work.

There are additional considerations and demarcations that we have applied to our literature survey in order to keep the work at a practical and reasonable level. Such considerations are reported in Chapter 3.

1.3 OUTLINE OF THIS REPORT

The report is outlined as follows: in the succeeding Chapter 2, we present an overview of the concept of sustainability which is followed by a method overview of our literature survey (Chapter 3). In Chapter 4, we report on the current status of nuclear power and a selection of scenarios for its role in future electricity supply at different regional levels, as reported by a number of relatively well-known scenario studies. In Chapter 5, we present what the literature has to say about the environmental, economic and social sustainability aspects on nuclear power. For each of these three dimensions, we list a number of key issues that are generally discussed in relation to nuclear power. These key issues include fuel availability, greenhouse-gas (GHG) emissions, risk of accidents, nuclear waste, economics of nuclear power and others. For each of these issues, we present some of the views taken by selected authors that we have found in reports. In Chapter 6, we present a final assessment of a selection of the literature included in our survey. The purpose is to qualitatively assess how the authors of that selection of scientific papers position themselves towards our two core questions: is nuclear power part of a sustainable energy system, and/or is nuclear power part of a climate change-mitigation solution? We have limited the number of papers in that assessment according to relevance and quality. In Chapter 7, we try to wrap things up by some final reflections and short discussions. Finally, Chapter 8 contains our reference list. In the Appendix we include those papers subject to the assessment in Chapter 6. Thus, literature sources in Chapter 8 (References) and in the Appendix together cover, with a certain overlap, all the literature that we have, in one way or another, used in this study.

2 The concept of sustainability – definitions

According to the Cambridge Dictionary, the word 'sustainability' means "*the quality of being able to continue over a period of time*", or in an environmental context (from the same source): "*the quality of causing little or no damage to the environment and therefore able to continue for a long time*".

The term or concept of 'sustainable development' is therefore rather contradictory in itself, since the word 'development' implicates progress and change as well as growth and *becoming more advanced*. In this chapter we try to give an overview of different definitions of the concept of *sustainability*, or rather the concept of *sustainable development*. We aim to comment on the concept itself, to discuss the possible interpretations of the definitions mentioned above as well as to show implications when trying to assess and discuss sustainability aspects in general and, in the context of this report, on nuclear power in particular.

2.1 HISTORY OF THE CONCEPT OF SUSTAINABLE DEVELOPMENT

The history of the concept of sustainability and sustainable development is closely linked to the growing concern over the status of the environment in the 1960s and 1970s. Building upon earlier works and discussions (such as Rachel Carson's *Silent Spring* from 1962 and the Club of Rome's report *Limits to Growth* from 1972), the concept of *sustainable development* was first used officially in the UN World Commission on Environment and Development commissioned in 1987.

The commission, which was led by Gro Harlem Brundtland (therefore more often called the Brundtland commission), defines sustainable development in its final report "Our Common Future" (WCED, 1987) as:

"*… development that meets the needs of the present without compromising the needs of future generations to meet their own needs.*"

Later work on sustainability and on the concept of sustainable development, such as for example *A Strategy for Sustainable Living* from 1991, which was a joint effort by the International Union for Conservation of Nature (IUCN), United Nations Environment Programme (UNEP) and World Wildlife Fund (WWF) (*Caring for the Earth*), pointed to the importance of "*improving the quality of human life whilst living within the carrying capacity of the ecosystems*". That report also stated that *sustainable use* can only be applicable to renewable resources.

Since the Brundtland Commission, the UN has continued its work on the principles of sustainable development. In the Earth Summit of 1992 in Rio de Janeiro the *Agenda 21* was adopted, which became the basis for working with sustainable development in general in many countries and regions. It was also at this summit that both the Climate Convention as well as the Biodiversity Convention were formed and adopted. In 2000, came the so-called *Millennium Development Goals* (MDGs), including eight targets that were to be reached before 2015. Following this, in 2012 work began to form new goals that would succeed the MDGs after 2015. Building upon both the MDGs and the work of Agenda 21, *The*

Agenda 2030 for Sustainable Development was finally adopted by all UN member states in 2015. This agenda encompasses 17 Sustainable Development Goals (SDGs), see Figure 1.

The agenda's main purpose is to "*recognise that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth – all while tackling climate change and working to preserve our oceans and forests*". This aim has a clear connection to the original definition of sustainable development by the Brundtland Commission.

Figure 1 The UN's 17 Sustainable Development Goals adopted in 2015 as part of the 2030 Development Agenda, titled "Transforming our world: *The 2030 Agenda for Sustainable Development*.

There are many other works with slightly different approaches on the definition of the term, and the concept, of sustainable development. One example is the work made by John Holmberg and Karl-Henrik Robért (Holmberg et al., 1996). They set up four principles for sustainable development, three of which concern how humans can avoid harming the nature. According to Hedenus et al. (2018), one important part of these principles is to identify the basic and systemic mechanisms and processes that have a long-term effect on nature, thereby to indicate the most prioritised actions that need to be taken. A similar approach is the work by Johan Rockström and Stockholm Resilience Centre that together with a large group of internationally renowned researchers, in 2009 proposed the concept of '*planetary boundaries*' to define a "*safe operating space for humanity*" as a precondition for sustainable development. The presented framework, consisting of nine boundaries focusing on different Earth-system processes such as climate change, biodiversity loss and land use, is based on scientific evidence showing that human actions have, since the Industrial Revolution, become the main driver of global environmental change. This work has been updated since then to show the state of the Earth-system as a whole and could therefore give an indication on which systems are most urgent to focus on. Thus, this could be used as a tool for assessing the sustainability of larger systems.

2.2 THREE DIMENSIONS OF SUSTAINABLE DEVELOPMENT

The concept of sustainable development consists of three fundamental dimensions, sometimes referred to as three pillars supporting the human needs of today and tomorrow. The three-sphere framework is said to have been initially proposed by the economist René Passet in 1979, and it consists of the *environmental (or ecological), the economic* and *the social dimension*.

There are as many ways to illustrate the relationship between these three dimensions as there are definitions of the concept, but a widely used illustration is the three spheres presented in Figure 2. In their book on sustainable development Hedenus et al. (2018) give a thorough presentation of the concept and its three dimensions.

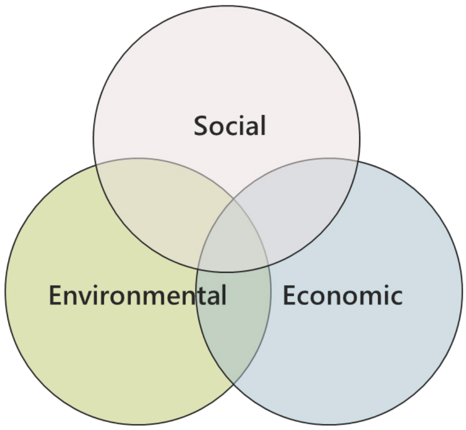


Figure 2: The three-sphered illustration of the three dimensions of sustainable development.

The environmental dimension is about sustaining natural Earth-systems and processes so that they can keep providing humans with important resources. Hedenus et al. (2018) divide this dimension in two parts, namely nature's ability to *produce* (i.e. to yield food and other natural resources that is necessary for human life) and its ability to *assimilate* (i.e. to be able to handle for example different kinds of pollution). In this context, one could also mention the term *resilience*, another rather complex concept to define. Resilience is "*the capacity of a system to deal with change and continue to develop*" and it stems from the belief that humans and nature are strongly coupled. The term is central to the work of planetary boundaries previously mentioned and could as such also be interpreted as a being a vital part of the environmental dimension of sustainable development.

The economic dimension is first and foremost about finding an efficient way to handle economic resources (both finite natural resources and manmade capital) in order to meet and maintain the needs of humans as well as balancing the needs of today's and future generations (Hedenus et al. 2018). As described in Kermisch &

Taebi (2017), economic viability of a technology depends on several factors such as affordability, predictability of costs in the long-term as well as the dependence of external parameters like geopolitics as well as the availability of future technologies.

The third dimension, i.e. the social dimension, has been subjected to greater dissonance compared to the other two dimensions of sustainability (Hedenus, et al. 2018). The social dimension is probably the least understood dimension in this context, even though it occupies a profound part in the Brundtland definition. It has been said to include such diverse aspects as equity, health, human rights, community rights, trust and cultural competence. According to Hedenus et al. (2018) one should however regard the social dimension in the same way as the other two, i.e. as prerequisites for being able to meet human needs. Human rights could then rather be seen as means, not prerequisites, to sustainable development. Many researchers within the field also highlight that trust is closely linked to this dimension.

The three dimensions are closely interlinked and as such are highly dependent on each other. The Brundtland commission put its emphasis on the social dimension as forming the basis of sustainable development, but there is often a tendency to give the environmental dimension greater importance when discussing sustainable development, with focus on sustaining natural resources and protecting the environment. However, looking at only one dimension without considering the others is most likely a less viable way of assessing what is sustainable and what is not. Because of its threefold character, the concept of sustainable development is complex and leads to questions that often do not have a single easy and correct answer.

2.3 HOW SHOULD WE INTERPRET THE CONCEPT OF SUSTAINABLE DEVELOPMENT?

Going back to the Brundtland definition of the sustainability concept, some of the many questions that follow are: how human needs should be defined (or rather what should be included in "needs"), if nature has a value in itself or only if nature meets the *needs of the present without compromising the needs of future generations to meet their own needs*[1] and how could we know the needs of future generations?

The Brundtland report clearly states that 'sustainable development' contains two key concepts, namely:

- The concept of "needs", in particular the essential needs of the world's poor, to which overriding priority should be given; and
- The idea of limitations imposed by the state of technology and social organisation on the environment's ability to meet present and future needs.

[1] This *'intergenerational dilemma'* constitutes a profound part of the discussions on sustainability, concerning the question on how to balance equity between generations, i.e. the needs of the humans of today and future generations.

Quoting from the report, these key concepts therefore imply: "*concern for social equity between generations, a concern that must logically be extended to equity within each generation*". As such, one of the general principles laid out in the report is the 'Inter-Generational Equity'-principle: "*States shall conserve and use the environment and natural resources for the benefit of present and future generation*". Interestingly, the report further states that "*the conservation of nature should not rest only with developmental goals. It is part of our moral obligation to other living beings and future generation*". The commission thus implies that we as humans have moral obligations to other organisms on this Earth (i.e. the biosphere) and to future generations (without stating a "time limit" on this moral obligation). Even though the Brundtland report also proposes a general principle of 'Conservation and Sustainable Use', it concludes that, among other things, the member states "*shall observe the principle of optimum sustainable yield in the use of living natural resources and ecosystems*".

Deriving from the original definition of the term 'sustainable development' in the Brundtland Commission, Kermisch & Taebi (2017) suggest that the concept of sustainability can be considered as a moral framework based on social justice. They focus on three key ethical questions, namely:

1. What should be sustained?
2. Why should we sustain it?
3. For whom should we sustain it?

In their article, Kermisch & Taebi (2017) describe how the suggested framework could be used to assess sustainability and to make the *intergenerational dilemma* comprehensible (i.e. how to balance the needs of both present and future generations). The result is a concept of sustainability as a set of values, including safety, security, environmental benevolence, resource durability, and economic viability of a technology, or a set of technologies. The authors' main argument for this approach is to move beyond the use of the term sustainability in a dichotomous sense (i.e. a 'yes' or 'no'), but rather to highlight the fact that a technology might be sustainable with respect to some values, whereas it might be unsustainable with respect to other values and groups that might both be geographically and temporally distant from each other. In this way, the complexities associated with different technological choices are understood and the framework could, according to the authors, facilitate a better and more informed decision-making compared to the dichotomous way of approaching the subject. According to Kermisch & Taebi, the vital message is the following: "*If we leave out the complexity associated with the concept of sustainability, this notion could be easily (mis)used for greenwashing and rhetorical purposes, leading to potential ideological and political manipulation".*

Other authors also highlight the potential pit-falls of leaving out the complexity of the concept of sustainable development, such as expecting a single answer to the question of what is sustainable (and what is not). Prandecki (2014) aptly points to the fact that there is no source of energy or energy technology that is entirely sustainable in the sense of causing no damage to the environment. Grunwald & Rösch (2011) state: "*different technologies could only make more or less large contributions to sustainability – or cause problems"*.

3 Literature survey – method

In this chapter we give a short description of our method for choosing the literature included in the survey.

3.1 MAIN CRITERIAS FOR SELECTING LITERATURE TO BE INCLUDED IN THE ASSESSMENT

In our literature survey, we have included a large amount of different publications with emphasis put on scientific papers in academic journals. Besides scientific papers we have also included reports and text from official bodies such as IEA, IPCC and IAEA, position papers from environmental NGOs (Swedish Society for Nature Conservation SNF, and Greenpeace), reports from the nuclear industry (IAEA, NEA, WNA), scientific books and articles from various (scientific and non-scientific) magazines. For our final assessment on how the literature positions itself to our core question, i.e. whether nuclear power is part of a sustainable energy system and climate change-mitigation, we have limited our survey to scientific papers (most of them peer-reviewed). These papers are listed in the Appendix while other sources used in our study are found in the reference list in Chapter 8. The final assessment of the scientific papers is presented in Chapter 6.

Our literature survey is based on searching through different databases of scientific literature (e.g. ScienceDirect) and searching online for literature containing words such as: *sustainable development, sustainability, climate change* and *nuclear power/energy*. As mentioned, our main focus for the assessment has been on scientific papers published in academic journals. Additional sources were found by studying the reference lists of papers that we had already found.

The search resulted in almost 60 scientific papers, many of which did not include the original search terms. A large part of the academic literature on nuclear power concerns the issue of public perception and acceptance (or not) of the technology. Since this issue is one of the most important aspects when it comes to the viability and possible use of nuclear technology in the long-run, we have chosen to include a number of articles related to this, even though they do not explicitly concern the sustainability concept as such or focus on nuclear power's potential as a climate mitigation option. In general though, our main criteria when selecting scientific papers to be included in the assessment was that they contained one or several of the search terms (mentioned above) either in the title, abstract, or in the subheadings.

In our survey, we mainly focused on articles published ***after*** 2010, with a few exceptions (mainly articles that are often cited within the field). This is due to practical reasons and because our ambition was to reflect mainly recent trends and knowledge. With some exceptions, the articles were written by authors from either Europe, USA or Asia, with their academic fields ranging from engineering and natural sciences to medicine and social sciences.

The majority of articles in our survey were published in the journal Energy Policy. The highest ranked journal included (one article) is Energy & Environmental Science.

Finally, in our assessment of the scientific papers, we also aimed at specifying their main focus, i.e. whether they mainly deal with the environmental, the social or the economic aspects of sustainability on nuclear power, or if the papers aimed at covering all, or at least most aspects, of these three dimensions and their sub-issues.

3.2 BIBLIOMETRICS USED FOR ASSESSING THE SCIENTIFIC PAPERS AND THE AUTHORS INCLUDED IN THE LITERATURE SURVEY

There are different quantitative bibliometrics (or simply *metrics*) that could be used in order to help evaluate research output, i.e. a way to value the quality, diffusion and outreach of the papers. There is a large range of metrics, many with their specific limitations and potential pit-falls, which one should be aware of when using these kind of assessment 'tools'. Since the aim of this report is first and foremost to give a general overview on the views on nuclear power when it comes to sustainability aspects, our intention with using metrics is only to give an illustrative, albeit simplified, overview of the 'scientific weight' of the papers included in the survey.

Despite its many limitations, we have chosen to use Google Scholar for this purpose, mainly because it is a freely accessible web search engine open for anyone to use (in comparison to academic metric databases for which you need a subscription). Google Scholar indexes metadata of academic literature, including most peer-reviewed online academic journals and books, conference papers, theses and dissertations, abstracts, technical reports and other scholarly literature.

3.2.1 Citation count or number of citations of a specific article

One of the most basic kind of metrics is how often an article has been cited in other articles, books or other sources. The number of citations of an article is very much dependent on the scientific discipline and the number of researchers within the field. Different databases include widely different number of sources, and some also include self-citations (e.g. Google Scholar) which distorts the metric. Despite its many potential drawbacks, a basic citation count gives at least a hint of how much attention a specific article has gained (although it says little of its 'real' scientific weight).

In Figure 3, an overview of all our assessed scientific articles and the number of citations per article is shown and in Figure 4 we show the topmost 20 scientific articles from the previous diagram. As guidance for potential factors influencing the high citation numbers, we have inserted some commentaries in Figure 3.

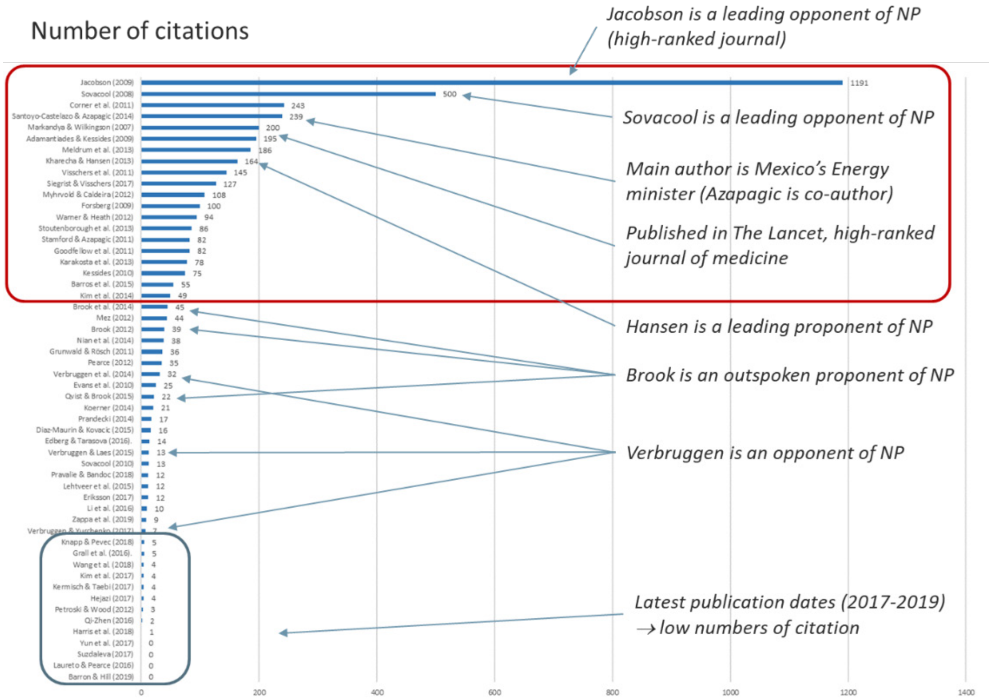


Figure 3: Number of citations of the articles included within the literature survey. The red marking highlights which articles that are shown in Figure 4. The blue marking shows papers with mainly latest publication dates, which can explain low number of citations in comparison to those higher up in the ranking (NP=Nuclear Power)

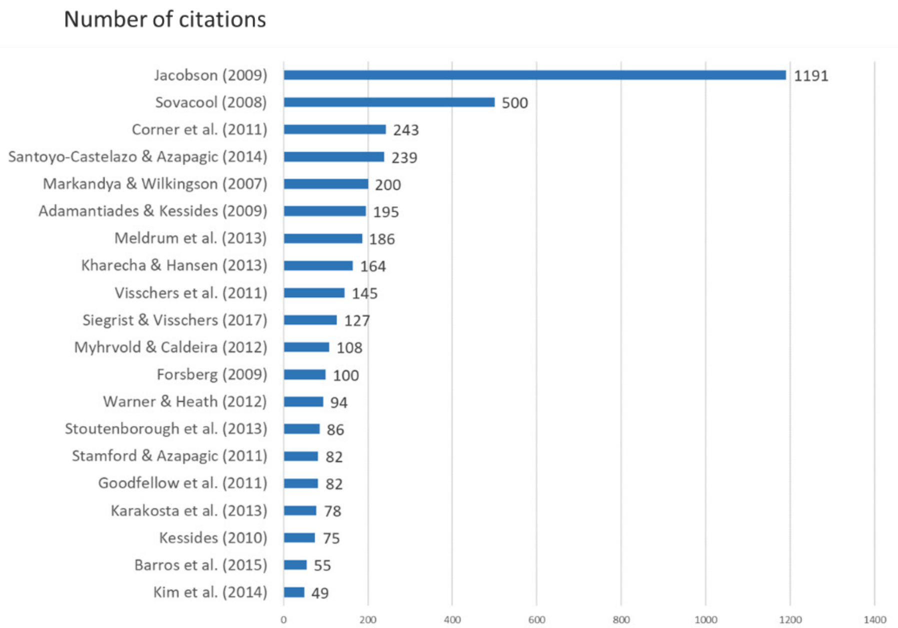


Figure 4: The topmost 20 articles when it comes to number of citations, as shown in Figure 3.

