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Natural resources and sustainable energy

Growth rates and resource flows for low-carbon systems

SIMON DAVIDSSON

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Abstract

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Large-scale deployment of low-carbon energy technologies is important for counteracting anthropogenic climate change and achieving universal energy access. This thesis explores potential growth rates of technologies necessary to reach a more sustainable global energy system, the material and energy flows required to commission these technologies, and potential future availability of the required resources.

These issues are investigated in five papers. Potential future growth rates of wind energy and solar photovoltaics, and the associated material requirements are explored, taking the expected service life of these technologies into account. Methodology for assessing net energy return and natural resource use for wind energy systems are analyzed. Potential future availability of lithium and phosphate rock are also investigated.

Estimates of energy and materials required for technologies such as wind energy and photovoltaics vary, and depend on the assumptions made and methods used. Still, it is clear that commissioning of low-carbon technologies on the scale required to reach and sustain a low-carbon energy system in coming decades requires significant quantities of both bulk materials and scarcer resources. For some technologies, such as thin film solar cells and electric vehicles with lithium-ion batteries, availability of materials could become an issue for potential growth rates. Future phosphate rock production could become highly dependent on few countries, and potential political, social and environmental aspects of this should be investigated in more detail.

Material and energy flows should be considered when analyzing growth rates of low-carbon technologies. Their estimated service life can indicate sustainable growth rates of technologies, as well as when materials are available for end-of-life recycling. Resource constrained growth curve models can be used to explore future production of natural resources. A higher disaggregation of these models can enable more detailed analysis of potential constraints. This thesis contributes to the discussion on how to create a more sustainable global energy system, but the methods to assess current and future energy and material flows, and availability of natural resources, should be further developed in the future.

Keywords: low-carbon technology, renewable energy, energy transitions, critical materials, energy metals, material flows, net energy, EROI, life cycle assessment, LCA, growth curves, curve fitting, resource depletion

Simon Davidsson, Department of Earth Sciences, Natural Resources and Sustainable Development, Villavägen 16, Uppsala University, SE-75236 Uppsala, Sweden.

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To my family

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Davidsson, S., Grandell, L., Wachtmeister, H., Höök, M. (2014) Growth curves and sustained commissioning modelling of renewable energy: investigating resource constraints for wind energy. *Energy Policy,* 73:767-776

II Davidsson, S., Höök, M. (2016) Material requirements and availability for multi-terawatt deployment of photovoltaics. *Submitted.*

III Davidsson, S., Höök, M., Wall, G. (2012) A review of life cycle assessments on wind energy systems. *International Journal of Life Cycle Assessment,* 17(6):729-742

IV Vikström, H., Davidsson, S., Höök, M. (2013) Lithium availability and future production outlooks. *Applied Energy,* 110:252-266

V Walan, P., Davidsson, S., Johansson, S., Höök, M. (2014) Phosphate rock production and depletion: Regional disaggregated modeling and global implications. *Resources, Conservation & Recycling,* 93:178-187

In Paper I and II, the author of this thesis initiated the studies, had the main responsibility for the conception and design of the work, executed the modelling, and wrote the largest part of the papers.

In Paper III, the author had the main responsibility for data gathering and analysis, and wrote the majority of the paper.

In Paper IV, the author made substantial contributions to data interpretation and writing the paper.

In Paper V, the author contributed substantially to the conception and design of the work, data analysis and interpretation, and writing the paper.

Other papers not included in this thesis:

i. Wang, J., Feng, L., Davidsson, S., Höök, M. (2013) Chinese coal supply and future production outlooks. *Energy,* 60:204-214
ii. Larsson, S., Fantazzini, D., Davidsson, S., Kullander, S., Höök, M. (2014) Reviewing electricity production cost assessments. *Renewable and Sustainable Energy Reviews,* 30:170-183
iii. Sällh, D., Höök, M., Grandell, L., Davidsson, S. (2014) Evaluation and update of Norwegian and Danish oil production forecasts and implications for Swedish oil import. *Energy,* 65:333-345
iv. Höök, M., Davidsson, S., Johansson, S., Tang, X. (2014) Decline and depletion rates of oil production: A comprehensive investigation. *Philosophical Transactions of the Royal Society A.* 372, 20120448

Contents

Abbreviations

CED	cumulative energy demand
c-Si	crystalline silicon
EOL	end-of-life
EROI	energy return on (energy) investment
EV	electric vehicle
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
NEA	net energy analysis
NER	net energy return
PHEV	plug-in hybrid vehicle
PR	phosphate rock
PV	photovoltaics
RRR	remaining recoverable resources
SC	sustained commissioning
TF	thin film
TW	terawatt (10^{12} W)
URR	ultimately recoverable resources
USGS	United States Geological Survey

1. Introduction

1.1 The global energy system

Access to energy is crucial for human development, and the global primary energy use has increased more or less constantly since the industrial revolution, leading to a global energy system completely dominated by fossil fuels (GEA, 2012). The combustion of fossil fuels is one of the major causes of anthropogenic climate change, contributing with a large part of the increase of greenhouse gas emissions (IPCC, 2014). This calls for a transformation of the current global energy system, but at the same time several billion people still lack access to modern energy services. The recently adopted Sustainable Development Goals include targets stating that universal access to modern energy services, as well as substantial global increases in the share of renewable energy and a doubling of the rate of energy efficiency improvements should be achieved by the year 2030 (United Nations, 2015). This implicates that a wide range of different low-carbon technologies enabling the use of renewable energy resources in efficient ways need to be commissioned in coming decades, both for decarbonizing the existing energy system, and providing energy services to those who currently do not have access.

An important part of an alternative low-carbon global energy system would be to rely on renewable energy flows as a primary energy source, instead of non-renewable fossil fuels. Several sources of renewable energy with significant potential exist, including bioenergy, direct solar energy, geothermal energy, hydropower, ocean energy, and wind energy. However, estimates of the technical potential of these resources vary greatly (IPCC, 2011). Fast growth rates of the use of renewable energy from solar, wind, and hydropower, reaching 100 percent renewable energy in a few decades has been proposed (Jacobson and Delucchi, 2009), although it has been stated that there are physical limits to the rate at which energy technologies can be deployed (Kramer and Haigh, 2009).

Modern society depends not only on the extraction of finite natural resources in the form of fossil fuels, but also a wide range of different materials from mineral resources. Economic growth has had a close relationship with the use of natural resources, and while economic growth and population growth have slowed in the past few decades, the global use of materials appears to have accelerated (UNEP, 2016). The global economy can even be described as a process of material transformation, where natural resources are converted into commodities and wastes (Bridge, 2009). Although low-carbon power generation technologies can be effective in reducing emissions of greenhouse gases, they are significantly more metal intensive than the existing power generation (Kleijn et al., 2011). It has also been argued that the net energy return (NER), or energy return on investment (EROI), is substantially lower for most renewable energy sources than for fossil fuels (Hall et al., 2014). A wide range of energy technologies, including wind turbines, solar photovoltaics (PV), electric vehicles (EV), and efficient fluorescent lighting, utilize materials facing a risk of supply disruptions, especially in the short term (U.S. DOE, 2011). In a longer time perspective, future availability of many resources including fossil fuels, critical metals, and biomass are highly uncertain (Speirs et al., 2015). It can therefore be interesting to further investigate the material and energy flows that are necessary for large scale deployment of low-carbon energy technology. This thesis aims to explore potential growth rates of low-carbon technologies, focusing on the required resource flows, and potential future availability of resources that can be required.

1.2 Aims

The aim of this thesis is to investigate the role low-carbon energy technology can have in the creation of a more sustainable, low-carbon, global energy system, by investigating potential growth rates of technologies, the energy and materials flows required for this growth, and the availability of the required resources. This can be condensed into three main research questions:

1. How fast can low-carbon energy technologies be deployed to reach and sustain a significant share of the global energy system?
2. What material and energy flows are required for low-carbon technology deployment?
3. How much mineral and energy resources will be available in the future?

