A systematic approach for energy technology assessment

Getachew Assefa1, Björn Frostell
Division of Industrial Ecology, Department of Chemical Engineering,
Royal Institute of Technology, 10044 Stockholm, Sweden.

Abstract

A systematic computer-based technology assessment(TA) tool involving a combination of systems analysis tools of material flow analysis (MFA), life cycle assessment (LCA) and life cycle costing (LCC) has been under development at the Division of Industrial Ecology, Royal Institute of Technology in Stockholm. Its focus, to start with, is assessment of the ecological and economic impacts of material- and energy-intensive energy technologies. The tool has shown merits of locating weak links along a chain of technologies. The modular structure of the tool enables scenario construction which, in principle, makes a comparative assessment of indefinite number of chains of technologies possible.

Two TA studies are used for illustration purpose. The first one has a focus on link between waste management and the transport system via fuel (biogas and hydrogen) production from waste and the second one on thermal technologies of energy production with gasification followed by catalytic combustion at the core.

Keywords: technology assessment (TA), material flow analysis (MFA), substance flow analysis (SFA), life cycle assessment (LCA), life cycle costing (LCC), technology, systems analysis, sustainable development.

Introduction

Different energy technologies have been in use ever since man has started using fire. Open fire places had a big role to play as contemporary energy technologies during the centuries before industrialisation. The tile stoves were improvements that replaced open fire places.

Depending on the nature of specific time of the post industrial revolution era, energy technologies have passed through various phases of discrete and continuous development. Energy technology in the context of this paper implies the technology involved in the areas of energy resources, conversion, transmission, distribution and efficient use of energy in industrial processes, space heating and transportation.

The early users of the energy technologies were the energy consumers themselves namely the households. With firewood as a fuel and the natural forest as a resource base, households were able to meet their energy need for heating, cooking and lighting all using open fire place. When utilities and energy supplies started to assume a centralised form through huge investments on urbanisation, the material and energy flow associated with production and distribution of energy has become increasingly enormous.

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[1] Tel: +46 8 790 85 79
Fax: + 46 8 790 85 80
E-mail: getachew@kth.se

Through the years, there have been different types of energy technologies with generation and distribution technologies for heat, electricity and liquid or gaseous vehicle fuels as major ones (Table 1).

Table 1. Examples of energy technologies used for heat, electricity and vehicle fuel generation and distribution.

Energy technology		**Applications**	
	Heat	**Electricity**	**Vehicle fuel**
Flame combustion	✓	✓	
Pyrolysis	✓	✓	✓
Thermal gasification	✓	✓	✓
Catalytic combustion	✓	✓	
Steam turbine		✓	
Gas turbine		✓	
Incineration	✓	✓	
Nuclear fission reactor	✓	✓	
Bio gasification (anaerobic digestion)			✓
Steam reforming	✓	✓	
Transmission and distribution systems	✓	✓	
Fuel storage, transportation and distribution infrastructures			✓

Two hitherto important factors that fuelled the search of alternative energy resource and/or technology are the depletion of global petroleum and natural gas reserves and the potentially damaging environmental effect of continued use of fossil fuels. This search should be paralleled by a thorough assessment of the alternative technologies.

Technology Assessment

The term technology assessment (TA) appeared for the first time in the US in the late 1960s and assumed an official status through the establishment of the US Congressional Office of Technology Assessment (OTA) in 1972.

Technology assessment strives to bring about an understanding of an otherwise unknown performance of a new or an existing technology. For technology assessment to be useful, it should represent adequately the phenomena of the real world and explain its behaviour in unambiguous terms. To this end, the use of quantitative approach is worthwhile due to the capacity to represent conditions, events, relationships or systems objectively and in easily manipulable form.

Energy technology assessment requires recognition and discrimination of the difference in performance of a range of energy technologies. Two types of performance can be distinguished, the traditional end-of-pipe performance and a life-cycle performance. The end-of pipe performance refers to the magnitude or quality of the energy produced whereas the life-cycle performance covers everything from the types of the raw-material used to the individual unit processes involved. The interdependence of these types of performances is not beyond recognition. Since the last ten years of the 20th century, the concept and practice of sustainable development has dominated different levels of world-wide discussions. Catching up with this relatively new order, there are attempts of presenting TA in the context of sustainable development (e.g. CEFIC, 1997 and Ludwig, 1997). The synthesis of such attempts and the distillation of recent TA literature, in light of the new order, boils down to re-categorisation of the impacts of technology into ecological, economic and social impacts.

In consistence with this notion of sustainable development and the need to make an informed decision, energy technologies should be assessed for their life-cycle performance from ecological, economic and social perspective. Combining systems analysis tools developed in different disciplines with a considerable magnitude of integration of ideas and concepts leads to a tool that can address the ecological, economic, and social aspects in an integrated fashion.

