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Life Cycle Exergy Analysis of Solar Energy Systems

Mei Gong[1] and Göran Wall[2]*

[1]*School of Business and Engineering, Halmstad University, PO Box 823, SE-30118 Halmstad, Sweden*
[2]*Oxbo gard, SE-43892 Härryda, Sweden*

Abstract

Exergy concepts and exergy based methods are applied to energy systems to evaluate their level of sustainability. Life Cycle Exergy Analysis (LCEA) is a method that combines LCA with exergy, and it is applied to solar energy systems. It offers an excellent visualization of the exergy flows involved over the complete life cycle of a product or service. The energy and exergy used in production, operation and destruction must be paid back during life time in order to be sustainable. The exergy of the material that is being engaged by the system will turn up as a product and available for recycling in the destruction stage. LCEA shows that solar thermal plants have much longer exergy payback time than energy payback time, 15.4 and 3.5 years respectively. Energy based analysis may lead to false assumptions in the evaluation of the sustainability of renewable energy systems. This concludes that LCEA is an effective tool for the design and evaluation of solar energy systems in order to be more sustainable.

Keywords: Exergy analysis; Sustainable development; Life cycle analysis

Introduction

With a dependence on finite natural resources, increasing energy demands and increasing environmental problems, the use of renewable resources becomes even more important. This is one part of a sustainable development. The ultimate source of most of our renewable energy supplies is the sun. The world's primary energy use is easily exceeded by the solar energy by a factor of about 10000 [1]. The renewable energies except geothermal and tidal energy depend on solar radiation. Thus, it is essential for future energy systems to rely on energy from the sun and presently, the use of direct solar energy is rapidly increasing. Solar energy systems can be classified into direct-solar systems and indirect-solar systems [2]. Here solar energy systems refer to direct-solar systems.

Exergy is a useful concept in the work towards sustainable development [3]. Exergy accounting of the use of energy and material resources provides important knowledge on how effective and balanced a society is regarding conserving nature's capital. This knowledge can identify areas in which technical and other improvements should be undertaken, and indicate the priorities, which should be assigned to conservation measures, efficiency improvements and optimizations. Hepbasli [4] offers a careful review of exergy analysis applied to renewable energy resources for a sustainable future. Thus, the exergy concept and exergy tools are essential to the creation of a new engineering toolbox or paradigm towards sustainable development.

In the literature, a number of studies applies energy and exergy analyses to the whole or part of solar energy systems, e.g. solar heater [5,6], solar power plant [7], solar photovoltaic (PV) system [8] combined solar photovoltaic and thermal (PV/T) plants [9,10]. Exergy of solar radiation is often regarded as input into the energy systems of these studies, and the overall energy efficiency is about 25% for solar power plant, 14-15% for PV/T system and less than 12% for PV system.

Life cycle analysis/assessment (LCA) is a tool used to evaluate the total environmental impact and total energy resource use of a product or service during its complete lifetime or from cradle to grave. It covers three steps – construction, operation and destruction. In previous studies LCA has been applied to solar energy system, e.g. PV system [11-14], solar thermal power system [15], solar heating system [16] and PV/T system [17,18]. However, none of these studies made use of exergy analysis. Some of the papers [11,13,18] estimated material recycling with present technology and future developed technology as well as using recycled material that will reduce the need for energy in the construction stage.

Two different methods combining LCA and exergy analyses have been proposed, e.g. Exergetic Life Cycle Analysis (ELCA) [19] or Life Cycle Exergy Analysis (LCEA) [20]. Cumulative Exergy Consumption (CExC) was introduced by Szargut et al. [21] to calculate the sum of all exergy input in all steps of a production process. Ayres with co-authors [22] stated the advantage of using exergy in the context of LCA, and concluded that exergy is appropriate for general statistical use, both as a measure of resource stocks and flows and as a measure of waste emissions and potential for causing environmental harm, which was also indicated by Wall in 1977 [3]. However, no detailed comparison has been made with existing methods, like the LCA. ELCA [19,23] introduced by Cornelissen is based on the framework of LCA with exergy applied to the inventory analysis and the impact assessment. Finnveden and Östlund [24] used exergy consumption as an indicator in LCA. Several metal ores and other natural resources were analyzed with system boundaries compatible with LCA. Since the cumulative exergy consumption index is just the sum of the chemical exergy contents of all original input flows, Valero [25] has introduced "exergetic cost for replacement of material" into the analysis. Lombardi (2001) performed an ELCA and a classical environmental LCA for a carbon dioxide low emission power cycle in which exergy was considered to be an indicator of resource depletion.