The methods that can be used to investigate these issues are also explored. In doing so, this thesis aims to contribute to the scientific discussion on how a more sustainable global energy system can be reached, as well as how this can be assessed.

1.3 Papers and outline

This thesis is based on five papers exploring different aspects of growth rates of low-carbon technology, material and energy flows required to commission these technologies, and potential future availability of natural resources. This comprehensive summary attempts to briefly describe the scientific debate on growth patterns of future low-carbon technology, mainly related to the first research question (Chapter 2), quantifications of resource requirements for low-carbon technologies, mainly related to the second research question (Chapter 3), and availability of natural resources, mainly related to the third research question (Chapter 4). The methods used in the five papers are described in Chapter 5, after which the papers are summarized in Chapter 6. In Chapter 7, the implications are discussed in a wider context. The main conclusions are presented in Chapter 8, and potential future work is described in Chapter 9. The five papers that follow address different parts of the aim of this thesis, and address the three research questions to various degrees.

Paper I explores potential future growth rates of wind energy and the associated material requirements, taking into account expected service life of wind turbines. The focus is on the first research question concerning growth rates of low-carbon technologies.

Paper II investigates growth rates of solar PV reaching multi terawatt (TW) PV capacity by the middle of the current century, taking account for the implications of different technology choices and potential improvements in material intensity, including potential future availability of materials from end of life (EOL) recycling. The aim is to address all three of the research questions, but the focus is on the second one dealing with how growth rates of low-carbon technology can be translated into material flows.

In paper III, a set of life cycle assessments (LCA) of wind energy systems are analyzed in detail, focusing on net energy return and the assessments of natural resources. This paper mainly addresses the second research question, by investigating the quantities of energy and materials required for commissioning wind energy technology.

Paper IV explores potential future availability of lithium that could be required for large-scale deployment of electric vehicles utilizing lithium-ion batteries. In Paper V, potential future availability of phosphate rock is explored, looking especially into production in individual countries. The emphasis in both these papers is on the third research question, by investigating potential future availability of mineral resources.

2. Growth rates of low-carbon energy

To reach a more sustainable energy system, a wide range of technologies must grow significantly from the current levels. It has been argued that these technologies must be able to scale up to a TW level of deployment to play a relevant role globally (Vesborg and Jaramillo, 2012), and numerous studies have explored future scenarios containing deployment of different low-carbon technologies at these levels (Deng et al., 2012; García-Olivares et al., 2012; Jacobson and Delucchi, 2011; Kleijn and van der Voet, 2010). The technologies believed to be important vary somewhat, but solar, wind, and hydropower are commonly suggested to provide the bulk of primary energy supply in such a system. Renewable energy sources such as biomass and geothermal energy can also be considered important for the future, as can significant improvements in efficiency.

The potentials of the different technologies are uncertain, but "old" renewables such as hydropower have already reached close to a practical maximum in most of the "rich" parts of the world, and most of the growth has to come from new renewables such as wind, solar, and biofuels (Smil, 2014). Since electrical energy generating technologies including wind and solar power are believed to have the greatest potential, an electrification of the energy system is likely to be required, although hydrogen is sometimes suggested as an alternative energy carrier (Kleijn and van der Voet, 2010). This means that the infrastructure necessary to transport the generated energy carriers to the users, and energy efficient end-use technologies that can utilize energy carriers such as electrical energy or hydrogen, are also required. The variable nature of the electrical energy generation from wind and solar could also require large amounts of technologies to handle these variations, such as energy storage, which also requires materials and energy (Barnhart and Benson, 2013).

Although most famous for suggesting a peak in U.S. oil production, Hubbert (1949) imagined that water and solar power would grow fast to replace the decline in energy from fossil fuels, before leveling off to a maximum value where it could be held more or less indefinitely. Just a few years later nuclear energy was described as a technology that could replace fossil fuels (Hubbert, 1956). Studies of historical growth rates show that all energy technologies have experienced fast exponential growth at early stages, but have always leveled off when reaching a significant share of the global energy system (Höök et al., 2012). Based on historic growth patterns, Kramer and

Haigh (2009) propose two laws of energy technology deployment. The first law states that all technologies grow exponentially with around 26% for a few decades until the energy technology becomes “material” at around 1% of the global energy supply. The second law states that after the exponential phase, the growth becomes linear, until the technology settles at a final market share. Apart from the time it takes to scale up new industries, the actual life expectancy can describe parts of the linear growth phase, since common life expectancies of 25-50 years in energy technologies, require only a 2-4% replacement rate of existing technology (Kramer and Haigh, 2009). The seemingly S-shaped growth curve of energy technologies has also been described using a logistic growth function (Wilson et al., 2013).

3. Energy and material flows

There are many existing low-carbon technologies that are capable of transforming renewable energy flows in nature into useful energy carriers, such as electricity or fuels. However, these technologies are built with materials from non-renewable mineral resources. Commissioning these technologies also requires energy that in the current energy system will likely come mainly from fossil fuels. Knowledge about the quantities of materials and energy required for commissioning these technologies, as well as when they are required, can provide useful information to fully understand the implications of a rapid deployment of these technologies.

It has been argued that the EROI (or NER), of the currently most important fuels used are declining, and that the alternative renewable energy technologies generally have a significantly lower EROI (Hall et al., 2014). Since great amounts of alternative energy resources, including conversion and storage technologies, are likely required in coming decades, net energy analysis (NEA) has been proposed to be an essential tool for guiding the transition to a more sustainable energy system (Carbajales-Dale et al., 2014).

The concept of energy analysis evolved in the 1970s to evaluate new energy technologies in relation to a concern of resource depletion and global warming (Mortimer, 1991). From the concern about energy requirements and attempts to prevent pollution, these methods evolved into LCA methodology, which is a framework for estimating a wide range of different environmental impacts during the life cycle of a product (Rebitzer et al., 2004). The interest in LCA increased fast in the 1990s, but this methodological framework has also received criticism (Finnveden et al., 2009). Still, LCA methods have been used to analyze the environmental impacts of renewable electrical energy generation systems, often focusing on NER and CO_2 emissions (Varun et al., 2009).

After deciding on the goals and scope of the study, an LCA can be described as having two main parts (Rebitzer et al., 2004). The first part is the life cycle inventory (LCI), where information about environmental exchanges such as emissions and resource consumption are compiled. This information is then usually used to calculate indicators of the potential impacts on the natural environment in a life cycle impact assessment (LCIA). Current estimates of net energy performance are commonly based on the cumulative energy demand (CED) from the LCIA, but it has been argued that CED is not designed to provide the information required for a EROI analysis

(Arvesen and Hertwich, 2015). Numerous potential issues with how net energy or EROI is calculated for energy technologies has been described in recent years, and a lively discussion on how this should be done has evolved, with different groups using somewhat diverging assumptions, and even goals and scope of the study (Carbajales-Dale et al., 2015; Pickard, 2014; Raugei, 2013; Raugei et al., 2015; Weißbach et al., 2014, 2013).

Apart from energy and CO_2 emissions, life cycle assessments are also potential sources of information about material requirements, such as quantities of metals used for low-carbon technologies (Kleijn et al., 2011). Information about natural resource requirements can come from the LCI, or as indicators from the LCIA, such as *abiotic resource depletion*. How the impacts from resource use should be quantified has been under debate (Stewart and Weidema, 2004), and the very inclusion of resource use in LCA studies has been suggested to be in use of further discussion (Finnveden, 2005).