The ecological and economic performance at which this paper focuses can be assessed through the use of material flow analysis (MFA), life cycle assessment (LCA) and life cycle costing (LCC).

MFA, LCA and LCC

The reasoning behind advocating the use of MFA, LCA and LCC in energy technology assessment is the conviction that technology can be defined as hard and soft means to transfer, transport and transform materials and energy in a given economy. This activity of processing materials and energy is in concurrence with shaping, forming, manufacturing, producing or generating a product or a service of an economic value.

Manahan (1999) discussed technology as the ways in which humans do and make things with materials and energy. On the other hand, Turner et al (1994) maintained that economic activity *can be viewed as a process of transforming materials and energy.*

Human activities employing different kinds of technologies have created the anthrosphere through flows of materials and energy together with money flows as new-comers to the human history.

Material/Substance Flow Analysis (MFA/SFA)

Material Flow Analysis or Material Flow Accounting or Material Flux Analysis (MFA) refers to accounts in physical units (usually in terms of tons) comprising the extraction, production, transformation, consumption, recycling, and disposal of flow of substances and materials. MFA covers approaches such as Substance Flow Analysis (SFA) and bulk Material Flow Accounting (b-MFA). Both approaches use the principle of material balances. On the other hand, Wrisberg et al. (2002) considered Material Input Per Unit of Service (MIPS) as a function-oriented variant of MFA.

Baccini and Brunner (1991) developed the concept of MFA for assessing the anthropogenic metabolism of regions in the early 1980s. They combined existing scientific methods and new approaches to connect and interrelate soil, water and air with the anthroposphere in a holistic manner.

Udo de Haes et al. (1997) distinguished between three phases of carrying out MFA/SFA:

1. goal and system definition
2. inventory and modelling
3. interpretation

The goal should be explicitly defined since the system boundary and other accompanying aspects are related to it. Examples of possible goals of an MFA/SFA modelling can be data acquisition and generation, error checking procedure, identification of missing flows, etc.

The inventory and modelling phase concerns the computation of the flows and stocks for a given year. This computation can use three types of modelling: bookkeeping, static modelling, and dynamic modelling. In bookkeeping, a flowchart for the given system with all stocks, flows and processes both in society and in the environment is developed. Then for the given period of time, empirical data are collected and attributed to the flows and stocks. The static modelling describes a static condition, apart from possible changes in the immobile stocks and from changes outside the given system. The core point here is the development of one consistent mathematical structure that renders the possibility to specify relations between the different flows and stocks within the system. In a dynamic model, the process equations include time as a variable. In this way, not only the long term equilibrium of a certain regime can be calculated but also the road towards this equilibrium and the time it will take to reach it.

In the third phase, the interpretation phase, MFA/SFA results expressed in terms of mass of flows and accumulations of the material/substance under study are used in different ways. If the relevance of the analysis is generally directly related to the toxic or other specific polluting character of a single material/substance, mass flow is enough. In the case that a number of substances are studied and the result becomes too much to handle on mass basis, an aggregation is required.

World Resources Institute (WRI) expresses the use of material flow analysis as a role of "measuring sustainable development" together with other metrics for environmental and social factors (WRI, 2002).The use of the concept of MFA/SFA within the energy TA gives the possibility of recognising the potential accumulation of toxic substances or depletion of resources, and identification of the most effective point of control of harmful concentrations and flows. MFA/SFA is a robust tool in a number of policy questions (Wrisberg et al., 2002).

For further readings on MFA/SFA, refer e.g. van der Voet et al. (1995).

Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a method for analysis and assessment of the environmental impacts associated with a product, service or activity throughout its entire life cycle (e.g. ISO, 1997).

LCA can be seen both as a procedure and a model. It has a step by step procedural framework consisting of:

1. goal definition and scoping
2. inventory analysis
3. impact assessment
4. interpretation

In the goal definition and scoping step the purpose and scope and level of detail of the study; the basis for comparison or the functional unit; procedure for data collection and handling of data quality are defined.

The second step of inventory analysis results in a list of quantitative inputs and output to and from the system under assessment. The inventory table is made up of material and energy requirements, products, co-products, waste and emissions that cross the system boundary. The important point in carrying out inventory is establishment of boundaries between the studied system and both the environment and other product systems using a logical cut-off procedure (Ekvall, 1999).

The third step in LCA referred to as impact assessment consists of selection and definition of environmental impact categories, classification (assigning resource and emission data to relevant categories), and characterisation (quantification and aggregation of the classified data using substance and category-specific conversion factors).