As we will show later in this report, there are some scientists/authors in this particular field that are viewed upon as (more or less) either opponents or proponents of nuclear power. As mentioned before, nuclear power is somewhat of a controversial subject for many and as such is highly influenced by perceptions, emotions and ideology. The fact that some articles have received a high number of citations can therefore be a result of the fact that the author is controversial both within and outside of the scientific field. This potentially has little relevance in terms of the 'real' scientific output or 'weight' of the article as such.

In Figure 3, four leading 'voices' of the 'nuclear power debate' are highlighted. First, there are two well-known proponents of nuclear power, namely James Hansen (formerly at NASA, now at Columbia University) who is a renowned climate-change scientist and Barry Brook, professor of environmental sustainability in Australia. The other two are Mark Jacobson and Benjamin Sovacool, both outspoken opponents of nuclear power. These four authors are often heard in the debate on whether nuclear power is a (desirable) climate change-mitigation option or not. Such debates usually revolve around nuclear opponent's critiques of the proponent's views on nuclear power being a necessary solution to climate change (more on this in chapter 5).

3.2.2 H-index – an author-level metric

When it comes to author-level metrics, the most widely used is the so-called h-index (*Hirsch index*), which attempts to measure both the productivity and citation impact of the publications of a scientist. The index is based on the set of the most cited papers of the scientist together with the number of citations that these cited papers have received in other publications. The h-index is thus intended to simultaneously measure both the quality and quantity of the scientific output from a particular scientist. As an example, an h-index of 10 means that ten of the author's articles have each received at least ten citations. This means that an author with only one published article that has been widely cited still only has an h-index of 1. In order to receive a high h-index, an author must be *both* productive and well-cited in the scientific community. The h-index is not skewed by a single highly cited paper, nor by a number of poorly cited documents.

In Figure 5 we have chosen to 'rank' the authors of the selected scientific papers in our survey which are listed in Google Scholar. We have excluded authors with less than 10 in h-index. We have also included, as comparison, h-indexes, of Albert Einstein and the 2018 Nobel laureate in Chemistry, Frances Arnold.

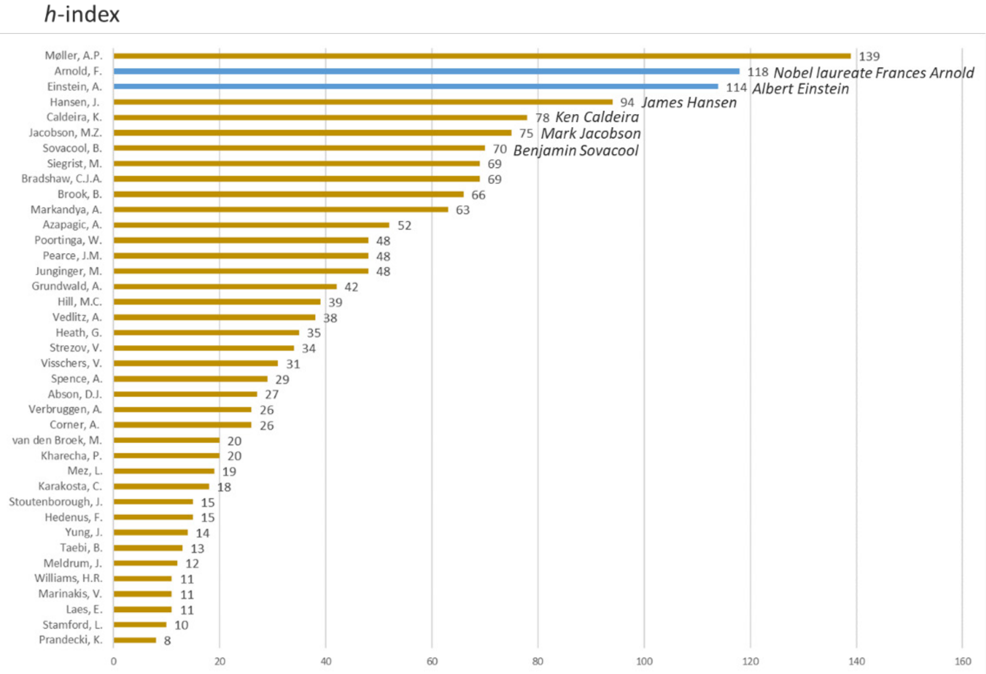


Figure 5 Authors included in the literature survey (which are listed in Google Scholar) ranked by their *h*-index. The blue staples are included as references, showing 2018 Nobel Laureate in Chemistry, Frances Arnold and Albert Einstein. The researcher with the highest h-index in this compilation is Anders P. Møller, a well-known (but somewhat controversial) evolution biologist and a co-author to Gralla et al. (2016). As a commentary, A.P. Møller has collaborated with another biologist, Timothy Mousseau, an outspoken opponent to nuclear power.

3.2.3 Some final remarks on the use of bibliometrics

Our intention with showing the number of citations of the different articles included in the survey along with the h-indexes of some of the main authors is not to conclude which articles or authors are the 'best'. Instead, we use these metrics to give the reader an overview of the included literature, its outreach, and a possible indication of which articles could be of relevance as well as an indication of their scientific value.

4 The role of nuclear power today and projections for the future

4.1 CURRENT STATUS

There are currently 450 nuclear power reactors in operation, corresponding to a total installed capacity of around 400 GW_e, and some 50 reactors under construction (World Nuclear Association, 2019). The age distribution allocated to rated power of the reactors currently in operation is shown in Figure 6. From the figure it is obvious that the majority of the global capacity is currently around 30-40 years old (due to the nuclear capacity boom during the 1980s). Furthermore, no reactor still in operation is older than 50 years (until the end of 2018).

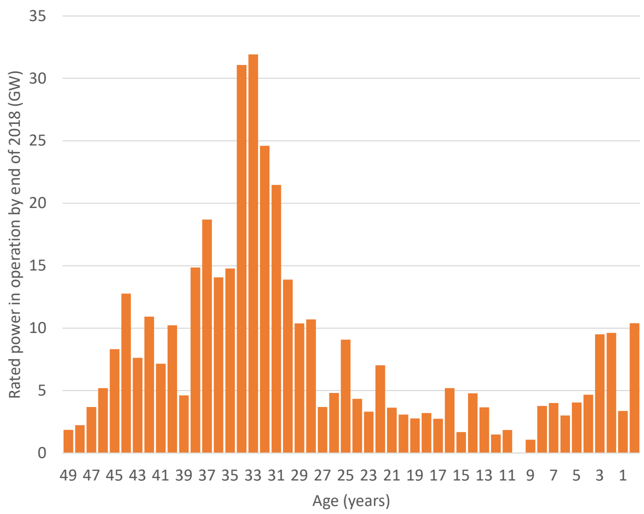


Figure 6: Age distribution of existing nuclear power plants currently in operation (end of 2018). Source: World Nuclear Association

The reactors currently under construction correspond to a total capacity of 54 GW_e. Most of that capacity is built in China (Figure 7). In the EU, there are ongoing projects in France, Slovakia and Finland. All these projects have faced significant cost and time overruns (World Nuclear Association, 2018a). In the UK, the construction of the Hinkley Point C reactor was initiated in late 2018. At the same time, decisions have been taken on a complete phase-out in Germany (by the end of 2022) and in Switzerland (political decision taken not to replace existing reactors with new ones). Decisions to close some of the existing reactors have also been taken in e.g. Sweden, France and the UK. There is, however, no ban on new investments in these countries. A certain interest in new investments is found, besides the UK in several Eastern European countries (World Nuclear Association, 2018a).

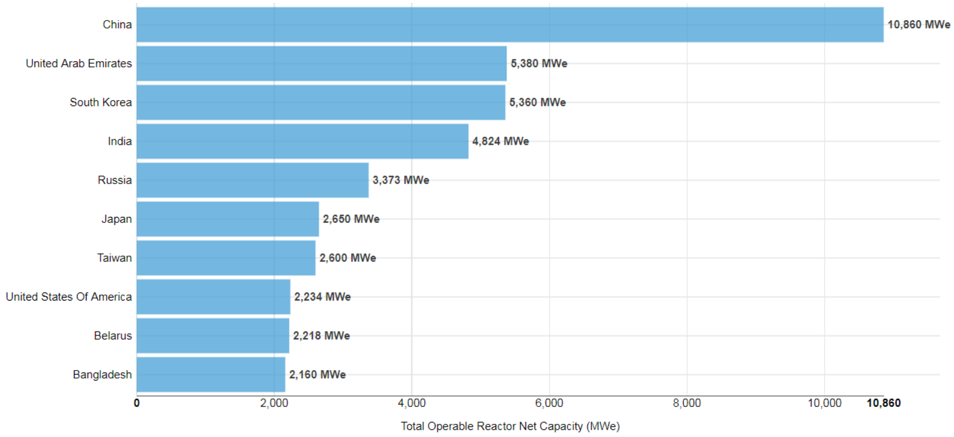


Figure 7: Reactor net capacity under construction in the ten top countries (Source: World Nuclear Association)

Global total electricity generation amounts to approximately 25 000 TWh annually (Figure 8) and the share supplied by nuclear power is around 10 percent. In recent years, the share of nuclear power has declined somewhat. In the EU-28, approximately 3300 TWh of electricity is produced annually, of which nuclear power supplies around 25 percent (Figure 9). Also in the EU-28, the share of nuclear power has declined somewhat during recent years.

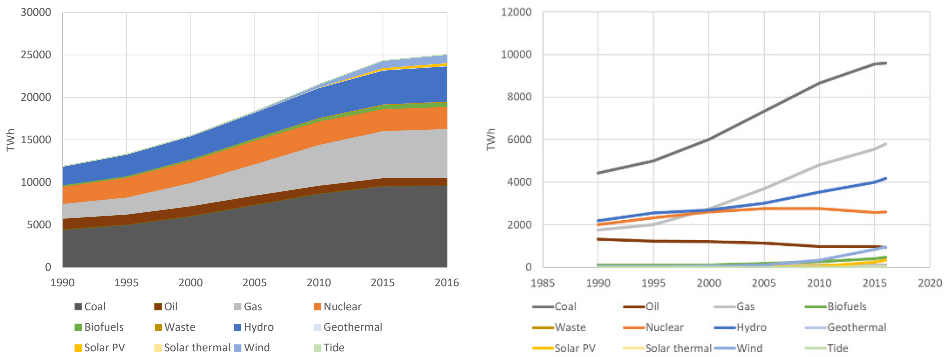


Figure 8: World electricity generation (Source: IEA)

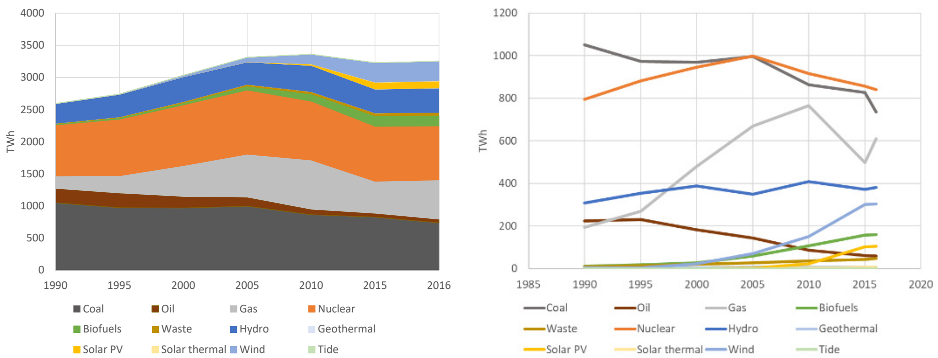


Figure 9: Electricity generation in EU-28 (Source: IEA).

The lion's share of investments in the electricity sector is linked to investments in renewables and grid infrastructure (Figure 10 and Figure 11). In relation to that, global investments in nuclear power are currently very small.

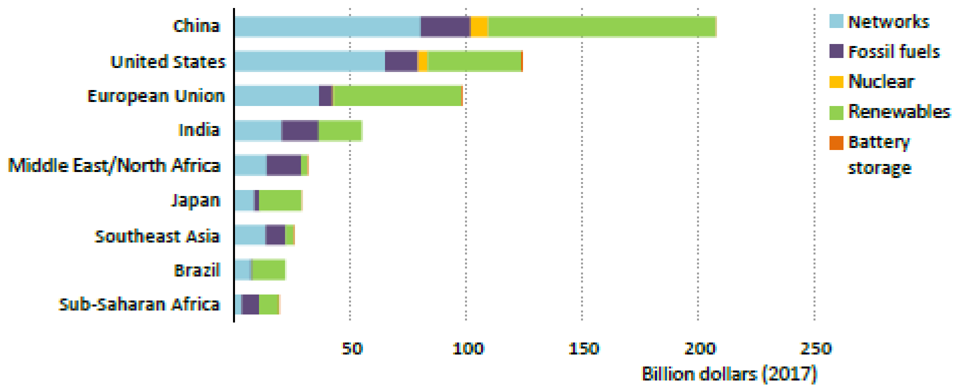


Figure 10: Investments in the electricity sector in selected regions in 2017 (Source: IEA/WEO, 2018)

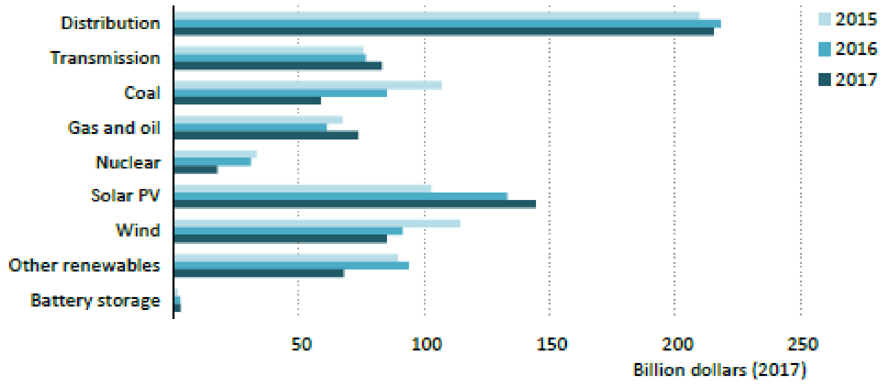


Figure 11: Global investments in the electricity sector by technology, 2015-2017 (Source: IEA/WEO, 2018)

The IEA summarizes the recent development for nuclear power across the World by stating: "*The nuclear power industry continues to face significant challenges, notably in advanced economies, linked to low gas and wholesale electricity prices as well as their costs of construction. It was announced that several reactors in the United States will be retired before their operating licences expire, citing financial hardship as the primary cause*" (IEA/WEO, 2018)

4.2 SCENARIOS FOR THE FUTURE

As mentioned in the previous section, the share of nuclear power today has stagnated during recent years globally and in the EU. Important drivers for building new nuclear power plants that are often mentioned are: replacing old nuclear-power facilities, meeting increased electricity demand and, which has gained in momentum over the past years, climate-change mitigation. The latter has also been decisive for massive investments in renewable electricity which, in turn, has provided additional arguments for nuclear power; that of being able to support the system with complementary, carbon-free and secure baseload production to a system where variability is steadily increasing.

In this chapter we will take a closer look at some of the scenario analyses and studies that have been published relatively recently, and that are often quoted on various occasions and span over a global as well as over a regional (European/Nordic/Swedish) perspective.

It must be emphasized that the scenarios presented here do not claim to predict the future. Furthermore, they should not even be considered as forecasts or projections (i.e. "best guesses" with respect to the future development). The scenarios are primarily used for exploring how the future *may* look like under a comprehensive set of assumptions.

4.2.1 Intergovernmental Panel on Climate Change (IPCC)

The IPPC's special report on mitigation pathways to reach a 1.5-degree target (IPCC, 2018) has gained widespread publicity and interest. The report includes a survey of no less than 90 scenarios, calculated and assessed by various research institutes and organizations across the World, each one meeting the target of a global mean temperature increase of 1.5°C above pre-industrial level at the end of the 21st century. Some of the scenarios do, however, face a certain temperature overshoot, i.e. a temporary temperature rise above the target during a certain period of time, which falls back in due time, meeting the stability goal at the end of the century. The scenarios of the IPCC study have been divided into five scenario groups, or archetypes, each defined by a unique combination of different surrounding (or external) conditions such as population growth, economic growth, technological development, fossil-fuel resources, degree of international cooperation etc. This means that all scenarios within the same scenario group share (basically) the same surrounding conditions. For four of these five scenario groups, we present in Figure 12 the world electricity generation in four relevant scenarios. Also included in the figure is the "Faster transition scenario" from the IEAs World Energy Outlook (2017). More on IEA's scenarios follows in the next section.

In Figure 12, we can see that nuclear power (in red) increases its contribution in absolute numbers substantially in two of the scenarios, while in other scenarios nuclear power remains roughly at current levels or even decreases. The IPCC concludes: "*Nuclear power increases its share in most 1.5°C pathways with no or limited overshoot by 2050, but in some pathways both the absolute capacity and share of power from nuclear generators decrease [..]. There are large differences in nuclear power between models and across pathways [..]. One of the reasons for this variation is that the future deployment of nuclear can be constrained by societal preferences assumed in narratives underlying the pathways [..]. Some 1.5°C pathways with no or limited overshoot no longer see a role for nuclear fission by the end of the century, while others project about 95 EJ yr−1*[2] *of nuclear power in 2100 [..]*".

