A thermodynamic perspective on technologies in the Anthropocene: analyzing environmental sustainability

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Chapter 6

Answers to research questions and reflection

6.1 Introduction

Evaluating technologies may pose the biggest challenges to IE and related sustainability sciences. This thesis has developed a hierarchical thermodynamic framework for the environmental sustainability analysis of technologies, from small (titania production) to large (global biofuels). The framework defines techno-systems at four levels, *viz.*, the ecosphere, the anthroposphere, the supply chain, and the foreground system.

This concluding chapter provides an integration of the preceding four chapters, which were written as independent journal papers, into a coherent thesis. First, I will answer the four sets of research questions that were formulated in Chapter 1. Next, I will give my reflection and discussion on the thermodynamic perspective. Finally, I will discuss the further development of thermodynamic analysis for sustainability.

6.2 Answers to research questions

The objective of this thesis is to offer insights into the potential offered by thermodynamics in the environmental sustainability analysis of technologies in the Anthropocene. To this end, four main sets of research questions have been raised, with answers as below:

Q1. What is the relevance of thermodynamics for environmental sustainability analysis of technologies? Can we link the key laws of thermodynamics to the development and use of technologies?

Answer: The environmental dimension of the sustainability of technologies is manifested in physical exchanges between technologies and between a techno-system and the ecosphere. These physical exchanges are expressed as energy flows and conversions from a thermodynamic perspective as demonstrated in the thermodynamic framework for sustainability analysis (Chapter 2). The thermodynamic framework models the physical reality of the ecosphere as the sum of techno-systems and the natural environment. A techno-system converts material and energy resources into products and services, which can be at the level of the foreground system or the supply chain of the techno-system, the anthroposphere, or the ecosphere. Its environment is the rest of the universe which is not thermodynamically affected by the techno-system. The thermodynamic structure of the techno-system is a conversion of inflows of high entropy raw materials and low entropy energy carriers into outflows of low entropy products and high entropy waste. The depletion of materials and energy resources and the generation of wastes and pollutants, as two major problems of technologies from the point of view of environmental sustainability, are explicitly represented in the model developed in this thesis, though the harmful nature of pollutants, like their toxicity, is not covered. This model converts the description of technologies into indicators representing their environmental sustainability in terms of (thermodynamics-based) resource consumption (Chapters 3, 4, and 5), resource renewability (Chapter 3), physical profit (Chapter 3), system efficiency (Chapter 3), and heat emission (Chapter 4). All the preceding chapters have shown that taking account of thermodynamics is a necessity when analyzing environmental sustainability of technologies. Without it, major options and constraints in technology development cannot be specified and specific techno-systems cannot be judged in this perspective.

Q2. What are the major thermodynamic metrics and methods that can be used for environmental sustainability analysis of technologies? Can we find a practical way to link the basic concepts of energy transformations within the boundaries of the first and second laws of thermodynamics?

Answer: Energy and exergy are shown to be the major thermodynamic metrics for environmental sustainability analysis of technologies (Chapters 2 and 3). Emergy, on the basis of energy definition, is another major thermodynamic metric (Chapter 3). Although being also one such metric, entropy is left out of consideration in this thesis because entropy is energy per kelvin and temperature is not relevant as such in this thesis. Energy analysis, exergy analysis, emergy analysis as well as entropy analysis are common methods for the environmental sustainability analysis of technologies. The role and applications of these major thermodynamic metrics and methods are reviewed in a sustainability analysis of broader human-environment systems which includes technologies (broadly defined) and their functioning to show how these metrics can be used in a practical manner. The quantitative relationship between the thermodynamic metrics is not self-evident so a quantified specification of the metrics based on a clear mathematical and conceptual formulation, as for example regarding boundary flows and stock changes, should clarify the relationship (Chapter 2). These thermodynamic metrics provide a basis to convert inflows of material and energy resources for a technology, *e.g.*, the bioethanol produced from corn stover in the U.S. (Chapter 2) into environmental sustainability indicators.

Q3. How can thermodynamics be integrated with LCA and MFA to achieve a better understanding of technologies at different system levels? Can we link the thermodynamic analysis to functional systems and to the main material flows in the anthroposphere?

