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Global energy transitions

Renewable energy technology and non-renewable resources

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Abstract

The global energy system is dominated by the use of fossil fuels. This system suffers from several problems, such as different environmental issues, while the long-term energy security is sometimes questioned. As an alternative to this situation, a transition to a global energy system based on renewable energy technologies, to a large extent solar and wind energy, is commonly proposed. Constructing the technology needed for such a transition requires resources and how fast this could happen is somewhat disputed. This thesis explores methods to assess the potential constraints for realizing such a transition by looking at potential technology growth rates and outlooks of production of the required natural resources.

The thesis is based on three papers presenting case studies that look at growth rates of wind energy as well as future production outlooks of lithium and phosphate rock. Using different types of growth patterns reaching proposed installed capacities of wind power, annual commissioning requirements are investigated, taking account for the limited life expectancy of technology. Potential outlooks of mineral production are explored using resource constrained curve-fitting models on global lithium production. A more disaggregated model looking at individual countries are used on phosphate rock production to investigate new perspectives on production outlooks.

It is concluded that the growth rates of individual energy technologies affect the resource requirements and prospective constraints on energy transitions. Resource constrained modelling of resource production can provide spans of potential outlooks for future production of resources required for an energy transition. A higher disaggregation of the modelling can provide new perspectives of potential constraints on future production. These aspects should be further investigated when proposing alternative future energy systems.

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

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

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Other papers not included in this thesis:

- 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
- 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
- Larsson, S., Fantazzini, D., Davidsson, S., Kullander, S., Höök, M. (2014) Reviewing electricity production cost assessments. *Renewable and Sustainable Energy Reviews,* 30:170-183
- Wang, J., Feng, L., Davidsson, S., Höök, M. (2013) Chinese coal supply and future production outlooks. *Energy,* 60:204-214
- 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

Contents

Abbreviations

EROI	energy return on (energy) investment
EV	electric vehicle
GEA	Global Energy Assessment
IEA	International Energy Agency
LCA	life cycle assessment
PHEV	plug-in hybrid vehicle
RRR	remaining recoverable resources
UKERC	UK Energy Research Centre
URR	ultimately recoverable resources
USGS	United States Geological Survey

1. Introduction

1.1 Background

Modern society is highly dependent on the use of energy resources, and energy has even been called the lifeblood of technological and economic development (Chow et al., 2003). The current global energy system is dominated by fossil fuels and suffers from environmental problems caused by increasing greenhouse gas emissions, air pollution at local and regional level as well as energy security issues, while at the same time 3 billion people still lack access to modern energy services (GEA, 2012). As a solution to these issues a transformation of the global energy system is commonly proposed, including a transition from the current situation to an energy system based on renewable energy resources.

Renewable energy can be extracted from various sources such as the wind, rivers, ocean waves, biomass from forests or agriculture, geothermal energy from the Earth's interior or directly from the Sun. However, wind and solar energy are commonly considered to have the highest technical potential (Honnery and Moriarty, 2011), especially in developed countries where "old" renewables such as hydroelectricity are close to maximum exploitation (Smil, 2014). Some believe that biomass will also be important in the future and a "bio-based" economy has been proposed as an alternative to the current fossil fuel based one (Vanholme et al., 2013). While some propose that a transition to a global energy system dominated by wind and solar energy could be reached in a few decades (Jacobson and Delucchi, 2009), others argue that such a transition would take much longer (Kramer and Haigh, 2009).

One potential issue that could limit such a transition is that for these technologies to grow on a scale sufficient for a transformation of the entire global energy system, large amounts of a wide range of resources would be required, including non-renewable natural resources. Not only would a complete transition of the energy system require growth of technologies transforming the renewable energy into a useful form, but it would also require changes in the transportation of energy carriers and use of energy services, which requires a growth of many different energy technologies.