[2] i.e. 26 PWh

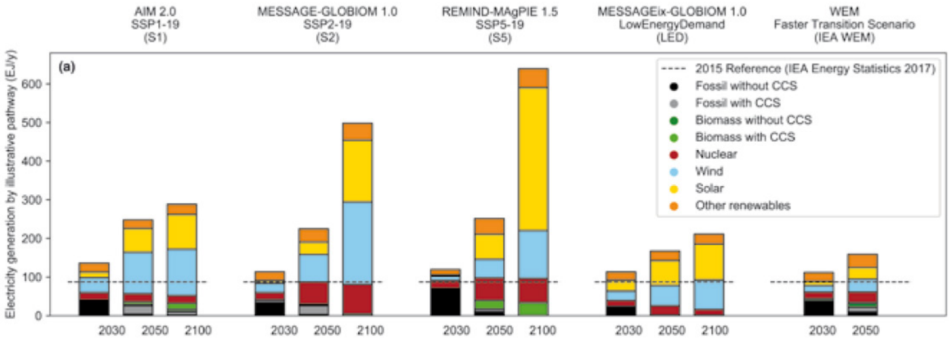


Figure 12: World electricity production in typical scenarios each representing the four IPCC scenario groups and the IEA "Faster transition" scenario (WEO, 2017) as reported in IPCC, 2018. The contribution from nuclear power today amounts to approximately 10 EJ/year. AIM: Asia-Pacific Integrated Model (a general equilibrium global model); MESSAGE: an energy-systems model used by IIASA in Vienna; REMIND: used by Potsdam Institute for Climate Impact Research; WEM: World Energy Model used by IEA ("Faster transition" scenario assumes accelerated mitigation policy before 2040); SSP= Shared Socio-Economic Pathways.

4.2.2 IEA

The IEA, mentioned above in relation to a specific scenario from the WEO (2017), annually updates its World Energy Outlook. The last update was issued in late 2018 (WEO, 2018). In that report, three main scenarios, based on extensive energy-systems modelling are analysed and discussed: the "Current Policies" scenario reflects the outcome of decided and implemented energy- and climate-policy instruments across the World by mid-2018; the "New Policies" scenario reflects the outcome of existing, decided and near-time planned changes in energy- and climate-policy instruments across the World and finally, the "Sustainable Development" scenario which reflects a development fully aligned with the Paris Agreement's goal of holding the increase in the global average temperature to "well below 2°C" by 2100 as well as fulfilling other sustainable development goals such as universal access to modern energy and clean air. This means a dramatic reduction in global GHG emissions. In contrast, the GHG emissions of "Current Policies" and "New Policies" are increasing over time, especially in the former scenario.

In the most relevant scenario for our purposes, i.e. the "Sustainable Development" scenario, nuclear power is slowly increasing its electricity generation until 2040 (Figure 13). However, the contribution is relatively modest compared to other low-carbon or carbon-free technologies such as wind and solar power.

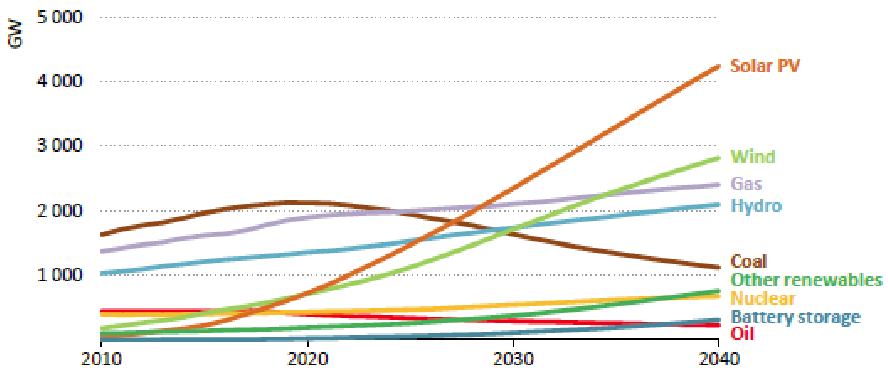


Figure 13: Total power generation capacity in the "Sustainable Development" scenario as reported by IEA in WEO (2018).

In their WEO 2018, IEA also presents a "Future is electric" scenario where world-wide electrification is taken to significantly higher levels than in the reference scenario which is "New Policies". The IEA concludes that such an electrification would increase demand for especially renewable electricity generation but also for fossil-based electricity generation (and to a lesser extent nuclear power). Therefore, increased electrification does not necessarily lead to sustainability. Increased electrification must be done in a carbon-constrained world in order to fulfil the requirements of climate change-mitigation. The contribution of nuclear power is somewhat higher in "Sustainable Development" than in "New Policies" implying that ambitious climate-policy targets may increase competitiveness and attractiveness of nuclear power. However, stringent climate-policy trajectories benefit renewables to a wider extent according to these scenarios. Nevertheless, the IEA concludes in the WEO 2018 that "*nuclear power remains an important low-carbon option for many countries*".

4.2.3 Greenpeace – The nuclear opponent's view

Greenpeace is a well-known and pronounced opponent of nuclear power and has stated, among other things, that: "*Nuclear energy has no place in a safe, clean, sustainable future*" (Greenpeace, 2019). In 2015, Greenpeace presented their view on how the global electricity system should, and can, evolve by 2050 in order to reach sustainability (Greenpeace, 2015). Three scenarios were presented: a "Reference" scenario, the "Energy [R]evolution" scenario and the "Advanced Energy [R]evolution" scenario. The "Reference" scenario is based on the IEA/WEO 2014 "Current Policies" scenario, i.e. a scenario that outlines a development where no additional policy efforts are made besides those already in place in 2014 (compare the WEO 2018 "Current Policies" scenario which uses the corresponding logic). The Energy [R]evolution" scenario depicts a future where policy targets lead the World to a widely decarbonised energy system by 2050 whereas the "Advanced Energy [R]evolution" scenario represents an even greater ambition aiming towards a fully decarbonised energy system by 2050. The results for the global electricity-supply system are presented in Figure 14 and for OECD Europe in Figure 15. It is clear that solar-based electricity (PV=Photovoltaic Cells; CSP=Concentrated Solar Power) together with wind power form the backbone of the future electricity-supply system across the world, according to Greenpeace. Nuclear power has no role to play in the two climate-policy oriented pathways.

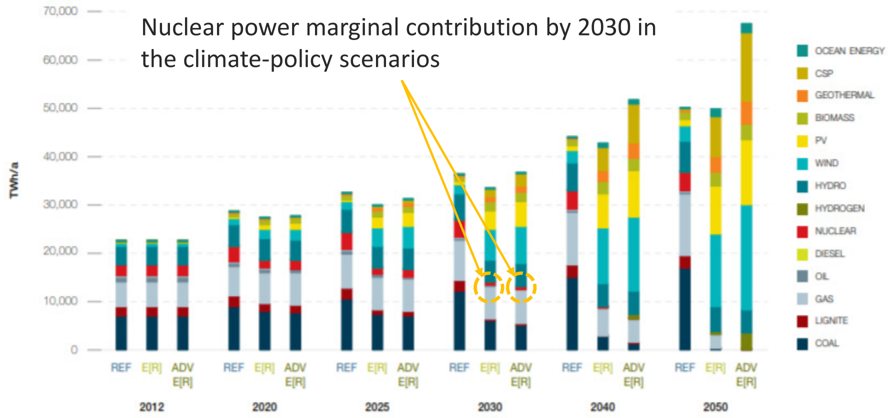


Figure 14: Global electricity generation in the "Reference", "Energy [R]evolution" and "Advanced Energy [R]evolution" scenarios as presented by Greenpeace in "Energy [r]evolution a sustainable world energy outlook 2015"

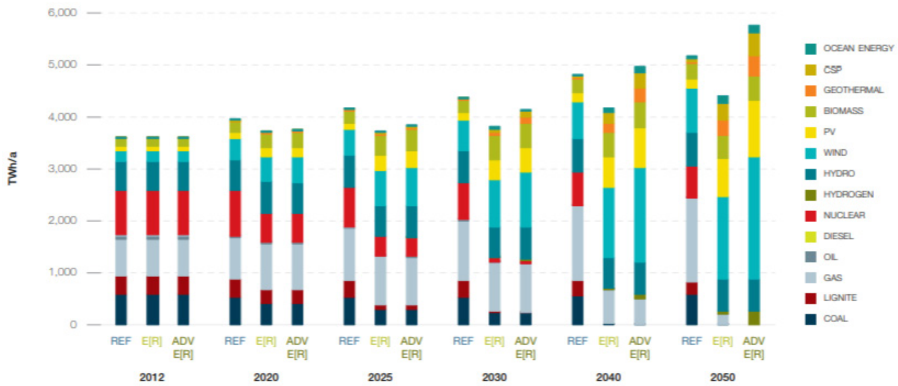


Figure 15: Electricity generation in OECD Europe in the "Reference", "Energy [R]evolution" and "Advanced Energy [R]evolution" scenarios as presented by Greenpeace in "Energy [r]evolution a sustainable world energy outlook 2015"

4.2.4 Pathways to 2050 by FORATOM and FTI – The nuclear industry's view

In November 2018, the report "Pathways to 2050: role of nuclear in a low-carbon Europe" (FTI Consulting/FORATOM, 2018) was released, written by FTI Consulting and commissioned by FORATOM, the Brussels-based trade association for the nuclear power industry in Europe. In that study, several European decarbonisation pathways towards 2050 were analysed using the FTI-CL power market model. The decarbonisation scenarios were assessed under three different assumptions on available capacity of nuclear power in the EU-28 (Figure 16). The study concludes that the probability of meeting the climate-policy objective is higher in the scenarios featuring at least a stable nuclear-power share. Moreover, the "High nuclear" scenario is found to decrease the mitigation costs considerably in terms of generation costs, electricity-grid and balancing costs. Furthermore, it is argued, new investments in nuclear power would also bring additional benefits to the European economy related to e.g. employment.

According to the model runs, the largest contributor to the future European electricity scenario is wind power, regardless of whether the development of nuclear power aligns with the “High nuclear” or “Low nuclear” capacity scenario (Figure 16). Assuming “High nuclear” would, however, imply less use of variable renewable electricity and back-up capacity than in the “Low nuclear” scenario.

An important assumption made in the modelling was that investment costs for new nuclear power plants decrease by 37% between 2020 and 2050. Cost reductions of various sizes were also assumed for renewable electricity generation during the same time span.

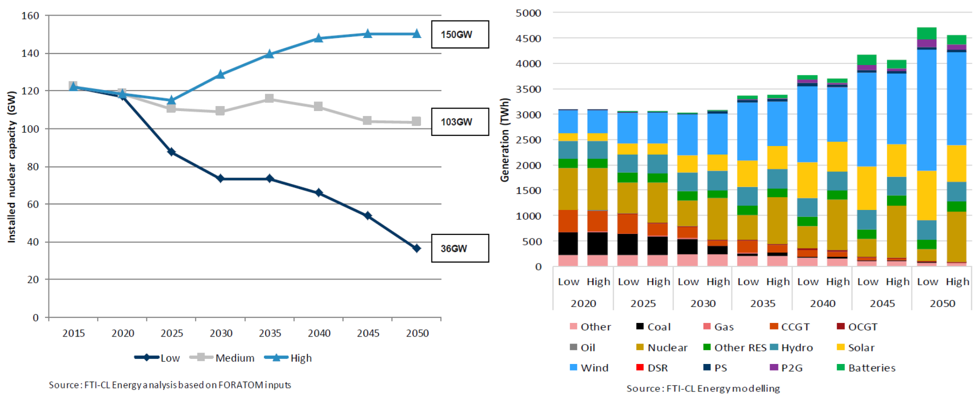


Figure 16: Nuclear power scenarios (left panel) and European electricity generation in the decarbonisation scenario featuring “High nuclear” and “Low nuclear” capacity (right panel) as presented by FTI Consulting/FORATOM

4.2.5 McKinsey’s Energy Insights

The global consultancy company McKinsey presented their latest view in early 2019 (McKinsey, 2019) on the global energy transition in a reference case reflecting all major key drivers for development until 2050. The result for global electricity generation is shown Figure 17. The two major trends are: the significant increase in solar and wind power and the decrease in coal-fired power production. Notable is also the rapid increase in electricity demand. Nuclear power remains approximately at current levels and is considered as a complement to renewable electricity. The “Reference” case is accompanied by an “Accelerated Transition” outlook, (McKinsey, 2018) analysing the impact on energy transition of eight shifts including a faster uptake of electric vehicles, improved efficiency gains, accelerated electrification, demand reduction, improved recycling, accelerated cost reductions of renewables and storage. In what way these shifts are affecting the prospects of nuclear power is not mentioned in the publicly available summary report.

Energiforsk

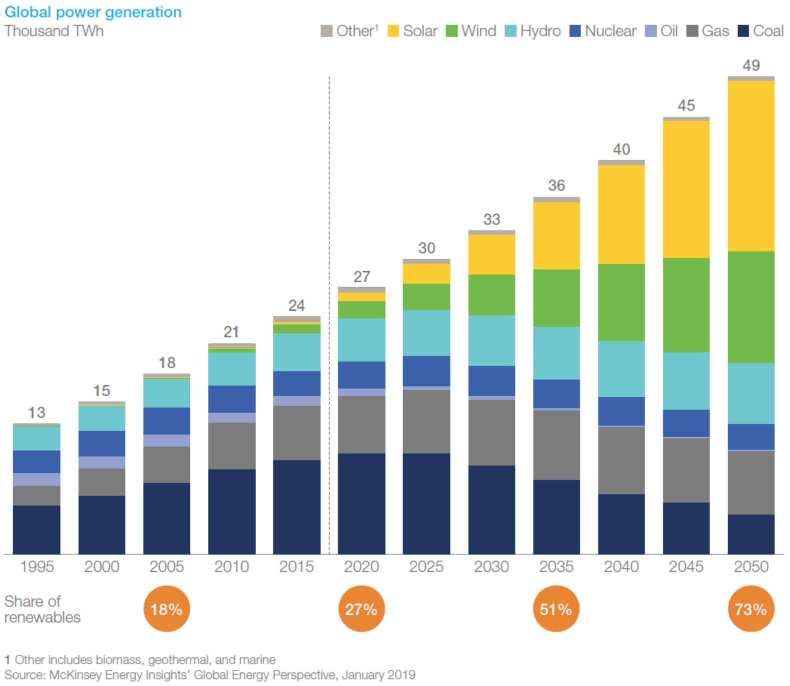


Figure 17: Global electricity generation in McKinsey's "Reference" case as presented in McKinsey, 2019.

4.2.6 The Chalmers Pathways project – a European outlook presented by researchers

In 2014, Chalmers finalized the second phase of the Pathways project which aims to analyse the transition of the European electricity system towards 2050 in detail, fulfilling zero or near-zero GHG emissions (Johnsson et al., 2014). In that study, four main scenarios were analysed by using comprehensive energy systems modelling (see Figure 18). The "Reference" scenario outlines a development resulting from existing (around 2014) policy instruments. The result is decreasing emissions but not near the 2050 ambitions expressed in the EU Roadmap 2050 (80% reduction for the entire energy system at the minimum based on emissions in 1990). The three other scenarios all share the long-term GHG-reduction targets implying near-zero emissions from EU electricity supply by 2050. The scenarios differ, however, with respect to the *way* this target is reached and with respect to the measures applied to reach that target. The "Regional Policy" scenario reflects a development where energy policy at the EU level is concentrated around three pillars: GHG emission reduction, increasing the share of renewables and reducing energy use (or increasing energy efficiency). The "Green Policy" scenario reflects a transition where renewables are specifically supported as the prime means to reduce GHG emissions. Thus, the goal is to increase the share of renewables to 100% rather than to reduce GHG emissions. Furthermore, nuclear power is assumed to be phased out across the entire EU based on this policy. This scenario is specifically designed to address the benefits and challenges of an entirely renewable electricity system. The "Climate Market" scenario reflects a development with increased electrification and where EU energy and climate policy is focused on primarily reducing GHG emissions. This leads to very high prices on CO_2 and, in turn, very high wholesale electricity prices. This is the scenario that benefits nuclear power the most. Renewable electricity is the most important component in the future electricity mix in this scenario as well but is supplemented by both nuclear power and carbon capture and storage (CCS).

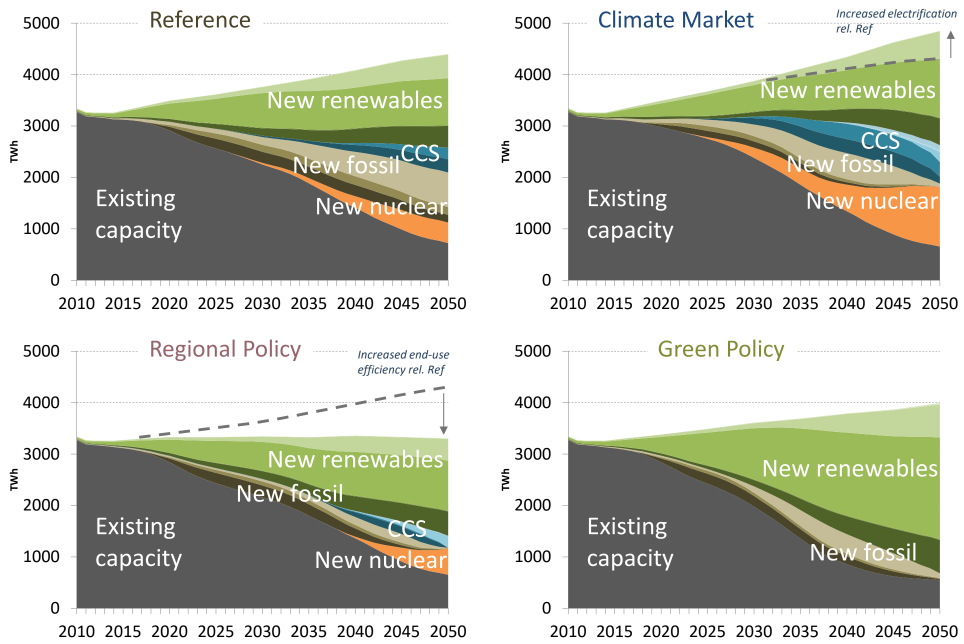


Figure 18: The four main scenarios analyzed by researchers at Chalmers in the Pathways project.

4.2.7 Nordic ETP – A Nordic perspective

In 2016 a Nordic Energy Research (an intergovernmental organisation under the Nordic Council of Ministers) funded project was carried out as a collaboration between IEA and Nordic research institutions resulting in the Nordic Energy Technology Perspectives (NETP, 2016). The analysis was carried out using the IEA model framework and highlighted the model results for the Nordic countries (Sweden, Norway, Denmark, Finland and Iceland). Two scenarios were analysed: the main scenario "CNS" (Carbon Neutral Scenario) assuming that Nordic energy-related emissions drop by 85% by 2050 (compared to 1990), and the "4DS" (Nordic 4-degree scenario) reflecting the Nordic contribution to the IEAs global 4-degree scenario (from the IEA ETP 2016). "CNS" is the Nordic contribution to a pathway that corresponds to a global effort to keep the global average temperature rise to "well below two degrees".