Life cycle exergy analysis (LCEA) includes sustainability aspects [20,26]. LCEA uses the same framework as LCA, but makes an important distinction between renewable and non-renewable resources. In LCEA, renewable resources as solar energy are excluded in the cost

***Corresponding author:** Göran Wall, Oxbo gard, SE-43892 Härryda, Sweden, Tel: 46 35 16 71 00; E-mail: gw@exergy.se

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of calculation due to being free of charge, and/or otherwise wasted. LCEA has also been applied to industrial processes [27,28] and to wind power systems [29].

Thus, LCEA is a powerful tool in the design of sustainable systems, especially in the design of renewable energy systems. The application of LCEA to different solar energy systems offers an excellent visualization of the exergy flows involved during the life time of the system. The analyzed plants are net producers of exergy, since the exergy consumed can be paid back during their life time, however, in a varying degree. The exergy of material that is part of the system in various components during its operation will turn up as a product in the destruction phase and is depicted in the LCEA diagram. The recycling of this material will considerably reduce the payback time for future energy systems.

In this paper we present the first application of LCEA to solar systems together with a proposal of how to evaluate the recycled material in the LCEA method. The aim is to: (1) increase the awareness of and encourage the use of LCEA, (2) show the advantages of exergy instead of energy in systems analysis, (3) apply LCEA to solar energy systems, and (4) introduce a new way to evaluate recycled material in LCEA.

Method

Concept of Exergy

The exergy concept originates from works of Carnot [30], Gibbs [31], Rant [32] and Tribus [33] and the history is well documented [34]. Exergy of a system is [3,35]

$$E = U + P_0 V - T_0 S - \sum_i \mu_{i0} n_i \quad (1)$$

where U, V, S, and n_i denote extensive parameters of the system (energy, volume, entropy, and the number of moles of different chemical materials i) and P_0, T_0, and μ_{i0} are intensive parameters of the environment (pressure, temperature, and chemical potential). Analogously, the exergy of a flow can be written as:

$$E = H - T_0 S - \sum_i \mu_{i0} n_i \quad (2)$$

where H is the enthalpy.

The exergy of material substances can be calculated by [3]

$$E = \sum_i (\mu_i - \mu_0) n_i \quad (3)$$

where μ_i is the generalized chemical potential of substance i in its present state.

The exergy of solar radiation is related to the exergy power per unit area of black body radiation e, which is [36]

$$e = u\left[1 + \frac{1}{3}\left(\frac{T_0}{T}\right)^4 - \frac{4}{3}\frac{T_0}{T}\right] \quad (4)$$

Where u is energy power emission per unit area which can be calculated according to Stefan-Boltzmann law, T is taken to equal the solar radiation temperature 6000K.

All real processes involve the conversion and consumption of exergy, thus high efficiency is of utmost importance. This implies that the exergy use is well managed and that effective tools are applied. Presently, an excellent online web tool for calculating exergy of chemical substance is also available [36,37].

Energy is always in balance, however, for real processes exergy is never in balance due to irreversibilities, i.e. exergy destruction that is related to the entropy production by

$$E_{in}^{tot} - E_{out}^{tot} = T_0 \Delta S^{tot} = \sum_j (\mathrm{E}_{in} - \mathrm{E}_{out})_j \rangle 0 \quad (5)$$

where ΔS^{tot} is the total entropy increased,

E_{in}^{tot} is the total input energy

E_{out}^{tot} is the total output energy and $(E_{in}\text{-}E_{out})_j$ is the exergy destruction in process j.

The exergy loss, i.e. exergy destruction and exergy waste, indicates possible process improvements. In general "tackle the biggest loss first" approach is not always appropriate since every part of the system depends on each other, so that an improvement in one part may cause increased losses in other parts. As such, the total losses in the modified process may in fact be equal or even larger, than in the original process configuration. Also, the use of renewable and non-renewable resources, as well as recycled resources must be considered. Therefore, the problem needs a more complete and careful approach.

Exergy factor and the reference state

Exergy factor is defined as the ratio of exergy to energy, and is sometimes referred to as quality factor, exergy coefficient and exergy quality factor.

The exergy factor for electricity and solar radiation is 1 and 0.93 respectively according to Eq. 4 with the temperature of the sun and the earth 6000K and 300K respectively, more detailed calculation can be found in [38].

When the heat capacity is independent of temperature and temperature decrease from T to T_0, the exergy factor for a heat flow can be calculated by [38]:

$$\frac{E}{Q} = \left|1 - \frac{T_0}{T - T_0}\ln\frac{T}{T_0}\right| \quad (6)$$

The exergy factor depends on the environment or reference state. The exergy reference state is carefully analyses by Gaudreau [39], and Dincer and Rosen [40] offer a summary of models of reference-environment state. The reference-substance model [40] is applied in this study, and the local environment temperature is used as reference temperature.