Materials that are required for technology can also be discussed in terms of *criticality,* or *critical materials.* What in fact constitutes a critical material is not self-evident, and the definitions vary. One way to assess the criticality of a material is to estimate criticality in two dimensions: its importance to “clean” energy, and the apparent supply risk (U.S. DOE, 2011). Alternatively, the criticality of metals can be quantified using the three dimensions: supply risk, environmental implications and vulnerability to supply restrictions (Graedel et al., 2012). The European Commission identifies raw materials critical for the European Union by estimating their economic importance and the apparent supply risk (European Commission, 2014). Other potentially important aspects could be production share of politically instable countries, toxicity, embodied energy, and the value to the economy (Goe and Gaustad, 2014).

The metal flows required for energy technologies have been analyzed with material flow analysis (Elshkaki and Graedel, 2013). Similar analyses of energy flows can also be done. In the case of PV deployment, it has suggested that the global PV industry was a net energy consumer up until just a few years ago (Dale and Benson, 2013). Dynamic assessments of energy and material flows have the potential to provide crucial information of large scale deployment of low-carbon technology over extended periods of time.

4. Availability of resources

4.1 Pessimists and optimists

Concerns that resource depletion could be problematic for the welfare of current or future generations have existed for hundreds of years. A name often mentioned in such discussions is Malthus (1798), who warned that a population, when "unchecked", grows geometrically (exponentially), while human sustenance can only grow arithmetically (linearly). An example more connected to energy and mineral resources is the suggestion by Jevons (1865) that the constantly increasing efficiency of steam engines and blast furnaces using coal would in fact increase the total demand for coal, warning that the British stocks of coal would not last indefinitely. Hubbert (1949) proposed that the production of fossil fuels, not limited to just oil, must eventually reach a maximum, and start to decline almost as sharply the growth phase, making the fossil fuel era a mere "pip" in a longer time perspective. One of the most famous examples of warnings of potential implications of the depletion of resources is likely the *Limits to Growth* report where global resource use and pollution was modelled using systems dynamics models to explore limits to exponential growth on a finite planet (Meadows et al., 1972).

Apart from the increasing use of natural resources, the above mentioned studies describe exponential growth of the global population as a major issue in a world with limited availability of non-renewable resources. However, it can be argued that a growing population is a positive thing, and that the human ingenuity is the ultimate resource for society (Simon, 1996). In fact, it is not fully agreed upon that natural resources are required for economic growth or development. A debate still exists between those who are concerned that earth cannot supply anticipated demand of exhaustible resources, and those who are unconcerned since they are convinced that market incentives, public policy, and technological development can provide for societies' needs for an indefinite future (Tilton, 1996).

Those who are concerned and unconcerned about these issues have been called pessimists and optimists, but these two arguments can also be described as proponents of "weak" and "strong" sustainability. The proponents of weak sustainability (optimists), believe that virtually all kinds of natural capital can be substituted by man-made capital, while those in favor of strong sustainability (pessimists), believe that there are many services provided by nature that are impossible to replace (Ayres, 2007). The pessimists often base their arguments on thermodynamics, as the second law of thermodynamics states that entropy increases in all processes, meaning that the extraction of low entropy (high exergy) resources such as fossil fuels and mineral ores must eventually run into limits. In the case of fossil fuels it is suggested that when these fuels, which have accumulated over hundreds of millions of years, are combusted, the material content remains on Earth in a more or less useless form, while the energy leaves earth as long wavelength and low temperature radiation. What is described is basically that high exergy (low entropy) fossil fuel is turned into low exergy waste.

Perhaps the most well-known discussion when it comes to the depletion of resources is the one on *Peak oil,* which had a comeback a couple of decades ago when it was proposed that the end of cheap oil was near (Campbell and Laherrère, 1998). A systematic review of the evidence conducted by the UK Energy Research Centre (UKERC) found it likely that *conventional* oil will reach a maximum production before 2030, with a significant risk of it occurring before 2020 (Sorrell et al., 2010). Production of other types of “unconventional” oil, especially the recent boom in production of tight oil in the United States, has increased significantly, likely contributing to a recent fall in oil prices (IEA, 2015). What the future of oil will look like appears uncertain, and some argue that a peak in oil production will even come from a peak in demand. In that case the focus should arguably switch from scarcity of conventional oil to the economic, environmental and social consequences of the different alternatives (Brandt et al., 2013). In order to reach goals to counteract global warming, a large part of the global oil reserves must be left unused, which could further limit the amounts of oil that can be used in the future (McGlade and Ekins, 2015).

It can be argued that not only fossil fuels, but also mineral resources, must eventually reach a “peak” in production (May et al., 2012). One mineral resource that has been suggested to be approaching an imminent peak in production is phosphate rock (PR), which is predominantly used as an important fertilizer in modern agriculture. After Cordell et al. (2009) predicted that a global peak in phosphorus from phosphate rock was to happen around 2030, a debate on the possibility of a “peak phosphorus” started. This was followed by a quite dramatic increase of global reserve estimates, especially in the case of Morocco and Western Sahara (Edixhoven et al., 2013). Availability of fertilizer from PR can be considered crucial for future food production, but could also be a potential hinder for biofuel production from agriculture.

4.2 Growth curves and resources

Different types of growth curve models have been used within biological sciences, and later to model new products and the diffusion of new technologies, but also within energy studies, including modelling energy resources, energy demand, fuel substitution and energy technology development (Ang and Ng, 1992). Hubbert (1949) proposed that since there is a limited amount of fossil energy, the production curve must rise, pass through one or several maxima, and then decline asymptotically to zero, with the area under the curve equal or under the amounts initially present. Hubbert is likely most famous for being attributed to predicting the peak in the United States oil production (Hubbert, 1956), and later proposed the use of a logistic function to describe the cumulative production curve (Hubbert, 1959).

The logistic growth function can be described as (Höök et al., 2011):

$$Q(t) = \frac{A}{1+e^{-k(t-t_0)}} \qquad (1)$$

where *Q(t)* is the cumulative growth, *A* is the asymptote of the S-curve, *k* is a growth factor, and t_0 is the year when the growth rate reaches a maximum and starts decreasing. When modelling extraction of natural resources, *A* corresponds to the total quantities of extracted resources, which can be referred to as the ultimately recoverable resources (URR).

Since these mathematical functions are usually fitted to historical data, these models can be referred to as curve fitting models. The logistic growth curve can represent cumulative extraction of a resource, but data on extraction is normally given as annual production. A bell shaped curve based on the annual extraction levels can be described mathematically by the first derivate of an S-curve. The first derivate of the logistic curve is sometimes given its own name, the *Hubbert curve* (Höök et al., 2011).

Apart from being used to project future production of a resource, growth curves have also been used to predict the total production, or the URR. For example, for oil, logistic curves can be fitted to cumulative oil production or cumulative discoveries in a region to estimate the URR (Sorrell and Speirs, 2014). Fitting a logistic curve has a proven ability to determine a final maximum, but the uncertainty is also larger at early stages (Debecker and Modis, 1994).

Growth curve models have also been frequently used for mineral resources, but a few key differences to fossil fuels should be taken into account. For mineral resources, there is generally a lack of reliable discovery data, the estimates of reserves and resources are uncertain, ore quality and quantity varies, and metals are recyclable, while fossil fuels are generally combusted at use (May et al., 2012).

The fact that metals are recyclable opens up for other potential sources than just primary ores. In theory, end-of-life (EOL) recycling can supplement primary resources, but the estimated service life should be considered (Graedel, 2011). The use of metals tends to increase over time, and the service life of many technologies are long, making the actual recycled content low for most metals (Graedel et al., 2011). Since the EOL recycling rates are low for many metals, large quantities of these materials are stockpiling in slag heaps and landfills, which could potentially be treated as "ore" in the future (Ayres and Peiró, 2013).