In Figure 19, the model results are presented. In both scenarios hydro power and wind power are the dominating sources of electricity supply in the Nordic countries by 2050. The difference between the scenarios is that in "4DS" there is still some fossil-fuel based electricity generation in place by 2050 while in "CNS" there is none of that due to a more stringent climate policy. Moreover, the electricity demand is significantly lower due to increased efficiency measures. A lower electricity demand explains why the contribution from nuclear power is somewhat smaller in "CNS" than in "4DS". The scenario analyses also point to the abundant and competitive wind power resources that are present in the Nordic countries.

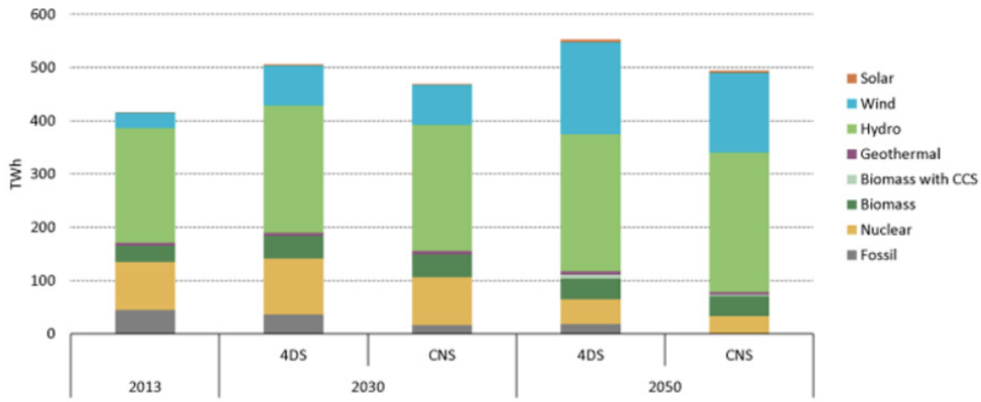


Figure 19: Model results of the Nordic ETP project showing electricity generation in all five Nordic countries in the "4 degree scenario" and in the main "Nordic carbon neutral" scenario (CNS).

4.2.8 Swedish Energy Agency – A Swedish Perspective

The Swedish Energy Agency (Energimyndigheten) produces every second year a broad and comprehensive view on how the Swedish energy system may evolve by 2050, given different assumptions of key parameters such as economic growth, fossil-fuel prices, prices on the EU-ETS market and so forth (Energimyndigheten, 2018). These scenario analyses are based on a model framework using the TIMES-NORDIC model for electricity and district-heating supply.[3] The reference scenario, mainly reflecting current policies, is shown for Swedish electricity generation in Figure 20. Important takeaways are the rapid increase in electricity supply due to the expansion of renewable electricity and the significant net export until 2035 due to stagnating domestic electricity demand. When existing nuclear power is phased out due to ageing (and not replaced by new power plants) the electricity-supply balance becomes tightened (i.e. the annual net export is significantly reduced).

New nuclear power was not found profitable in any scenario, given the assumptions and external conditions that were used in the model analysis. Wholesale electricity prices rarely exceeded 60 EUR/MWh whereas assumptions on levelized costs of electricity (LCOE) for new nuclear power plants are around 60-65 EUR/MWh.

[3] TIMES-NORDIC is a comprehensive energy systems model describing the electricity and district-heating systems in the four Nordic countries, in Germany, Poland and the three Baltic States. In the model description of Sweden other sectors such as industry and heating are also included. The model is managed and developed by Profu.

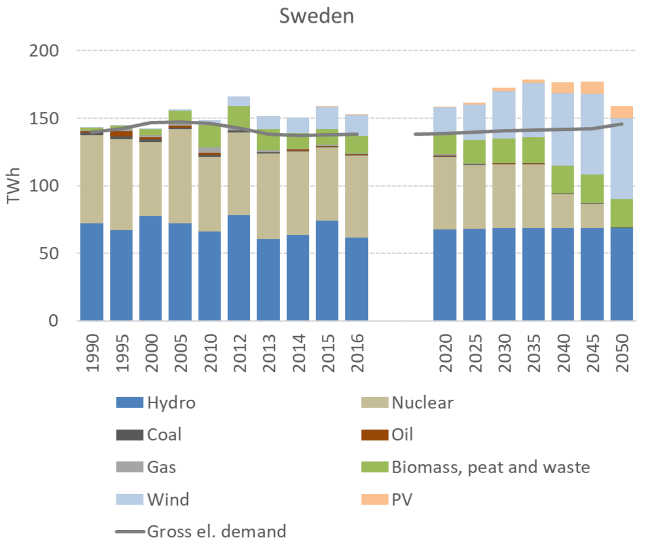


Figure 20: Model analysis of Swedish electricity generation in the reference case (Source: TIMES-Nordic model calculations used as input to the 2018 long-term scenario analysis by the Swedish Energy Agency).

5 Sustainability aspects on nuclear power

In this chapter, we present a number of views taken by different authors and sources (from researchers as well as others) on the three main dimensions of sustainability: environment, society and economy. The aim is to present a broad overview and not to delve into details on each of the issues and fields that we touch upon. However, since our main objective is to shed light on the possible climate benefits of nuclear power, we put some extra effort in reporting the different views and arguments taken in relation to GHG emissions, climate change-mitigation and nuclear power.

Our objective is to show the variety of arguments and findings reported in different sources where views can sometimes significantly diverge. We like to remind the readers that our purpose is not to rate specific authors in terms of credibility or correctness but to show the span of arguments found in (preferably scientific) literature.

As we have mentioned earlier, the concept of sustainability is not crystal clear and is subject to different interpretations. As noted by e.g. Stamford & Azapagic (2011), approaches to sustainability assessments differ greatly in their scope and methodology, as no standardised approach currently exists. However, it is somewhat of a consensus in the field that sustainability assessment should use a life cycle approach and take into account all relevant environmental, techno-economic and social sustainability factors.

Sustainability is widely used as a concept and as an objective for policy making around the World. In a study by Gralla et al. (2016), the national energy polices of nine countries that currently have nuclear power in their energy mix or where new power plants are being planned/are under construction were scrutinized to find out if sustainability is framed within national energy strategies and whether nuclear power is a part of such a sustainability framing. The authors concluded that in three of the national energy strategies investigated (USA, UK and India) there was no clear link between sustainability and nuclear power while in the other national strategies such a link could either be explicitly found (Hungary) or implicitly embedded within the narratives of the energy strategies.

5.1 ENVIRONMENTAL ASPECTS ON NUCLEAR POWER

The environmental aspects related to nuclear power include both negative and positive sides which is also obvious in the literature. Some of the positive aspects mentioned in the literature include:

- (Very) low emissions of GHGs and other pollutants (mentioned by e.g. Adamantiades & Kessides, 2009; Qvist & Brook, 2015; and often emphasized by the nuclear industry)
- Relatively small amounts of waste produced, especially compared to fossil fuels when including emission volumes (see e.g. FTI/FORATOM, 2018)
- Land-use efficient when allocated to generated electricity (e.g. Stamford & Asapagic, 2011; and Evans et al., 2010)

while the negative aspects typically refer to:

- Radioactive waste that needs to be stored for a long time, featuring the so-called intergenerational problem (Kermisch & Taebi, 2017; Santoyo & Azapagic, 2014 among others)
- Nuclear-fuel mining leading to pollution and destruction of land and nearby waters (discussed in e.g. Pearce, 2012 and Jacobson, 2009)
- Uranium resources are finite. Using low-grade ore implies increased abundance but also increased exploitation costs (mentioned in e.g. Mez, 2012).
- Water use in nuclear power plants is among the highest compared to other electricity generation (see e.g. Meldrum et al., 2013; and Evans et al., 2010)
- Cooling water (incl. intake) causes harm to marine organisms (mentioned in e.g. Stamford & Azapagic, 2011, and in Pearce, 2012)
- Far-reaching environmental impacts of accidents (e.g. Jacobson, 2009; Adamantiades & Kessides, 2009)

In the 5th IPCC Assessment report (Bruckner et al., 2014), besides climate change-mitigation, the main environmental co-benefits of replacing coal with nuclear are presented as reduced air pollution and absence of adverse effects of coal mining, while the risks of nuclear accidents are mentioned as being on the down-side.

Consequently, it is clear that several of the issues mentioned above are not subject to consensus. The availability of nuclear fuel is one such matter, which we will get back to in Section 5.1.4 There are other aspects that could be characterized as "environmental" in their character, but we have chosen to mention such additional aspects in the next section which deals with social aspects on nuclear power. In the coming sub-sections, we elaborate further on the key issues related to environmental aspects.

5.1.1 Climate benefits and GHG emissions

In the literature on sustainability aspects on nuclear power compared to other energy sources, there has been a specific focus on the climate change mitigation aspects of nuclear power, especially since the year 2000.

Many authors, such as e.g. Adamantiades & Kessides (2009) and Kharecha & Hansen (2013), point to the fact that nuclear power worldwide significantly contributes (and has historically contributed) to mitigating GHG emissions from the electricity sector. The former state that emissions of CO_2 globally would be some 2.5 billion tonnes higher per year if nuclear power was not used. Kharecha & Hansen calculate that nuclear power has prevented an average of 2.6 $GtCO_2$-eq annually between 2000 and 2009. Hansen has in several cases expressed his view on the necessity to also include nuclear power, along with renewables, efficiency measures and CCS, as viable means to tackle climate change.

The conclusion that nuclear power has saved GHG emissions is also recognised by the European Commission (2010) which in its 2020 Strategy for competitive, sustainable and secure energy states that without nuclear power, the EU power plant carbon dioxide emissions would have been about one-third higher compared to today. In that respect, nuclear power is considered by many researchers (see also

Knapp & Pevec, 2018; Prăvălie & Bandoc, 2018; Brook, 2012) as a means of mitigating climate change.

Generally, lifecycle GHG emissions (i.e. emissions calculated based on lifecycle assessment, LCA) from nuclear power are found to be significantly lower than for electricity generation based on fossil fuels making nuclear power a potential climate-change mitigation measure. However, estimates of GHG emissions may differ widely between sources. The bulk of GHG emissions from the nuclear-fuel cycle stems from the upstream side, i.e. fuel mining, milling and fuel fabrication. GHG emissions from operation of nuclear power plants and downstream activities (waste management and decommissioning) are comparatively very low (Toth, 2014).

Differences in estimates of specific GHG emissions (kg CO_2/kWh electricity) originate from differences in energy efficiency of enrichment techniques (the two major ones being diffusion techniques and centrifuge techniques – but there are also others (e.g. laser-based techniques), different energy mixes of the regions studied, as well as differences in methodology and system boundaries when assessing emissions (Pearce, 2012). Uranium ore source and quality, which affects mining, milling and transportation, also has an impact on the final estimates of specific emissions (Verbruggen et al., 2014) as well as plant construction, decommissioning and waste management. Enrichment by diffusion is significantly more energy-intensive than enrichment based on centrifuge techniques. Since the former option is no longer used globally since 2013 we can expect lifecycle emissions to be lower in estimates using recent data than in studies using older data, all else held constant (Analysgruppen 2018).

An ambitious lifecycle-emission meta-study by Warner & Heath (2012) found the interval for nuclear power to be within the range of close to zero up to 220 kg CO_{2eq}/MWh for LWRs[4] with a median value of 13 kg CO_{2eq}/MWh. After harmonization for e.g. differences in operational characteristics of nuclear power plants and differences in system boundaries the interval increased from close to zero up to 110 kg CO_{2eq}/MWh with a median value of 12 kg CO_{2eq}/MWh. The remaining (after harmonization) interval is explained by differences in LCA methodology and datasets such as enrichment method which largely determines electricity input, and energy mixes determining the characteristics of the electricity used. The study, however, concludes that lifecycle GHG emissions related to nuclear power can be seen as very low, far lower than for fossil-fuelled alternatives and in the same range as renewables. However, the authors also find that with increasing exploitation of nuclear power, the uranium ore grade will gradually decrease. Thus, electricity input for nuclear fuel preparation will increase accordingly, leading to higher CO_2 emissions compared to uranium ore with higher grade. This may change the comparison to renewables and affect the climate change-mitigation potential of nuclear power. The study by Warner & Heath (2012) is relatively well-known and is also cited in IPCC's Fifth Assessment Report (Bruckner et al., 2014), which refers to the range of 4-110 kg CO_{2eq}/MWh electricity generated by nuclear power. In comparison, the IPCC report from 2014 also reports corresponding figures for PV (18-180 kg CO_{2eq} /MWh el), wind power

[4] Light Water Reactors

(7-56 kg CO_{2eq}/MWh el), coal power (675-1 689 CO_{2eq}/MWh el) and natural gas power (290-930 CO_{2eq}/MWh el). Based on these findings, one may conclude that the lifecycle emissions from nuclear power are on the same level as renewables, while both sources of electricity exhibit significantly lower lifecycle GHG emissions than fossil-fuelled electricity generation. The estimates for the various electricity-generation technologies are however partly taken from different sources which makes the comparison less than straightforward.

One of the lowest LCA-figures on GHG emissions for nuclear power is reported by the Swedish utility Vattenfall (2012), 5 kg CO_{2eq}/MWh, and is derived specifically for the Swedish nuclear power plant fleet (those owned by Vattenfall). A lifecycle emission factor of 23 kg CO_2/MWh was reported in Nian et al. (2014) for typical Singaporian-Japanese conditions.

Other authors emphasize that nuclear power is not free of GHG emissions and that this should be considered. Mez (2012) e.g. argues that global nuclear power in 2010 accounted for more than 117 Mton CO_{2eq} based on nation-specific estimates ranging between 126 kg CO_{2eq}/MWh el (South Africa) and 7 kg CO_{2eq}/MWh el (Belgium).[5] Other authors take a different view, instead asking what emissions *would have been* if the electricity supplied by nuclear power was supplied by other sources instead (see upcoming section).

Jacobson (2009) also includes a so-called opportunity cost emission due to construction delays (alternative fossil generation must be used over a longer time period compared to other technologies were lead times are shorter) and a CO_2 penalty in the event of a nuclear war (CO_2 emissions from the destruction of buildings and other man-made structures from a potential nuclear war). This leads to a total specific emission factor of 68-180 kg CO_{2eq}/MWh for nuclear power which is considerably higher than for renewables. Jacobson is one of the more well-cited researchers in our survey but his research and findings, which tend to rule out nuclear power as a viable option for a sustainable energy system, are not without controversy (The Mercury News, 2017; Analysgruppen, 2018)

Another meta study on the same topic, by Sovacool (2008), assessed 103 lifecycle studies of GHG equivalent emissions for nuclear power plants. Discarding a large majority of these LCA-studies based on criteria such as year of publication, non-transparency, inaccessibility etc., the remaining 19 studies exhibited a large range of emissions for nuclear power over the lifetime of a plant from 1.4 to 288 kg CO_{2e} per MWh electricity. Thus, according to Sovacool, when critically examining these studies, the mean value of emissions over the typical lifetime of a nuclear power plant is 66 kg of CO_{2eq}/MWh, entailing much higher emissions than those of renewable energy sources. Like Jacobson, Sovacool is somewhat of an outspoken opponent of nuclear power, and the estimates of the lifecycle emissions by Sovacool have been questioned by Analysgruppen (2018).

That nuclear power polarizes also researchers and hosts clear dividing lines between proponents and opponents is illustrated by a joint commentary by

[5] Other countries' specific emissions include e.g. France and Canada (8 kg CO_{2eq}/MWh el each), Germany (28 CO_{2eq}/MWh el), Sweden (32 CO2eq/MWh el), Finland (62 CO_{2eq}/MWh el), USA (59 CO_{2eq}/MWh el), UK (32 CO_{2eq}/MWh el) and China (82 CO_{2eq}/MWh el).

Jacobson and Sovacool, together with five other authors, which criticizes the conclusions of Kharecha & Hansen (2013) on prevented mortality and GHG emissions from nuclear power (Sovacool et al., 2013). Sovacool et al. (2013) wrap up their commentary stating that Kharecha & Hansen's article is "incomplete and misleading" when it presents nuclear power as a viable solution to climate change.

Climate impact from phasing out nuclear power

Environmental impact analyses of phasing out existing nuclear power prior to its estimated technical operational lifetime have also been carried out in order to assess the climate change-mitigation benefits of using existing nuclear power. The results of such studies depend, of course, on system boundaries and other methodological choices. Qvist & Brook (2015) assume that the alternative to continuing the use of existing nuclear power in Sweden is mainly coal-fired condensing power plants (partly through imports from surrounding countries but also through new investments) in a 30-years perspective, which is the reason they end up with a very large figure for CO_2 emissions that would have occurred if the nuclear power fleet would have been prematurely phased out. Another study (NEPP, 2016) with the same focus, that used a comprehensive energy-system model which included investment changes over time in alternative electricity supply in response to the nuclear phaseout, ended up at a considerably smaller (approximately one third of the former figure; the studies are not entirely comparable why this figure is a relatively rough approximation), but nevertheless significant, emission figure. The investment changes due to the phaseout could also include investments in renewable electricity which dampened the negative emission effects of an early nuclear phaseout.

A third view is to assume that the European emission-trading scheme effectively puts a cap on emissions from the electricity sector (and other included sectors). In that case, a nuclear phaseout would initially lead to increased emissions from the electricity sector (more fossil-based electricity generation to compensate for the nuclear phaseout) but this increase would be offset by emission reductions elsewhere within the cap-and-trade system. The net effect would, therefore, be negligible in terms of emissions but instead lead to an increase in the ETS price (see e.g. European Energy Pathways, 2014 in the case of the German nuclear phaseout).

Myhrvold & Caldeira (2012) construct a quantitative model of an energy system transition that includes life-cycle emissions and central physics of greenhouse-gas warming. The study aims to assess the effects on global warming from an energy transition on a global scale from coal-based high GHG-emitting electricity generation to low-emission technologies. In their study Myhrvold & Caldeira show that rapid deployment of low-emission energy systems, including nuclear power, can do little to diminish the climate impacts in the first half of this century. This is because during a transition, energy is used to both create new infrastructure and to satisfy other energy demands, resulting in additional emissions. Only in the second half of this century does wind, solar, nuclear power, and possibly carbon capture and storage appear to be able to achieve substantial climate benefits. The authors argue that "*energy system transitions cause reductions in high-greenhouse-gas-emission warming only once they are well underway, and it takes much longer still for any new system to deliver substantial climate benefits over a conventional coal-based system*". The study concludes by underscoring the urgency in developing realistic plans for the rapid shift to the lowest emitting energy technologies.