Exergy analysis

In engineering, Sankey diagrams are often used to describe the energy or exergy flows through a process. The energy/exergy efficiency is defined as the ratio of output energy/exergy to input energy/exergy of the systems.

Figure 1 shows a medium-temperature solar thermal power plant with solar collector, heat exchanger, turbine, condenser, regenerator and pump, its main components and roughly the main energy and exergy flows of the plant. This diagram shows where the main energy and exergy losses occur in the process, and also whether exergy is destroyed from irreversibility or whether it is emitted as waste, often waste heat, to the environment. In the energy flow diagram energy is always conserved, the waste heat carries the largest amount of energy into the environment, far more than is extracted as work in the turbine. However, in the exergy flow diagram the temperature of the waste heat is close to ambient so the exergy becomes much less than the energy.

In the solar collectors the energy efficiency is assumed to be about 55%. This depends on type of collector, average temperature difference between absorber and environment, and saturation temperature in the boiler [41]. The exergy efficiency of the concentrated medium-

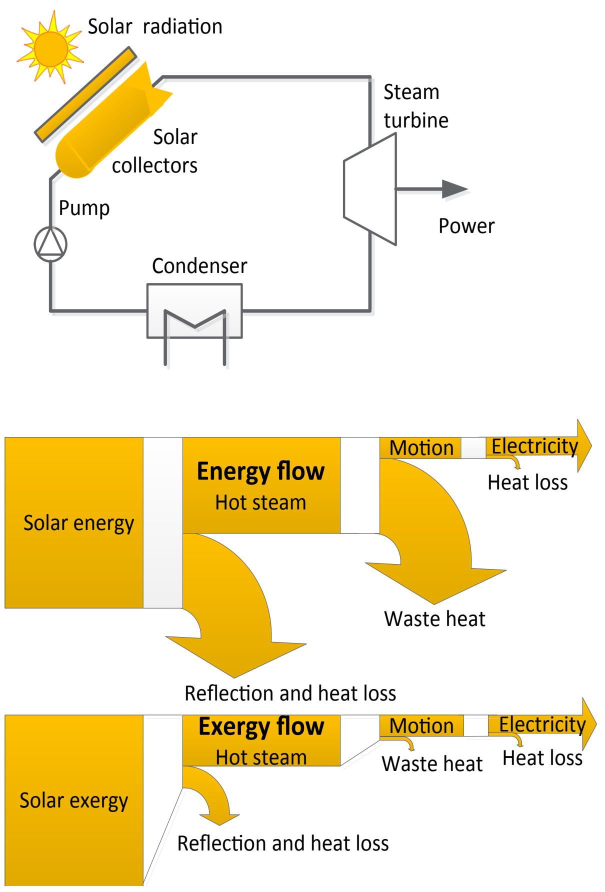

Figure 1: Energy and exergy flow of a simple solar thermal power plant.

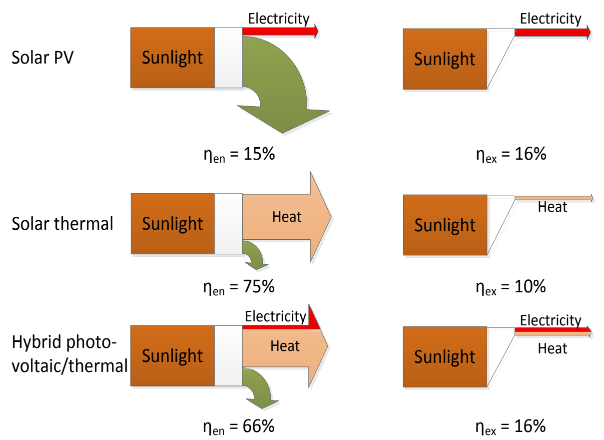

Figure 2: Energy and exergy flows through typical some solar energy systems.

temperature solar collectors is much lower or about 30% due to the low saturation temperature needed in order to drive a steam turbine. The exergy efficiency of solar collector, PV and hybrid solar collector are about 4%, 11% and 13% respectively [42].

Figure 2 illustrates the energy and exergy flows of solar PV cells, solar thermal and hybrid PV/thermal as an example. The produced heat is used for hot water and/or space heating. In the solar PV systems, the energy and exergy efficiencies are almost the same or 15% and 16% since for solar radiation exergy is 93% of the energy [38] and for the outflow of electricity both energy and exergy is identical. In a PV cell solar radiation is directly transferred to electricity by means of photons of light exciting electrons into a higher energy state to act as carriers of an electric current. The low energy efficiency of a PV cell is partly due to physical limitations in the photo-electric conversion, and the energy losses are mainly due to this that instead becomes heat radiation to the environment. A solar thermal converter has an energy efficiency of about 75%, however the exergy efficiency is very low or 10% because the temperature of the heat is close to ambient and thus of low exergy. In the case of hybrid PV/thermal systems, the energy and exergy efficiency is about 66% and 16% respectively.