Impact valuation, a part of the third step, in which the environmental impacts are translated into a single-value parameter, is an optional element according to the ISO 14040 standard. Impact valuation involves normalisation, grouping, and weighting.

In the last step of LCA called interpretation, the validity of the results is examined against the goal of the study using different ways such as sensitivity analysis for checking data uncertainties and effect of methodological choices. This data quality analysis is described as mandatory in comparative assertions.

The need to differentiate between different types of LCA is emphasised in the literature. This is helpful in understanding the discussion around methodologies, guidelines and standards and interpreting results. Ekvall (1999) surveyed different literature on LCA and showed that two types of LCA can be distinguished under different terms: an LCA with an accounting perspective called retrospective, and an LCA, modelling the effect of changes, called prospective. In delimiting the system boundary in a prospective LCA, the main question is whether a process or a subsystem is relevant to the change under consideration. Other subsystems outside the core that can be affected by the change are also included by expanding the system.

Ekvall (1999) further pointed out that LCA is established among decision makers, has structured procedure and international standard (ISO), and established platform for methodological development and harmonisation (SETAC[2]-UNEP). From the perspective of the methodological deficiencies of conventional TA, the use of tools with LCA as a building block enhances the position of the TA tool. LCA has also the merit of avoiding problem shifting (Wrisberg et al., 2002) from one stage in the life cycle to another, from one sort of environmental issue to another and from one location to another.

Further readings on LCA can be found on e.g., ISO (1998 and 2000).

Life Cycle Costing (LCC)

The discussions in this section concerning life cycle costing are entirely based on Wrisberg et al. (2002).

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[2] The Society of Environmental Toxicology and Chemistry.

Life Cycle Costing (LCC) is a tool that looks at the entire life cycle of a product, process or activity and calculates the entire life cycle costs, which include all internal costs and plus external costs, incurred throughout the entire life cycle. The internal costs include conventional costs and less tangible, hidden, indirect company costs. Conventional costs are the ones which appear in typical company accounts for use in process control, product costing, investment analysis and capital budgeting, and performance evaluation. They include both annual operational costs such as labour, material and product transportation, and one-time capital costs such as new equipment and buildings, engineering and design for new installations, and utility connections. The less tangible, hidden, indirect company costs tend to be less measurable and quantifiable, frequently are contingent or probabilistic in nature, and often are obscured by placement in overheads account. For example they include environmental permitting and licensing, reporting, waste handling, storage and disposal. External costs are those for which a company, at a specified time, is not responsible, in the sense that neither the marketplace nor regulations assign such costs to the firm, they address emissions and resource use and their environmental and human health effects. LCC places a monetary value on those impacts. Simplified version of LCC does not include all external costs.

LCC aims at the analysis of the processes in connection with a given function, like LCA. The type of system definition is therefore function-oriented. Environmental impacts in comprehensive LCC can be translated into monetary metric at three stages. These are initial interventions (e.g. emission of kg of SO2), "midpoint" effects (e.g. increased acidity in water bodies) and impacts on endpoints (e.g. the fish kills and loss of biodiversity resulting from increased acidity). LCC uses different costing approaches and techniques that vary by where in the impact chain the impacts are assessed.

Several methods are available for valuing physical impacts in monetary terms. The methods involve assuming or creating a fictitious market in order to gather the value that individuals might assign to an externality (contingent valuation); examining behavioural responses that are, or might be, influenced by an externality (e.g., hedonic pricing); or analysing the implicit value placed on pollution abatement by society through the actions of its regulatory agencies (e.g., regulators' revealed preferences).

Three types of quantitative data are required in LCC. These are data on internal costs, data on external environmental effects (in physical or monetary units), and data for valuation of environmental impacts if they are not already in monetary terms.

LCC is important in comparing technical systems that has functional equivalence but possible difference in cost of investment, operating, maintenance and importantly different environmental performance that can be interpreted into monetary terms. Use of LCC in energy TA tools enhances the economic assessment capability of the tools. The advantage of simplicity that LCC offers in the form of a single indicator could also be positive with respect to decision making.

For further readings on LCC, refer to the reference list in Wrisberg et al. (2002).

The quantitative nature of MFA/SFA, LCA and LCC enhances both measuring and understanding issues addressed. Quantification in conventional TA was limited only to cost-benefit economic analysis (Durbin and Rapp, 1983). The inspiration from the efforts made to develop sustainable development indicators to measure social phenomenon around mid 1990s dictates the importance of quantitative analysis in social sciences let alone in natural science type problems related to energy technologies.