The IEA (2018) also remarks on the possible climate impact of a (premature) phaseout of nuclear power in EU, USA and Japan: "*Should such a situation materialise* [nuclear phaseout in USA, EU and Japan], *the loss of large amounts of baseload zero emissions supply would have major implications for the energy mix, for energy security and for the emissions trajectory*".

In conclusion, by looking at the different studies covered by our survey, it is difficult to argue with certainty that the use of nuclear power is linked to GHG emissions (in an LCA perspective) that significantly deviates from renewable electricity. Nevertheless, there are scientists claiming that nuclear power has considerably higher lifecycle emissions than renewable in general (e.g. Jacobson, 2009; Sovacool, 2008 and Mez, 2012) as well as scientists reporting the opposite (e.g. Brook 2012; Adamantiades & Kessides, 2009; and Evans et al., 2010). As mentioned above, such estimates depend on the assumption on e.g. enrichment method, system boundaries, ore-grade of uranium and region-specific electricity-generation mix. This may also open up for the possibility for some authors to make a case for their argumentation by choosing an emission figure that aligns with their own (personal) views.

5.1.2 Air pollution

Compared to coal power, nuclear power has significant environmental benefits since it produces almost no airborne pollutants except very small quantities of radioactive gases, which are under strict supervision (Adamantiades & Kessides, 2009). Most of the emissions (in a life-cycle perspective) of air pollutants such as sulphur dioxide (SO_2), nitrogen oxides (NO_X) and volatile organic compounds (VOC; a ground-level ozone precursor) occur during mining and milling of uranium (Stamford & Azapagic, 2011).

5.1.3 Material use in construction

Wind power, ocean-based electricity generation and CSP (Concentrated Solar Power) need more iron and cement than fossil-fuelled power plants, while photovoltaic power relies on a range of scarce materials (IPCC, 2014). The use of materials, especially scarce materials, is not a prominent topic in our literature survey of (primarily) nuclear power. As the IPCC concluded, these issues are likely to be more relevant when it comes to photovoltaics (and probably also wind power and battery technologies, at least for current-state technologies) and less of an issue for nuclear power, especially when material use is allocated to the total amount of electricity generated. Brook et al. (2014) concludes by stating that none of the materials used in the construction of nuclear power plants are in short supply. On the other hand, Tokimatsu et al. (2018) find that the supply of scarce metals in a global energy-systems modelling study may become a significant challenge for several carbon-mitigation technologies, including nuclear power. Especially vanadium is identified as distinctly critical (used, among other things, as a steel additive). The issue of scarce material (metals) and their use in certain technologies is described in e.g. Bruckner et al. (2014), who also point to the fact that there are adverse environmental effects from mining on a local scale. Moreover, Stamford & Azapagic (2011) point to the fact that concrete has low recyclability compared to steel used for construction of e.g. wind turbines.

5.1.4 Nuclear-fuel availability

Several studies discuss the question of uranium-supply capacity. Prăvălie & Bandoc (2018) mention that the availability of uranium could be a challenge for meeting the Paris Agreement goal since nuclear development would require an expansion of the fuel cycle globally, leading to an increase of uranium mining production as well as enrichment capacity. NEA's (Nuclear Energy Agency) and IAEA's recent estimates suggest that there are currently 5.7 Mton of uranium in known reserves, Prăvălie & Bandoc state that there are uranium resources enough for at least 100 years of nuclear electricity production (considering the current exploitation rate of almost 57 000 tonnes of uranium per year according to IAEA).

Stamford & Azapagic (2011) also mention resource availability of approximately 100 years when it comes to uranium, citing estimates by NEA and IAEA from 2009. Adamantiades & Kessides (2009) mention lower numbers, approximately 75 years, citing estimates from IAEA from 2007. They conclude that, setting aside unconventional resources, the number of years known and recoverable uranium resources would last is not impressive and thereby indicating that nuclear power is not a long-term sustainable technology (when it comes to technologies available today).

Sovacool (2010), on the other hand, states that the security of future supplies of uranium is uncertain, referring to IAEA's warning in 2001 that low-cost ores are rapidly being exhausted and that countries are being forced to increase exploration efforts to reach more expensive sites. He also highlights accusations made by others that IAEA's so-called Red Book has historically overestimated uranium mining capacities and availability of reserves, with upward exaggerations of 20-30 % (Sovacool, 2010). According to Sovacool, the secondary sources for fuel such as civilian and military stocks of uranium and plutonium, are also rapidly getting exhausted, referring to NEA and IAEA stating in their 2007 Red Book that "*most secondary resources* [of uranium] *are now in decline and the gap will increasingly need to be closed by new production*".

The aspect of resource durability as an important aspect of sustainability is also discussed by Kermisch & Taebi (2017). In their article they consider sustainability as a moral framework based on social justice. In this respect one could argue that "resource durability" favours the use of a retrievable geological disposal of nuclear waste, since it is easier to recover the waste in order to reuse the remaining fissile material in the future.

Other authors take on a considerably more optimistic view on fuel availability for nuclear power, especially when considering non-conventional fuel cycles (Knapp and Pevec, 2018, Brook, 2012). Furthermore, Petroski & Wood (2012) outline a scenario where nuclear power could fuel the entire world with energy services at a growing rate, reaching potentially a fully sustainable way. This would, however, require a large-scale utilization of uranium dissolved in sea water, deep borehole repositories for spent fuel and safe breeder technology development to close the fuel cycles. The authors argue that sea water uranium is truly renewable if exploited at a rate corresponding to the constant feed-in to the seas from rivers and originating by erosion from the Earth's crust. In a breeder reactor energy system, this renewal rate would be sufficient to meet demand for the entire world several times over. The authors state that the supply of uranium in the Earth's crust is effectively inexhaustible (not limited to ore-grade uranium) and that uranium from the Earth's interior is constantly being pushed upwards through tectonic processes, thereby being subject to erosion and transport to the seas. However, such a nuclear-fuel system requires exploitation of significantly lower grade of uranium, thus raising mining costs considerably, as stated in for example IPCC's Fifth Assessment Report (Bruckner et al., 2014). Coupled with a large-scale introduction of safe breeder technology, this would require a rate of technological development that other authors or publications of our literature survey simply do not believe in (e.g. Verbruggen et al., 2014; Adamantiades & Kessides, 2009; Mez, 2012). An increased reliance on breeder technology is also considered by some authors (e.g. Karakosta et al., 2013) to increase the proliferation risk.

5.1.5 Waste management

Waste management of spent fuel is a common topic in many publications. Adamantiades & Kessides (2009), Karakosta et al. (2013), Prandecki (2014), Pearce (2012), among others, mention waste management as a crucial issue to be resolved if nuclear power is to be considered as sustainable in any way. Adamantiades & Kessides (2009), however, also point to the fact that waste volumes are small compared to other forms of man-made wastes. The challenges related to waste management are also identified by Bruckner et al. (2014), Sovacool (2010) and Prăvălie & Bandoc (2018). The latter argue, in contrast to Adamantiades & Kessides, that waste volumes are to be considered as (quote) "large". Furthermore, Barron & Hill (2019) argue that costs for waste management are underestimated.

There is no doubt that waste management of spent nuclear fuel is an issue that concerns large parts of the public (more on that in the following section). One interesting possibility is that this mistrust or scepticism from the public towards waste handling may decrease once the nuclear industry proves the feasibility of deep storage in practice (personal communication with Dr Henri Paillere at NEA, 2019). Such storage facilities will probably be commissioned within the coming decade in Finland and Sweden, countries that are closest to inaugurating their deep repositories.

Figure 21 shows a simplified view on the nuclear fuel cycle.

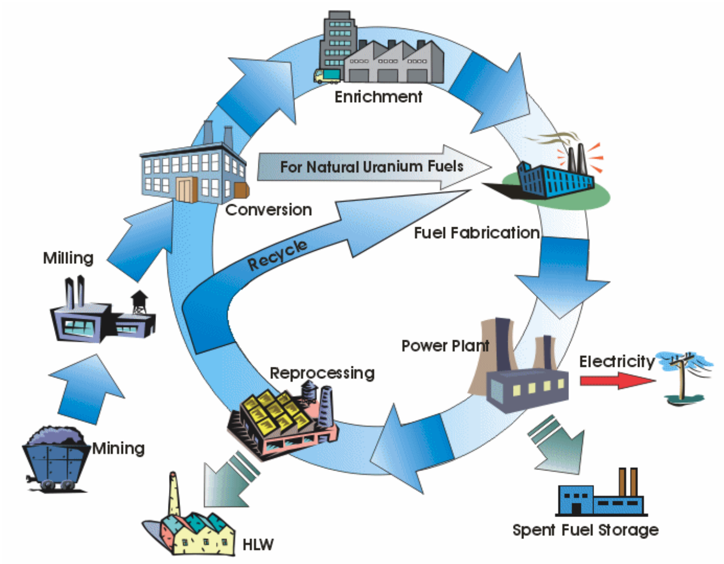


Figure 21: Simplified view on the nuclear fuel cycle (Figure taken from IAEA, 2009)

5.1.6 Radiation during normal operation

Handling of radioactive material poses a continuous challenge throughout the entire nuclear fuel chain, potentially leading to release of radiation. The most significant parts of the fuel chain process in this respect are fuel mining and processing (Bruckner at al., 2014). During normal operation the handling of radioactive materials is subject to thorough control.

5.1.7 Water and land use

Nuclear power plants use considerable amounts of water (most of which is recirculated), virtually all of it used for cooling the reactor core. In Sweden, the existing nuclear power plants use more than 4 times the amount of water compared to manufacturing industries as a whole (SCB, 2017). Generally, nuclear power plants require larger volumes of cooling water than fossil-fuelled power plants due to relatively low operating temperatures in nuclear power plants (in order to reach lower operating temperatures more heat needs to be cooled). New generation high-temperature reactors will potentially have the same cooling water requirements as fossil-fuel based power plants due to the possibility of corresponding (higher) operating temperatures (Brook et al., 2014).

Meldrum et al. (2013) review the lifecycle of water use for electricity generation. They conclude that published estimates vary substantially, mainly because of differences in production pathways, analysis boundaries, and performance parameters. Despite the limitations in available data, the authors estimate that water used for cooling in thermal power plants dominates the lifecycle of water use in most cases. Coal, natural gas, and nuclear fuel cycles have the largest life-cycle water usage per MWh electricity in most cases. On the basis of the best available data for the evaluated technologies, total life cycle water use, according to the authors, appears lowest for electricity generated by PV and wind, and highest for thermal power plants. The use of cooling water in nuclear power plants is also discussed in Jacobson (2009) and Pearce (2012).

Land use is measured by how much land is required for a technology to operate (typically expressed as footprint per square meter per generated electricity) and is found by Evans et al. (2010) to be lowest for nuclear power in comparison to other means of electricity generation. This contrasts somewhat to the estimates made by Jacobson (2009) who distinguishes between footprint (including all actual land surface removed for alternative use in order to host the entire chain associated with operation of a given technology) and spacing (the physical and “visible” space over which a given technology is spread and, thus, affecting people’s notions of the actual presence of the given technology). In terms of spacing, nuclear power scores relatively well among different supply option while in terms of footprint the outcome is somewhat less appealing even though better than e.g. photovoltaics, hydro power, coal-CCS and, above all, some biomass-based options.

5.2 SOCIAL ASPECTS ON NUCLEAR POWER

In this section, we elaborate on some of the findings and arguments put forward by different authors on the topic of social sustainability, and its relevance to nuclear power. The key component is public acceptance and trust. Public acceptance, or perception, may cover factors such as risk perception, benefit perception, affective feelings and trust (Visschers et al., 2011). This, in turn, is a result of public perceptions on e.g. risks of nuclear accidents, waste handling and the link to nuclear arms and proliferation.

Besides the positive aspects on climate change-mitigation and air pollution discussed previously, employment and supply of abundant electricity spurring economic growth are mentioned as typical positive aspects of nuclear power to the public (see e.g. Bruckner et al., 2014; Stamford & Azapagic, 2011; Adamantiades & Kessides, 2009; Edberg & Tarasova, 2016). On the negative side, risk of accidents, health aspects, proliferation, working conditions in uranium mines and the longevity of nuclear waste are commonly mentioned as concerns of the public.

In the 5th IPCC Assessment report (Bruckner et al., 2014), the social co-benefits of replacing coal with nuclear, besides climate change-mitigation, are presented as improved air quality and reduced risks of coal mining accidents, while the risks of nuclear accidents, uranium mining and milling as well as safety and waste concerns are considered as negative aspects.

The two reappearing opposite views on nuclear power are well summarized by Karecha & Hansen (2013) claiming that: “*In conclusion, it is clear that nuclear power has provided a large contribution to the reduction of global mortality and GHG emissions due to fossil fuel use*” and by Sovacool (2010), who takes on a fundamentally different view: “*When compared to fatalities from other energy sources, nuclear power ranks as the second most fatal source of energy supply (after hydroelectric dams) and higher than oil, coal and natural gas systems*”.

5.2.1 Public acceptance and perception

Even though the nuclear industry makes a strong case for nuclear policy as a prominent climate change-mitigation strategy (see e.g. IAEA, 2018a and NEA, 2012a), it is of course not obvious that this view is shared among the public. There are studies indicating that the public places a higher value on energy-supply benefits, i.e, a secure electricity-supply option and only to a lesser extent benefits related to climate change-mitigation (Visschers et al, 2011).

Public perception or acceptance is of vital importance to the prospects of nuclear power. Negative public attitudes towards nuclear power have historically proven to have far-reaching impacts on the nuclear industry, both in terms of delays and cancellations of proposed constructions (Goodfellow et al., 2011). Bruckner et al. (2014) states that when it comes to nuclear power, public concern and anxieties for the technology often focus on health and safety such as accidents, disposal of wastes and proliferation. They conclude that perceptions seem to be dependent on how the debate around nuclear power is framed relative to other sources of energy. Harris et al. (2018) maintain that arguments for or against nuclear power are fuelled by each individual's values and beliefs. In their study they show that gender, trust, perceived risk and benefits as well as environmental values contribute to the acceptance of nuclear power.

In surveys, where nuclear power is explicitly framed as a climate-policy measure, public acceptance seems to increase significantly (Corner et al., 2011; OECD/NEA, 2010). A further increase in willingness to accept nuclear power was identified when a climate-policy framing of nuclear power was accompanied by a reluctant acceptance, i.e. people accept nuclear power as a means to combat climate change but are not especially happy about it and only if other more preferred options have been exhausted.

There are indications that the level of public acceptance is more stable than one might think, even when measured before and after a large and traumatic accident. The Chernobyl and Fukushima accidents certainly had negative impacts on public acceptance but according to certain studies the overall impact can be described as "moderate" (Siegrist & Visschers, 2013). Thus, a large part of the public seems to preserve their beliefs and perceptions, even after a significant event such as a major accident. However, Kim et al. (2014) argue that governments should be very aware of the fact that catastrophic events like the Fukushima accident or large-scale terrorist attacks (September 11th) can considerably reduce public acceptance for nuclear power. Fear of terrorist attacks is another issue related to public acceptance of nuclear power. According to Jacobson (2009), centralized low-carbon supply technologies (CCS, hydro and nuclear) are more vulnerable to disruptions (terrorist attacks, war or natural disasters) than decentralized technologies (PV, wind power, wave power).

The importance of trust

Trust in social structures, authorities, governments, industry and other important societal functions is essential in a socially sustainable society (Hedenus et al., 2018). "Trust" is also a concept that frequently appears as a key parameter in our literature survey. Hence, potential lack of trust is a major challenge for the nuclear industry in overcoming negative public attitudes. This includes trust in authorities, regulatory bodies, the industry itself and in the information given by officials (Edwards et al., 2019; Kim et al., 2014). Trust in the nuclear industry together with perceived benefits of nuclear power, are often mentioned to be the most influential factors affecting public acceptance of nuclear power (e.g. Harris et al., 2018; Kim et al., 2014).

If nuclear policy can successfully establish nuclear power as a prominent means of generating electricity securely, cost-efficiently and with a high degree of climate benefit, then there is a possibility that such benefits tend to outweigh the safety concerns of the public (Kim et. al., 2014)

In their sustainable, nuclear power scenario on a global-scale, Petroski & Wood (2012) introduce the concept of ”manifest safety”, i.e. a constitutional commitment to achieving very high safety levels and at the same time being fully transparent and open with the risks that inevitably are at hand but deemed acceptable by society and considered smaller than other alternatives. Once again, trust is essential in order to reach such a degree of sustainability.

Perceived and calculated risks

Risk science distinguishes between *objective* risk, which can be calculated, and *subjective* risk, which is perceived by one person or a group of persons but is nevertheless highly relevant in understanding formation of opinions and actions. Research is mainly focused on studying subjective risk when it comes to nuclear power (Kim et al., 2014). Calculated risk is an engineering and analytical question (e.g. probabilistic risk assessment; PRA) which generally ends up concluding that nuclear power is significantly safer than many other everyday activities. Nevertheless, in the eyes of the public, the perceived risk may still associate nuclear power as a high-risk activity. What drives perceived risk among the public is in itself a highly complex matter but must be considered in the policy process (Goodfellow et al., 2011, Suzdaleva, 2017). An improved handling of perceived risk among the public may also reduce the financial risks of constructing new nuclear power plants.

Public attitudes are not necessarily more positive in countries where nuclear power has an important role in the energy mix, even though it may be argued that the public could potentially perceive the advantages of nuclear power that is already in place or simply from getting used to it. Eurobarometer (2010) conducted a survey to find out, among other things, whether the public considers the advantages of nuclear power to outweigh the risks or vice versa. The nuclear-power countries Germany, Spain and even France are examples of countries where the public’s views leaned towards the latter, i.e. the risks outweigh the advantages. It should be noted that this survey was done prior to the Fukushima accident. Furthermore, in non-Western countries such as Russia, there exists also a certain resistance or scepticism towards nuclear power (Suzdaleva, 2017).

The role of media

Public perceptions are significantly formed by media coverage and media coverage is inclined to focus more on the negative aspects than on the positive ones, which partly is linked to the incentives of selling points for the media (according to Koerner, 2014). The author argues for the importance of complementing the media coverage with scientific information to the public. But scientific information to the public is also associated with challenges since 1) there is no easy method to provide the public with complex information such as the issue of nuclear power 2) there exists a lack of consensus among scientists with respect to nuclear power (which is certainly obvious in our literature survey), and 3) scientific information can be used incorrectly.

Diaz-Mourin & Kovacic (2015) argue that government policy and stakeholders advocating for the use of nuclear power frequently assess the viability and desirability of nuclear power in relation to narratives about future prospects based on an optimistic engineering view, overlooking the mismatch with some present realizations (costly investments, waste-disposal issues and operational challenges in the US example as discussed in the article). The authors argue that this implies an important and possible inconsistency between expectations and experience.