It has been argued that many of these technologies are substantially more metal intensive than the currently common technologies and a transition to an energy system based on renewable energy would require a substantial

upscaling of the mining capacities of a many different metals (Kleijn et al., 2011). It has been pointed out that additions of long distance transmission would be needed for using significant amounts of wind and solar energy from optimal locations, which would require large quantities of metals such as copper (Kleijn and van der Voet, 2010). Others argue that the use of wind and solar energy would necessitate energy storage to balance supply with demand (Barnhart and Benson, 2013). Since all these technologies are built using different materials, there are many potentially interesting natural resources to investigate in the context of energy transitions. Some examples of materials and resources that have been mentioned as important are steel (iron ore) and copper for wind turbines and infrastructure (Kleijn and van der Voet, 2010) and lithium for energy storage and electric vehicles (Bradshaw and Hamacher, 2012). Also, a growth of non-food crops for biofuels requiring phosphorus fertilizer, as well as an increased use of phosphate containing batteries for electric vehicles, could significantly increase demand for phosphate rock (Cordell and White, 2011).

1.2 Aims

A hypothetical transformation of the global energy system is a highly complex issue and there are many potential problems that could obstruct or limit the pace of such a transition. The aim of this thesis is to explore methods to assess these potential constraints, focusing on the required growth rates of energy technologies and its associated resource requirements as well as the potential future production of natural resources needed.

More specifically, an attempt is made to investigate how the growth rates of individual energy technologies can affect the resource requirements and potential constraints on growth, when taking account for the expected service life of a technology. Further, it is explored how resource constrained models can be used to assess potential future production of non-renewable resources required for a transition to such an energy system. Combining these perspectives could potentially provide new perspectives on global energy transitions. By increasing understanding of these relationships, the aim is to increase knowledge on which energy transitions are possible and desirable in the future.

1.3 Papers and outline

This thesis consists of three papers and a comprehensive summary. The comprehensive summary starts with describing the conceptual framework that is the foundation of the thesis, before the methods used in the three papers are described. Then, the main results of the respective papers are pre-

sented before the implications of the results are discussed in more detail. Finally the major conclusions are drawn and propositions for future work are presented. The three papers present three case studies of issues that could be important for a global energy transition.

Paper I investigates potential growth rates of wind energy and its implications for annual requirements of various resources. The annual commissioning requirements to reach installed capacities suggested in other studies are modelled, taking account for the limited expected service life of wind turbines, and combined with annual requirements of some important materials.

In Paper II the implications of an electrification of the transport sector using electric and hybrid vehicles with lithium-ion batteries are investigated. Possible outlooks for future availability of lithium is modelled and compared with potential requirements of lithium to supply a fast growth of electric and hybrid vehicles.

Paper III describes potential outlooks of future production of phosphate rock and possible limitations for future production. By modelling production in individual major producing countries, an attempt is made to present new perspectives on future production of phosphate rock that could also be useful for analyzing other resources.

2. Conceptual framework

2.1 Global energy transitions

Alternative global energy futures showing wide spread both in methodology and content are commonly proposed in literature, and are also used for decision-support (Grunwald, 2011). Although the meaning can vary between situations or perspectives, an energy transition can be defined as a transition of an economic system from being dependent on one or several energy technologies to others (Fouquet and Pearson, 2012). On an aggregated global level such a transformation could be considered a *global energy transition.*

Smil (2014) describes two major global energy transitions from one dominant fuel to another that appear to have happened in modern history. First the change from wood to coal and later from coal to oil, both of which took 50 to 60 years. Despite these energy transitions, the use of coal continues to increase on a global scale and according to most statistics biomass still makes up around 10% of global primary energy supply (IEA, 2014). Since these apparent historical energy transitions has been correlated with increases in energy consumption, the absolute consumption of the individual energy sources have continued to increase, despite the fact that the share of individual energy sources might have decreased (Fouquet and Pearson, 2012).

Many transitions that are proposed today are complete transformations of the energy system, reaching a *low carbon economy*, not just a switch in the dominating energy source. It has also been argued that a shift towards low carbon energy does not, however, guarantee a reduction in the use of fossil fuels (Fouquet and Pearson, 2012). On a more disaggregated level, an energy transition can mean something completely different. For instance, in many developing countries with current low energy use the important transition can be considered to be a switch from traditional biomass to modern energy sources (Leach, 1992). The concept *energy transition* can simply mean different things in different situations, but what is more or less inevitable for all energy transitions is that the use of some energy resources increases, meaning that some energy technologies must grow. The focus in this thesis is on the growth rates of energy technology and its associated resource requirements.

Since an energy transition inevitably means that individual energy technologies must grow, how fast such a transition can happen must to some extent depend on the growth rates that are possible for these technologies.