5. Methods used

5.1 Modelling growth rates of technology

The path to a future deployment level of a technology can be described in different ways. Assuming a constant growth per unit of time gives a linear growth, while a fixed fraction per time unit means exponential growth (Bartlett, 1993). However, growth patterns will eventually be subjected to some type of limitation, which is why S-curves or bell shaped curves are common in most systems, including energy systems (Höök et al., 2011). S-curves, such as the logistic function (Equation 1), can be fitted to historical data using advanced computer programs, but also in simple spreadsheet programs using least squares methods (Brown, 2001). Growth curves have been used extensively within energy studies, including for modelling energy resources, energy demand, fuel substitution and energy technology development (Ang and Ng, 1992). In Paper I, both exponential and logistic growth is used to describe potential growth rates of wind energy.

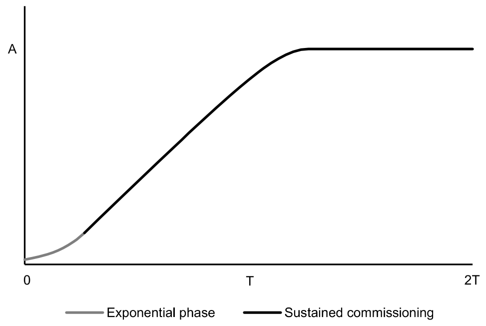
An alternative approach for describing growth of low-carbon technology is the *sustained commissioning* (SC) model (Paper I). The SC framework is based on the sustained manufacturing model described by Laxson et al. (2006), but with some alterations, especially on the growth rates for the exponential growth phase. The word commissioning replaces manufacturing, to highlight that the commissioning of an energy technology is not only about manufacturing technologies, but includes a whole industrial process chain, such as extracting and refining materials, manufacturing technologies, and connect them to a functioning energy system.

In the case of an electrical energy generation technology, such as wind turbines (Paper I) and solar photovoltaics (Paper II), the installed generation capacity, $P(t)$, in the year t can be described as (Figure 1):

$$P(t) = P(t-1) + p(t) - p(t-T) \qquad (2)$$

where $p(t)$ is the commissioned capacity in year t and T is the expected service life of the technology. The required sustained commissioning C, which is the level that is theoretically required for sustaining the target capacity A indefinitely, can then be described as:

$$C = \frac{A}{T}. \qquad (3)$$



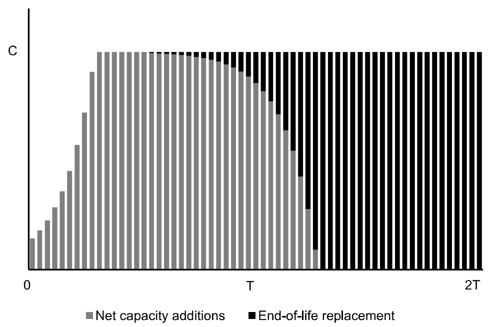


Figure 1. The cumulative capacity and annual commissioning of an energy technology with a life expectancy *T* growing according to the sustained commission framework to an installed capacity of *A,* and sustaining this level for an indefinite future with a constant annual commissioning equal to *C*.

Annual commissioning grows exponentially with an annual relative growth rate *r*, until the year when *p(t)* is equal to or greater than C, according to:

$$P(t) = P(0)(1 + r)^t, \qquad p(t) \leq C. \qquad (4)$$

According to Kramer and Haigh (2009), energy technologies appears to have grown exponentially with around 26% in history, before switching to a more linear growth. The best estimate of *r* can therefore be considered to be 0.26, especially on the global level. After the exponential growth phase, the linear growth phase can be described as:

$$p(t) = C. \qquad (5)$$

5.2 Assessing energy and material requirements

The quantities of energy and materials required for commission of energy technologies can be assessed in different ways, but common sources of these numbers are LCA studies. Numerous estimates circulate in the literature, where for some technologies different estimates can vary greatly.

For estimates of the quantities of refined bulk materials, such as steel and copper for wind energy (Paper I), LCA databases can be used (Kleijn and van der Voet, 2010). LCA studies can provide information about scarcer materials as well, although it appears that the use of these materials can be omitted from analysis if they make up a small part of the total mass (Paper III). Combining material intensities with growth rates of technologies can provide estimates of required material flows.

Potential improvements in material intensities can also be included in a model of future material flows. For instance, Kavlak et al. (2015) propose three different potential material intensities for different PV technologies in the year 2030. To translate material intensities into flows, assumptions have to be made on the material intensities in the years leading up to 2030, as well as what will happen after that (Paper II).

Reliable quantifications of the energy required during the life cycle are more difficult to find, and a quite vivid discussion within the scientific community about how net energy return for energy technologies should be measured has occurred. This thesis does not attempt to quantify the energy requirements for commissioning of energy technologies, or the resulting energy flows. However, Paper III contains a thorough analysis of different potential issues with how LCA methodology is used to assess energy performance, material requirements, and environmental impacts from natural resources used for the commissioning of wind energy.

5.3 Estimating future availability of resources

There are a multitude of methods that can be used when estimating future availability of natural resources. An important metric is reserve estimates measuring quantities that are considered recoverable under current conditions, and can be used as indicators of resource availability. For critical materials most studies rely on reserve data from the United States Geological Survey (USGS) (Speirs et al., 2015). This measure of the potentially available stock does not necessarily say much about the future flows of these resources, and the papers in this thesis utilize several different approaches to analyze prospective future resource flows depending on the resource under investigation and the availability of data.

One way of modelling availability of resources is to use growth curve models fitted to historical data. Apart from the logistic function (Equation 1), the Gompertz function (Paper IV and V):

$$Q(t) = URRe^{(-e^{k(t-t_0)})} \quad (6)$$

and the Richards function (Paper IV):

$$Q(t) = URR(1 \pm e^{(\mp k(t-t_0))})^{M} \quad (7)$$

are used, where *Q(t)* is the cumulative production of a resource, URR is the asymptote of the S-curve, k is the growth factor, and t_0 is the year of maximum growth. The Gompertz and Logistic functions are special cases of the more generalized Richards function, which contains the extra variable *M* (Höök et al., 2011).

These models can be used without a constraint, making the URR an output from the model, or constrained by a URR quantified based on other information. One way of approximating the URR is to estimate how much resources remain to be extracted in the future, the remaining recoverable resources (RRR), and combine this with the cumulative historical production.

A potential modification of growth curve models is to use multiple cycles, potentially improving the fit to historical data. This can be especially useful if historical production has been affected by external factors causing disruptions in production (Anderson and Conder, 2011).

One way of making sure that the results coming out of such a model will not appear unreasonable, is to include a maximum depletion rate on remaining recoverable resources. The depletion rate of remaining recoverable resources, $d(t)_{RRR}$, can be defined as (Höök, 2014):

$$d(t)_{RRR} = \frac{q(t)}{URR - Q(t)} \quad (8)$$

where *q(t)* is the annual production at time *t*, URR is the ultimately recoverable resources, and *Q(t)* the cumulative production. Including a maximum RRR as a constraint in a growth curve model has been proposed as a way of ruling out results that can be mathematically valid, but appear practically unreasonable (Höök and Aleklett, 2010). What constitutes a reasonable maximum depletion rate is not obvious, but it is based on the notion that too large fractions of resources are not plausible to extract at once.

6. Summary of papers

6.1 Paper I

Several different growth patterns are used to illustrate potential annual commissioning levels that would be required to reach multi-TW installed capacities of wind energy explored in other studies (Jacobson and Delucchi, 2009; Kleijn and van der Voet, 2010), as well as sustaining this capacity in longer time perspectives, assuming a 20 year service life for wind turbines. By letting the annual installations grow with a fixed fraction per unit time at a rate required to reach 19 TW of installed wind capacity by 2030 and 24 TW by 2050, exponential growth is used as an example of unconstrained growth. A logistic growth curve (Equation 1) constrained by a maximum cumulative capacity of 24 TW is fitted to historical data of global installed wind power capacity, as an example of a constrained growth pattern. Also, the sustained commissioning model is used to model growth of wind energy reaching 24 TW installed wind power capacity, with the theoretical ability to sustain this level indefinitely. The estimates of annual commissioning of wind energy are then combined with common estimates of steel and copper requirements, to explore the required flows of bulk materials. The material intensities are assumed to remain constant throughout the time period studied. Combined with annual commissioning of wind power in the growth models, the annual requirements of steel and copper for the wind industry are quantified.

