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Life Cycle Analyses and Resource Assessments

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Abstract Prof. Ulgiati stresses that we should always use an ecosystem view when transforming energy from one form to another. Sustainable growth and development of both environmental and human-dominated systems require optimum use of available resources for maximum power output. We have to adapt to the laws of nature because nature has to take care of all the waste products we produce. The presentation addresses a much needed shift away from linear production and consumption pattern, toward reorganization of economies and lifestyle that takes complexity—of resources, of the environment and of the economy—into proper account. The best way to reach maximum yield from the different kinds of biomass is to use biorefineries. Biorefinery is defined as the sustainable processing of biomass into a spectrum of marketable products like heat, power, fuels, chemicals, food, feed, and materials. However, biomass from agricultural land must be used for the production of food and not fuel. Prof. Voss focuses on the sustainability of energy supply chains and energy systems. Life cycle analyses (LCA) provides the conceptual framework for a comprehensive comparative evaluation of energy supply options with regard to their resource requirements as well as the health and environmental impact. Full scope LCA considers not only the emissions from plant operation, construction, and decommissioning but also the environmental burdens and resource requirements associated with the entire lifetime of all relevant upstream and downstream processes within the energy chain. This article describes the results of LCA analyses for state-of-the-art heating and electricity systems as well as of advanced future systems. Total costs are used as a measure for the overall resource consumption.

Keywords Systems ecology · Bioenergy/biofuels · Sustainability · Resource consumption · Discounting

INTRODUCTION

It is well known that transformation of energy from one form to another is connected with, sometimes very severe, environmental impacts. These range from local pollution problems (corrosion and impaired health are examples) to regional impacts (acid rain, brown clouds in South Asia) and to global effects of which climate change may be the most important example. Sometimes, the impacts are directly felt by man, but most often they lead to changes in natural systems. Apart from the climate change caused by emissions of greenhouse gases, the effects on ecosystems will rank as one of the most serious consequences of our use of fossil fuels.

These external factors were treated by Professor Sergio Ulgiati in his talk on *A systems ecology view on bioenergy/biofuels* and by professor Alfred Voss in his talk on *Life cycle analyses for different energy sources*. Short summaries of their talks are given below followed by a few comments.

A SYSTEMS ECOLOGY VIEW ON BIOENERGY/BIOFUELS

Professor Ulgiati pointed out that sustainable growth and development of both environmental and human-dominated systems require optimal use of available resources for maximum power output, in accordance with Lotka–Odum's Maximum Power Principle (Lotka 1922; Odum and Odum 2001). In times of declining resources this principle translates into increased efficiency and optimum use of any kind of waste and co-products. "You cannot protect the environment. The environment is going to protect you." This statement by H. T. Odum may be difficult to understand. Nature may be considered to be too

slow in providing services, for taking up CO_2, for absorbing the toxic chemicals we release etc., but we have to adapt to the laws of nature. Nature has to take care of all the waste products we produce. When calculating input and output of a process, all driving forces have to be included. We need a macroscope, not a microscope in order to expand the scale of the investigation. As a consequence of such an ecosystems view, focus should always be put on:

1. Upstream and downstream aspects (LCA)
2. Side aspects (unexpected consequences or features)
3. Demand for environmental support (environmental accounting methods)

A systems thinking approach is needed in all aspects of societal and economic dynamics, including the energy sector. The shortage of energy and material resources is a never-ending source of concern. The problem is twofold, since it involves material and energy scarcity as well as price increases, due to competition for the scarce resources by many potential users in developed as well as developing countries. An additional kind of scarcity is embodied in the excessive exploitation of environmental services (fresh water, clean air, topsoil, material cycling) or, in other words, in the decreased ability of the nature to act as a sink of pollutants released by human activities.

According to Ulgiati, a shift is needed away from linear production and consumption patterns, toward a reorganization of economies and lifestyle that takes complexity (of resources, environment, economy) into proper account. Energy is crucial in such a reorganization.

Ulgiati gave some examples of how it is possible to be more energy efficient. First he demonstrated this by unpacking a CD. The cardboard box was 30 times larger than the CD, thus needing 30 times more space for storage, more energy for handling, etc. To be more effective the volume of the box should be minimized. However, the optimal efficiency in this case would be to eliminate the box and CD by downloading the message of the CD from internet.

A Hummer is a big, heavy car which costs 45,000 USD and consumes lots of fuel while Tata Nano is a small car developed in India, which costs 2,500 USD and needs very little fuel. Which car will generate most harm to the atmosphere in terms of emissions? Tata Nano has been bought by 500,000 people in India and China followed by new roads, parking places, traffic lights, and garages. Two per cent of the arable land was taken over for this purpose, leading to increased lack of food. The best way to avoid these kinds of problems is to abandon private car transportation and stimulate public transports.