Höök et al. (2011) point out that all growth patterns must ultimately be subjected to some form of limitation. Looking at historical growth rates of energy technologies, it has been argued that although energy sources have grown at high relative rates at early stages, no energy sources have sustained several decades-long growth of more than a few percent (Höök et al., 2012). Kramer and Haigh (2009) suggest that energy technology deployment in history has been remarkably similar between different energy technologies, where a technology has gone through a few decades of exponential growth at around 26% annually until reaching around 1% of world energy, after which the growth becomes linear until the technology settles at a market share.

Renewable energy is commonly described as being preferable to fossil fuels since it is based on energy sources that are constantly replenished, unlike non-renewable or exhaustible resources. However, it is sometimes pointed out that energy technologies such as wind and solar energy are built using non-renewable resources. Since fossil fuels dominate the current energy system it has been argued that they would also need to power a transition to a system based on renewable energy (Moriarty and Honnery, 2009). The energy required as inputs to get the desired energy services is commonly expressed in terms of *net energy* or *energy return on (energy) investment* (EROI) (Murphy et al., 2011). Others point to the fact that a transition to renewable energy would demand large quantities of exhaustible raw materials, especially metals, some of which are already regarded scarce (Bradshaw and Hamacher, 2012). It has been argued that a disruption in the supply of a critical material could limit an energy transition and endanger future energy security (Roelich et al., 2014).

2.2 Using non-renewable resources

Whether dependence on non-renewable resources should be seen as a problem or not is still somewhat disputed within the scientific community. Tilton (1996) even describes two different schools or paradigms concerning resource depletion consisting of those who are "concerned" and "unconcerned". The concerned claim that Earth cannot support current or expected future demand for non-renewable natural resources while the unconcerned think that market incentives, public policy and new technology will be able to provide for society's needs in an indefinite future. This could also be connected to the notion of weak and strong sustainability, where the proponents of weak sustainability thinks that all kinds of natural capital can be substituted by man-made capital, while others believe that there are limits to this kind of substitutability (Ayres, 2007).

A common argument against potential limitations for access to natural resources is to simply point at the fact that the reserves or resources are very large, or much larger than the current production. This argument is true for

many resources, but how it will affect future production is not clearly predictable. Taking the large global reserves and resources of coal as an example it has been claimed that they are sufficient to meet demand for "many decades" (BGR, 2009). Others point to the fact that more than 20 countries already appears to have reached a maximum coal production (Lin and Liu, 2010), or argue that the available coal might be less abundant than commonly assumed, which combined with a rapidly growing global demand could cause problems in the future (Heinberg and Fridley, 2010).

While similar discussions have occurred for a wide range of different natural resources, the most vivid debate on exhaustibility of resources has been about oil. Studies concerning if or when the global oil production will reach a maximum level (peak) as well as whether this is a problem or not lead to the formation of the concept commonly referred to as *peak oil*. Hubbert (1949) stated that the production of fossil fuels, not limited to oil, will inevitably rise until it passes through one or several maxima (peaks) and then decline to zero, where the area under the curve must be equal or lower than the initially present quantity. This can be seen as the foundation of resource-constrained modelling based on the finite nature of oil and other non-renewable resources (Jakobsson et al., 2009). Since then, a wide range of different attempts to describe potential future oil production has been made, leading to a range of different conclusions. However, in a study reviewing over 500 studies on these matters, the UK Energy Research Centre (UKERC) concludes that a peak in production of what is commonly referred to as *conventional oil* is likely before 2030, with a significant risk of it happening before 2020 (Sorrell et al., 2010). While some argue that a peak in conventional oil production is imminent, others argue that this peak could happen due to a peak oil demand (Brandt et al., 2013). The reasons for a peak in oil production are the result of an interplay between below ground constraints, such as physical depletion of resources and above ground limitations, for instance prices and demand, and could also be affected by increased production of what is commonly referred to as unconventional resources (IEA, 2013).