ORWARE as a TA tool

ORWARE (Eriksson et al, 2002) is a computer-based simulation tool built up on Matlab's Simulink with a structured result presentation on Microsoft Excel. It involves concepts of systems analysis(Miser and Quade, 1995), material flow analysis(MFA)(Baccini and Brunner, 1991), substance flow analysis(SFA)(van der Voet, 1995), life cycle assessment(LCA)( ] ISO, 1997) and life cycle costing (LCC)(Wrisberg et al, 2002). The tool has been under development and use for the last ten years through a collaboration between The Division of Industrial Ecology, Royal Institute of Technology; Swedish Environmental Research Institute (IVL); The Swedish Institute of Agricultural and Environmental Engineering (JTI); and Departments of Agricultural Engineering and Economics at the Swedish University of Agricultural Sciences (SLU).

ORWARE starts with characterising the technology system under assessment in the form of a vector of a number of component materials and substances. In principle, there are seventy four vector elements that characterise the input, although only a number of them are used in a specific study.

At the model level, ORWARE is composed of different submodels. From the point of view of TA applications, each submodel represents a specific technology unit in reality. Once the submodels for different technologies are developed, they are available for future use of constructing scenarios of different technology chains. Once simulated, the results of assessment are also accessible. Hence, the whole work of assessment including developing the submodels and simulation work makes up a library of knowledge that can be accumulated, retrieved, processed and used accordingly. Besides ORWARE gives the flexibility of carrying out the ecological part independent of the economic part.

MFA, LCA and LCC in ORWARE

Generally every quantitative LCA involves MFA/SFA for producing life cycle inventory (LCI) but every flow in a multiple MFA/SFA is not part of LCA. Hence, MFA/SFA and LCA are treated as two distinct parts in ORWARE.

MFA/SFA

The MFA/SFA describes the static situation of different material/substance flows between different subsystems in a defined system. The ORWARE model handles a large number of physical flows and may therefore be characterised as a multidimensional material and substance flow analysis. Normally, MFA/SFA is often used in relation to macro level application at region or city level. In this case, however, the same principle and methodology is used at a relatively micro level of processes/technologies and process/technology chains.

The MFA/SFA modelling in ORWARE is important specifically with regard to flows that are not characterised using LCA methods into impact categories. Examples, in this case, are heavy metal flows. The use of MFA/SFA facilitates the task of tracing down specific substances of interest. Recycling issues and stock issues within the energy sector for example can be identified using the information from the MFA/SFA model in ORWARE. Emissions such as NOX are also of interest in terms of the absolute value of the amount emitted due to some regulating requirements, etc. It is the material flow modelling that generates data on such emissions from the energy system.

The flows of pollutants and in some cases nutrients between parts of the systems under study, and then their final destination in either of the three compartments of the natural environment namely air, water, and soil are mapped using the MFA/SFA part.

In addition to the role MFA/SFA plays in locating and displaying the amount of different flows and emissions for self-enabled analysis, it provides inputs to the other two conceptual tools incorporated in ORWARE namely LCA and LCC.

The MFA/SFA part maps the flow of each material and substance inside and outside the system. It is possible to pick any one of the flow steams corresponding to any vector element at any point along the technology chain for an ad hoc assessment.

The use of multidimensional MFA/SFA renders an immunity to the limitations of conventional MFA/SFA that deals with a single material or substance. Such limitations are associated with the incapability to avoid shifting of problems to other materials or substances. Although the MFA/SFA modelling is static, the interaction between the different substances and hence the formation and consumption of different substances is modelled using formation coefficients. For non-interacting substances, their co-ordinate is modelled both in terms of the process streams they flow through and their destination (air, water or soil) after leaving the system.

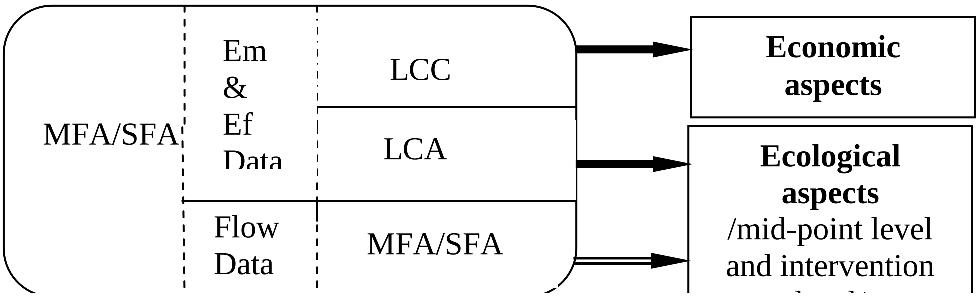
LCA

The LCA part in ORWARE uses most of the data, not all, generated by MFA/SFA and processes it further into different ecological impact categories. In other words, the MFA/SFA carried out on different substances contained in emission and effluent streams are translated to relevant impact categories using standard LCA methodology. The life cycle modelling is carried out for all the chains of technologies through which the feedstock passes until the final product joins its final recipient in the environment. As the main feedstock is processed along the technology chain, relevant emissions and effluents occurring during the course of the process are characterised into impact categories. The flows of materials and energy required for running the technology chain are followed from "cradle-to-grave". The emissions and effluents associated with the "cradle-to-grave" life cycle of the material and energy inputs are also characterised into impact categories.