Answer: Our research confirmed that combining thermodynamic analysis with the main modeling approaches in IE – LCA, MFA as well as environmentally extended IOA – is both feasible and useful. (Chapter 2). There are three ways to integrate thermodynamics with LCA as reviewed, *viz.*, employing thermodynamic metrics in life cycle impact assessment of resource depletion, using thermodynamic metrics to approximate environmental impact, and incorporating thermodynamic analysis into life cycle thinking for multi-criteria studies. Material and energy flow analysis is presented as the most common framework to integrate thermodynamics with MFA. Thermodynamics can also be integrated with MFA in other, more *ad hoc* ways, such as in the investigation of the natural resource demand of global biofuels (see *e.g.*, Chapter 4). Exergy is used as a measure of resources. Various estimations of primary exergy sources to the ecosphere, *i.e.*, solar radiation, moon gravity, and geothermal heat, are summarized. The global anthropogenic exergy demand is estimated by linking energy flows from the ecosphere to the anthroposphere with their exergy-to-energy ratio. Natural resource demand of different first generation liquid biofuels (biodiesel and bioethanol) is determined using cumulative exergy demand. Flows of heat emitted to the ecosphere by the supply chain and the foreground production of global biofuels as well as by the anthroposphere are also determined. Employing thermodynamic metrics in life cycle impact assessment of resource depletion has been illustrated as a way to integrate thermodynamics and LCA (Chapter 5). The pros and cons of seven life cycle impact assessment indicators are investigated by comparing four recently implemented thermodynamic resource indicators with three non-thermodynamic resource indicators and testing their feasibility in the case of titania produced in China.

Q4. How can we apply thermodynamic analysis integrated with LCA and MFA to support decision-making on environmental sustainability? To what extent does the thermodynamic analysis overlap with the sustainability concepts covered in the impact categories of LCA, or is it an add-on, or can it help classify diverging mechanisms? Can we get to grips more effectively with the resource issues currently on the agenda?

Answer: There are three ways in which thermodynamic analysis enriches the analysis based on LCA and MFA. The first is by referring to the performance of a specific technology in terms of certain environmental concerns, *e.g.*, natural resource depletion and climate change (Chapter 4). The problem of natural resource depletion is commonly reflected in thermodynamic analysis, LCA, and MFA, for instance, via cumulative exergy extraction from the natural environment, abiotic resource depletion, and material input per service unit, respectively. Among these three indicators, cumulative exergy extraction from the natural environment as the thermodynamic one has the highest completeness of resource scope. Thermodynamic analysis reflects heat emission of technologies as one mechanism of climate change. This supplements global warming through the emission of greenhouse gases as another mechanism covered by LCA. The second is by assessing the sustainability of a specific technology against some indicators, *e.g.*, resource renewability and system efficiency. For instance, the lower cumulative degree of thermodynamic perfection of bioethanol compared to that of diesel indicates that bioethanol technology is less efficient in delivering energy/exergy than conventional energy technology (Chapter 3). These indicators are not an explicit part of the standard impact categories of LCA. The third is by comparing technology alternatives, such as the chloride route and the sulfate route, for titania production (Chapter 5). The comparison is based on the developed framework, where thermodynamic indicators represent resource properties and other non-thermodynamic indicators characterize resource scarcity.

6.3 Reflection and discussion

6.3.1 The thermodynamic perspective: evaluation of environmental sustainability problems

The thermodynamic perspective effectively addresses the environmental problem of the depletion of materials and energy resources, while providing limited added value in terms of evaluating that of the generation of wastes and pollutants. The potential to cause instability to the ecosphere due to the generation of wastes and pollutants can be quantified based on their exergy value or the abatement exergy loss but the impact of environmental pollutants on human and ecological health, *e.g.*, toxicity, cannot be measured based on exergy or other thermodynamic metrics. Environmental sustainability in this aspect is to be assessed more effectively using other tools such as specific LCA impact categories, or substance oriented risk assessment.

6.3.2 The thermodynamic framework: resolution of environmental sustainability analysis

The spatial and temporal resolution in the hierarchical thermodynamic framework developed and applied in this thesis can be further refined to improve its relevance in supporting decision-making on environmental sustainability. Environmental sustainability is a concern about what ought to be, or ought to be avoided, in the future. Making a decision on environmental sustainability needs knowledge about not only the present situation but also what would be possible situations in the future. Be it predictions, projections, or descriptive scenarios, the most relevant analysis includes, among others, time series and description of the evolution of technologies while the thermodynamic framework applied as such mainly includes snapshot-type of analysis, which is determined by thermodynamics primarily as an equilibrium science *per se*. In addition, the spatial differentiation of technologies, as an important factor to improve the precision of the results, should be considered when scaling up a specific local technology. For instance, the electricity input to the titania production in China is not the same as that to the global situation (Chapter 5). The solar radiation to the corn production and the corn grain yield in the State of Iowa in the U.S. are different from that in the Province of Ontario in Canada (Chapter 4).

