Modelling energy systems
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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2006

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

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1. General introduction

1.1. Relevance of natural resource analysis

Natural resources\(^1\)\(^2\) 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 (OECD 2001d). Consequently, many resources are valued directly as inputs in the production of economic goods and services (Johnstone 2001). Natural resources are normally classified according to their ‘type of resource’ and ‘type of use’ as shown in Table 1.1.

Natural resources are – in general – divided into three different types: non-renewable resources, renewable (but exhaustible) resources, and non-exhaustible resources. The resource type has implications for the management of the resource.\(^3\) Natural resource use is categorised into energy, materials, and other. Energy is divided into the energy source\(^4\) and the energy carrier\(^5\) that delivers the final energy service.\(^6\) Materials are categorised according to their appearance in national statistics into stocks and flows. Since national statistics are generally published annually, materials are considered stocks when they persist for several years.

1.1.1. Environmental effects of resource use

Resource use is associated with environmental effects. Three broad classes of environmental effects are arising from the resource classification presented in Table 1.1. First, ‘resource rents’ are the scarcity effects, arising from resource use, on future potential users. Second, ‘bundled values’ are the role natural resources (particularly forests and freshwater) play in supporting ecosystems and species habitat. Third, ‘environmental externalities’ are the variety of wastes and pollutants (including GHGs) generated by resource use (Johnstone 2001). Changes in resource use efficiency can be attributed to: resource-saving, resource-reusing, and resource-substituting (Johnstone 2001).\(^7\)

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\(^1\) “Natural resources are naturally occurring substances that are considered valuable in their relatively unmodified (natural) form. A commodity is generally considered a natural resource when the primary activities associated with it are extraction and purification, as opposed to creation. Thus, mining, petroleum extraction, fishing, and forestry are generally considered natural-resource industries, while agriculture is not. The term was introduced to a broad audience by E.F. Schumacher in his 1970s book Small Is Beautiful.” (<http://en.wikipedia.org/wiki/Natural_resource>, accessed 1 February 2006).

\(^2\) In this thesis ‘Natural resources’ are defined more broadly as shown in Table 1.1.

\(^3\) Paradoxically scarcity is mainly a problem for renewable resources (Johnstone 2001), and oil is more plentiful now than in 1973 in an economic sense (Watkins 2006).

\(^4\) Often referred to as: ‘primary energy’

\(^5\) Often referred to as: ‘final consumption’

\(^6\) The ultimate service that energy consumption provides (OECD 2001d, p362).

\(^7\) Additional options: resource-broadening, resource-prolonging, and resource-increase (Johnstone 2001).
Table 1.1: natural resource taxonomy

<table>
<thead>
<tr>
<th>Resource use</th>
<th>Resource type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-renewable</td>
</tr>
<tr>
<td></td>
<td>Renewable (exhaustible)</td>
</tr>
<tr>
<td></td>
<td>Non-exhaustible</td>
</tr>
<tr>
<td>Stock</td>
<td>Metal ic capital equipment and consumer durables</td>
</tr>
<tr>
<td>Flow</td>
<td>Wooden structural materials</td>
</tr>
<tr>
<td></td>
<td>Paper products, agricultural products, fish products</td>
</tr>
<tr>
<td></td>
<td>Limestone</td>
</tr>
<tr>
<td></td>
<td>N₂, CO₂</td>
</tr>
<tr>
<td>Flow</td>
<td>Packaging plastics, aluminium foil, cooling water (aqui fer)</td>
</tr>
<tr>
<td>Energy (dissipative)</td>
<td>Crude oil, coal, and natural gas</td>
</tr>
<tr>
<td></td>
<td>Biomass for fuel</td>
</tr>
<tr>
<td></td>
<td>Petrol, diesel, electricity</td>
</tr>
<tr>
<td></td>
<td>Ethanol, biodiesel, electricity</td>
</tr>
<tr>
<td></td>
<td>Tidal, wind, solar</td>
</tr>
<tr>
<td>Other</td>
<td>Biodiversity</td>
</tr>
<tr>
<td></td>
<td>Soil, freshwater</td>
</tr>
</tbody>
</table>


Note:
The time-frame determines the resource type classification; in the long run solar energy will exhaust and atmospheric nitrogen is a renewable resource." Non-renewable' resources are also referred to as 'depletable' resources.