In Figure 1, a solar thermal power plant, the exergy efficiency is about the same as for a PV plant (Figure 2). This can be better understood from the exergy diagrams. The main exergy loss in the thermal power plant occurs in the conversion of solar radiation into high temperature heat for the turbine. The total exergy efficiency depends on the quality of heat, i.e. the temperature and pressure of the heat. The exergy efficiency would be higher in a concentrating power plant (CSP) due to higher temperatures and pressures.

Energy/Exergy payback time

Energy/exergy pay-back time means time to recover primary energy/exergy use throughout its life cycle by the energy/exergy of the product, which is calculated as ratio of total energy/exergy input to the energy/exergy of the annual production.

Stepanov [43] compiles some of the different methodologies proposed for analyzing solar energy systems. The models developed by Valero and Lozano [44] for obtaining the chemical exergy of fossil fuels are applied here. However it must be pointed out that more complex calculation procedures do not necessarily mean more reliable results. Both, the experimental error associated to the determination of the heating values and the error associated to the correlations are in an interval close to ±2% [45]. Additionally, the chemical exergy of fuels is approximated to the higher heating value (HHV). The HHV assumes that water is in liquid state after combustion.

In this paper all primary thermal energy inputs are converted into primary electrical energy, with an assumed efficiency of 35%, i.e. 1 MJ (1/3.6 kWh), primary thermal energy becomes 0.097 kWh primary electrical energy. Thus, primary energy and primary exergy value becomes the same. Since the efficiency from primary thermal to primary electric energy varies from country to country local conditions are recommended.

Life Cycle Exergy Analysis (LCEA)

Life Cycle Analysis (LCA)

To estimate the total exergy used in a process, it is necessary to take all the different inflows of exergy to the process into account. This type of budgeting is often termed Exergy Analysis [3,35], Exergy Process Analysis, see Figure 3, or Cumulative Exergy Consumption [46], and focuses on a particular process or sequence of processes for making a specific final commodity or service. It evaluates the total exergy use by summing the contributions from all the individual inputs, in a more or less detailed description of the production chain.

Life Cycle Analysis or Assessment (LCA) is common to analyze

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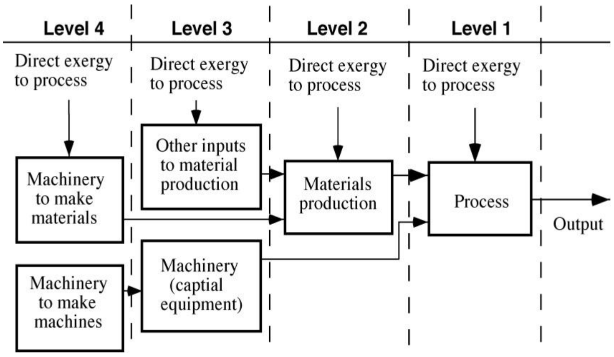

Figure 3: Levels of an exergy process analysis.

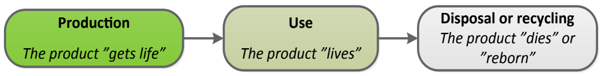

Figure 4: The life cycle "from cradle to grave".

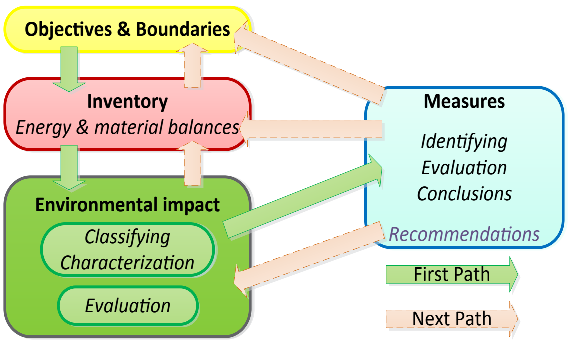

Figure 5: Main steps of a LCA.

environmental impacts associated with three "life processes": production, use and disposal or recycling of products or product systems, or as it is sometimes named "from cradle to grave", see Figure 4.

For every "life process" the total inflow and outflow of energy and material is calculated, thus, LCA is similar to Exergy Analysis. In general Exergy Analysis and LCA have been developed separately even though they are very similar. In LCA the environmental burdens are associated with a product, process, or activity by identifying and quantifying energy and materials used, and wastes released to the environment. This inventory of energy and material balances is then put into a framework in order to assess the impact on the environment, Figure 5. Four parts in the LCA can be distinguished: (1) objectives and boundaries, (2) inventory, (3) environmental impact, and (4) measures. These four main parts of an LCA are indicated by boxes, and the procedure is shown by arrows. Green arrows show the initial path and red dashed arrows indicate suitable next paths, in order to further improve the analysis.