Public acceptance in Sweden – The SOM institute study

The SOM-institute (*Society Opinion Media*), a public opinion analysis institute at Göteborg University, has been conducting opinion polls on Swedes perceptions on different energy sources since at least the late 1990s. As part of these annual opinion polls, answers to questions on whether the Swedish respondents want the government to invest more, as today or less in (or altogether stop using) nuclear power, are reported (see Figure 22). In the figure, the green bars represent the share of respondents with a positive attitude to nuclear power in Sweden (around 35- 40% today), while the red bars represent those being clearly negative to nuclear power (around 20-25% today). Somewhere in-between we find people that wish to see less investments than today (i.e. likely to accept the existing fleet to be used as long as it is feasible and safe to operate but discard nuclear power as a viable option in a more long-term perspective), represented by yellow bars. In the figure, we may also recognize a certain "Fukushima effect" in 2011 when the share of respondents with a positive attitude decreased somewhat.

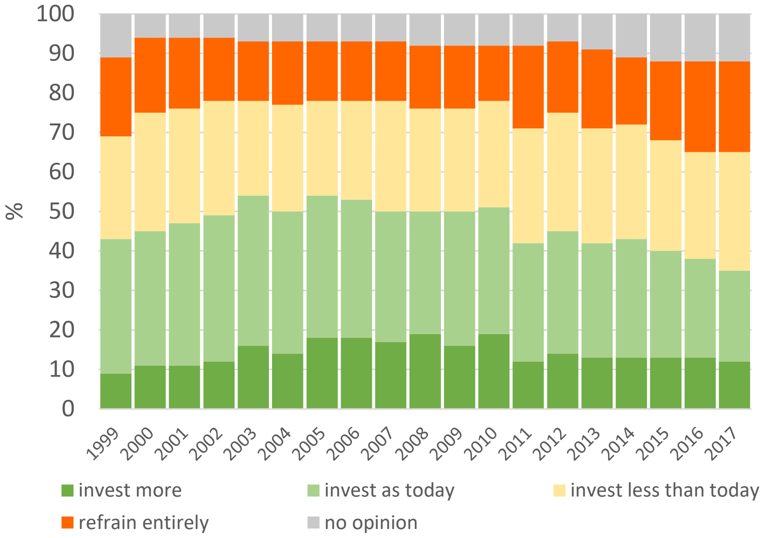
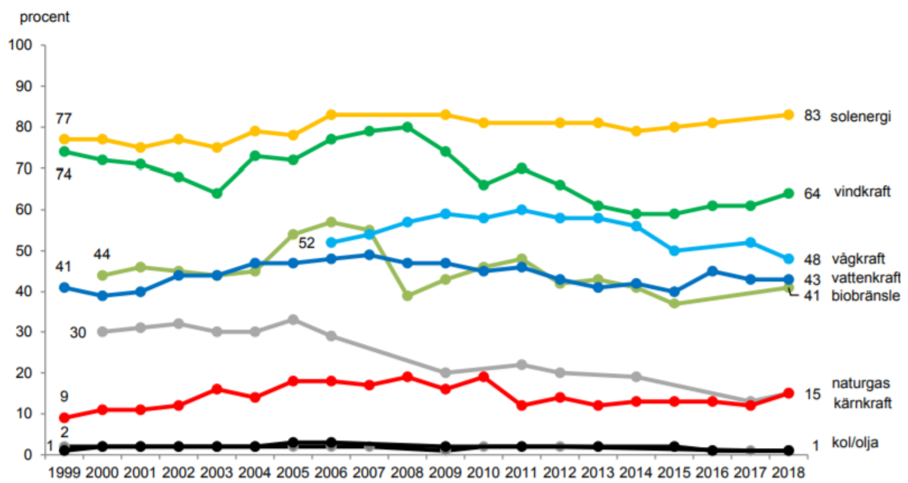


Figure 22: Share of Swedes participating in the poll that wish to invest more, invest as today or invest less than today in nuclear power (represented by green and yellow in the figure), or that wish to refrain entirely from nuclear power (represented by red in the figure), when asked "How much should Sweden invest in nuclear power the coming decade?". The number of respondents is between 1 500 and 2 000. Source: SOM (2018).

The share of the respondents that wish to see *more* investments in nuclear power (dark green bars in Figure 22) is, nevertheless, comparatively small to the corresponding share of people wanting to see more investments in renewable electricity according to the opinion poll by the SOM Institute, see Figure 23. The information in this figure may, thus, indicate the preferences of the public in a more long-term perspective.



Kommentar: Procenten har beräknats bland svarspersoner som besvarat frågan om respektive energislag. Alla energislag har inte ingått i SOM-studierna varje år. Svarsalternativen var "satsa mer än idag", "satsa ungefär som idag", "satsa mindre än idag", "helt avstå från energikällan" och "ingen åsikt". I figuren redovisas andelen svarspersoner som vill satsa mer på respektive energikälla. När det gäller biobränslen och naturgas var resultaten 29 respektive 21 procent i 1999 års SOM-undersökningen. De förhållandevis låga siffrorna redovisas inte i figur 1 eftersom vi misstänker att de är orsakade av kontextuella effekter i frågeformuläret.

Figure 23: Share of swedes participating in the poll that wish to see *more* investments in different sources of energy (yellow=solar energy; green=wind power; light blue=wave power; dark blue=hydro power; light green=biomass; grey=natural gas; red=nuclear power; black=oil). The number of respondents is between 1500 and 2000. Source: SOM Institute (2019).

The SOM Institute has performed other studies on Swedes' perceptions of nuclear power where the questions concentrated around phasing out nuclear power or not (SOM, 2017). In that study, the alternative "phase-out" accounts for the largest share but includes, however, a range of different sub-alternatives from immediate phase-out to continue to use the existing fleet as long as possible (but not to replace it with new units). Analysgruppen, which is a part of Swedenergy and whose task is to provide publicly available information on nuclear power and reactor safety, reports on a comparison between three different polls on the subject "public opinions on nuclear power in Sweden" (Analysgruppen, 2019). The questions and assessments of the polls differ somewhat, and the interpretations of the polls may, therefore, also differ.

Edberg & Tarasova (2016) have examined the arguments used in the Swedish political debate on nuclear power. They state that framings of nuclear power are closely related to the different political ideologies and that there is a clear dividing line between those who believe that nuclear power competes with renewables and those who consider them as complements. Furthermore, the authors point out that the majority of politicians in Sweden, regardless of political views, consider nuclear power to be expensive (more on costs in an upcoming section).

5.2.2 Nuclear weapons and proliferation

Several authors raise concern with respect to the civil use of nuclear power and use for military purposes. The World Nuclear Industry Status Report (2018)[6] argues that civil use of nuclear power will always be tightly linked to the production of nuclear weapons since nuclear reactors are the only effective means to generate crucial materials for nuclear weapons such as Pu-239 (plutonium).[7] Stamford & Azapagic (2011) also point specifically to the close link between nuclear waste and waste management and the risk of nuclear proliferation. Furthermore, besides such "material links", the World Nuclear Industry Status Report also raises concern for more subtle "industrial interdependencies" between the civil use of nuclear power and the manufacturing of nuclear weapons such as education, research, engineering skills and industrial capabilities that results from the civil use of nuclear power (and may diffuse to the manufacturing of nuclear weapons).

Cottrell (2017) argues that a "nuclear renaissance" implies an expansion of nuclear power which could, in fact, lead to unwanted consequences regarding nuclear security and disarmament. More nuclear power plants could increase perceptions of security risks such as diversion of nuclear weapons which, in turn, might make states hesitant to take steps towards nuclear disarmament. The author concludes by stating that if global disarmament of nuclear weapons is a goal in itself then the best would probably be to move away from nuclear power globally in the long run, even though we face a global goal of reducing GHG emissions to zero. On the other hand, the Gen-IV nuclear concept includes the development of proliferation resistance and physical protection, making diversion or theft of nuclear material

[6] Despite the name of the organisation, the authors of the World Nuclear Industry Status Report, sometimes tend to take on a more critical view on nuclear power.
[7] Highly enriched uranium (U-235), which is also a potential source for nuclear weapons, is e.g. used in specially designed nuclear reactors (for example in research and material testing reactors).

near impossible or at least highly non-attractive (Gen-IV International Forum 2018). Whether this is a sufficient counterargument against the arguments put forth by Cottrell (2017) is another issue.

Knapp & Pevec (2018) are generally optimistic when it comes to the ability of nuclear power to become a cornerstone in a future low-carbon energy supply, along renewables. However, they underline that an important precondition for such an era of abundant and competitive nuclear power is an efficient, international system for controlling traffic of fissile materials, based on the Non-Proliferation Treaty (NPT) and an extended mandate of the IAEA for safeguarding.

The IAEA (2018a) also mentions the challenge of combining a global nuclear-power expansion with minimal risks of proliferation: "*However, if nuclear capacity expands significantly after 2020 there will be a need for new large-scale facilities in additional countries. Building new conversion and fuel fabrication facilities as required should not cause difficulties. But the technology involved in enrichment is sensitive from a non-proliferation perspective, which will limit the potential locations for new facilities. For some countries concerned about security of energy supply, this may be a disincentive to rely on nuclear energy*". However, the authors of the report also suggest a solution: "*One solution could be to establish "black box" enrichment plants, where the host country would not have access to the technology. Discussions are also underway in international forums on creating mechanisms to provide assurances of nuclear fuel supply to countries that do not have their own enrichment facilities. Progress with such proposals could facilitate nuclear expansion in a broader range of countries after 2020. In the longer term, the development of proliferation-resistant advanced nuclear systems may offer technological solutions to this issue*". The latter issue, relating to technological development, is also mentioned elsewhere in the literature (and above as regards Gen-IV technology).

5.2.3 Health issues and death tolls from accidents

Another issue that is heavily debated among scientists and others and where perceptions and beliefs diverge significantly is related to the death toll of the civil use of nuclear power (and other means of energy supply). Berger et al (2017) argues, for instance, that the death toll, calculated as deaths per produced unit of electricity, is the lowest for nuclear power among all electricity generation technologies used around the world. One important explanation is air pollution, which is a key source of premature deaths across the world, and one that heavily affects the outcome for fossil fuels and biomass. In their assessments, the authors have assumed two nuclear accidents with significant radioactivity release per century for the entire fleet. It must be said, however, that the estimated death toll from the Chernobyl accident, which hitherto is the only nuclear-power accident that has taken a significant toll in terms of human casualties, is still subject to diverging estimates (more on this below).

Table 1: Number of deaths per 1000 TWh of final energy for different energy production technologies. For nuclear power, Chernobyl and Fukushima victims were accounted for (Source: Berger et al., 2017)

Technique	*Deaths per 1000 TWh*
Coal (world)	170,000
Coal (China)	280,000
Coal (USA)	15,000
Oil	36,000
Natural gas	4000
Biomass	24,000
Solar PV	440
Wind	150
Hydroelectricity	1400
Nuclear	90

Source: Data from ExternE (*Forbes Magazine*, http://www.forbes.com/sites/jamesconca/2012/06/10/energys-deathprint-a-price-always-paid/)

Like Brook (2012), Karecha & Hansen (2013) share the view by Berger et al. (2017) and conclude that nuclear power has actually saved large numbers of human lives by assuming that the alternative would have been fossil energy leading to far higher levels of air pollution across the World.

In contrast, Jacobson (2009) includes in his assessment of death tolls from different energy-supply options the risk of a nuclear exchange (due to war) and applies that to the figure for nuclear power. In that way, the author makes a very direct link between civil use of nuclear power and military use of nuclear energy. Hence, death toll estimates for nuclear power by Jacobson (2009) clearly rank among the highest of all energy-supply options included in the study.

As mentioned above, there are still diverging beliefs and views on the actual death toll from the Chernobyl accident. Due to uncertainties and the complexity of the matter the true figure will most likely remain unknown to us (Physics World, 2017). Greenpeace (2006), for instance, reports an estimated 93 080 premature deaths (in total in all affected countries) caused by the Chernobyl accident during 1986-2056 (a time frame corresponding to a typical normal life time of a human being). In comparison, the Chernobyl Forum, a group of specialists including participation from IAEA, the UN Scientific committee on the influence of atomic radiation, the WHO, the World Bank and participating experts from the closed affected countries (Belarus, Russia and the Ukraine), report an estimate of 9000 deaths in total during a lifetime and due to the accident (WHO 2006).[8] The Chernobyl Forum emphasizes that uncertainties in such estimates are large, especially for areas not in close proximity to the accident due to the low average dose which is close to the natural background radiation (Chernobyl Forum, 2006; low-dose health effects is a widely debated research area, see e.g. Socol, 2015).

Adamantiades & Kessides (2009) base their arguments on the findings by Chernobyl Forum and conclude that "*although the Chernobyl accident was large-scale and severe, it was not out of line relative to other serious industrial accidents—such as the one in Bhopal, India, in 1984, when a large leak of methylisocyanide occurred*". The authors also add: "*Still, political decision makers cannot afford to ignore public*

[8] According to the Chernobyl Forum, around 4 000 of the total estimated 9 000 death casualties are estimated to origin from the most contaminated areas, while the rest originates from areas further away from the site of accident (WHO, 2006).

perceptions. Thus, the Chernobyl accident had a dramatic, decisive effect on the fate of nuclear power worldwide".

Stamford and Azapagic, (2011) discuss the difficulties in estimating accident risks with different types of energy supply. Using Probabilistic Risk Assessment (PSA), for instance, they imply that estimates based on many accidents can carry the same uncertainty as estimates based on a single accident. The nuclear industry has so far been subject to a very small number of accidents, albeit with extensive impact, while other sources of energy supply, the authors argue, experience accidents with a higher frequency but with fewer consequences per incident.

Finally, there are not only disputes around the true death toll from the Chernobyl accident but also around other health-related effects caused by the accident such as non-mortal diseases and depressions (Physics World, 2017).

The Brundtland report (WCED, 1987) also mentions nuclear power and its "*unresolved problems*" in the wake of the Chernobyl accident. The report concludes that national reactions after the accident tended to take up three possible positions on nuclear power:

- To remain non-nuclear and develop other sources of energy
- To regard their present nuclear power capacity as necessary during a finite period of transition, to safer alternative energy sources; or
- To adopt and develop nuclear power with the conviction that the associated problems and risks can, and must, be solved with a level of safety that is both nationally and internationally acceptable.

When it comes to normal operation of nuclear power plants, the IPCC's Fifth Assessment report (Bruckner et al., 2014) points to uncertainties regarding childhood leukaemia in nearby areas, and that the significance of a potential effect remains unresolved.

5.3 ECONOMIC ASPECTS ON NUCLEAR POWER

The third dimension of sustainability, the economic dimension, relates to the way human society must economize resources that are important to satisfy human needs (Hedenus et al., 2018). The economic dimension of sustainability may be divided into two parts: finite natural resources and capital created by humans.

In relation to nuclear power and economic aspects of sustainability, we include issues dealt with in literature such as

- Capital costs of (new) nuclear power plants
- Insurance costs and liability in case of accidents
- The ability of technological development to reduce investment costs
- Competition with other electricity-generating technologies
- The integration of nuclear power plants into an electricity system with increased variability

In the 5th IPCC Assessment report (Bruckner et al., 2014), the economic co-benefits, besides climate change-mitigation, of replacing coal with nuclear are presented as increased energy security (reduced exposure to price volatility) and local employment impact (stated as uncertain) while the legacy cost of waste and abandoned reactors are mentioned as examples on the down-side.

5.3.1 New investments

In an extensive MIT study on prospects of nuclear power (MIT, 2018), investment costs of new nuclear power plants are mentioned as the main current obstacle for a more positive development of nuclear power: "*One obstacle is that the cost of new nuclear plants has escalated... This may limit the role of NP in a low-carbon portfolio and raise the costs of deep decarbonization. The good news is that the cost of new nuclear plants can be reduced*."

MIT (2018) estimates of overnight costs[9] of selected ongoing LWR (Gen III+) projects mainly in the Western world are shown in Figure 24. Clearly the absolute majority of the ongoing projects are far from the proposed 2009 MIT benchmark for such projects. However, in other parts of the world, as in China, costs are significantly lower, typically half of the estimated costs shown for the Western World projects in Figure 24. One important reason for this is that wages of engineers and other necessary labour forces are considerably lower in China than in the Western World. Taesik et al. (2017) found nuclear power to be the most cost-efficient way to reduce greenhouse-gas emissions from coal-fired electricity generation in South Korea. The study includes monetary estimates of external costs, including severe nuclear power accidents. Nuclear power was compared to CCS, renewable electricity and natural-gas fired combined cycle power plants. The authors used investment costs for Korean nuclear power plants that are, on average, significantly lower than Western World estimates. The choice of technology costs and discount rates (as well as assumptions on the competing technologies) does, of course, have an impact on the final result.

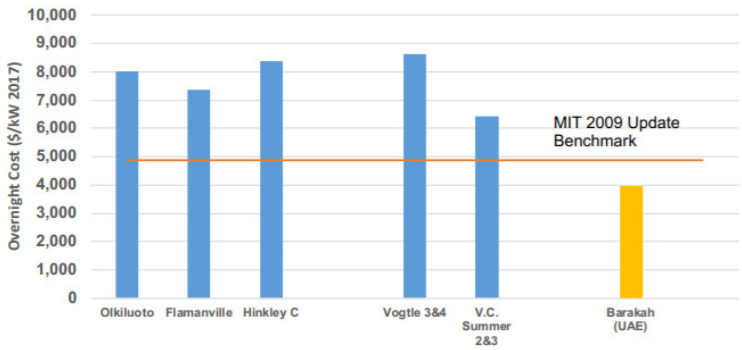


Figure 24: Overnight costs of recent Gen III+ projects. The three left bars show ongoing projects in Europe, the two bars in the middle show ongoing projects in the US and the rightmost bar show a South Korean build in United Arab Emirates. In the last project, cost estimates are very uncertain (Figure from MIT, 2018). Note that the V.C. Summer 2&3 project was abandoned in 2017.

[9] The cost of a construction project as if the project was completed overnight and, thus, without interest costs during construction.

Typical breakdowns of capital costs are shown in Table 2 (from MIT, 2018). It is important to note that only some of the capital costs, approximately 10-20%, are uniquely related to nuclear engineering and the reactor core, i.e. "nuclear island equipment". The rest is related to engineering and financial costs which are also common in other large-scale and capital-intensive projects in e.g. manufacturing industries or in other large-scale (non-nuclear) thermal power plant constructions. By improving such skills and learning from other similar non-nuclear projects, those cost components may be reduced for state-of-the art nuclear technology. This is also emphasized by the authors of the MIT report as being key to increasing economic attractiveness of new investments: "*Focus on using proven project and construction management practices to increase the probability of success in the execution and delivery of new nuclear power plants*".