Everything that is green is not always necessarily environmentally friendly. For example, it was suggested by an Irish company to grow sugar beets for ethanol production in the contaminated area around Chernobyl in Belarus, an area of 4 million ha, corresponding to 1/10 of Sweden's territory. Apart from the fact that the project would consume much energy (fuel for tractors, etc.), the real serious point would be the dispersal of dangerous radioactive contaminants in the soil to the air, breathed in by the workers and transported to the groundwater.

Another example when "green" is not enough is when huge areas of rainforests in the Mato Grosso state in Brazil were cut down and the land converted into soybean fields for the production of bioethanol and feed for exportation to Europe and Asia.

In 2006, the pattern of consumption of energy carriers in Europe (EU 27) was: electricity 21%, heat 48%, and fuel 31%. To produce these energy carriers fossil energy (coal, oil, natural gas) dominates with 78%, nuclear power contributes 14%, and renewable energy (hydro, solar, geo, wind, biomass, and others) only 8%. Ulgiati suggested that biomass will contribute 10% in 2020 and 20% in 2050. But to replace 10% of fossil energy with bioenergy in Europe about 20% of all current agricultural land would be needed for this purpose.

When biomass is converted into bioenergy/biofuels it is necessary to minimize the resource investments (labor, environmental services, energy, materials), maximize the yield per ha, and the conversion efficiency. But competition with food production has to be avoided and the environment protected. The following environmental aspects are involved when fuels are produced from biomass:

- Need for good arable land (lower yields on marginal land).
- Water for irrigation.
- Fertilization (if not, yields decrease over time).
- Need for pesticides (due to monocultures).
- Simplification of the ecosystem (decreased biodiversity).
- Polluting effluents from conversion processes.
- High labor demand, mainly in the agricultural step.

It is enormously difficult to replace fossil fuels with biofuels because the power density in biofuels is much lower than in fossil fuels. Figure 1 shows that it is not a good idea to use food crops for fuel production because the energy return on the investment (EROI) is poor. Corn, wheat, and other cereals should be used for food production and not for bioethanol. Bioethanol may be made from ligno-celluloses, and for example in the USA Switchgrass is cultivated on commercial fields, but the yield never exceeds 4–6 tons fuel per ha.

The use of fossil energy made industrial revolution possible, but at the same time had a number of consequences for mankind. The human population

Biofuels from food crops
(average values from literature)

	Corn	Wheat	Sunflower
EROI	1.20-1.50	1.10	1.41
Conversion efficiency	20-25%	20-28%	40-45%
Biomass yield (dry t/ha)	8-9	4.3-4.5	2-2.5
Fuel Yield (t/ha)	1.96	1.2	0.9-1.1

Fig. 1 Biofuels from food crops (average values from literature)

> increased drastically during the industrial era, from less than half a billion to about 6.7 billion, the consumption of energy increased in a similar way and the area of arable land per capita decreased simultaneously. Ten per cent of the world's population must now produce food for all the rest, 50% of whom live in large cities. Obviously, it is necessary to reduce the global consumption of energy as much as possible, minimize the use of fossil energy and increase the supply of nuclear and renewable energy.
>
> Concerning biomass it is urgent to shift away from linear production patterns where waste is a problem toward complex production patterns where waste is regarded as a resource. As an example of good use of biomass resources, Ulgiati mentioned the production of electricity and heat in Enköping, a small town in Sweden. Large willow plantations are irrigated by water from nearby dams with urban waste water. The nutrients in the waste water are thus of use and at the same time unwanted chemicals and heavy metals like cadmium can be taken up by the plants and removed from the soil. The willows are harvested and burnt in a biomass-based power plant for production of electricity and heat. Heavy metals are filtered away.

The existing constraints to bioenergy exploitation and use were also dealt with in Ulgiati's speech and the potential of photosynthesis, to become a new source of materials, and energy for a growing world population was analyzed. Focus was on two main aspects:

(a) the implementation of complex systems that take maximum advantage of the available typologies of biomass (biorefinery).

(b) the need for innovative environmental accounting methods for proper sustainability assessment of proposed solutions.

> According to Professor Ulgiati the best way to reach maximum yield from the different kinds of biomass is to use biorefineries. Biorefinery is then defined as the sustainable processing of biomass into a spectrum of marketable products like heat, power, fuels, chemicals, food, feed and materials. The biorefinery concept is central for closing the loop: biomass – biorefinery – value-added products – disposed waste – biorefinery.

A final conclusion of Ulgiati's talk is that in the future our society has to be completely reorganized and that the reorganization has to be done in close collaboration with the environment.