The exponential growth patterns imply that a very large part of the total installations take place in the final years of growth. A continuation of exponential growth at the historical levels of around 26% reaching 19 TW of wind power capacity by 2030 means that 68% of all the installations happens in the last five years, and 21% in the final year of growth. For a slower exponential growth to 24 TW by 2050, the corresponding numbers are 45% and 11% respectively. Due to the assumed 20 year life expectancy of wind turbines, very little wind capacity will be taken out of use in the years following this. Given that the installed wind capacity is assumed to remain constant, most of the commissioning capacity will not be needed in the years after these levels have been reached.

Logistic growth reaching 24 TW of wind power capacity by 2050 ends up in a maximum annual commissioning of 1.5 TW. This equals to around 6% of the total installations, which is close to the results in the SC growth case with a maximum of 1.2 TW, or 5% of the total. The SC case can be seen as a way to describe a system that can be sustained over longer time perspectives, as the annual installations of 1.2 TW can in theory be assumed to continue beyond 2050 and sustain the system indefinitely.

The construction of as much as 24 TW of wind power capacity would only demand a few per cent of the total USGS reserve estimates for iron ore and copper. From a more flow based perspective, the exponential growth cases requires 27-37% of the 2012 global steel production in the maximum commissioning year, and 34-46% of the 2012 copper production. The logistic and SC growth patterns require significantly less, equaling to 11-14% of the 2012 steel production and 14-17% of the copper production.

Commissioning wind power at a multi-TW level requires significant quantities of bulk materials such as steel and copper production. However, even in the growth patterns with the highest annual installations, the requirements are still well below the current production levels of these materials.

6.2 Paper II

A sustained commissioning model is used to describe a potential growth pattern of solar PV technology reaching 9.3 TW of installed capacity by 2050, similar to a PV deployment scenario suggested by Greenpeace (2015). The service life is assumed to be 30 years, which is the most common assumption in the literature. Three currently commercial PV technologies are modelled individually in two different market cases, one crystalline silicon (c-Si) case and one thin film (TF) case. Also, two different cases of material intensity for photovoltaics are used, one with a constant intensity at the current level, and one where the intensity decreases rapidly between now and 2030 according to estimates from other studies. In the c-Si case, all future PV growth is assumed to come from currently dominating c-Si technologies. In the TF case the future growth is assumed to come from the currently commercial thin film (TF) technologies CIGS and CdTe.

The annual and total quantities of different materials required for reaching an energy system with multi TW installed PV capacity varies greatly depending on assumptions on technology choices and improvements in material intensity, but some general conclusions can be made. In order to reach the PV capacity in the c-Si case, annual production of solar grade silicon must be scaled up to several times the current level, unless silicon intensity decreases significantly. The annual requirements of silver correspond to significant parts of, but are still far under, the current silver production. Eliminating the use of silver and decreasing the silicon requirements for c-Si technology appears like sound strategies to enable continued fast growth and decreasing costs of this technology.

Realizing the TF case with equal shares of CIGS and CdTe technology, requires significant quantities of indium, gallium, selenium, tellurium and cadmium. Although future availability of these materials is uncertain, indium and tellurium appear likely to become problematic for rapid growth of TF technologies. Efforts to decrease material intensity and increased production of the required resources are necessary for these technologies to reach significant levels.

Due to the expected service life of solar panels, end of life recycling does not have any significant impact before 2050, but can play a major role in sustaining the system in a longer time perspectives. Material quantities on the same level or above, the annual requirements become theoretically available from EOL recycling every year beyond 2050.

6.3 Paper III

In Paper III, a detailed analysis of 12 LCA studies of wind energy is undertaken, with focus on the quantification of net energy return and natural resources. The main aim is to examine how energy inputs and outputs, and requirements and impacts of other natural resources, are assessed in these studies.

The different LCI and LCIA methods are analyzed and compared between the studies. The quantifications of net energy return are analyzed in more detail, and the different methods and assumptions used for the energy inputs and outputs over the life cycle are scrutinized. Also, how non-energy natural resources are considered in the studies is analyzed, including methods to quantify resource inputs and its environmental impacts, and the impact of assumptions on recycling of materials.

The analysis show that different studies use widely different methods for assessing the environmental performance of wind energy, reaching different results that are presented in diverse ways, making it difficult to compare the results with other studies of wind energy, as well as the environmental performance of other renewable energy technologies.

In most of the reviewed studies it is difficult to see how the energy inputs are accounted for, especially concerning how much energy is used in the form of electrical energy, and how the electrical energy is converted into primary energy equivalents. For the most transparent studies in terms of how the primary energy conversions are done, their use of electrical energy generation mix varies. Apparently these assumptions can alter the estimated energy input significantly. Another aspect that is important for the quantification of the energy input is the crediting of future recycling of the materials used.

Some studies present the energy output from a wind turbine in generated electrical energy, and others translate the generated electrical energy into primary energy equivalents. This makes comparisons between different studies difficult, since they in actuality measure different things. A further problem is that in some studies, it is difficult to deduce if and how these primary energy conversions are done.

The required material or mineral resource inputs are presented in disparate ways in the reviewed studies. LCA studies are potential sources of information on the quantities of mineral resources required for commissioning of wind energy systems, as well as the environmental impacts of the use of materials, including potential future recycling. Most studies present quantities of different refined materials that are used, but commonly only for materials making up a significant fraction of the total weight. Therefore, it appears as though potentially important elements, which make up only a small fraction of the total mass of the wind turbine, could be ignored in the presentations of material requirements. For instance, none of the studies mention any use of neodymium or other rare earth elements that are likely to be used in some of the wind turbines.

Several of the reviewed studies translate the apparent material use into environmental impacts using various LCIA methods. This is expressed in impact categories such as *natural resource depletion* or *abiotic depletion.* Many of the studies use crediting of the assumed future recycling of the elements, which significantly reduces the impacts of the resource requirements.

To conclude, the results point out several potentially problematic aspects of how LCA methodology is used to assess energy and material aspects of wind energy systems, and a continued discussion about how LCA methodology can be used to evaluate low-carbon technologies is welcomed.

6.4 Paper IV

Paper IV explores potential future availability of lithium that could be required for a fast growth of electric vehicles (EV) utilizing lithium-ion batteries. Variations in reserve and resource estimates in different studies are reviewed and discussed. Also, growth curve models are used to model potential future production patterns of lithium, using different assumptions on URR, and different mathematical functions.

Six different potential future production outlooks are generated by using logistic (Equation 1), Richards (Equation 7), and Gompertz (Equation 6) growth curves, and two different URR estimates. 15 Mt is concluded to be a reasonable estimate for current reserves, which is used to calculate an URR estimate for a base case. An alternative high case uses an RRR estimate that is double the base case to calculate an alternative URR. Also, outcomes of the lithium production model are compared to potential lithium quantities required to fulfil a scenario of EV and plug-in hybrid vehicle (PHEV) deployment from the International Energy Agency, and common assumptions on lithium requirements for these vehicles. Lithium requirements are assumed to be 1.4 kg for PHEV and 4 kg for an EV, which is within the range of estimates in other studies. Demand from other uses is assumed to remain constant, and the estimated lithium requirement for electric vehicles is added to this level. The spread in results from using different mathematical models and URR assumptions is quite large. It is impossible to say with certainty what the future lithium production and demand will be, but the results indicate that it is possible, not to say likely, that there will be issues with lithium availability for a rapid expansion of EVs, given that they rely on lithium-ion batteries. To limit these potential issues, alternative battery technologies and efficient recycling systems need to be developed. It is clear that reserve and resource estimates vary greatly between studies, but also that a very large fraction of the reserves and resources are found in few countries and few big deposits, which could increase the risk of other issues with lithium availability, which should be further investigated in the future.