Table 2: Cost breakdown for various LWRs (Table taken from MIT, 2018)

	Cost Breakdown (% of total cost)				
	Generic AP1000	Historic U.S. LWR Median Case	Historic U.S. LWR Best Case	South Korean APR1400	EPR
Nuclear Island Equipment	12.6	9.9	16.5	21.9	18.0
Turbine – Gen. Equipment	4.9	7.0	11.9	5.6	6.3
Yard, Cooling, and Installation	47.5	46.3	49.3	45.5	49.7
Engineering, Procurement, and Construction Cost	15.9	17.6	7.7	20.0	15.3
Owner's Cost	19.1	19.2	14.6	7.0	10.7

Another recent study on investment costs for nuclear power (and other generation technologies) was made by the US Energy Information Administration (2019), "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2019", see Table 3. The cost for a new advanced nuclear power plant is estimated at almost 80 USD(2018)/MWh which is considerably higher than e.g. onshore wind power and solar PV. The estimates are valid for typical US conditions. Conditions for nuclear power and especially renewable electricity (which indeed is regional and site specific) may differ in other regions of the World.

Table 3: Estimated levelized cost of electricity (unweighted average) for new generation resources entering service in 2023, USD(2018)/MWh (Table taken from US EIA, 2019)

Plant type	Capacity factor (%)	Levelized capital cost	Levelized fixed O&M	Levelized variable O&M	Levelized transmis-sion cost	Total system LCOE	Levelized tax credit[1]	Total LCOE including tax credit
Dispatchable technologies								
Coal with 30% CCS[2]	85	61.3	9.7	32.2	1.1	104.3	NA	104.3
Coal with 90% CCS[2]	85	50.2	11.2	36.0	1.1	98.6	NA	98.6
Conventional CC	87	9.3	1.5	34.4	1.1	46.3	NA	46.3
Advanced CC	87	7.3	1.4	31.5	1.1	41.2	NA	41.2
Advanced CC with CCS	87	19.4	4.5	42.5	1.1	67.5	NA	67.5
Conventional CT	30	28.7	6.9	50.5	3.2	89.3	NA	89.3
Advanced CT	30	17.6	2.7	54.2	3.2	77.7	NA	77.7
Advanced nuclear	90	53.8	13.1	9.5	1.0	77.5	NA	77.5
Geothermal	90	26.7	12.9	0.0	1.4	41.0	-2.7	38.3
Biomass	83	36.3	15.7	39.0	1.2	92.2	NA	92.2
Non-dispatchable technologies								
Wind, onshore	41	39.8	13.7	0.0	2.5	55.9	-6.1	49.8
Wind, offshore	45	107.7	20.3	0.0	2.3	130.4	-12.9	117.5
Solar PV[3]	29	47.8	8.9	0.0	3.4	60.0	-14.3	45.7
Solar thermal	25	119.6	33.3	0.0	4.2	157.1	-35.9	121.2
Hydroelectric[4]	75	29.9	6.2	1.4	1.6	39.1	NA	39.1

IAEA (2018a) argue that new nuclear power is already a competitive source of electricity, especially when including system-integration costs (grid connection and upgrading costs, short-term balancing costs and long-term costs for maintaining back-up capacity) for the competing variable renewable technologies PV and wind power. NEA (2018) estimates both plant-level costs (Figure 25) and additional grid-integration costs (Figure 26). Adding costs in Figure 26 to the plant-level costs in Figure 25 tends to favour dispatchable electricity generation such as thermal power (including nuclear power). However, the basis for the estimates of grid-integration costs in Figure 26 were made in 2012 and may, therefore, be perceived as a bit conservative especially in the wake of the rapid development of variable renewable electricity. Furthermore, renewable electricity (and other) integration costs are highly dependent on the system context and such estimates tend to vary quite significantly (see e.g. Hirth et al., 2015). For instance, large amounts of variable electricity generation are likely to be easier integrated into electricity markets with a significant share of flexible hydro power (as the Nordic electricity market) than in markets that rely mostly on thermal-based electricity generation. Moreover, the prospects for end-use flexibility will also be a key component in facilitating the integration of increasing volumes of variable renewable electricity.

Even though it is difficult to fully estimate (and highly dependent on the system context), system-integration costs should not be overlooked and cost comparisons between technologies should not be limited to plant-level costs. A complete system-based estimate of the costs and benefits of different generation technologies and/or different technology strategies can only be assessed by using comprehensive energy-systems modelling including both an appropriate time perspective and the relevant system context.

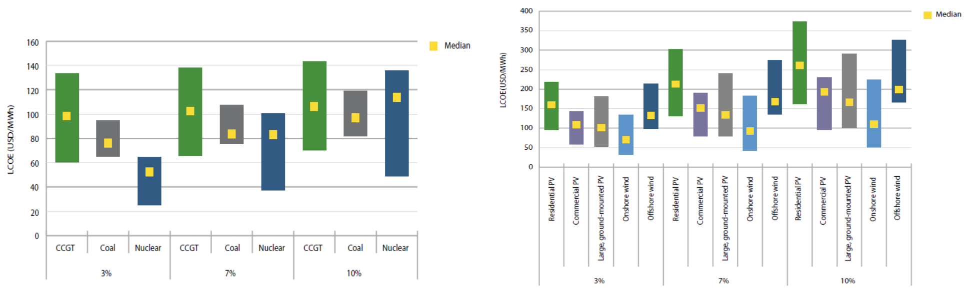


Figure 25: Plant-level costs for different electricity-generation technologies, USD/MWh (figures from NEA, 2018)

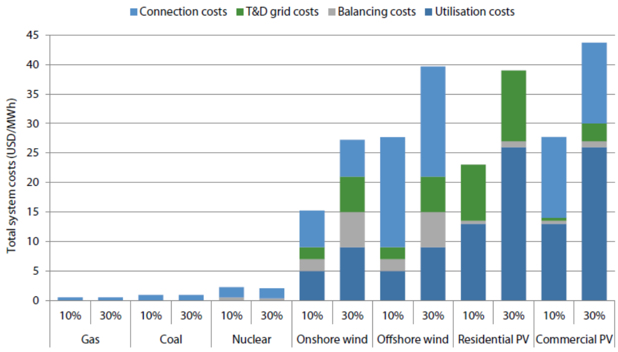


Figure 26: Grid-level system costs of selected generation technologies for shares of 10% and 30% of variable renewable electricity, in USD/MWh (figure from NEA, 2018)

As concluded in MIT (2018) and in several of the scientific papers included in our survey, the high cost of investment is commonly referred to as a major obstacle to nuclear power and its ability to become a significant climate-mitigation measure (e.g. Mez, 2012, Pearce, 2012; Adamantiades & Kessides, 2009).

Finally, also worth mentioning in this context, life-time extension and upgrading of existing plants is likely to be substantially cheaper than building new power plants. (Hejazi, 2017; Energy Times, 2018; NEA, 2012b).

5.3.2 Lead times and risks during planning, construction and operation.

Construction times for new nuclear power differ among regions and may depend on various conditions such as regulation processes and construction experiences. Typical construction times in China (from "first concrete" to grid connection) are 60-70 months (reported by IAEA, Power Reactor Information Service). In the Western World, ongoing projects exhibit considerably larger construction times. For instance, the O3 reactor in Finland was due to commence operation in 2009 but is still not ready for operation. Flamanville 3, with its construction start in 2007, was initially targeted for operation in 2012 but is now expected to start delivering electricity to the grid in 2020 (Business News, 2018). Both reactors are so-called European Pressurized Reactors (EPR). The TVA-owned Watts Bar-2 in the US is a remarkable example of long lead times: construction started in 1972 and the plant was connected to the grid in 2016. However, the construction had come to a halt in 1985 due to a projected insufficient electricity demand.

Consequently, there is a need for substantial improvements in construction and lead times related to new nuclear power plants in the Western World. A benchmark for a typical construction time frame including approval and contracting amounts to roughly 9 years, out of which the actual construction phase (from "first concrete") amounts to 4-5 years (World Nuclear Association, 2018). Kessides (2012) uses the two mentioned projects in Finland and France as examples of when significant time and cost overruns pose considerable project- and financial risks. And since these units are still not commissioned, this specific argument holds even more firmly today.

Kim et al. (2017) developed a risk-assessment tool for power-plant construction based on an extensive literature survey and expert interviews and they conclude that nuclear power plants generally have significantly higher risks in all relevant areas of the project life cycle compared to coal and natural gas fired power plants. The authors stress that such risk factors of nuclear power plant construction need to be continuously monitored and evaluated in order to explore sustainable nuclear power plants.

Mez (2012) argues that it is not only rising construction costs for nuclear power that are a relevant obstacle for a "nuclear renaissance" but also bottlenecks related to industrial and production capacities and shortages of technical experts and engineering resources. Environmental NGOs (e.g. Greenpeace and Swedish Society for Nature Conservation) typically argue that mankind has a limited amount of capital and time for dealing with climate change-mitigation and should, therefore, invest in safer and more reliable options as e.g. renewables. On the other hand, Brook (2012) argues that if the world can repeat the rapid build rate of the 1980s (peaking around 1984 with 30 GW) than this would be sufficient for a significant, global and necessary expansion of nuclear power in order to tackle climate change.

5.3.3 Insurance costs and liability

Another issue related to the economic dimension of sustainability and mentioned in a few of the surveyed articles, is that of limited liability of nuclear power utilities when it comes to accidents. It is argued that the insurance amount paid for by a utility does not cover the estimated costs of an accident (e.g. Pearce, 2012). Furthermore, the economic assets owned by the utility will most likely be insufficient to cover the costs of an accident. Society must therefore cover the remaining costs in the event of a nuclear accident. Verbruggen et al. (2014), for instance, argue that non-insurable activities should not be permitted and that this is the case with nuclear power since insurance companies are unwilling to provide full indemnity coverage of nuclear power plants. The limited liability of nuclear power utilities and its implications for economic sustainability are also mentioned as concerns in a paper by Laureto & Pearce (2016). They have estimated that the costs of the Fukushima accident are at least 4 times (up to several orders of magnitude) the amounts of insurance premiums pre-emptively paid and that the true costs of nuclear power are, thus, underestimated. Furthermore, the authors argue that nuclear power countries ideally should maintain the ability of their nuclear industry to economically support recovery costs for at least one environmental disaster. Another conclusion by the authors is that the cost estimates from the Fukushima accident are highly uncertain or difficult to calculate due to, among other things, the quality of sources (see previous section). The authors argue that in order for nuclear power to become a prominent and sustainable energy source such cost implications must be fully understood. The authors go on to say that the same goes for safety and climate-change impacts. Environmental NGOs also tend to mention the limited liability as reasons for questioning the economic sustainability of nuclear power (e.g. Swedish Society for Nature Conservation, 2013)

In Sweden, since 2019, the operators of a nuclear power plant must take financial responsibility for covering costs of a potential nuclear accident to an amount of approximately 12 Billion SEK (Swedish Parliament, 2019). Furthermore, the nuclear utility is obliged to guarantee that amount through a liability insurance. As mentioned, there is a limit to what insurance companies currently are willing to provide in terms of insurance amounts (around 15 Billion SEK according to OKG (2019)). For accident costs exceeding the amount covered by the liability insurance, economic assets of the responsible utility may be used but ultimately, the state will have to provide funding to cover the potential cost gap. One argument used to justify state involvement is that political decisions laid the foundations for nuclear power in Sweden (KSU, 2019)

5.3.4 The role of nuclear power in the electricity system

The increasing volumes of variable renewable electricity generation will increase the demand for flexible generation in thermal power plants (and other flexibility measures). Due to high capital costs and low running costs, nuclear power stations are preferably run in baseload operation. This is one reason why many nuclear power plants around the world operate at rated power with a minimum of variability. Another reason for a non-flexible production is inherent reactor design limitations, such as xenon reactor poisoning that effectively hinders fast up-ramping after down regulation of a nuclear power plant and thermal stress, induced by temperature variations due to power variations, affecting the pellet-clad interaction (PSI) (IAEA, 2018b; Jenkins et al., 2018). These limitations affect the minimum load of the power plant, which is typically relatively high compared to e.g. gas fired power plants (and generally also coal power plants). However, alternative designs and design improvements, alternative fuel arrangements in the core and upgrades of existing nuclear power plants may present possibilities to operate in a significantly more flexible mode (IAEA, 2018b; Stamford & Azapagic, 2011). Nuclear power plants in e.g. France and Germany are designed for load following and such tests with Swedish nuclear power plants (that originally were not designed for load following) have also proven successful (Elforsk, 2012). In fact, nuclear power may potentially contribute to several system and ancillary services necessary in the electricity market (IAEA, 2018). This, however, may reduce full-load hours and would require additional income streams from e.g. providing system services. One way of increasing utilization of a future nuclear power plant in a context where electricity demanded is increasingly intermittent (depending on the availability of non-dispatchable renewable electricity), is to co-produce other goods such as hydrogen, desalination, district heating and process steam (see e.g. Brook et al., 2014; MIT, 2018).

Knapp & Pevec (2018) argue that existing LWR technology is necessary for supplementing renewables, for combatting climate change due to the intermittent nature of renewables and because renewables alone cannot provide for the expansion rate necessary for climate mitigation. Other authors and organisations argue that nuclear power plants are indeed inflexible and therefore not suited for a future electricity-generation mix where flexibility will be increasingly necessary to host large volumes of renewable electricity (e.g. Verbruggen et. al., 2014; Swedish Society for Nature Conservation, 2013).

6 Synthesis and assessment of the literature survey

Hitherto, we have reported on the diverse views, perceptions and diverging knowledge found in the literature on nuclear power and the concept of sustainability. In this chapter, our intention is to assess and summarize to what extent the literature considers nuclear power to be part of a future sustainable energy system, if at all. In the preceding chapters we included a broad range of literature such as scientific papers, conference papers, books, reports and position papers of various kinds. In this chapter, we narrow our focus to only including scientific papers. We found 53 such papers in total, dealing with nuclear power and sustainability in one way or another. Out of these 53 papers, we kept 31 of them for our final assessment presented in this chapter. The additional filtering was a result from lack of relevance and level of quality. This is, of course, based on our own judgement. The 31 papers included in this assessment are listed in Appendix 1 in this report. Many of these papers are also referenced in the previous chapters of this report and, therefore, also included in the reference list (Chapter 8).

6.1 RESULTS FROM THE ASSESSMENT

In Figure 27, we present our attempt to position the scrutinized scientific papers (the 31 papers mentioned above) in relation to their findings and views on our two main questions: whether nuclear power can be considered as being part of a future sustainable energy system or not (left panel) and whether nuclear power is a part of a climate change-mitigation solution or not (right panel). Since the concept of sustainability is broad and covers much more than the issue of climate change, we have tried to distinguish between these two questions, which are, as mentioned in the introduction of this report, the two main questions that we address in this study. In many cases, the articles were not specific in their conclusion. Consequently, we either labelled them as "Not specified", which was the default procedure, or we labelled them as belonging to one of the other three groups depending on the information that could be "read between the lines". In some cases, the authors' positions were rather clear even though they did not specifically answer our main two questions. Once again, it is our judgement that lies behind this assessment and, though far from being an exact science, we have put our best effort in making the assessment as unbiased and illustrative as possible.

Our first conclusion from the assessment is that there is no clear consensus among scientists regarding these questions. In fact, positions are quite divergent, as we have pointed out earlier in this report. A clear majority of the relevant papers do not answer the question whether nuclear power is part of a sustainable energy system or not. Almost one quarter consider nuclear power not to be part of such a system, while 13 percent of the papers clearly believe it is. Papers that we consider belong in the "Maybe" group are open to nuclear power playing a part in a sustainable energy system but also raise several concerns that must be overcome. Pearce (2012) is a typical example of a paper that we have put into the "Maybe" group. The author concludes by listing a number of crucial issues that must be dealt with and "*If this can be done, nuclear power will enjoy a long and sustainable future. If these requirements are not met, nuclear power will be eliminated by more sustainable rival technologies*". It is far from obvious whether the authors in the "Maybe" group believe that these concerns or obstacles can be sufficiently dealt with or not.

When it comes to the question of whether nuclear power is part of a climate-mitigation strategy, the positions seem to become somewhat more specific and clear. Papers that clearly discard nuclear power as a sustainable option also discard nuclear power as part of climate change-mitigation. However, among the papers labelled as "Not specified" or "Maybe" we find that some take a clearer positive position on whether nuclear power has a role to play in climate mitigation or not.

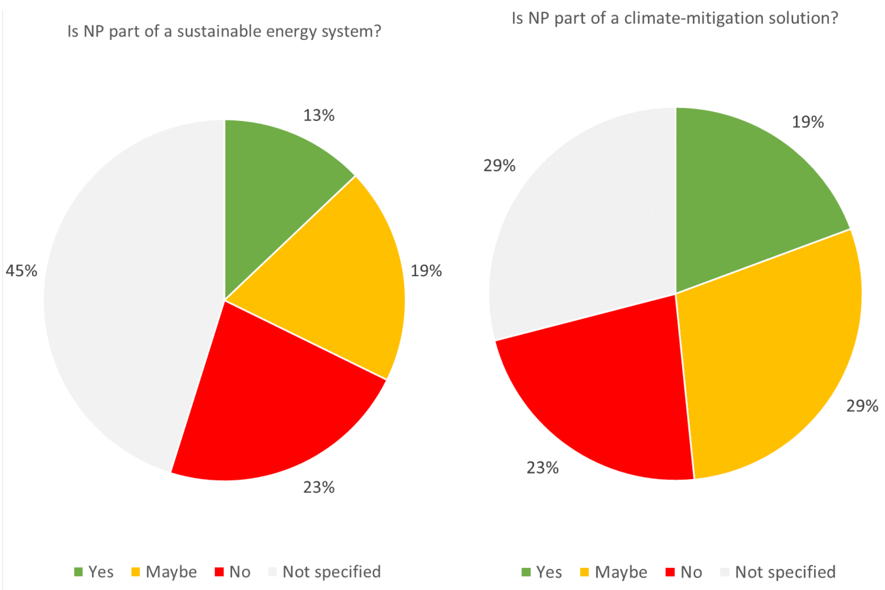


Figure 27: Position of the assessed papers as regards their view on nuclear power and its link to sustainability.

In Figure 28, we present the distribution among the papers with respect to scientific discipline and with respect to focus area. Scientific discipline is based on our estimate of the main author's scientific residence. In some cases, this is not obvious, especially since scientists within energy and climate policy can have several scientific residences. Based on our judgement, the majority of the authors are within the field of engineering followed by natural sciences (including geosciences, biology, etc). Focus areas are what we consider to be the main area of interest, or main topic of each paper. We consider the absolute majority of the papers included in our final scrutiny to apply, or at least have the ambition to apply, a broad perspective on the issue of nuclear power and its link to sustainable energy systems and climate change-mitigation. A significant part of the papers focus more on the environmental dimension of sustainability, and its implications for nuclear power.