1.1.2. Focus on energy systems

Energy is a natural resource that deserves special attention. Since the beginning of the industrial era⁹ energy systems allowed mechanisation of all productive sectors, increased productivity and improved labour conditions, while availability of energy services increased the quality of life. The downside of these developments is the ever-increasing dependence on energy. Abrupt increases in oil prices have initiated economic crises in the early 1970s (Doroodian & Boyd 2003), high transport fuel prices have resulted in social unrest and strikes,¹⁰ and high energy prices threaten to push the purchasing power of the poorest households in developed countries below socially acceptable levels. Real shortage, for example due to electricity blackouts, weather conditions, strikes and war, deeply affects the life of virtually everyone in the

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⁸ Atmospheric nitrogen is around 2-3% on Venus, Mars, and Earth without life (Lovelock 1988, p9). Life is a key driver of global geochemical cycles on Earth (Westbroek 1991).

⁹ Before the industrial era windpower and hydropower allowed mechanisations of some sectors. Notably, Jan Adriaanszoon Leeghwater used windpower to create polders in the early 17th century and therefore determined the landscape of large parts of the Netherlands.

¹⁰ E.g. French farmers tend to strike when fuel prices are high, Dutch populist politicians often plead for less tax on fuel, and in late 2005 a majority of the Dutch cabinet seemed to be willing to compensate households for the high oil-prices.
society concerned (IEA 2005a). The search for alternatives for oil is seen as one of the most important scientific quests for this century (Kerr & Service 2005).

Energy systems are also associated with several adverse environmental effects ranging from landscape distortion from wind turbines (as perceived by Dohmen & Hornig 2004) to global climate change from CO₂ emissions from fuel combustion (IPCC 2001), and human deaths because of air pollution (OECD 2001b, Ch21). Therefore efficient management of energy systems is beneficial for the wellbeing and ‘sustainable development’11,12 of societies.13

Analysis of these particular energy systems is referred to as ‘energy analysis’ in this thesis. One specific technique to perform energy analysis – and thus to assess energy systems – is by the application of models. Sections 1.3-1.5 give an overview of different types of modelling techniques. Next Section 1.6 introduces the relevance of materials in energy analysis. But first Section 1.2 introduces the need for forecasting.

1.2. Forecasting

The main issues associated with energy resources – security of supply and GHG emissions (see Section 1.1.2) – require long-term planning because of the life-spans of energy-related capital stock (see Figure 1.1), time-lags in the climate system, and etceteras. Therefore information on (possible) future developments is highly important.

Energy related (possible) future developments are associated with a high degree of uncertainty. High-uncertainty and high-stakes science is awkward in the scientific arena and referred to as ‘post-normal’ science (Funtowicz & Ravetz 1993).

High-uncertainty and high-stakes science is one hand complementary with the scientific method – observations and the construction of theories dominate – but on the other hand it lacks the possibility to perform numerous experiments to falsify theories. Therefore, in addition to the ‘normal’ science approach, methods are needed to deal with the associated uncertainty (see Section 2.4.2). ‘Forecasting’ is the appropriate method to deal with high uncertainty and high stakes.

11 ‘Sustainable development’ stems from the ‘Brundtland report’ (WCED 1987), and relies on two key concepts: first, the idea of ‘needs’, and second, the idea of ‘limitations’ on the environment’s ability to meet present and future (generational) needs (OECD 2001d, p38; Pearce 2002). For a historical perspective on sustainable development see: (van Zon 2002).
12 The depletion of exhaustible resources and sustainable development appear to be competing paradigms (Tilton 1996).
13 Energy security and climate change mitigation interfere with each other in such a way that a country will prefer to cut emissions more greatly with those fuels that it imports and less greatly with those that it exports (Huntington & Brown 2004).
There are several grounds for ‘forecasting’\textsuperscript{14} in the post-normal scientific arena. First, forecasting provides insights in expected (or likely) future developments. This type of forecasting allows quantification of future consequences of decisions and therefore decision making based on possible future developments. Second, the single scenario can be extended by alternative scenarios that cover a wider range of future developments and help to assess uncertainty. Third, scenarios can be used to change ‘locked-in’ thinking and therefore allow people to escape from conventional worldviews. Break-through solutions can be considered by exploring futures that were never thought of.\textsuperscript{15} Fourth, scenarios can test the robustness of policies or decisions against a wide variety of possible future developments, in contrast to ‘betting the company’ on the most likely (or desired) development.\textsuperscript{16}

\textsuperscript{14} In energy and environmental sciences the word ‘forecast’ is used for every systematic attempt to explore the future. Forecasting is defined in this thesis as thinking about possible future developments (Schwartz 1999; Turkenburg 1993), rather than the Oxford definition: “to say in advance what is expected to happen” or “to predict something with the help of information”. Later the word ‘outlook’ came into use, e.g. ‘OECD Environmental Outlook’ (OECD 2001b), and ‘Global Environmental Outlook’ (UNEP 2002). Scenarios are the development paths described by a forecast or outlook.