6.5 Paper V

Future production of phosphate rock (PR) is explored using logistic and Gompertz growth curve model approaches, with two different levels of aggregation. In the aggregated growth curve model, these growth curves are fitted to historical global data, constrained by three different URR estimates. The URR in the low case is based on the USGS reserve estimate from 2009, before a sudden increase in estimated reserves. The medium case is based on the current USGS reserve estimate, while the high case is based on an assumed doubling of current reserve estimates.

The lowest URR case generates results similar to earlier studies proposing an impending "peak" in PR production, reaching a maximum production in 2030 and 2041 respectively. The medium case based on current USGS reserve estimates, reaches a maximum production in the mid-2080s, while the high case postpones the maximum production far into the 2100s, at levels many times the current production. The results show how different URR estimates, as well as the mathematical functions used, can alter the results of a resource constrained growth curve model. Looking at the medium or high cases, future availability of PR at current levels or above seems possible for a long time, at least far into the next century.

In the alternative disaggregated model, instead of fitting the growth curves to global data, the countries producing significant quantities of phosphate rock are modelled individually. The growth curves are constrained by an URR based on the current USGS reserve estimate, except for China and Morocco (including Western Sahara). These two countries dominate current production, and hold the absolute majority of the estimated USGS reserves. They are given two different URR estimates to investigate alternative situations, assuming that Morocco's reserves are exaggerated, and Chinas are underestimated. Together this creates four different cases for each mathematical function used, creating eight different production outlooks.

In the disaggregated model the results look somewhat different. In the two cases with the low reserve estimate for Morocco, the maximum production is reached around 2030 using the logistic curve, although at higher production levels. Using the Gompertz curve for the same two cases provide similar results, although the maximum production is reached as soon as the early 2020s in the case with the low URR estimate for Morocco, as well as for China. In the cases with the high reserve estimate for Morocco, the PR production appears to be able to continue to rise well into the 2100s, and reach far beyond current production levels if necessary.

Assuming current estimates for PR reserves, PR production would depend to an increasing extent on production in Morocco including Western Sahara. When analyzing future PR availability, exploring production in the individual countries can provide new perspectives on bottlenecks in the individual producing countries. Factors that could hinder a country such as Morocco to increase PR production to several times the current level include water availability, environmental impacts, or fear of geopolitical implications for importing countries that depend on few countries for imports.

7. Discussion

7.1 Sustained low-carbon growth

The current global energy system is both unsustainable and unequitable, and large changes are required quite rapidly if there is to be any chance of limiting the effects of global warming. A wide range of potential alternative systems have been proposed or explored in other studies. This thesis explores a few aspects that could be important for reaching such a system, especially the implications of potential growth patterns of individual technologies.

Thinking in exponential growth is simple and intuitive, and it is tempting to see a continuation of the double digit exponential growth rates that are currently seen in many low-carbon technologies as the way towards more sustainable energy systems. However, in most systems, including energy systems, growth eventually tends to meet some kind of constraint (Höök et al., 2011). The sustained commissioning model, that is described in Paper I, and used in Paper II, is a potential theoretical framework for estimating alternative growth rates that can in theory be more sensible, or even sustainable, than continuous exponential growth.

The models used in Paper I and II can be described as “top down”, since the starting point is the proposed stock of a technology, which is connected to metal requirements (Elshkaki and Graedel, 2013). An alternative “bottom up” approach is to start with the availability of a material and see what the possible deployment of a technology leads to. Excluding the materials from this equation, the sustained commissioning framework can be used in a similar fashion. By assuming a commissioning capacity and a technology service life, it is theoretically possible to estimate at which level the growth of a technology will level off. The SC framework could then potentially be used as a guiding tool to avoid the creation of boom and bust cycles in low-carbon industries, or as a theoretical guide in more comprehensive energy system models.

7.2 The circle of life cycles

Dynamic analysis of resource flows necessitates information about the required quantities of these resources, as well as when in time they are needed. LCA studies or databases are common sources of information for quantifications of the materials and energy required for low-carbon energy technologies. Several issues with using these information as inputs for dynamic modelling have been found, some of which have been highlighted in other studies.

Paper III points out several discrepancies in the methods used in LCA studies of wind energy, including how the energy requirements and generated energy is quantified, as well as how material inputs and impacts on resource depletion, especially concerning recycling, is handled in the analyzed studies. Some of the issues pointed out in Paper III have been further discussed since then. Garrett and Rønde (2012) address some of the issues put forward, especially regarding transparency of LCA studies. Martínez et al. (2015) analyze the different results of using various LCIA software tools for a wide range of different impact categories. LCA methodology has had a strong methodological development and is broadly used in practice, but it has also been argued that further development is necessary (Finnveden et al., 2009). Regarding energy indicators of electrical energy generation technologies, other methodological issues have been pointed out (Modahl et al., 2013), and a vivid discussion on how net energy return should be calculated has been ongoing (Raugei, 2013; Raugei et al., 2015; Weißbach et al., 2014, 2013), more recently with a focus on solar photovoltaics (Carbajales-Dale et al., 2015; Pickard, 2014).

These issues do not disprove the usefulness of LCA studies of low-carbon energy technology. However, they point out some potential problems with relying on current LCA studies as inputs for dynamic models, and raise to question the usefulness of relying on the information from an LCA study for planning a complete transformation of a system. A continued discussion on how LCA and NEA can be used as guides towards more sustainable energy systems are called for, including alternative approaches to quantify the energy and material flows required for an energy transition.

7.3 Growth curve fitting reality

Under some circumstances predicting the future might be useful, but it can also be argued that exploratory or normative scenarios are favorable for planning, especially concerning energy where attempts of forecasting have tended to be massive failures in history (Smil, 2000). Although commonly used for predictive purposes, Hubbert-type growth curves can be seen as a kind of empirical rule-of-thumb (Jakobsson et al., 2009). Especially when using several different URR estimates as constraints, based on highly uncertain reserve estimates, or even pure guesses, the predictive merits can be questioned. However, in the study where Hubbert is considered to have made an accurate prediction of the peak in U.S. oil production (Hubbert, 1956), two different URR estimates were used, one that proved to be closer to the actual outcome than the other. The predictive merits of these models are also affected by when in the production cycle the attempt of prediction is made, as the chance of an accurate prediction increases significantly the later in the cycle the prediction is made. After the peak in production, the chance of an accurate prediction of the decline phase is significantly higher than when attempting to predict the peak. Some studies utilize multi-cyclic models, to improve the fit to historical data, which could indicate better predictive powers. However, multi-cycle growth curve models tend to lead to results with very fast decline, such as the coal predictions by Patzek and Croft (2010). Multi-cyclic growth curve models should be used with caution, and additions of extra curves should be clearly justified (Anderson and Conder, 2011).

One way of avoiding decline or depletion rates that appear unrealistic is to include a maximum depletion rate as a constraint in the model. Exactly what the maximum depletion rate should be is not completely clear, and can be especially difficult to estimate since the URR is never completely known beforehand. Wang et al. (2013) investigated coal production in countries that appear to have passed their peak in production, which means that the URR are fairly well-known, and the maximum depletion rates appear to have stayed below 5%. Extraction of different metals appears to have been made at depletion rates below this level (Paper IV).