Although the focus is commonly on fossil fuels, and especially oil production and the notion of peak oil, there is a growing debate on the depletion of other non-renewable resources, sometimes referred to as *peak minerals* (May et al., 2012). With regard to non-energy minerals, one important difference is that while energy resources, such as oil and other fossil fuels, are usually combusted and destroyed, the metals that are produced from other materials are recyclable (May et al., 2012). Due to the recyclability of metals, it is theoretically possible to continue to use the materials without mining virgin material, but due to increased use of metals over time combined with long in-use timeframes of metals, the actual recycled content is usually low, and are expected to remain low in the near future (Graedel et al., 2011). Also, while the metals are recyclable, minable mineral deposits are non-

renewable over human timescales and can be considered finite stocks (Prior et al., 2012). Therefore, the same fundamental assumption can be assumed to apply, meaning that production of virgin ore will start from zero, at some point reach a maximum, before starting to decline. Another important difference is that reserve and resource estimates as well as discovery data is less certain for minerals than for fossil fuels (May et al., 2012).

2.3 Modelling energy transitions

Different kinds of models are used to explore potential future energy systems and the transition getting there. Many models used are very complex, which can sometimes be required to make a forecast more realistic, but it can also necessitate an increased amount of assumptions, generally affecting each other, which can work against the desired realism (Smil, 2000). Common methods today include energy systems optimization models, energy systems simulation models, power systems and electricity market models as well as qualitative and mixed-methods scenarios (Pfenninger et al., 2014). In this thesis, less complex models are used, focusing on a few aspects of an energy transition. Two specific aspects of an energy transition, namely the potential growth rates of individual energy technologies and production curves for resources required are modelled using different kinds of growth curves that are commonly used to describe future energy systems.

Hubbert (1949) stated that the production of fossil fuels must inevitably rise, pass through one or several maxima and then decline to zero, but what is not as commonly mentioned is that in the same study a growth curve for the renewable energy resource hydro power is also described. It is suggested that hydro power should rise in a similar manner as fossil fuels at first, but instead of declining to zero again it should level off asymptotically and reach a maximum when all the available resources are brought to use. This suggests that an S-shaped growth curve could be used for renewable energy instead of the bell shaped growth curve proposed for fossil fuels. Similar kinds of growth curve analysis has been used in a wide range of energy studies, such as energy resource analysis, energy demand modelling, fuel substitution and energy technology development (Ang and Ng, 1992). This is commonly done by fitting a mathematical function to historical data, usually referred to as curve-fitting models.

If it is assumed that the growth is constrained in any way, the estimation of this constraint becomes highly important for the analysis. For non-renewable resources, is commonly referred to as the *ultimately recoverable resources* (URR), which can be estimated in different ways. Some authors, such as Hubbert (1956), estimate the ultimate recovery from the discovery trend, while others use curve-fitting methods to estimate the URR itself (Sorrell and Speirs, 2010). Another common approach is to use resource or re-

serve estimates and combine with historical cumulative data and combine them into a URR estimate that are used as a constraint in the model. In this kind of resource constrained modelling, the estimation of the URR is highly important for the results. There are many different ways of handling this, but a common approach is to use a range of estimates of resources or reserves to identify a range of possible results (May et al., 2012).

3. Methods

3.1 Describing growth rates of energy technology

A wide range of studies have proposed global energy systems based on renewable energy in coming decades. Such a transition would require a fast growth of individual energy technologies, and there are many different ways to describe this growth. Paper I investigates the implications of different growth patterns by modelling growth of wind energy reaching two different future levels of installed capacity of wind energy proposed in other studies. The two studies chosen reaches 19 TW of installed capacity wind by 2030 (Jacobson and Delucchi, 2009) and 24 TW by 2050 (Kleijn and van der Voet, 2010). The annual installations required for reaching these levels of installed capacity are modelled using exponential and logistic growth, as well as a *sustained commissioning* model, taking account of the expected service life of the turbines.

In the exponential growth model, the installed wind capacity grows at a fixed fraction per unit time (Bartlett, 1993), from the current level to the proposed future installed capacities. The logistic model is fitted to historical capacity and constrained with a maximum level of the proposed future capacities. This type of constrained growth curve models is discussed in detail in Höök et al. (2011). In the sustained commission model, proposed in Paper I, installed capacity grows exponentially by 26% per year until reaching a level of one twentieth of the proposed future capacity, which is what is needed to sustain this level in the future, assuming a 20 year service life of wind turbines. This level of annual installations is then assumed to continue in the future, making the capacity settle at the proposed level.