6.3.3 The thermodynamic mechanism: one aspect of technology complexity

The developed model accurately represents the thermodynamic mechanism of technologies, while further case studies, including dynamic ones, may reflect the complexity of technology to a wider extend as well as in greater depth. Techno-systems as well as the ecosphere are complex adaptive systems. This thesis applies thermodynamic analysis mainly as static linear models and the causality of the interactions between techno-systems is pre-assumed typically by fixing transformation ratios to represent the system behavior, as usual in LCA, MFA as well as environmental extended IOA. This makes it quite challenging to link a specific technology as a full system into higher-level systems analysis, be it in the context of environmental sustainability analysis or others, since causality is ossified and the dynamics caused by other non-thermodynamic constraints and real-life feedbacks are left out of consideration. Examples include the limits to land availability and other feed back mechanisms in the biofuel case studies. In addition, how the anthroposphere as the sum of techno-systems evolves from one regime to another is not easy to explain by only applying the thermodynamic mechanism. Thermodynamics sets constraints on options, and can indicate the relative performance of techno-systems but does not specify the dynamic drivers. These are mainly social in nature, covering cultural, institutional, political, and economic mechanisms.

6.3.4 The dimensions of thermodynamic analysis: metric and level

The developed model provides a framework which is able to incorporate major thermodynamic metrics and relationships. As thermodynamic models should reflect physical reality as accurately as possible, the quantitative relationship between energy and the other metrics should be clarified when these metrics are to be used together. This relies on semantical and mathematical definitions of theses metrics, which will help define the two dimensional (scale level and metric) linear sequence of various types of thermodynamic analysis within the framework as illustrated in Chapter 3. The metric dimension in principle can distinguish energy, entropy, and exergy. The entropy dimension and the application of exergy at the level of the ecosphere may be examined in future research. While emergy has been shown to be based on energy, the system boundary and the time frame difference between these two concepts should be formulated quantitatively. For instance, some gas deposits may have formed already hundreds of billions years ago, partly based on solar radiation and partly of geothermal heat from the condensation of the earth and from nuclear reactions. This does not help much in the sustainability analysis for our future generations.

6.4 Further development of thermodynamic analysis for sustainability

Based on the work conducted in this thesis, some interesting research lines to explore further can be identified.

1) Thermodynamic analysis should be developed further so as to better inform sustainability decision-making. Changed technologies, and their market volumes, are considered as solutions for un-sustainability and are supposed to limit the level of influence of the Anthropocene. However their implementation will have both positive and negative environmental, economic, and social impacts. Economic and social aspects of sustainability have not been treated in this thesis. They may be analyzed according to a set of coherent rules in terms of system boundaries, data quality, *etc.* and

analytical methods at all levels discerned. An IE-type of approach is a necessity since problem-shift should be avoided when making system-level decisions.

2) The developed thermodynamic framework should be extended to answer questions that go beyond the scope of sound stewardship of natural resources. For instance, is large-scale implementation of emerging energy technologies limiting or enlarging the level of influence of the Anthropocene? Thermodynamic measures may give one answer. How can we better embed these outcomes in the sustainability discussion, with broader applicability to different technologies? We may then consider further energy technologies besides biofuels, *e.g.*, solar photovoltaics, solar thermal, geothermal, wind, hydro, wave, tidal, and nuclear fusion and fission. Climate mechanisms such as greenhouse gas emissions, heat emission, albedo change, land use change, *etc.*, should be covered together for a full analysis of the impact on the climate system. In addition, system analysis approaches at a higher level than IE, *e.g.*, earth system analysis, might be introduced to give reference climate threshold more directly since climate modeling is better covered there.

3) The case studies should be strengthened to enable better results of environmental sustainability analysis. On the one hand the thermodynamic model of a case technology should be as specific as possible. For instance, in the case of bioethanol, individual plants in the State of Iowa use co-produced electricity as process energy rather than purchasing from the national grid. This should be reflected in the model. On the other hand more data should become available. Examples of the missing data, as shown in the case of global biofuels and titania, include the global metal and mineral exergy resources consumption and the total anthropogenic demand of non-renewable resources in the indicator of solar energy demand. In the practice of thermodynamic analysis, modeling specification and data comprehensiveness is interrelated and balanced via making assumptions. For instance, the case study of bioethanol has been done by assuming that fossil fuel inputs to the transportation in the U.S. are not considered, although this assumption may have little effect in the global model. The uncertainty due to modeling assumptions should be analyzed better.

These three items seem most worthwhile directions for the further development of thermodynamic analysis of sustainability.