The maximum depletion rates can be seen as an expression of reasonable constraints to how fast things tend to change on larger scales. In that way, the concept of maximum depletion rate can be connected to the sustained commissioning framework, where the estimated service life is used as a guide for the appropriate growth rate. Similarly, a life expectancy of 20 years means that 5% of the total capacity is installed per year. Perhaps it is simply not desirable, or sustainable, to install more than this fraction of the total capacity per year, in the same way as it is likely not conceivable to extract more than 5% of the total mineral resources per year.

7.4 Sustainable energy systems

The global community has agreed on sustainable development goals attempting to integrate and balance the three dimensions of economic, social, and environmental sustainability (United Nations, 2015). One of the goals is to ensure access to affordable, reliable, sustainable, and modern energy for everyone. However, it is not completely given what *sustainable energy*, and especially a *sustainable energy system,* really is.

It can be argued that the foundation of a sustainable energy system is that the primary energy comes from renewable sources, which should mean that it can be sustained over long time periods. However, if the priority is to solve the issues with climate change, low-carbon technologies such as nuclear energy, and carbon capture and storage, can also be considered sustainable. Depending on what is deemed the most important goal, the choice of technologies deployed for a transformation of the global energy system can vary significantly. Another thing to consider is that the energy technologies utilizing renewable primary energy sources require materials to be constructed, most of which are based on non-renewable resources. Considering the required material flows, including where the required materials should come from, enables analysis of whether these resources can be extracted and used in a way that can be considered sustainable, both environmentally, economically and socially.

As an example from Paper V, the current agricultural system is dependent on fertilizers from phosphate rocks, where a very large portion of the known reserves are located in one single country. Future food production, as well as potential biofuel production from agricultural sources, will likely depend on these sources for an indefinite future. This can be considered unsustainable for the people in parts of the world who can become dependent on these resources, but also for Morocco since mining phosphate rocks at a much higher rate could be unsustainable in the sense of increased environmental impacts and water use. In a similar way, the production of lithium for electric cars (Paper IV) will likely need to be scaled up rapidly for a fast deployment of electric vehicles, which can be considered a good thing for sustainable development. However, it is not obvious that the few countries with significant lithium reserves consider a fast increase in lithium production sustainable for them, neither from an environmental, economical, or social perspective.

Imagine a global energy system that can be sustained at a level where it supplies the world with 100 percent renewable energy, regenerated by using energy from renewable energy and recycled materials from EOL recycling. In theory, metals could be recycled infinitely, so if the net energy return is high enough to commission technology to replace the ones taken out of use, this system could be a sustainable system running forever. This would be the closest to what can be called a sustainable energy system. Unfortunately, it is clear from the second law of thermodynamics that a recycling process will always be imperfect (Ayres and Peiró, 2013). Recovering 100% of the materials available for recycling is not feasible. It has also been argued that most applications of metals require high purity and low contamination levels, and secondary production often yields products with limited usability due to impurities (Verhoef et al., 2004). Lastly, it is questionable if all technologies taken out of use can make it to recycling.

Although a perfectly sustainable energy system might be theoretically impossible to achieve, at least from a "pessimists" perspective, the goal can be to get as close to this as possible. To make sure that as much technology as possible is recycled in the future, designing the technologies so that they can be easily recycled can increase the likelihood that they will in fact be recycled at their end-of-life (Graedel, 2011). Hence, not only are the industries required to extract and refine the materials for the desired low-carbon technologies needed, but also recycling industries. Ultimately, the industries should be able to produce new technology with the materials contained in the technology reaching its end-of-life. Taking a more “optimistic” view, continued technological advances could be important in sustaining such a system.

One of the main conclusions in this thesis is that we need to consider the growth rates of the industries required for rapid deployment of technology, including manufacturing the technologies, as well as extracting, refining, and recycling the required materials. As indicated in Paper I and II, more sustainable growth rates of technologies can be estimated by taking account for the estimated service life of the technologies. Some of the methodology used and proposed within this thesis could perhaps be used as guiding tools towards more sustainable energy systems, whatever a sustainable energy system might be.

8. Conclusions

Vast amounts of a wide range of low-carbon technologies need to be deployed to reach a more sustainable global energy system. Commissioning of technology require inputs of resources, such as energy and materials, which should be considered when proposing energy futures that depend on rapid growth of different technologies. The exact quantities of the required resources are often uncertain, and could also improve with time, why it is important to have a dynamic perspective on the required material and energy flows. Analyzing the required commissioning capacities of can provide crucial information about conceivable, and even desirable, growth rates of these technologies. Taking account for the expected service life, the growth rates necessary to reach and sustain a system in a longer time perspective can be estimated, as well as potential availability of materials from end-of-life recycling.

A detailed analysis of life cycle assessments on wind energy shows that the methodologies and assumptions vary, as well as the resulting estimates of net energy return. These studies can also be problematic sources for quantifications of material requirements and impacts on resource depletion. Still, it can be concluded that reaching multi-terawatt installed wind power capacity requires non negligible flows of steel and copper, although the maximum annual requirements are well below the current global production. Estimates of the quantities of materials required for commissioning of solar photovoltaic capacity on a multi-terawatt level depend heavily on assumed technology choices and potential improvements in material intensity. However, it appears that availability of certain materials could become problematic for potential growth rates of currently commercial photovoltaic technologies. Improvements in material intensities, as well as a decreased use of scarce materials, would counteract these issues.

For many mineral resources crucial for low-carbon energy technology, future availability is highly uncertain. As an alternative to analyzing estimates of available stocks of resources, different types of growth curve models can be used to explore potential future resource flows. In the case of lithium, the quantities required for a rapid expansion of electric vehicles utilizing lithium-ion batteries could surpass the anticipated lithium flows coming out of a growth curve model on global lithium production. A higher level of disaggregation of growth curve models, such as modelling individual countries or regions instead of global aggregated production, can provide new perspectives into these issues. In the case of phosphate rock, where a vast majority of the reserve estimates is located in one country, potential implications of and constraints on production in that particular country can be explored in this way.

Large scale deployment of low-carbon technologies is crucial for sustainable development and for counteracting anthropogenic climate change, but the potential growth rates of technologies, the required energy and material flows, and the availability of required resources should be considered when planning for future alternative energy systems. These issues are far from fully understood, and the methods to evaluate such aspects needs to be further developed in the future.

9. Future work

This thesis aims to contribute to the ongoing scientific debate on the possibilities of reaching a more sustainable global energy system by commissioning large quantities of low-carbon energy technologies. The growth rates of a few selected technologies and resources are studied. It would be highly interesting to continue to evaluate the methodologies used, and to include them in larger more holistic models considering interactions between different industries. The use of the sustained commissioning framework can enable the inclusion of life expectancies of technologies, which in turn may facilitate the inclusion of end-of-life recycling in such energy systems models.

Several potential issues with using current LCA methodology to assess low-carbon energy technology have been mentioned in this thesis, some of which have been pointed out in other studies . Since these LCA methodologies are commonly used, and well founded in many parts of the scientific community, the discussion on how they can be further developed, as well as their limitations for analysis of energy infrastructure, needs to continue.

A few case studies of availability of resources are presented in this thesis. More detailed studies of potential future flows of different resources, as well as the implications of such flows, are needed. If possible, analyses of several different technologies and resources required for a transition to a low-carbon energy system should be combined in larger models of the implications of such a transition. Methods to analyze this should be further developed. Models including interactions with other industries could potentially also take account for interaction with competing uses.

Renewable or low-carbon energy can be argued to be a means to improve energy security, but may also cause new challenges. The concept of energy security can also be connected to availability of critical materials. There appears to be a growing interest for analyzing critical materials required for renewable energy technology, but exactly what should be considered as a critical material, and what implication it can have for energy security on a bigger scale needs further investigation.