The building phase of the infrastructure or the facility that "houses" the technology chains is not so far part of the LCA in ORWARE. An overview study done within the research group showed that the building phase is important to consider in those systems that are less energy intensive or emission-free during the operating phase. This hitherto exclusion of the building phase has to do with the fact that the material and energy flow during the operating phase, for the systems under assessment in ORWARE so far, outweighs that occurring during the building phase.

LCC

In the LCC part, the operating cost of the technology system, the investment costs and other costs of maintenance and demolition or management of demolition waste are considered. However, these costs make up the internal-cost part of the LCC only. Unlike the cost consideration of conventional cost-benefit analysis (CBA), LCC includes external costs.



In calculating the external costs, LCC uses the emission data from the MFA/SFA modelling (figure 1).

Figure 1 The use of MFA/SFA, LCA and LCC in the ORWARE model
(Em= Emission, Ef= effluent).

The "*mid-point level*" in figure 1 refers to the impact categories of LCA whereas the "*intervention level*" implies the data directly provided by the MFA/SFA part (e.g. emission and resource depletion data).

While the LCA classifies the emissions leading to the same type of impact and aggregates into impact categories (mid-point level), the LCC translates the mass of each emitted substance into monetary terms. It is not necessarily the case that exactly the same type of emissions are used by both LCA and LCC since there is a difference in the level of knowledge reached with regard to the tools and the scientific and social thinking underlying them. ORWARE uses LCC including both internal and external costs. The external-cost dimension of LCC covers both extractions and emissions.

The information from the LCC complements the information from LCA in two ways. In the first place, it provides an economic dimension of the assessment of the building phase of the physical structure, the magnitude of which is otherwise left out as negligible from the point of view of LCA. Secondly, it serves as an economic variety of characterisation of the emissions along the life cycle. In this case, emissions from both the core system, just covering the system under study, and the external system including upstream and downstream units are accounted for separately or in aggregated form.

In general, MFA/SFA, LCA and LCC complement each other enhancing the capacity of a combined tool such as ORWARE in terms of the quality of the TA-related information generated. Besides they cross fertilise in systematising the whole work of assessment of the ecological and economic impacts of technical systems .

Characteristic features of ORWARE

The system boundary in ORWARE defined as geographic, temporal or functional boundary is important particularly in discussing results. While the geographic system boundary can vary depending on the scope of the specific assessment study, the temporal aspect is delimited to one year. In other words, for an energy technology assessment, the amount of resource, the emissions and the costs and other calculations are done based on feedstock of one year. The functional boundary is defined using the type and magnitude of functional units identified in the assessment. *Functional units.* In the ISO standard (ISO, 1997) a functional unit is defined as “the quantified performance of a product”. It is, thus, a measure of the function a product (or a system) is able to fulfil. It is critically important to clearly define the functional unit in assessments for comparisons of different systems.

The input : Data

Specific data related to unit processes of the technology under assessment

- Emission factors
- Energy production and consumption
- Efficiency
- Investment and operating costs

Generic data are common to all

- Characterisation factors
- Environmental cost of emissions

The output: information

- Energy flow
- Material flow
- Economic performance
- Environmental impact categories

Result presentation

The output data is presented in terms of environmental impact categories namely,

- Global warming
- Ozone depletion
- Photochemical oxidation
- Acidification
- Eutrophication.

Life cycle costs in terms of financial economy (internal costs) and welfare economy (external cost) are also presented.

One of the important features of ORWARE is its structured presentation of huge amount of data and complex information. This includes the input data, the model made up of different submodels, the generic data used in LCA and LCC, the mathematical equations of partitioning and transfer coefficients and, importantly, the output data. MATLAB® SIMULINK® is used as a graphical interface for the modelling part providing the possibility of visualising and analysing the modelled systems. While the results can be saved in MATLAB® for future retrieval, the main result presentation is done in Microsoft® Excel. Both the ecological and economic output data are displayed both in tables and different diagrams in such a way that cause-effect relations can be traced down. Since the assessment is done in terms of scenarios, bar diagrams that show each impact category with each bar corresponding to a scenario is one possible way of presentation. Such result presentation is possible for both core systems and the total system that includes the compensatory system (see figure 2).