LIFE CYCLE ANALYSES FOR DIFFERENT ENERGY SOURCES

The title of this presentation could alternatively have been Social Cost Benefit Analysis of Different Energy Sources, as it gives very useful information on the total social costs of producing useful energy from a number of sources which could possibly be used for assessing the social value of these. As modern energy technologies increasingly tend to reduce the direct environmental burdens of the energy conversion process, the detailed assessment of all life cycle stages of the fuel chain is a prerequisite for a comprehensive assessment of their resource intensity and relative sustainability. The presentation described the results of LCA analyses for state of the art of heating and electricity systems as well as of advanced future systems. Total costs are used as a measure for the overall resource consumption.

Professor Alfred Voss started his presentation by quoting the famous definition of sustainable development in the Brundtland commission's report "Our Common Future"

> Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

There have been many attempts to interpret this definition, but at least in the economic literature, a consensus is growing that this definition requires the current human generation to transfer enough with productive capacity to the future generations so that they will be able to create as good a living as the one we are experiencing today. The transfer of productive capacity to future generations can only be made from the creation of enough capital stocks:

stocks of natural capital: ecosystems, exhaustible resources, climate, human capital, knowledge, health, institutions, and what economists usually call real capital: machines, buildings, infrastructure, etc.

Note that we are not talking about conserving all stocks, but the requirement is instead that future generations should inherit a mix of capital which will enable them to produce the needed social well-being which implies that the net total value of the stocks must not decline over time. The stocks must be valued with appropriate accounting prices. With growing populations, we should interpret this as a requirement on stocks per capita (see Dasgupta and Mäler 2000; Arrow et al. 2003).

Voss stated that total resource consumption, including the natural resources, is an important aspect with respect to the sustainability of energy supply chains and energy systems. In particular he pointed out that there is sustainable energy provision, if

the potential for the economic provision of energy services increases (or does not decrease) for the next generation
the environmental impact caused by substances released from the energy system does not exceed the assimilation capacity of the natural environment, and climate change is limited to a tolerable level
the energy-related risk for human health is smaller than the natural risk avoided through the provision of energy services
energy services are provided with the lowest possible input of resources, including environmental resources.

The second law of thermodynamics implies that life and development of economical and cultural achievements require permanent input of workable energy and material. Increasing knowledge and the connected technological progress create the base for preserving and expanding the abilities of future generations. It is "a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional change are made consistent with future as well as present needs."

Use of finite resources requires a compensation. The state of technology determines the technological economical accessible base of raw materials and energy as well as the productivity of the resource base. Environmental pollution results from the release of substances into the environment, not from the energy degradation.

Life Cycle Assessment (LCA) provides the conceptual framework for a comprehensive comparative evaluation of energy supply options with regard to their resource requirements as well as their health and environmental impact. Full scope LCA considers not only the emissions from plant operation, construction and decommissioning, but also the environmental burdens and resource requirements associated with the entire lifetime of all relevant upstream and downstream processes within the energy chain.

As modern energy technologies increasingly tend to reduce the direct environmental burdens of the energy conversion process, the detailed assessment of all life cycle stages of the fuel chain is a prerequisite for a comprehensive assessment of their resource intensity and relative sustainability.

Voss presented results of the LCA analyses for some state of the art of heating and electricity systems. A set of reference technologies for electricity generation were selected: pulverized combustion for coal, combined-cycle for gas, pressurized water reactor for nuclear, combined heat and power for wood, polycrystalline for photovoltaics, horizontal for wind power and run-of river for hydropower. The results of LCA analyses are of course dependent on the assumptions of the input parameters and the assumed life times are critical parameters. The assumed technical life times were 20 years for wind, 25 for photovoltaics, 35 years for the fossil and wood power stations, 40 for nuclear and 60 for hydropower. The assumed installed power varied from 0.005 MWe for solar to 1.5 for wind, 20 for wood and 1375 MWe for nuclear technologies.

Total resource consumption is important with respect to the sustainability of energy supply chains and energy systems. Supply of energy service requires the use of workable energy, but also the use of non-energetic resources and materials. For any energy option, the use of finite (*non-renewable*) resources must thus be considered. The use of renewables must therefore be scrutinized from sustainability criteria and the question should also be asked if the

Material and Resource Use

	Iron [kg/GWh$_{el}$]	Copper [kg/GWh$_{el}$]	Bauxite [kg/GWh$_{el}$]
Hard Coal	1700	8	30
Lignite	2134	8	19
Gas CC	1239	1	2
Nuclear, PWR	457	6	27
Wood CHP	934	4	18
PV poly 5 kW	4969	281	2189
Wind 1500 kW (5.5)	3066	52	35
Wind 1500 kW (4.5)	4471	75	51
Hydro 3.1 MW	2057	5	7

