7. Summary & conclusions

7.1. Introduction

Natural resources are essential for human societies. Natural resources are crucial for economic development, help to fulfil basic needs such as food and shelter, and contribute to social development by improving education and public health. Resource use is, however, associated with environmental effects.

Energy is a natural resource of particular interest. Energy systems allowed mechanisation of all productive sectors, increased productivity and improved labour conditions, while availability of energy services increased the quality of life. Consequently, energy demand has been increasing since the beginning of the industrial era. The main downsides of these developments are the economic dependency on cheap oil, and the arising global climate change due to CO$_2$-emissions from fuel combustion. Energy can, however, not be examined in isolation of other resources. Particularly materials resources are of importance for energy systems.

The issues of security of supply and greenhouse gas emissions require long-term planning. Therefore information on (possible) future developments is highly important. This information can be obtained using a combination of two distinctive approaches: analysis of past and present energy systems, and scenario analysis of future energy systems. Both approaches require energy models.

Energy models consist of three basic building blocks: mental models, empirical data, and theoretical causalities. In most energy models, however, emphasis is on one or two of the building blocks.

The aim of this thesis is to increase insights in energy systems, with the intention to be able to change energy systems in a more sustainable way. Previous research of energy systems at the ‘Center for Energy and Environmental studies (IVEM)’ indicated that crucial knowledge gaps regarding energy systems exists at relations between the management of energy and materials resources. Therefore the main thesis objective is to explore environmentally relevant relations between the management of energy and materials resources with emphasis on energy systems. In order to achieve this objective, the preceding Chapters 3 through 6 consider the subject of energy systems using different methodological approaches. The resulting relations between the individual chapters and the different methodological approaches are visualised in Figure 7.1.
7.2. Key findings & methodologies

Energy analysis can be performed with an emphasis on one (or two) of the modelling building blocks shown in Figure 7.1. In this section the key findings of the individual thesis chapters are summarised and related to specific methodologies applied.

The review of the IPCC’s emissions scenarios (Chapter 2) is not explicitly shown in Figure 7.1, because scenario analysis is conceptually broader than modelling. Chapter 2 focuses on the “storylines” and the communication of the analysis, and does not deal with the modelling itself. Chapter 2 finds that the simultaneous goals combined in one scenario analysis made the analysis vague and fuzzy. Scenario analysis should preferably be performed with a single and clear goal, rather than with mutually incompatible goals. Therefore the main message of Chapter 2 is: keep the analysis as simple as possible (but no simpler). The storylines of the IPCC’s emissions scenarios contain several politically coloured elements like “improved equity”, while the scenarios are meant to be descriptive. Not only are the politically coloured elements unnecessary, they also obstruct the communication of the scenarios to the audience. The extraordinary science-policy relation wherein the IPCC operates demands for an extraordinary approach.

The analysis of renewable energy for electricity production and the production of hydrogen from renewable resources (Chapter 3) reveals that although increasing wind energy capacity generally results in decreasing fossil fuel consumption, the benefits of wind energy suffer from diminishing returns due to losses when the wind blows at times of low electricity demand. Moreover it finds that the production of hydrogen
from (discarded) wind energy can help to reduce these losses. However, this would require much electrolysis capacity and sophisticated regulation. In addition to the numerical results the research revealed that some of the inefficiencies of the electricity sector result from the organisation of that sector. This insight ultimately initiated the research of Chapter 6. The analysis of Chapter 3 was performed with an electricity production simulation on the interface of microscopic data and individual actors as shown in Figure 7.1. The associated methodological approaches are bottom-up data analysis and rule-based simulation modelling. The model simulates the behaviour of individual power plants based on hourly data of electricity demand and available wind energy. The simulated behaviour of the individual power plants is driven by simple decision rules. Aggregation over 8760 hours provides bottom-up produced data of national energy totals.

The analysis of the energy efficiency of waste paper recycling (Chapter 4) reveals that, although waste paper recycling is more energy efficient than waste paper incineration, the benefits of recycling suffer from diminishing returns (Figure 4.3). Chapter 4 further reveals that recycling vs. incineration of waste paper implies a trade-off between fossil (energy) resources and biological (energy and materials) resources (Figure 4.4). Therefore, increasing recycling rates result in increasing CO₂-emissions (when the pulp and paper industries are considered separately). The analysis of Chapter 4 was performed using a top-down/bottom-up approach. The top-down data is used to calibrate a white-box materials flow model. The combination of white-box, top-down, and bottom up is visualised with the ellipsoid in Figure 7.1. The main advantage of this approach is that the non-linear relationship between national recycling rates and national virgin fibre requirements is not only based upon their correlation (black-box), but also on theoretical causalities (Figure 4.2).