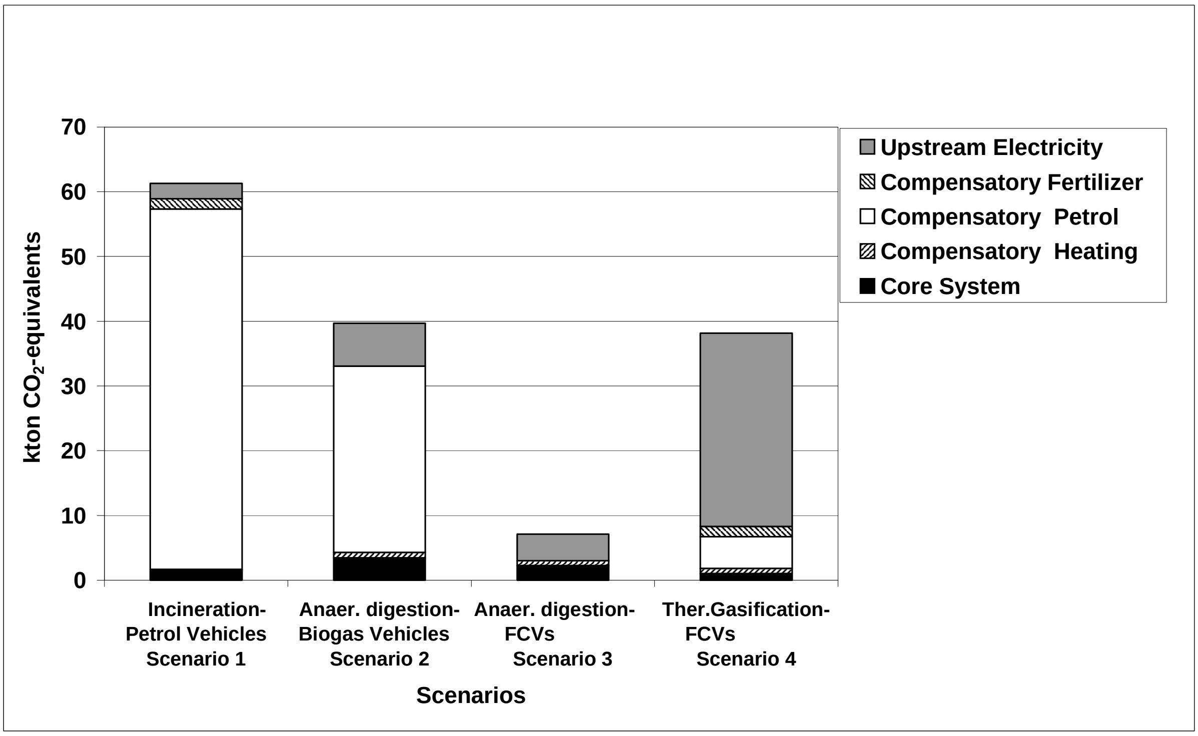
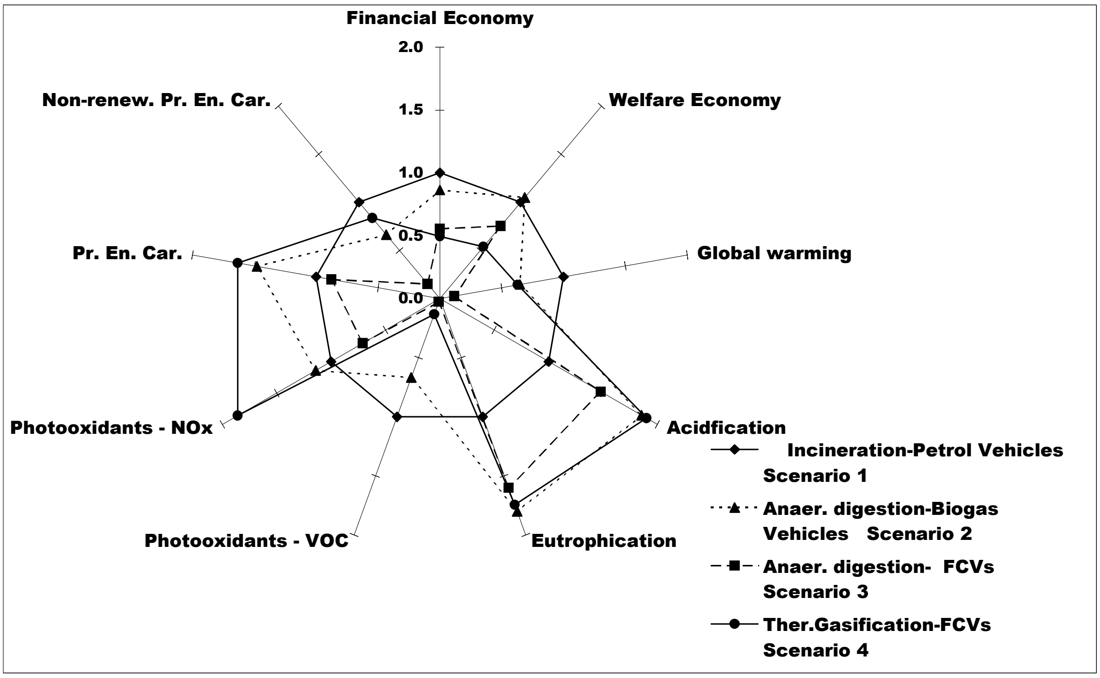


Figure 2 Example of core and compensatory system result presentation in ORWARE (Assefa et al, 2002).