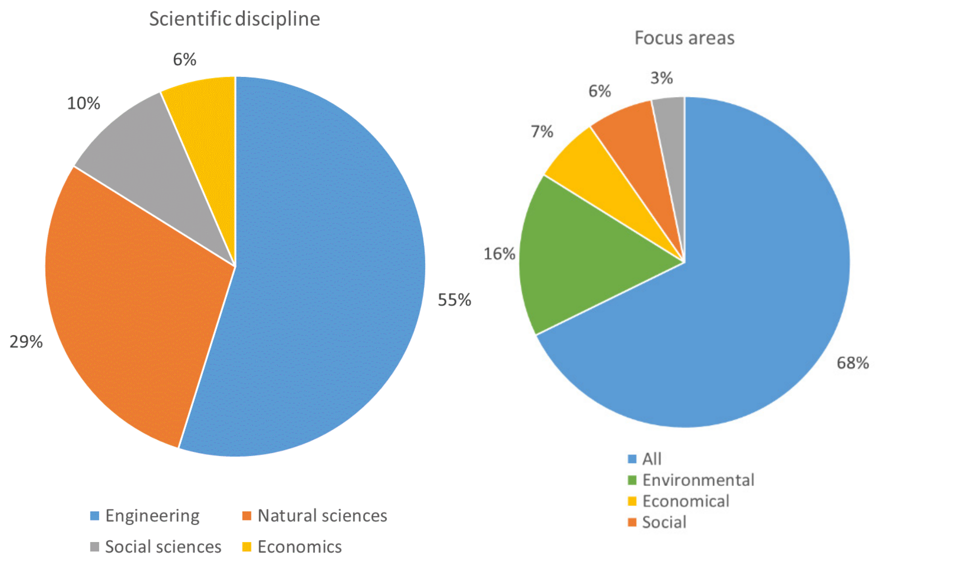


Figure 28: Position of the assessed papers as regards their origin of scientific discipline (left) and their focus area (right).

Finally, in Figure 29, we present the papers according to the main author's country of affiliation. In this figure, contrary to the assessment in Figure 27 and Figure 28 we have chosen to include all 53 originally scrutinized papers and not only the ones used in the final assessment above. It is clear that most of the contributions come from the US but that many countries are represented within this field of research.

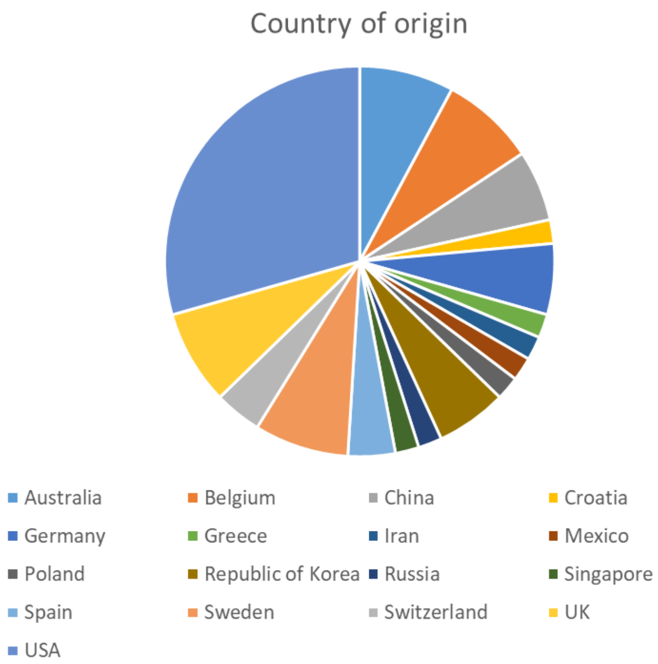


Figure 29: Country of origin of main author's affiliation in all papers in the original scrutiny (53 papers)

6.2 COMMON ARGUMENTS

In this section we summarize several key issues related to the use of nuclear power and where interpretations and arguments differ depending on whether the author or authors take on a supportive view towards nuclear power or whether the author or authors take on a sceptical or negative view towards nuclear power. We do not intend to cover all arguments for or against nuclear power but rather give the reader an idea of the more common arguments put forward in relation to these key issues. Here we try to reflect all the literature that we have come across in this study and not limit ourselves to the scientific papers assessed in the former section. Several of the arguments that we summarize in this section are probably well-known and familiar to many readers. Kermisch & Taebi (2017) summarize the positions present in the scientific community by concluding that proponents of nuclear power tend to argue that nuclear power is sustainable because it gives access to affordable electricity with low carbon emissions, while opponents argue that it can never be sustainable due to the short and long-term radiation and security risks involved.

Resource base

The proponent's view: *There is an abundance of resources when considering also uranium dissolved in seawater, thorium fuels and reprocessing of spent fuel and weapons-grade fuel.*

The opponent's or sceptic's view: *Uranium sources, as they are exploited today, are finite and thus not sustainable. Typical estimates are that they will last less than 100 years, considering the current demand.*

GHG emissions from nuclear power

The proponent's view: *The future nuclear-fuel cycle will rely heavily on spent fuel reprocessing and use of depleted uranium making the mining and enrichment process, a significant contributor of the GHG emissions associated with nuclear power, obsolete. However, already today the current state of enrichment is generally associated with low GHG emissions. Furthermore, future electricity will be generated by low-carbon sources leading to a lower climate impact from the use of electricity. (Proponents tend to use the low-end (or zero) figures in the interval of lifecycle emissions)*

The opponent's or sceptic's view: *Increased exploitation of nuclear fuels will lead to increased use of lower-grade uranium ores with increased electricity use in mining and fuel processing as a consequence and thus increased emissions.*
(Opponents tend to use the high-end figures of lifecycle emissions)

Economy

The proponent's view: *Current reactors deliver electricity at a very low cost and technological development will reduce costs for new investments. Lifetime extension is one of the most cost-efficient climate change-mitigation measures. The nuclear power operator bears the full costs of operation and nuclear power is not subsidized. Liability is financially covered within the means currently offered by the insurance market.*

The opponent's or sceptic's view: *Very high costs and very long lead times for ongoing projects (in the Western World). The necessary technological development has yet to manifest in practice. The nuclear industry does not carry its own costs since the estimated costs of a nuclear power plant accident, e.g, estimates of Fukushima, are significantly larger than insurance amounts and liability of plant operators.*

Consequences of accidents

The proponent's view: *The death toll caused by accidents is extremely small when allocated to cumulative electricity production (even smaller than many renewable supply options).*

The opponent's or sceptic's view: *A nuclear-power accident creates fear, trauma, negative publicity and a lack of trust among the public that goes beyond the risks of accidents posed by other supply options. Such public conceptions cannot be underestimated or neglected.*

Waste management

The proponent's view: *Technological development will reduce waste volumes and, thereby, the significance of this issue. Furthermore, the waste will be disposed of in an environmentally inert form implying that the risk of leakage is negligible. Waste generated by nuclear power is, measured in volume, far smaller than waste (including emissions) generated by fossil fuels.*

The opponent's or sceptic's view: *Potentially hazardous problems for future generations as well as safety issues and information challenges (how can the waste be sufficiently safeguarded for generations to come?).*

Proliferation

The proponent's view: *Weapons-grade material is preferably produced from highly enriched fuel (or low burnup fuel) and is usually extracted from depleted uranium reactors specifically designed for that purpose. Thus, common nuclear power plants are generally unfit to produce weapons-grade material.*

The opponent's or sceptic's view: *The use of civil nuclear power is tightly interlinked with military use of nuclear weapons in many aspects, including nuclear-engineering know-how.*

Nuclear power and flexibility

The proponent's view: *Load-following abilities and increased flexibility of nuclear power plants is a matter of technological design, and France and Germany have flexible units in their fleet. In Sweden, experiences with load following have been proven feasible but have not been further utilized (hydro power is currently used as main load follower). The energy-intensive industry argues for secure and necessary baseload power generation.*

The opponent's or sceptic's view: *Nuclear power is not able to handle the amplified variations due to increased penetration of variable renewable electricity generation, Other means must be used (batteries, end-use flexibility, interconnectors, flexible generation (not* *nuclear) and digitalization). Baseload demand corresponding to a great number of full-load hours will not be available in the future due to the significant penetration of low-cost (running costs) renewables.*

The inter-generational dilemma

The proponent's view: *The long-term and drastic effects of climate change forced upon future generations require the use of nuclear power today. Increased wealth through economic growth requires the use of a secure and stable source of electricity such as nuclear power.*

The opponent's or sceptic's view: *The longevity and potential hazards of nuclear waste, inflicted upon future generations, makes it irresponsible to continue to use nuclear power.*

7 Final reflections

In this final chapter we summarize our findings and include some additional reflections.

The book by Professor David Elliot (2017) concludes with "*The nuclear power field is contentious, with strong pro- and anti-nuclear views often being expr*essed". After having finalized our literature survey we could not agree more. Although pro- or anti-nuclear views are sometimes explicitly expressed in the scientific literature, they are more often than not expressed in a more subtle way than in the media, among the public or among politicians. However, for a large share of the publications included in our survey, we found no clear bias. The complexity of the subject and the diverging perceptions and beliefs present in the scientific community makes it difficult for laymen and the public to get a clear picture on this matter. It is important for policy makers to realize that.

Growing concern for climate change has in several ways increased interest, or at least spurred the debate also among scientists, in relation to nuclear power. Edberg & Tarasova (2016) write with respect to the debate in Sweden: *"Climate change is a game changer for energy transition because, at least for some actors, it removes the focus from questions of nuclear waste, accidents, and weapons to a discussion about energy sources with low carbon dioxide emissions. Accordingly, the "new situation" also makes it possible to take another stance in the current debate than was possible in the referendum in 1980. For other actors, the main arguments surrounding nuclear power remain. The desire to achieve sustainable development of the Swedish energy system is, however, a common thread among all actors".* On the other hand, opponents of nuclear power generally argue that growing concern of climate change is not a reason to reconsider nuclear power since the flaws of nuclear power simply are too large (se e.g. Swedish Society for Nature Conservation, 2019).

The Fukushima accident in 2011 seemed to have spurred a certain (and fairly recent) increase in publications and other reporting on nuclear power. Many of these articles are especially focused on public perception and acceptance.

As noted by Kermisch & Taebi (2017), sustainability as a concept seems to be used both by proponents and opponents as a way to help endorse or reject nuclear power as an energy source. Kermisch & Taebi argue that sustainability could best be conceived as a moral framework that consists of several moral values. In this aspect they conclude that, if we can escape dichotomous positions such as the ones above, sustainability could be a helpful notion for understating important dilemmas of nuclear power. In doing so, the choice as to which aspect that should prevail (when it comes to a certain option, that can be seen as both sustainable and unsustainable depending on what definition is used) can be viewed as a moral question. As we mentioned in Chapter 2, the moral framework, according to Kermisch & Taebi, should answer three questions, namely: what should we sustain, why should we sustain it and for whom should we sustain it?

We have also reported on different scenario analyses and studies and focused especially on what they say on the prospects of nuclear power. Once again, results and findings differ. Such scenario analyses are generally based on comprehensive energy systems modelling. Differences in scope (geography and energy sectors included in the model framework), methodology and mathematical formulations, time frame and the choice of key input data such as policy, costs, development and availability of different technologies (and fuels), economic and energy-demand growth and discount rates are factors that explain such differences. The climate change-mitigation scenarios presented in IPCC (2018) reflect the width of the outcomes in regards to nuclear power and include pathways that point to increasing reliance on nuclear power as well as pathways showing a decreasing contribution from nuclear power across the world. Furthermore, there are scenario analyses where the actual starting point is that nuclear power is not optional (Greenpeace, 2015). Scenarios presenting an increasing importance and relatively high penetration of nuclear power generally assume positive technological progress for nuclear power with decreasing costs for new plants (e.g. FTI Consulting/FORATOM, 2018). Common for all scenario analyses that we have looked into in this study, is the rapid growth and the dominating role (in a long-term perspective) of renewable electricity generation. The question is, therefore, whether nuclear power can play a role as an important complement to renewables or not.

In short, and in addition to our reflections above, our findings in the present literature survey may be summarized as:

- There is no scientific consensus whether nuclear power is a part of a long-term sustainable energy system or not. Views differ, sometimes significantly between authors, as regards different aspects on nuclear power such as GHG emissions from the nuclear fuel cycle, economics, fuel availability and other sustainability aspects, as we reported on and discussed in the previous chapter ("common arguments"). In that sense, science reflects society at large.
- We have not found any clear indication that a "nuclear renaissance", a phrase occasionally used in the media, has an equivalent in the scientific literature. Climate-change mitigation and sustainable energy systems have been subject to research for quite some time now. In that sense, no new scientific evidence has appeared in recent years to either promoting nuclear power or discarding nuclear power.
- A minority of our scrutinized scientific paper gives a clear answer as to whether nuclear power is part of a sustainable energy system and whether nuclear power is a key component in climate mitigation. In that context, some of these authors are clearly against nuclear power while others consider nuclear power as vital. The majority of the authors and papers take on a more cautious perspective without clear statements. They instead raise concerns and present challenges that must be overcome for the nuclear industry in order to present nuclear power as a viable option. However, some of these authors are open to the idea of nuclear power being a part of a future sustainable energy system, once such concerns are overcome.
- Public acceptance is considered a key issue by both proponents and opponents alike and is, therefore, a key topic in many research papers and other

publications. The issue of "trust" is considered as essential in this context. This includes the public's trust in authorities, regulatory bodies, the industry itself and in the information given by officials.

- For new investments high upfront costs and highs risks are often regarded as key obstacles. A few authors argue that insurance costs for nuclear power plant operators should be significantly higher to be able to cover the total costs from potential accidents. With that in mind, they argue, nuclear power has very limited prospects of being economically sustainable.
- Besides costs and economic risks, waste management, proliferation and risks of nuclear accidents are frequently mentioned in the literature as obstacles and concerns to be dealt with.
- Sustainability is in itself a concept with different definitions and a concept that is used differently. Sustainability seems to be used by both proponents and opponents as an evaluative notion that could help endorse or reject nuclear power. Nevertheless, the use of the concept of sustainability is increasing.
- Several sources in our literature survey indicate that no energy option/technology may currently be considered as fully sustainable.
- Several scientific publications that we have scrutinized aim at dealing with the entire matter of sustainability (i.e. apply a broad perspective including environmental, social and economic aspects), while other publications' focus is on specific issues (public perceptions, lifecycle emissions or profitability).
- Even though there is significant deviation among different sources on the amount of GHG emissions from nuclear power in an LCA perspective, the general conclusion is that nuclear power most likely has low lifecycle GHG emissions of the same order as renewable electricity. Corresponding emissions from the use of fossil-fuelled alternatives are much larger.
- Subjective perceptions exist in certain scientific publications on "both sides". We base this on choice of words as well as phrasing and, occasionally, the use of biased data without a supplementary discussion, or reflection, on the underlying uncertainties.
- Many researchers study the same issues or problem areas – their conclusions or findings, however, may be different.

The arguments used in the debate on nuclear power and sustainability (in science and in other parts of society) may have become somewhat refined over the past years but have not changed significantly during the course of time. In an article by Bickerstaffe & Pearce from 1980, health risks due to accidents, proliferation, waste management and public acceptance and risk perceptions are considered to be critical issues to deal with. In the same article nuclear power is also presented as an abundant resource for replacing depleting fossil resources. Concerns for climate change and air pollution have evolved since 1980s, which has led to beneficial implications for nuclear power but also for competing renewables, as we have reported in our study. The world has also experienced two major nuclear accidents since 1980, which have, of course, produced material for research on e.g. public acceptance and on costs of nuclear accidents.

Finally, since we have concluded in the summary above (based on the literature survey) that nuclear power is generally seen as a technology with (very) low GHG emissions, in the same order as renewable electricity, we may conclude that nuclear power exhibits climate-mitigation *potential* during a foreseeable future. If we can agree on this, the question whether nuclear power can be part of a viable climate-mitigation *solution* may boil down to answering two questions that, at least, people with a more sceptical or cautious view on nuclear power might consider: do I consider the risks of climate change to be larger than the risks associated with nuclear power, and do I believe that the alternative to nuclear power, either from phasing out existing plants or refraining from building new plants, includes the use of fossil fuels and not only emission-free sources? If the answer is "yes" to both these questions, than it is likely that you consider nuclear power to be part of a viable climate-mitigation strategy which even could motivate financial support to overcome the economic hurdles currently typical for investments in the Western World. Public financial support has been, and is being, given to other sources of electricity that we consider desirable for different reasons. If, on the other hand, the answer is "no" to either of these two questions than it is likely that you may discard nuclear power as a viable alternative for a future climate-efficient energy system. The effect of saying "no" to the first question is plausible, while saying "no" to the second question implies that you believe that the climate-efficient alternatives to nuclear power, i.e. renewables and other emission-free sources of electricity as well as end-use measures, will be sufficient to replacing fossil fuels within reasonable time and, hence, make nuclear power obsolete.

7.1 FURTHER WORK

As mentioned in the introduction, we have not covered climate change-adaptation of different energy sources and technologies (nuclear power and others), nor whether there are any significant differences in robustness between technologies and systems, nor to what extent such knowledge may affect the choices we make for our future energy systems. In that respect, a key question for nuclear power is whether it is better or worse equipped to adapt to climate change compared to other competing sources of electricity.

Another issue is the need for supporting technologies for variable renewable electricity in different system contexts. We know that nuclear power may become significantly more flexible than is normally the case in many nuclear power plants, where baseload operation is the prime mode of operation. Will increased flexibility suffice to make nuclear power an efficient complement to variable renewable electricity or is the competition from other flexibility solutions superior, such as increased flexibility of variable renewables, end-use flexibility, storage and other thermal power production?

There are other environmental concerns to address besides climate change, which has been a core issue of our study (we have also mentioned e.g. air pollution). Growing concern for e.g. biodiversity may be one environmental challenge that is likely to receive increased attention, especially in the wake of the global status report presented by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) in 2019. To what extent such considerations may, or should, affect our future energy systems and what the implications are for the use of nuclear power and other sources of electricity, is also a question for further work.

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Appendix: List of articles included in the assessment in Chapter 6

In this appendix, we list the articles that are included in the assessment on articles and their position towards the two main questions dealt with in this report: 1) Is nuclear power a part of a sustainable energy system? 2) Can nuclear power be considered as a climate-mitigation technology? For each article in the list below, we also define how we have interpreted the article's position towards these two questions. (Sustainable=yes;maybe;no;not specified) and Climate=yes;maybe;no;not specified)

The full list of literature used in this study (and not only for the assessment in Chapter 6) is included in the reference list (Chapter 8).

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SUSTAINABILITY ASPECTS ON NUCLEAR POWER

As the issue of climate change gains more prominence, nuclear power is increasingly mentioned in the media and by some politicians as having an important part to play in a future, sustainable energy system. The question is then how the academic world views nuclear power, not just as part of a climate change mitigation strategy but also as part of the transition towards a sustainable energy system.

In this review of mainly scientific papers, there is no clear consensus among researchers regarding nuclear power's role in a sustainable energy system. There is polarization in the academic world, just as there is in the media, among the public and among politicians, which, perhaps, is not surprising. This polarization may be partly explained by the complexity of the issue of sustainable energy systems and partly due to the fact that the academic world reflects the society in general.

Despite a certain polarization, we find that most of the scientific articles that we have reviewed reflect a relatively balanced position on the matter of nuclear power and sustainability. Such views acknowledge the positive aspects and benefits of nuclear power but also consider the often well-known issues and challenges.

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