Life Cycle Exergy Analysis (LCEA)

The multidimensional approach of LCA causes large problems when it comes to comparing different substances, and general agreements are crucial. This problem is avoided if exergy is used as a common quantity, which is done in a Life Cycle Exergy Analysis (LCEA) [26].

In this method we distinguish between renewable and non-renewable resources. The total exergy use over time is also considered. These kinds of analyses are of importance in order to develop sustainable supply systems of exergy in society. The exergy flow through a supply system over time, such as a power plant, usually consists of three separate stages (Figure 6). At first, during the construction stage ($0 \le t \le t_{start}$) exergy is used to build a plant and put it into operation. The exergy is spent, of which some is accumulated or stored in materials, e.g. in metals, as well as exergy used for transportation etcetera. Secondly the system need to be maintained during time of operation ($t_{start} \le t \le t_{stop}$), and finally the cleaning up and disposal stage during destruction stage ($t_{stop} \le t \le t_{life}$). Eventually, some material, i.e. stored exergy, can be recycled. These time periods are analogous to the three steps of the life cycle of a product in an LCA. The exergy input used for construction, maintenance and destruction are called indirect exergy Eindirect and it is assumed that this originates from non-renewable resources. By using recycled material in the production stage, the indirect exergy may be considerably reduced. If exergy is recovered by recycling in the destruction stage, this is accounted for as an additional product of the system, E_{rec}. When a power plant is put into operation, it starts to deliver a product, e.g. electricity with exergy power E_{pr} , by converting the direct exergy power input into demanded energy forms, e.g. electricity. In Figure 6, the direct exergy is a non-renewable resource, e.g. fossil fuel and in Figure 7 the direct exergy is a renewable resource, e.g. solar radiation.

In the first case as shown in Figure 6, the system is not sustainable, since the system use exergy originating from a non-sustainable resource and it will never reach a situation where the total exergy input will be paid back, simply because the situation is powered by a depletion of resources, i.e. $E_{pr}+E_{rec}<E_{in}+E_{indirect}$. In the second case, as shown in Figure 7, at time $t= t_{payback}$ the produced exergy that originates from a natural flow has compensated for the indirect exergy input, i.e.

$$\int_{t_{start}}^{t_{payback}} E_{pr}t(dt)+E_{rec}=\int_{0}^{t_{life}} E_{indirect}(t)dt=E_{indirect}$$

Since the exergy input originates from a renewable resource, we

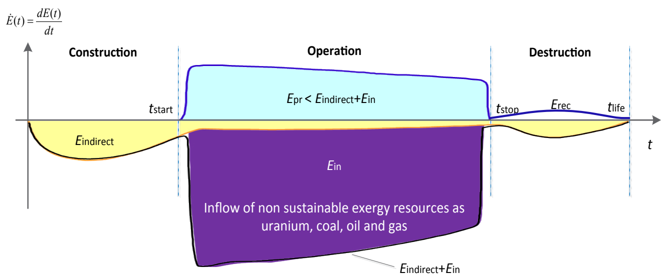

Figure 6: LCEA of a fossil fueled power plant.

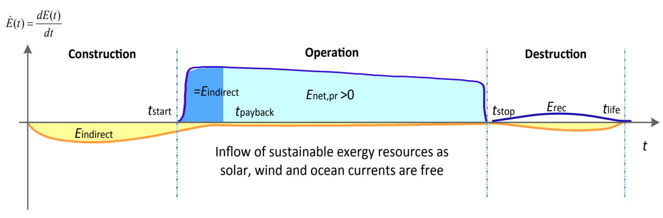

Figure 7: LCEA of a solar power plant.

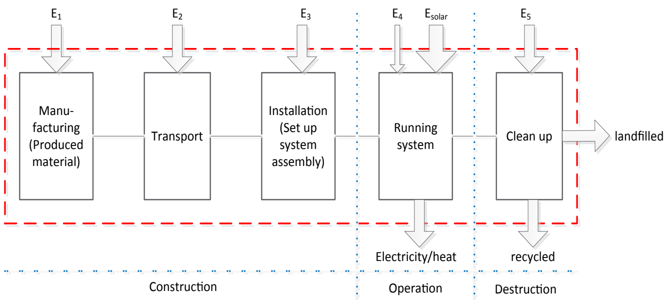

Figure 8: LCEA boundary of solar energy system.