The industrial energy demand scenario analysis based on physical indicators (Chapter 5) reveals that the use of physical indicators for industrial energy demand scenarios tends to produce different outcomes compared to monetary approaches. This result should, however, be interpreted as complementary to monetary approaches because the physical approach comes with simplifications, like neglecting trade. Chapter 5 further reveals that industrial energy demand scenarios based on monetary indicators may imply unrealistically large accomplished materials flows. Therefore, a potential application of physical indicators is to provide a reality check for industrial energy demand scenarios based on monetary approaches. The analysis of Chapter 5 was performed using a pure ‘black-box’ model as indicated in Figure 7.1. An obvious disadvantage of the use of a black-box model is the lack of insight. The black-box model does not ‘explain’ why certain developments take place, because it focuses on the highest aggregation level. An advantage of a black-box model is, though, that it can project developments that are hard to simulate with high precision using white-box models, like convergence (Figure 5.4), because white-box models tend to be sensitive for variations in input data. The ‘mental model’ that supports the ‘black-box’ model includes key elements from other methodological approaches, e.g. the assumption of commodities saturation is derived from micro-economic analysis. The ‘flexible extrapolation’ method allows the development of different scenarios, while being still in line with historical data.

The meso-level analysis of energy systems (Chapter 6) reveals that meso-level dynamics do explain phenomena that are hardly caught at micro- or macro-levels.
Chapter 6 further reveals that institutional frameworks are a dominant driving force regarding autonomous developments of energy systems and regarding energy policies. Moreover, considering agents as heterogeneous, rather than homogeneous, results in different over all behaviour, and in different responses tot policies. These conclusions have considerable implications for both energy forecasts and energy policies. The outcomes of energy forecasts differ when it is acknowledged that income is only one explanatory variable for household consumption among many others (rather than a key driver). The effectiveness of energy policies can be improved when policy makers abandon their attempts to cope with the ‘difficult’ sectors for energy policies – i.e. personal transport and electricity consumption – by means of ‘one size fits all’ policies. Non-traditional policy solutions are needed to cope with these sectors. The analysis of Chapter 6 was performed using a ‘mental model’ as indicated in Figure 7.1. An obvious disadvantage of the use of mental models is the lack of quantification. Consequently, mental models are hard to calibrate against real-world observations. The advantage of mental models, however, is that phenomena can be observed that are hard to model quantitatively. Models that simulate meso-level phenomena – like technological lock-in – are sensitive to variations in data input and thus may produce strongly different outcomes when the starting variables are modified slightly. Mental models – like the NOA model of consumer behaviour in Figure 6.3 – can help to understand phenomena that can hardly be captured with quantitative approaches.

7.3. Over-all conclusion

This thesis observes energy systems from different angles, i.e. it considers interactions between different resource types, it considers different aggregation levels, and it considers different methodologies.

Resources of different types and uses (see Table 1.1) do interact with each other within the context of societal metabolism. The interactions between energy and materials resources are generally non-linear. Consequently, diminishing returns and saturation effects are persistent. As a result of diminishing returns the potentials for environmentally benign changes are smaller than observed at first sight. On the other hand, as a result of saturation effects future pressures on resources and the environment may be smaller than expected on linear models. The combination of both diminishing returns and saturation effects make the energy system more difficult to understand intuitively.

The aggregation level may limit and determine the outcome of research. Therefore, energy analysis needs to assess all three levels – micro, macro, and meso – simultaneously. Simultaneous analysis of all three levels, though, is in general not feasible. Nevertheless, single-level energy analysis can be improved significantly by incorporating key elements of the other levels. In this context, the meso-level is of particular interest, because it captures system organisation and institutional frameworks. System organisation and institutional frameworks have also been identified as key driving forces of changes in energy systems, and as key barriers of intended changes of energy systems. Therefore, the meso-level is of particular interest regarding energy policies.
Closely related to the aggregation level is the applied methodology. Each methodology reveals different aspects of energy systems, but also neglects other aspects of energy systems. All methods displayed in the modelling pyramid (Figure 7.1) are applied in the different chapters. Even more than the aggregation level, the applied methodology limits and determines the outcome of research. Different methodologies (and their associated outcomes) should be interpreted as complementary rather than contradictory. Accordingly, in this thesis energy systems are methodologically triangulated from an integrated resource perspective.