\textsuperscript{15} E.g. scenarios for South Africa initiated the peaceful regime change from apartheid to democracy (Schwartz 1999).

\textsuperscript{16} Very closely related to the grounds for forecasting are the tree archetypes of scenario analysis: policy optimisation, advocacy and vision building, and strategic orientation (Bakkes 2004).
Figure 1.1: average life-spans for selected energy-related capital stock

Source: (OECD 2001d)

1.3. Energy models

Models are simplifications of real-world systems by definition.\(^\text{17}\) Models are used inside and outside the scientific world to increase understanding of complicated or complex systems.\(^\text{18}\) Computer aided modelling is used “for representing hitherto hardly accessible complex systems, for simulating their dynamics, and for understanding systems and dealing with them better than before” (Bossel 1994, p2).\(^\text{19}\) Because models are simplifications, models always have shortcomings (Worrell et al. 2004). Some weaknesses associated with the use of models have been identified:

- Models tend to represent only one point of view about how the future will unfold and can be therefore unnecessarily narrow in view (Alcamo 2001).
- Computerised models can give opinion and subjective judgement an air of robust analysis and formal calculation (Keepin & Wynne 1984).
- Models should not be applied to problems they were not designed to address (Sanstad & Greening 1998). Although disobeying this rule has benefits (Bakkes 2004; Rizzoli & Davis 1999), because the circumstances are favourable for ‘serendipity’.\(^\text{20}\) Therefore, this rule should not be taken too strictly.

\(^{17}\) “Simplification is the goal and not the restriction” (Schrattenholzer as quoted in van der Sluijs 1996).
\(^{18}\) E.g. ball-on-stick models are used to increase insight in molecular dynamics in chemistry.
\(^{19}\) “Computers are incredibly fast, accurate and stupid. Humans beings are incredibly slow, inaccurate and brilliant. Together they are powerful beyond imagination.” Albert Einstein.
\(^{20}\) The unsought finding (van Andel 1994).
These weaknesses originate from the anatomy of energy models. Section 1.4 lists the model building blocks, and Section 1.5 shows how different classes of energy models are constructed from these building blocks.

1.4. Model building blocks: mental models, empirical data, and theoretical causalities

Energy models consist of basic building blocks: mental models, empirical data, and theoretical causalities.\(^{21}\)

Empirical data is analysed to provide generic properties of the system. Regarding empirical data, the aggregation level is the major factor to distinguish different methods. At the lowest aggregation level, data describes individual processes.\(^{22}\) Process-level data is often favoured because it is the closest to the actual process relevant for energy analysis. At the highest aggregation level, data describes over-all properties of a system, highly aggregated data is often favoured because it provides data wanted by policy makers, e.g. national GHG emissions.

Theoretical causal relations between variables are used to reveal the dynamics of the system by simulation. Theoretical natural resource analysis is relevant in order to understand system behaviour, and thus to predict the systems’ possible responses on stimuli from outside the system (policies). Analogous to empirical data, causal relations can be observed at different aggregation levels.

A mental model is the fuzzy-structured ‘world according to the modeller’. This mental model is constructed from: observations, scientific discipline, culture, values, and \textit{etceteras}. Formal models are formalisations of mental models, and therefore the mental model of the modeller determines the final model outcome. The dynamic behaviour of the formal model and the accuracy of the formal model to reproduce historical developments may force the modeller to alter his mental model. Consequently, advancement in modelling is an iterative process between mental models, formal models, and real-world data.

1.5. Model pyramid: a taxonomy of environmental models

The era of energy models is squeezed between the modelling building blocks: mental models, empirical data, and theoretical causalities, described in Section 1.4. Figure 1.2 visualises the position of the energy models regarding the building blocks, and the associated methodologies. The model building blocks are represented here as pyramids, because both regarding empirical data, and regarding theoretical causalities, the bases of the pyramids represent heterogeneous data or agents.

\(^{21}\) Also referred to as: ‘idealised systems’.
\(^{22}\) On a slightly more aggregated level one can find data on plant level, or the sub-sectoral level.
Due to the diversity of modelling approaches, choices need to be made. The choices in modelling are determined by the purpose of the model, or – to be more specific – the question that needs to be answered.

The bottom-up and top-down approach are both associated with empirical data. The bottom-up approach is used to compare energy technologies and to provide parameter input data for predictive models, while the top-down approach is used to monitor long-term trends, to monitor over-all system performance, and to provide input for predictive models.