do not account for it. By regarding renewable resources as free, then after $t = t_{payback}$ there will be a net exergy output from the plant, which will continue until it is closed down, at $t = t_{stop}$. Then, exergy has to be used to clean up and restore the environment, which accounts for the last part of the indirect exergy input Eindirect. Exergy in recycled materials Erec now turns up as an additional product of the system. By considering the total life cycle of the plant the net produced exergy becomes $E_{net,pr} = E_{pr} - E_{indirect} + E_{rec}$. These areas representing exergies are indicated in Figure 7. Assume that, at time t=0, the building of a solar PV/power plant starts and at time t = tstart the plant is completed and put into operation. At that time, a large amount of exergy has been used in the construction of the plant, which is indicated by the area of Eindirect between t = 0 and $t = t_{start}$. Then the plant starts to produce electricity, which is indicated in Figure 7 by the upper curve Epr. At $t = t_{payback}$ the exergy used for construction, maintenance and destruction has been paid back. The payback time will be further reduced if exergy is recycled from the destruction. For solar PV/power plants this time is only some months. Then the system has a net output of exergy until it is closed down, which for a solar energy system usually last for 20-25 years. Thus, LCEA diagrams could be used to show if a power supply system is sustainable.

LCEA is very important in the design of sustainable systems, especially in the design of renewable energy systems. Take a solar panel, made of mainly aluminum and glass that is used for the production of hot water for household use, i.e. about 50°C. Then, it is not obvious that the exergy being spent in the production of this unit ever will be paid back during its use, i.e., it might be a misuse of resources rather than a sustainable resource use. The production of silicon, aluminum and glass require a lot of exergy as electricity and high temperature heat or several hundred degrees Celsius, whereas the solar panel delivers small amounts of exergy as low temperature heat. LCEA must therefore be carried out as a natural part of the design of sustainable systems in order to avoid this kind of misuse. Another case to investigate is the production of biofuels in order to replace fossil fuels in the transport sector. This may not necessarily be sustainable since the production process uses a large amount of fossil fuels, directly for machinery or indirectly as fertilizers, irrigation and pesticides. This would be well described by a LCEA.

In order to be sustainable, energy supply systems must be based on a use of renewable resources in such a way that the input of non-renewable resources will be paid back during its life time, i.e. $E_{pr} > E_{in} + E_{indirect} - E_{rec}$. In order to be truly sustainable, the used deposits must also be completely restored or, even better, not used at all. Thus, by using LCEA and distinguishing between renewable and non-renewable resources we have an operational method to estimate the sustainability of energy systems.

LCEA diagrams are of particular importance in the planning of large scale renewable energy systems of multiple plants. Initially, this system will consume most of its supply within its own constructions phase. However, sometime after completion it will deliver at full capacity. Thus, the energy supply over time is heavily affected by internal system dynamics.

LCEA of solar systems

LCEA of a solar energy system

Figure 8 indicates a LCEA of a solar energy system where the red dashed box indicates the system boundary and blue dotted lines indicate the three steps of a life cycle. Construction includes manufacturing, transport and installation in order to set up the system.

The indirect exergy E_1 can be exergy of used electricity, fuels and material from natural resources. The produced materials for solar systems contain the PV module, metal, and electrical equipment. For large systems there are also electrical substations, fence and land. Fabrication of PV modules includes silicon production, PV cell manufacturing and supporting structures. Electrical equipment has inverters, transformers, cables and low and medium voltage switchboards, charge regulations (control panel) and bank of batteries (only for standard-alone-system). In the case of solar thermal system the produced materials are solar collector, storage tank, pipes and so on. The electricity used for manufacturing material during indirect use can be from both non-renewable and renewable energy. In this study electricity is, for practical reasons, assumed to be only from non-renewable resources.

The indirect exergy E_2 is exergy used for transportation of material from the manufactures to the installation site, and E_3 is exergy consumption during installation.

During operation phase the indirect exergy E_4 can be material used for maintenance. The direct exergy from solar is not accounted for during LCEA analyses since it is renewable energy and would other vice most probably be wasted. The product is electricity and/or heat. Part of the electricity production may be used for the control system.

The destruction phase restores the process to its original state. The indirect exergy E_5 is the exergy consumption for cleaning up; land filled and recycled material, such as aluminum and the PV module. Land filled and recycling depends on technology applied.

The total indirect exergy is $E_1+E_2+E_3+E_4+E_5$ and recycled exergy is an additional product of the system from its destruction.

LCEA applied to PV solar energy systems

There are numerous publications on LCA of different solar energy systems [11-18]. The energy use for construction, operation and destruction are often presented. However, some do not consider recycling at the destruction phase. The use of recycled material will often reduce the amount of energy needed from using fresh resources. Two studies use recycled material in the construction [11,15].