Source: IER 2005/07

Fig. 2 Material and resource use. The resource use over the whole fuel cycle chain is included and is calculated by a combined process chain and input–output analysis

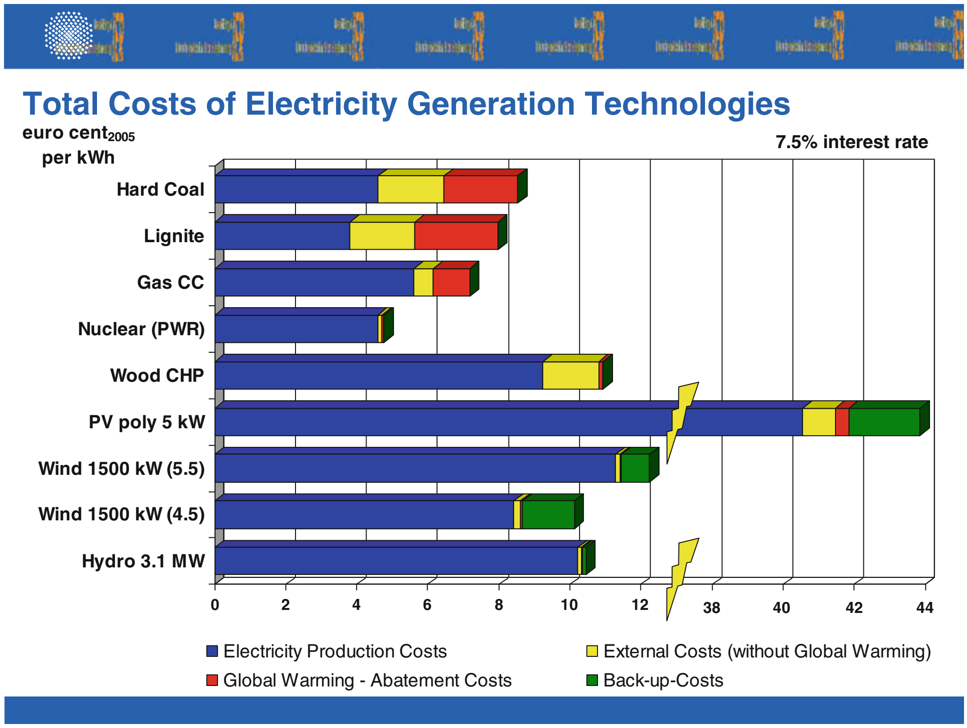

Fig. 3 Total costs of electricity generation technologies. The interest rate of 7.5% is to be understood as a real interest rate on capital and not a social discount rate. For the total cost analysis also a 5% interest rate has been used, which does not change the relations of the total cost figures of the various technologies

use of finite resources (e.g., oil, gas, and coal) can be consistent with the principles of sustainability?

Values for material and resource use were presented (see Fig. 2). Gas power is the most material efficient for copper, 1 kg/GWh_e, and for bauxite, 2 kg/GWh_e. For iron, nuclear power is the most material efficient requiring 457 kg/GWh_e, an order of magnitude smaller than what is required for wind and solar.

Results can be exhibited in the form of a simplifying LCA, cumulative energy demand (CED), where the accounting of energy and material inputs is seen as part of an inventory analysis. It is defined as the entire demand valued as primary energy which arises in connection with the production, use, and disposal of an economic good. With the chosen parameters the primary energy demand is lower than 10% of the produced electricity for nuclear, wood, wind, and hydro whereas the fossil and solar technologies are above 10%, for solar as much as 60%.

Total costs were calculated using an interest rate of 7.5%. The costs include all social costs connected with construction, operation, fuel, and waste handling and all external costs connected with damage on health, environment, and climate. The results are summarized in the Fig. 3 shown from the presentation by Voss. The total costs for nuclear power is about 5 eurocent per kWh and about half of the total costs for wood, wind, and hydropower. It is comparable to that of the fossil power alternatives without external costs.

Professor Voss' choice of a discount rate for estimating the costs of electricity generation technology is 7.5%. This discount rate is very high. Most other researchers who have studied the carbon emissions have decided on a rate close to 4%, and Lord Stern in his climate review for the British Government chose 0.1%. These differences are of extreme importance. In fact Lord Stern's result on the impact of climate change depends mainly on his assumptions on discounting.

Other LCA analyses of electricity generation technologies arrive at similar conclusions as Voss. For example one of the most extensive studies, the EU project Cost Assessment for Sustainable Energy Systems (CASES) using a discount rate of 5% arrived at similar relations between the different technologies although the kilo Watt hour costs were smaller. The costs of the capital intensive technologies such as wind and nuclear are reduced proportionately more than the fossil technologies which have a greater share of fuel costs in their kilo Watt hour prize.

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