Rule-based\textsuperscript{23} models and differential equation models are both associated with theoretical causalities. Rule-based models of individual agents provide insights in the complex dynamic aspects of energy systems, while differential equation models\textsuperscript{24} provide insights in the over-all functioning of energy systems.

Black- and white-box models are used to aid energy forecasting (see Section 1.2), and therefore referred to as ‘predictive models’. Black-box models emphasise on data, while white-box models emphasise on causal relations between variables. Predictive models are associated with mental models.

\textsuperscript{23} Also referred to as ‘agent-based’ or ‘stochastic’ models.

\textsuperscript{24} This type of models is also referred to as ‘system dynamics’ or ‘stock-and-flow’ models.
1.6. Aim of the thesis: integrating materials in energy models

Societal metabolism\(^{25}\) requires energy and other resources as inputs (see Section 1.1). Within the societal metabolism framework, energy and other resources do interact with each other, e.g. materials substitution and recycling affects energy use, energy infrastructure like the ‘hydrogen economy’ affects materials requirements. Therefore – in environmental terms – energy and materials resources cannot be examined in isolation (Gielen 1999; Haberl 2001a; Johnstone 2001; Kram et al. 2001; Moll 1993; Sedjo 2002; Tromp 1995b; Wernick & Themelis 1998; Zackrisson 2005).

The aim of this thesis is to model and explore environmentally relevant relations between the management of energy and materials resources (see Table 1.1) with an emphasis on energy systems.\(^{26}\)

Because the environmentally relevant relations between the management of energy and materials resources are complicated, they cannot be assessed using a single methodology. Therefore this thesis uses different methodological approaches from Figure 1.2 to assess different case studies.

This research further aims to provide policy-relevant conclusions based on a literature study and three case studies. Together they illustrate energy modelling and the energy and materials interactions, each from a different angle, using a different methodological approach. The insights derived from the case studies are used as input for a policy-oriented study. The next Section gives a brief introduction to the individual Chapters.

1.7. Guide for the reader

Natural resource management is one of the main focuses of this thesis. The 2x3 matrix in Table 1.1 is used to identify possible interactions between types and uses of natural resources. Two of these interactions are considered: ‘renewable energy vs. renewable materials’ and ‘non-renewable energy vs. non-exhaustible energy’.

This thesis starts with a review of – probably – the most comprehensive energy scenario study until present: the IPCC’s special report on emissions scenarios (SRES). Forecasting is an important aspect of energy analysis (see Section 1.2), but also an aspect of energy analysis that is often difficult to communicate. Chapter 2 researches communicative aspects of SRES.

A case study on electricity production is used to study the interactions between non-renewable energy and non-exhaustible energy. Wind energy is an often favoured strategy to reduce GHG emissions in the electricity sector. However, at higher wind energy penetration rates the over-all system-efficiencies decrease because the remaining fossil fuelled plants need to adjust their operating policies, which cause losses. Chapter 3 researches the trade-offs between non-renewable energy and non-

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\(^{25}\) For a historical perspective on ‘societal metabolism’, see: (Fischer-Kowalski 1998; Fischer-Kowalski & Hüttler 1998).

\(^{26}\) When focus is on materials resources the trade-offs can be classified according to the materials type: inorganic materials require energy, fossil fuel based materials compete with energy, and bio-based materials compete with food (Huppes, SENSE Core 4, 2004).
exhaustible energy for the Netherlands. Hydrogen production from wind energy is considered as an option to increase over-all system efficiency.

A case study on waste paper recycling is used to study the interactions between renewable energy and renewable materials. Recycling is a typical way to manage materials and improve efficiency. However, recycling also requires energy. Chapter 4 researches the trade-offs between waste paper recycling and the production from virgin fibre in Western Europe.

A case study on societal materials flows as drivers for industrial energy demand scenarios is used to study the relation between energy and materials from a dynamic perspective. Chapter 5 researches the effects of the use of materials-based indicators for long-term industry energy scenarios for two world regions: Western Europe and China.²⁷

A synthesis of the explorative research of Chapters 3 to 5 is used to provide the reader with general aspects of the level where energy and materials closely interact: the meso-level. Chapter 6 describes policy-relevant aspects of the meso-level of energy systems and finishes with policy recommendations.

Finally, Section 7 (summary & conclusions) discusses the individual chapters based on Figure 1.2 and relates the used methodologies with the modelling elements and modelling approaches.

²⁷ Actually ‘Centrally Planned Asia’.