Solar exergy is often used to produce heat and/or electricity. The amount of solar exergy captured and converted by solar collectors and/or solar PV cells depend on the location, type of solar PV cell and collector, and working conditions. For a solar thermal plant, the produced heat often has low temperature which means low exergy values. For a solar thermal power plant, e.g. concentrate solar power (CSP) plant, the heat usually have high temperature, e.g. 500-1000°C for solar power tower, as steam with high exergy to drive a turbine and

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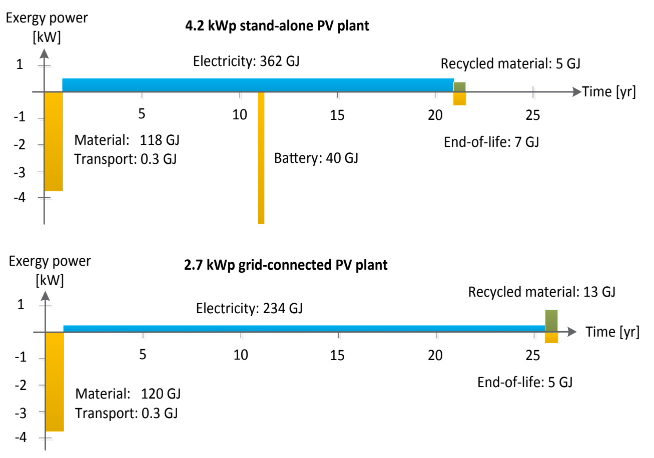

Figure 9: LCEA of a stand-alone and a grid-connected PV plant.

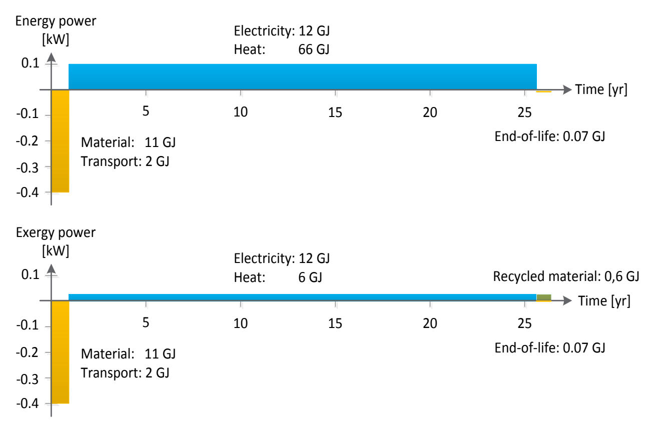

Figure 10: LCA and LCEA of a solar Photovoltaic-Thermal (PV/T) plant.

generator to produce electricity. The efficiency of PV cells is usually less than 20%, and the rest is mostly converted into waste heat to the environment. It is also very sensible to the working temperature, e.g., the efficiency of crystalline silicon (c-Si) cells typically decreases 0.4% when temperature rise 1 degree [47]. A PV/solar thermal (PV/T) system directly converts solar exergy to electricity and thermal exergy. In such systems the PV cells also work as thermal collectors in which the cell temperature can be controlled in order to prevent the decrease of efficiency.

Garcia-Valverde et al. [11] analyzed a 4.2 kWp stand–alone photovoltaic system in Spain. The system consists of 40 mono-crystalline modules (24V, 106Wp) mounted on a building rooftop. In the construction phase the exergy requirements for production is divided into two parts: manufacturing with and without recycling. Recycled materials use less exergy in its production. It is assumed that 35% of aluminum, 50% of the lead-acid batteries, 90% of the steel, and 43% of the copper came from recycled materials in the original. The highest exergy requirements in the production relates to PV modules and lead-acid batteries. In the operation phase the only exergy needed is to replace the lead-acid batteries after 10 years. The electricity for regulators and inverters come from the system itself. In the destruction phase exergy is required in recycling and transport to the recycling plant, and then PV modules will become landfill.

Kannan et al. [12] studied a 2.7 kWp grid-connected mono-crystalline solar PV system in Singapore. The system consists of 36 mono-crystalline modules (12V, 75Wp) mounted on a building rooftop. Most primary exergy was used in the production of PV modules which is about 81.4% of the life cycle primary exergy use. In the operation phase, no external exergy is used since produced electricity is transferred to the electric grid; however, this implies special conditions and consequences. In the destruction phase, it is assumed that the solar PV module would be landfill and 90% of aluminum frames are recycled with 90% recovery rate.

LCEAs of these two PV plants are depicted in Figure 9. By use of some recycled material during construction phase, the indirect exergy is about 118 GJ [11] for the stand-alone plant and if we assume no use of recycled material this would instead become about 130 GJ. For the grid-connected plant that does not make use of recycled material in the construction about 120 GJ is used. In addition about 40 GJ are used to replace batteries after 10 years in the stand-alone plant. The exergy of the metal will show up as a product as we have indicated in the diagrams, 5 GJ for the stand-alone and 13 GJ for the grid-connected plant. This material and exergy is available for recycling. In the grid-connected plant the authors assumed that 90% of the metal is able to recycle [12]. Probably, in the future more material will be recycled.