This thesis contributes to the discussion on how to create a more sustainable global energy system, but a great deal of work remains to be done to fully understand what it takes to reach a more sustainable future.

Svensk sammanfattning

Att stoppa de antropogena klimatförändringarna och samtidigt säkra framtida tillgång till efterfrågade energitjänster är en av vår tids stora utmaningar. Dagens globala energisystem domineras helt av fossila bränslen, vilket är en av huvudorsakerna till de utsläpp av växthusgaser som orsakar en global uppvärmning. Samtidigt är tillgången till energi ojämnt fördelad över världen, och omkring tre miljarder människor saknar tillgång till moderna energitjänster. FN:s mål för hållbar utveckling innehåller förutom riktlinjer för att motverka den klimatförändringarna och ge hela världens befolkning tillgång till energi, specifika mål för utökad andel förnybar energi och ökad energieffektivitet. Detta innebär att en mängd olika tekniker som kan användas i ett energieffektivt system baserat på förnybar energi med låg klimatpåverkan behöver byggas. Tillverkningen av energiteknik kräver material och energi, och hur stora dessa resursflöden måste vara är intressant att undersöka för planering av framtida mer hållbara energisystem.

I denna avhandling utforskas möjliga tillväxthastigheter av energitekniker, vilka mängder av material och energi som kan komma att krävas, samt potentiell framtida tillgång av naturresurser. I fem vetenskapliga artiklar studeras olika aspekter av dessa frågor i detalj, med exempel från vindkraft, solceller, litium, och fosfatsten. Målet är att bidra till diskussionen om hur energitekniker med låga klimatutsläpp kan bidra till ett mer hållbart globalt energisystem, samt vilka metoder som behövs för att utvärdera detta. I denna svenska sammanfattning presenteras kort den vetenskapliga bakgrunden till studien, de fem vetenskapliga artiklarna, samt de huvudsakliga slutsatserna.

Varningar om att utarmning av jordens ändliga naturresurser är ohållbart i längden och kommer att skapa problem för samhället på längre sikt är inget nytt. Än idag förs dock en vetenskaplig diskussion om huruvida planeten vi bor på inte kommer kunna bistå med de icke-förnybara resurser som efterfrågas av samhället, eller om marknadsmekanismer och teknisk utveckling gör att tillgången är säker för en obestämd framtid. För att beskriva eller förutse framtida tillgång av naturresurser, så som olja och mineraler, kan olika typer av matematiska modeller användas.

För att bygga teknik krävs energi, vilket även gäller för energitekniker med låg klimatpåverkan. Förhoppningen är dock att mängden energi som fås tillbaka under teknikens livslängd större än vad som investerats så att nettoenergiutbytet blir positivt. Dessutom behövs olika former av material, som ofta baseras på icke förnybara resurser och kan orsaka andra typer av miljöpåverkan. Dock är många material möjliga att återvinna när den tekniska livslängden uppnåtts. Både energianvändningen och miljökonsekvenser av materialanvändning för energitekniker kan uppskattas med hjälp av livscykelanalyser. Användningen av dessa metoder har dock kritiserats, och en diskussion förs angående om och hur de kan och bör användas för att utvärdera energitekniker.

För att göra någon verklig skillnad på global skala måste förnybara energitekniker troligen nå flera terawatt installerad effekt, vilket innebär att industrierna som tillverkar dessa tekniker i många fall måste skalas upp till många gånger dagens storlek. Det har föreslagits att det är möjligt att nå ett energisystem med 100 % förnybar energi så snabbt som inom ett par decennier, samtidigt som möjliga fysiska begränsningar för sådan snabb tillväxt också har framhållits. Hänsyn till olika teknikers beräknade livslängd kan tas för att undersöka lämpliga och hållbara tillväxthastigheter, liksom när de använda materialen åter finns tillgängliga för återvinning.

Vindkraft är en förnybar energiteknik som växer snabbt och troligen har stor potential att bidra till en ökad förnybar elproduktion globalt. I den här avhandlingen utforskas möjliga tillväxthastigheter av vindkraft som krävs för att nå och upprätthålla ett framtida energisystem där vindkraft står för en stor del av den globala energiförsörjningen, förutsatt att vindkraftverk har en beräknad livslängd på 20 år. Vilka flöden av koppar och stål som kan krävas beräknas också. Resultaten visar att det är viktigt att ta hänsyn till beräknade livslängder när möjligheten till ett mer hållbart energisystem undersöks. För att nå ett globalt energisystem med stor andel vindkraft behövs signifikanta flöden av vanliga material så som stål och koppar, dock fortfarande långt under dagens totala produktionsnivåer.

Tillväxthastigheter av solceller till nivåer där de kan stå för en stor del av den globala energiförsörjningen undersöks också. Hänsyn tas till möjligheten att upprätthålla ett system i längre tidsperspektiv, med antagandet att solceller har en livslängd på 30 år. Modellerna utgår ifrån olika teknikval och möjlig framtida minskad materialintensitet för att uppskatta åtgången av olika material. Beroende på dessa antaganden kan resultaten variera mycket, men tillväxten av både kristallina kiselsolceller och tunnfilmssolceller skulle kunna stöta på problem med tillgången av somliga material om inte användandet av material som silver, indium och tellurium minskas avsevärt. Det är också tydligt att den beräknade livslängden på omkring 30 år gör att bara små mängder av material som krävs kan komma från återvinning under tillväxtfasen. Däremot kan återvinning av material spela en viktig roll i ett längre tidsperspektiv för att kunna upprätthålla systemet utan att tillföra stora mängder material från primära källor.

En ingående genomgång av livscykelanalyser av vindkraft visar på stora metodologiska skillnader när det gäller hur nettoenergiutbytet beräknas, samt behovet av material och den miljöpåverkan detta innebär. Även resultaten av dessa varierar och är svåra att jämföra med varandra, vilket gör dem svåra att använda i andra mer dynamiska modeller. En fortsatt diskussion angående hur livscykelanalyser kan och bör användas för att utvärdera vilka energitekniker som är lämpliga efterfrågas.

En sammanställning av reservuppskattningar för litium visar på stor spridning mellan olika studier. Sex möjliga framtida tillväxtkurvor för global litiumproduktion modelleras med olika antaganden av mängden tillgängligt litium. En snabb ökning av elbilar med litium-jonbatterier ser ut att kunna driva upp efterfrågan långt över dessa produktionsnivåer. Tillväxten av litiumproduktionen måste alltså skalas upp mycket fortare än så om inte tillgång på litium ska bli problematiskt för en snabb tillväxt av elbilar.

Efter att varningar om en kommande ”peak” i produktion av fosfatsten, som används som ett helt avgörande gödningsmedel i konventionellt jordbruk, ökades för några år sedan de uppskattade reserverna i Marocko (inklusive Västsahara) mycket och problemet verkade därmed minska betydligt. En produktionsmodell över individuella länder visar på att framtida produktion skulle kunna bli väldigt beroende Marocko. Där skulle produktionen, liksom den möjliga exporten, kunna begränsas av många anledningar, allt från politiska, miljömässiga och ekonomiska.

För att nå något som kan liknas vid ett hållbart energisystem måste troligen stora mängder alternativ energiteknik byggas, vilket kräver energi och material. Exakt hur mycket av dessa resurser som kommer att behövas är svårt att förutse, men en tillväxt till nivåer som krävs för en total omställning av energisystemet kommer oundvikligen att kräva stora resursflöden. Det är svårt att säga huruvida detta skulle kunna begränsa, eller till och med förhindra, en sådan utveckling, och metoder att undersöka detta behöver fortsätta att utvecklas. Den här avhandlingen bidrar till diskussionen om hur vi kan skapa en mer hållbar framtid, även om mycket arbete återstår innan vi på allvar kan förstå vad som krävs för att nå dit.

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