All impact categories can be collected into the same bar diagram or a radar diagram. The latter provides an axis for each ecological or economic impact category with lines connecting the axes through points corresponding to the values of the relative impacts of each scenario



(see figure 3).

Figure 3 Example of radar result presentation in ORWARE.

Illustration

The hydrogen- from-waste study

The research used as an illustration was an assessment of prospects of hydrogen production from waste for use in fuel cell vehicles (FCV). The illustration aims at showing the type of result that can be obtained from ORWARE and the TA-related information it gives. The waste management sector was linked to the transport sector.

The technology chains assessed in the form of scenarios were: incineration with internal combustion engine vehicle, anaerobic digestion with biogas vehicle, anaerobic digestion followed by steam reforming with fuel cell vehicle, and thermal gasification with fuel cell vehicle.

An aerobic digestion of organic waste followed by steam reforming of the biogas to hydrogen was assessed in comparison with thermal gasification of organic waste followed by hydrogen gas reforming and conventional gasification.

The gas from the gasification is used tom produce hydrogen gas which in turn is used as fuel for fuel-cell-driven passenger car. The biogas is used either to produce heat and electricity or hydrogen. The anaerobic digestion further more gives, rest product that contains phosphorous and nitrogen. The rest product is assumed to replace mineral fertilisers.

The common input was the biodegradable waste from Stockholm. The transport part was limited to the fuel component and associated issues of energy and transport work, not to the vehicle it self.

The functional units used in this study were:

- MJ of district heating
- MJ of electricity
- km vehicle transport and
- kg of phosphorous and nitrogen available for plants.

The alternative means of production for the different functional units provided by the waste:

- District heating : biomass
- Electricity: coal condense
- Vehicle fuel: petrol
- Nutrient: phosphorus and nitrogen from mineral fertilisers

Results of transport work, energy recovery and use, and environmental impacts in terms of global warming were used as illustrations. No economic assessment was done at the time. No specific stakeholder was addressed either. The results showed that it is better to use biogas to produce hydrogen for FCV compared with the less efficient direct use of biogas in cars. Despite high recovery of hydrogen in the scenario with thermal gasification, which is efficiently used in FCVs, the typically high electricity consumption in the thermal gasification modelled resulted in overall poor energy efficiency of this scenario.

The catalytic-combustion study

In this research study, full ecological and economic assessment of thermal technologies was carried out. The scenarios of chains of thermal technologies assessed were: gasification with catalytic combustion, gasification with flame combustion, incineration and landfilling. The landfilling scenario was used as a reference of comparison.

The functional units used in this study were:
- MJ of district heating
- MJ of electricity

The alternative means of production for the different functional units provided by the waste:
- District heating : biomass
- Electricity: coal condense

The results are presented in terms of global warming potential, acidification potential, eutrophication potential, consumption of primary energy carriers, and welfare costs. From the simulations, gasification followed by catalytic combustion with energy recovery in a Combined cycle appeared to be the most competitive technology from an ecological point of view. On the other hand, this alternative was more expensive than incineration. A sensitivity analysis was done regarding electricity prices to show which technology wins at what value of unit price (per kWh) of electricity.

Within this study it was possible to make a comparison both between a Combined cycle and a Rankine cycle (a system pair) and at the same time between flame combustion and catalytic combustion (a technology pair). To use gasification just as a treatment technology is not more appealing than incineration but the possibility of combining gasification with a Combined cycle is indeed attractive in terms of electricity production.

This research was unique in the fact that it was linked to an empirical R&D work on both gasification of waste and catalytic combustion of the gasified waste at the Division of Chemical Technology, Royal Institute of Technology (KTH), Stockholm.

In going from the first study to this one, a new type of interest group namely the researchers working with R&D work at the laboratory and pilot scales came into the scene. Such a study addresses a perspective normally lacked by technology developers i.e., a systems perspective of looking at the broad implications of their R&D.

Discussion and conclusions

The whole purpose of combining the tools of systems analysis within ORWARE is to inject a relatively objective and scientific basis to the impact identification part of TA while leaving the choice of priorities to individual and collective decision makers.