These models result in annual installation requirements of wind energy, which can be combined with requirements of different resources, such as materials, energy, investments, mining capacity, or other resources. Although it can be somewhat problematic to estimate the actual requirements of resources such as energy and materials (Davidsson et al., 2012) or investment costs (Larsson et al., 2014), looking at these resource requirements in a dynamic way makes it possible to explore potential constraints caused by access to these resources. In Paper I, annual requirements of steel and copper are used as an example where potential annual requirements of these materials are compared to current annual global production.

3.2 Aggregated modeling of global resource production

In Paper II, three different mathematical models are fitted to historical cumulative production data, using two different URR estimates as constraints, to produce six different possible outlooks for future global lithium production. The mathematical models used are Gomperz, Richards and logistic growth curves (Höök et al., 2011).

The models are constrained by a URR that are estimated by combining the estimated historical production with estimated remaining recoverable resources (RRR). Two different URR estimates are used, where the first case uses the current lithium reserve estimate by the U.S. Geological Survey (USGS) as a RRR estimate. An alternative high case that the current reserves are underestimated and twice this amount will be produced in the future.

To compare the lithium production outlooks to what could be required for a transition from combustion engine cars to electric cars, a simple demand scenario for a fast growth of electric cars (EV) and plug-in hybrid vehicles (PHEV) using lithium-ion batteries are created. To avoid making assumptions of demand for other uses, this demand is assumed to be constant at the current level. The sales of EVs and PHEVs are assumed to follow a scenario presented by the International Energy Agency (IEA). This estimate for annual car sales are combined with a lithium requirement estimate for each car based on a mean value of several other studies. This scenario can be considered an example of potential annual requirements of lithium for a fast growth of electric and hybrid cars.

Paper III uses a similar approach to Paper II as logistic and Gompertz functions are fitted to historical production data of phosphate rock, constrained with three different URR estimates. In the standard case, the RRR is assumed to be the same as the 2012 reserve estimate by the USGS. The low-URR case is based on an RRR similar to the reserve estimate before the sudden multiplication of the global reserve estimate in 2011. Just as in Paper II, a high-URR case is also used that based on an RRR that are double the current reserve estimate by the USGS.

3.3 Disaggregated modeling of resource production

In Paper III, an additional disaggregated model is constructed. The same mathematical models as in the aggregated model are used, namely logistic and Gompertz curves, but instead of modelling global production directly, individual major producing countries are modelled individually. The ten countries with the highest production, covering a vast majority of the total global production, are modelled individually, using current reserve estimates as RRR estimates to create a URR, while the remaining production is mod-

elled as a unit. A similar approach has previously been used in used to project global coal production (Höök et al., 2010).

Two countries are considered extra important for future phosphate rock production and are given some extra attention. These countries are Morocco (including Western Sahara), holding the majority of the global estimated reserves, and China that accounts for over 40% of the current global production. As a very large part of the global estimated reserves are controlled by Morocco, an alternative low case is created where the Moroccan reserves are much smaller. Since the Chinese reserve estimate appears small compared to the current production, an alternative case is created where the Chinese reserves are significantly larger than the current estimate. The different models of individual countries are then combined to form eight different global production outlooks.

4. Results of papers

4.1 Paper I

The assumed growth pattern of an energy technology influences the annual installation requirements and associated natural resource requirements significantly. Taking account of the expected service life, and the fact that replacement of old technology will be needed in the future, further adds to the annual commissioning requirements. The maximum annual installation requirements from four different examples of potential wind energy growth are summarized in Table 1.

Table 1. *Maximum annual installations in the different cases in absolute numbers and fraction of total installations.*

	Exponential 19 TW 2030	Exponential 24 TW 2050	Logistic 24 TW 2050	Sustained commissioning 24 TW
Maximum annual installations (TW)	3.9	2.9	1.5	1.2
Fraction installed in maximum growth year	21%	12%	6%	5%

In the two exponential scenarios, very large parts of the installations needs to be commissioned in the final years, while the requirements for replacing old turbines drop after reaching the proposed level and then rise again, eventually leading to a cyclic behavior.

The logistic and sustained commissioning cases reach a maximum annual installation that is much lower than the exponential cases, but reaching these levels of installed capacity of wind energy still necessitates significant annual installations to be done. The logistic case also shows a cyclic behavior in the requirements of replacing old turbines, while the sustained commissioning model describes a case where a constant annual commissioning of wind turbines is reached in the future.