The exergy pay-back time becomes about 7 years for the stand-alone plant and about 9 years for the grid-connected plant. With improved PV module production technology and increased use of recycled material the pay-back time could be further reduced. These results relate to a thermoelectric conversion efficiency of 35% as indicated in Section 2.4 above. However, if the thermoelectric conversion efficiency varies from 30 to 40% the energy and exergy payback time will vary from 6 to 11 years and 8 to about 11 years, respectively.

Compare between LCA and LCEA with a PV/T system

A photovoltaic/thermal (PV/T) system in Hong Kong is investigated by Chow and Jie [18]. PV/T is a combination of photovoltaic and solar thermal system that produces both electricity and heat. In the construction phase, energy is used for the collector panels and PV module. For the solar thermal system, a water tank is needed. The yearly production thermal energy and electricity energy is 2650 MJ and 473 MJ respectively. The year average temperature in Hong Kong is 23ºC, the temperature from solar collector is 85ºC. Thus, the yearly thermal exergy production becomes only 244 MJ due to the relatively low temperature of the heat. Figure 10 shows an energy based LCA, the upper energy diagram, and an LCEA, the lower diagram, of this plant. In both cases the input of solar energy is excluded. Clearly, the LCA and LCEA show a large difference during operation phrase. The output of electricity and heat amounts to 78 GJ in the energy case but only 18 GJ in the exergy case, due to the low exergy value of the heat. In addition, the exergy of the metal of the equipment used turn up as a product in the destruction phase, i.e. about 0.6 GJ is available for recycling. The total input of non-renewable resources amounts to 12.8 GJ in both cases. The total energy output becomes more than 6 times the input. However, this is misleading since the value of heat does not reflect its true physical value. Instead, from the LCEA the output and input is more or less the same. If materials used at construction stage came from non-renewable mostly, this implies an inefficient energy usage. Such system can hardly be regarded sustainable. From a pure resource conservation perspective, it may be better to use the input of non-renewable resources directly for other purposes with less conversion energy loss instead. Considering that energy is also used for transport and destruction or end-of-life, the energy and exergy payback time is 3.5 and 15.4 years respectively.

Thus, the exergy payback time is more than four times longer than the energy payback time since the production consist of both electricity and thermal energy. Thus, the LCEA offers a better tool than LCA in the evaluation of energy systems for a sustainable future.

Conclusion

In a solar thermal plant the energy payback time is much shorter than the exergy payback time since the exergy of the output of heat is much lower than its energy value. This may lead to false assumptions in the evaluation of the sustainability of renewable energy systems. From Figures 6 and 7 we see the advantage of LCEA when applied to systems based on non-renewable and/or renewable energy resources.

Solar energy systems producing electricity have less exergy back time than system for heat production. The exergy payback time of PV/T system is much longer than the energy payback time or about 4 times longer. This indicates that LCEA gives a completely different view of these systems that is of essential importance in scientific evaluations.

Among the three solar thermal power plants the PV/T plant has the shortest energy payback time or 3.5 years. However, by applying exergy the 4.2 kWp stand-alone PV plant has the shortest payback time or 7 years, since the product in this case has a higher exergy value, i.e., more of electricity. This system is also the larger of the two pure PV systems.

LCEA is shown to be advantages in the study of solar based energy systems and is recommended as a suitable tool for the design and evaluation of renewable energy systems.

Nomenclature

E: Exergy, J

e: Exergy power per unit area, W m^{-2}

E*: Exergy power, W

H: Enthalpy, J

n: The number of moles of substance, mol

P: Pressure, Pa

Q: Heat or thermal energy, J

S: Entropy, J K-1

t: Time, s

T: Temperature, K

u: Energy power per unit area, W m-2

U: Internal energy, J

V: Volume, m3

μ: Chemical potential, J mol-1

η: Efficiency

Superscripts

^{tot} :Total system, i.e. the system and the environment

Subscripts

$_0$: Reference or state time

$_{en}$: Energy

$_{ex}$: Exergy

$_i$: Unit for different chemical materials

$_{in}$: Input

$_{indirect}$: Indirect input

$_j$: Unit for different process

$_{life}$: When a process or product exist

$_{net,pr}$: Net of product

$_{out}$: Output

$_{payback}$: All input is paid back

$_{pr}$: Product

$_{rec}$: Recycled material

$_{start}$: Operation starts

$_{stop}$: Operation stops

$_{tot}$:Total

$_{waste}$: Not used products

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