ORWARE has the potential of providing information regarding the ecological and economic performance of chain of technologies from a systems perspective. This information after validation in relation to appropriate contexts leads to a knowledge of a variety of importance. Specifically those involved in the R&D of technologies require knowledge that is beyond the traditional knowledge that Edwin Layton refers to as " knowledge of how to do or make things".

The familiarity of different sections of society including decision makers with the tools that are combined in integrated tools such as ORWARE facilitates their role in the decision-making world. LCA for example is one of the tools that has received much attention from both the scientific world and the decision makers. This feature would enhance the decision-making relevance of TA tools such as ORWARE that contain LCA methodology.

Positive features of ORWARE in light of energy technology assessments are its quantitative, even-handed and holistic features and as mentioned earlier its structured result presentation.

Since ORWARE uses and produces quantitative data, it is easier to add, compare and identify parts of the life-cycle with significant ecological and economic implications and to specify what can be gained by alternative chain of technologies that fulfil the same function. This is true in terms of both ecological and economic impacts both at a system and subsystem levels.

As a computer-based model, ORWARE gives even-handed analysis and structured handling of input and output data, covering both ecological and economic dimensions, consistently and coherently. This is important since it allows reference to previous results in a comparable way and helps identify important factors that steer different aspects of the technical system. This can not be done when analyses are performed in a non even-handed way. People may tend to take the issue of even-handedness for granted, but the absence of an appropriate tool in the impact assessment part of conventional TA has precipitated its criticism.

The systems perspective involved in using the concepts of core system and compensatory system gives the opportunity to have insight into different sectors at the same time and provide understanding on how they influence each other in a holistic manner. The cross fertilisation of MFA/SFA, and LCA, and LCC aids in determining the weak points along the chain of technologies in terms of ecological, economic and technical performance. This advantage of identifying the otherwise unrecognisable weak links in technical systems has also been pointed out by people of different backgrounds who used ORWARE as a systems analysis of waste management (Björklund, 2000).

Despite its positive features mentioned above, ORWARE suffers from different levels of limitations.

The problem with using tools such as ORWARE in TA applications can be categorically identified as specific and general. The specific problem is related to the application of ORWARE for technologies that are still at R&D stage. This involves the use of data about technologies for which no real life experience is available. The uncertainty in acquiring such data through estimation, inference and extrapolation from other technologies is a limitation. The problem emanates from the prerequisite for conducting TA using ORWARE, that the technology should be described in terms of material and energy flows.

The general problems are those associated with the relationship between the model and the reality modelled and data quality at different levels and the component tools. Most of the uncertainty and data quality problems in ORWARE are well described in Björklund (2000). A survey of approaches for handling different types of these data quality problems are also given in this reference.

In addition to the data-intensive nature and quality problem of LCA, some inherent weaknesses in today's LCA concept can be mentioned. One limitation is related to effects such as rebound effects where an increase in economic activity resulting from cost-efficient changes offsets the savings obtained through the original change. A second weakness is associated with the underlying assumption that when a demand for a material increases in the life cycle investigated, the production of that material is increased by the same amount (Ekvall, 2002). Moreover only known and quantifiable ecological impacts are considered in LCA (Wrisberg et al., 2002). This limits the scope of the assessment. LCC may be compromised by the confidentiality of data for economic processes. Another limitation lies in the problems incurred with monetarisation of physical impacts which do not exist on the market. The uncertainty is highly dependent on the question at stake and the data and models used.

The timing for employing a TA tool for energy technology R&D is of considerable importance. Carrying out a TA during the R&D phase parallel to a basic research work at a laboratory scale or pilot scale is a good point in time. This gives insight to the R&D about the far-reaching implications of the research work in terms of impacts of the technology under development. Getting better information from a systems perspective facilitates the integration of ecological and economic concerns into the research, design and development of technologies. This, in turn, avoids unnecessary investment.

The contribution and reliability of TA tools in the development of energy technologies would, by and large, depend on improved knowledge on how to deal with data gaps, data uncertainties and data qualities.

If the finding that knowledge is currently doubling every year and will double every 73 days by 2020 (Bosseau, 1998) has a direct relevance to the case at hand, we are in a better position to address the knowledge gaps that lurk behind efforts of carrying out systematic technology assessment.

Further research

Efforts of setting up databases for environmental data at different levels should be strengthened.

There is a need to do research on possibilities of combining more systems analysis tools to address other issues in such a way that weaknesses in MFA/SFA, LCA and LCC can be compensated for.

Research is required on conceptual and model development that would improve ORWARE both in its scope and data processing mechanism. As an example, there is a need to examine the possibilities of incorporating social impacts of technologies in the form of indicators.

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