The annual commissioning can also be coupled with requirements of different resources and materials. Table 2 describes estimates of the required amounts of steel and copper for commissioning the annual turbine installations described in the four different cases.

Table 2. *Estimates of annual requirements of steel and copper in the different wind energy growth cases, in absolute numbers and as fractions of the total global production in 2012.*

	Exponential 19 TW 2030	Exponential 24 TW 2050	Logistic 24 TW 2050	Sustained commissioning 24 TW
Maximum annual steel demand (kt)	550,000	410,000	200,000	170,000
Fraction of 2012 steel production	37%	27%	14%	11%
Maximum annual copper demand (kt)	7900	5900	2900	2400
Fraction of 2012 copper production	46%	34%	17%	14%

Commissioning the turbines required for reaching these levels of installed capacity with an exponential growth would require significant shares of the global production of the base materials steel and copper in one single year, which shows some of the potential issues connected to assuming exponential growth over extended periods of time. However, even the sustained commissioning scenario of keeping installed capacity wind energy of 24 TW over time would require an equivalent of around 11% of the current global steel production and 14% of the copper production.

4.2 Paper II

The three different models and two URR estimates provide six different potential outlooks for global lithium production, making up a span of potential future production. In a short time perspective, the results of the different models are similar, but a few decades into the future the results begin to differ more significantly. All cases but one reaches a maximum during the final 25 years of the current century, but the maximum level of production varies greatly. In the different cases, the maximum reaches around 2 to 11 times the current production.

When compared to the scenario of future lithium requirements for a growth of electric and hybrid vehicles using lithium ion batteries, the demand exceeds the span of the production models somewhere between 2020 and 2025. To provide enough lithium for a fast growth of electric cars with lithium based batteries, the global lithium production needs to grow much faster than the trends that can be seen in these models.

4.3 Paper III

The aggregated model in Paper III provides six different possible production outlooks based on two different models and three different URR estimates,

showing a wide range of different projections of potential future production of phosphate rock. The standard case of the aggregated model, using an URR constraint based on current reserve estimates, reaches a maximum production by the mid-2080s, which gives a somewhat different picture than the 320-year R/P ratio that is otherwise associated with the current reserve estimates. Using a higher or lower URR as a constraint, the model outcomes look significantly different.

The disaggregated model where the major producing countries are modeled individually provides alternative perspectives than can be provided by the aggregated model. In the logistic cases, global production are able to increase production throughout the current century before starting to decline, while the Gompertz model reaches a maximum production within a couple of decades, but with a much slower decline after the maximum production are reached. In the cases using the high URR estimate for Morocco, based on the current reserve estimate, global production will be relying to an increasing extent on Morocco, and finally be completely dominated by this single country. In the cases based on a lower reserve estimate for Morocco, the global production relies to a high extent on China, before the global production reaches a maximum within a couple of decades, followed by a rapid decline. The production in Morocco appears to become increasingly important in the future, and potential constraints to this production could be important to investigate further.

5. Discussion

A wide range of studies have proposed that a global transition to an energy system based on renewable energy technology could happen in the near future. While some propose that this transition could happen in just a few decades, others point out potential constraints and call for a more dynamic perspective on these issues. The three papers included in this thesis attempts to address some of these issues, focusing on the growth rates needed of individual energy technologies, with the associated resource requirements, and potential future production of the natural resources required for commissioning these technologies. These issues cover far from all potential constraints regarding a global energy transition, but these issues or commonly overlooked and could potentially provide valuable insights.

A certain installed energy generating capacity could be connected to requirements of a corresponding amount of materials and energy, commonly collected from life cycle assessments (LCA) of these technologies. However, several studies have pointed out issues with using LCAs for estimating resource requirements for energy technology, especially for the energy demand or EROI (Arvesen and Hertwich, 2015; Davidsson et al., 2012; Modahl et al., 2013). Apart from the requirements of resources for commissioning the energy technologies themselves, other more indirect resources could also be needed, such as for constructing supporting infrastructure. This means that a complete transformation of the energy system could require much more resources than only building energy technologies such as wind turbines and electric cars, but also transmission grid and energy storage facilities. All of this also requires other resources such as financial capital, skilled labor and industrial capacity for commissioning the technology.

Different types of growth curves or curve-fitting models have been used for a long time within energy system research. Although most commonly used for projecting future oil production, they have been used for a wide range of other energy applications, as well as other natural resources. This type of modelling has received a great deal of critique throughout the years, both well motivated and less well argued. Resource constrained curve-fitting models, such as the ones used in Paper II and III, has many limitations, but also has merits. Although the results are expressed as potential peak years and peak production levels, these results are not necessarily the most important, but can be seen as spans of potential future outlooks that can give insights of what is possible in the future. Jakobsson et al. (2009) propose that

these "Hubbert" type curves can be seen as an empirical rule of thumb to be used to distinguish between reasonable and unreasonable scenarios. If a technology is coupled with a requirement of a resource, it can be investigated if a growth of this technology is backed up by a potential growth in availability of the resource. For instance, it can be investigated if the proposed growth of renewable energy is backed up by planned mining expansion and how fast production of this can realistically happen. In turn, this kind of mining expansion could be constrained by issues such as environmental impacts, water constraints or access to infrastructure and energy.

As discussed in Paper III, disaggregated models can provide alternative perspectives to more aggregated models. In the case of phosphate rock it can be seen that since such a large majority of the estimated reserves are controlled by one single country, it can also be discussed on a more disaggregated level what this means. On top of the fact that the global phosphate rock production does not likely want to be too dependent on one country, potentially causing energy security issues in the future, it can also be seen from the opposite perspective of how much specific countries can and want to scale up production. If Morocco and Western Sahara are to multiply phosphate rock production several times, this would have large implications for them. The associated environmental impacts and water use would also increase along with increased production. Empirical studies indicate that most resource abundant countries have suffered from stagnation in economic growth, inspiring the term "curse of natural resources" (Sachs and Warner, 2001). The issue then is if it is possible for Morocco to scale up production enough to support the global phosphate rock demand, but also an issue if they would even benefit from doing this. This becomes even more complicated by the fact that some of these reserves are located in Western Sahara that are occupied by Morocco.

The implications of transitions from the current fossil fuel based energy system to an energy system based on renewable energy technology have implications for a wide range of different aspects such as energy security and sustainable development, but these connections are not fully explored. For instance, while some propose that renewable energy are becoming crucial for enhancing energy security (Valentine, 2011), others state that while renewable energy systems can improve some aspects of energy security, new problems can also arise (Johansson, 2013). These issues should be further investigated and discussed within the scientific community.

6. Conclusions

The growth rates of individual energy technologies and the associated resource requirements should be investigated when assessing the feasibility of global energy transitions. These growth rates can be associated with requirements of a wide range of different kinds of resources that needs to be in place before the technology is taken into use. Using a dynamic perspective on these transitions, potential constraints can be discovered and potentially prevented.

A fast growth of an energy technology requires a high industrial capacity that will not be useful after growth discontinues. Taking account for the expected service life of an energy technology, a theoretical "sustainable" growth rate can be described using a *sustained commissioning model,* where technology grows at a rate required to sustain a desired future installed capacity. In a case study of a fast growth of wind energy, assumed to have a service life of 20 years, it is concluded that the growth rate have large implications for the requirements for natural resources and industrial capacity. A fast growth reaching levels of installed capacity of wind energy capable of contributing with large parts of global energy demand could require significant amounts of materials such as steel and copper.

The construction of renewable energy technology requires non-renewable natural resources. Resource constrained curve-fitting models can provide spans of production outlooks of natural resources that can be regarded more likely than other even more simplistic models. These production outlooks can be compared to associated resource requirements for a growth of energy technology and used to indicate potential constraints to growth caused by natural resource scarcity. It can also be used to indicate that an increase in production of resources will be needed. A case study of lithium indicates that a fast growth of electric and hybrid cars could be constrained by access to lithium for batteries.

A higher disaggregation of modelling of future resource production can provide more detailed outlooks of production, but also indicate where future resource production will need to take place and potential constraints can be investigated on a more local or regional level. Taking phosphate rock as an example, it is concluded that future production could be increasingly dependent on Morocco in the future, and potential constraints on production could be investigated in specific countries.

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