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ENERGY BALANCE AND CLIMATE IMPACT OF RENEWABLE POWER: IS THERE CAUSE FOR CONCERN?

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INTRODUCTION

It is generally acknowledged that the conversion of renewable energy flows into electricity in itself has no or negligible climate impact.[1] However, the conversion will always require production, maintenance and end-of-life treatment of power plants. These processes may very well involve emissions of greenhouse gases. It has thus been pointed out that the whole life-cycle of the power plant needs to be taken into account in assessments of the climate impact of renewable power production.

Most of the life-cycle emissions stem from the use of fossil fuels in different production steps. Hence, the climate impact of renewable power is tightly linked

1 Bioenergy is an energy stock, or fund, and not a flow in the perspective taken in this book, and is therefore not considerd. If renewable electricity were to be converted and stored in the form of electrofuels (Chapter 12), greenhouse gases could leak or be formed in a later combustion step. Massive deployment of wind, solar and ocean thermal energy conversion (OTEC) may to a limited extent impact local climate (see also Chapter 3 for discussions on global limits to wind and OTEC deployment and some references on the topic).

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to energy requirements and more specifically to the balance between energy input and energy output.

The discussion on energy balances, in fact, predates the concern for climate impact by a couple of decades and deserves some attention in its own right. The debate goes back at least to the beginning of the 1970s when it was observed that the energy payback time of some solar cell (PV) modules could be as high as 40 years and that the net energy output was zero or even negative. The concern for low energy return on energy investment has gained renewed interest in recent years, now with the low net energy output of some biofuels in focus.

One primary rationale for the concern with low energy return on energy investment relates to the viability of individual technologies. A technology with a small or negative net yield can be useful in specific niches where the technology is able to supply small quantities of electricity for specific purposes, such as solar cells powering satellites or providing light in rural villages in developing countries. However, if the technology is going to contribute significantly to world energy supply, a relatively high energy return is needed. This concern has also been taken beyond the level of individual technologies, to the set of all available energy technologies. It has been argued that the decreasing energy return on energy investment in oil extraction and refining due to exhaustion of easily accessible resources of high quality, together with the, by some evaluations, low energy return on investment from renewables, could have macroeconomic consequences and slow down economic growth in the coming decades.[2]

Measures of energy balance may also be used as a performance indicator to benchmark technologies, to argue for one or the other. This rests on an assumption that energy efficiency is important, either due to limited availability of energy resources or some specific energy carriers, or due to the fact that all energy conversion carries environmental and social costs. One benefit of using energy indicators in technology assessments, compared to indicators of more specific resource scarcities or environmental effects, is that they capture an intrinsic property of the technology itself rather than the properties of the particular background energy system which may change between regions and over time.

The question in focus in this chapter is if there is cause for concern related to the energy requirements and greenhouse gas emissions in the life cycles of renewable power technologies. To answer this question we will first introduce some measures of energy balance and climate impact and point out some important methodological considerations and then provide some empirical evidence. The scope is restricted to the power plants (Chapter 4), while electric grids and energy storage systems are not included (Chapter 5). One needs to observe that the climate impact and energy requirements are only two aspects out of many environmental issues that require the attention of decision makers, albeit two important ones (see e.g. Chapter 3 on resource availability and Chapter 6 and 8 on other environmental effects).

2 Hall, C., et al. (2009) What is the Minimum EROI that a Sustainable Society Must Have? *Energies* 2(1):25-47.

MEASURES OF LIFE-CYCLE ENERGY BALANCE AND CLIMATE IMPACT

The simplest measure of energy balance is the *energy payback time* (EPBT). It is particularly useful in assessments of technologies that is characterised by a large initial energy investment, which can, so to speak, be paid back over time as the device generates electricity. At the EPBT the cumulative output balances the initial input. To generate a significant amount of net output the EPBT needs to be significantly shorter than the lifetime of the device. To be complete the energy investment also needs to include energy required for operations and maintenance, and end-of-life treatment (Figure 7.1).

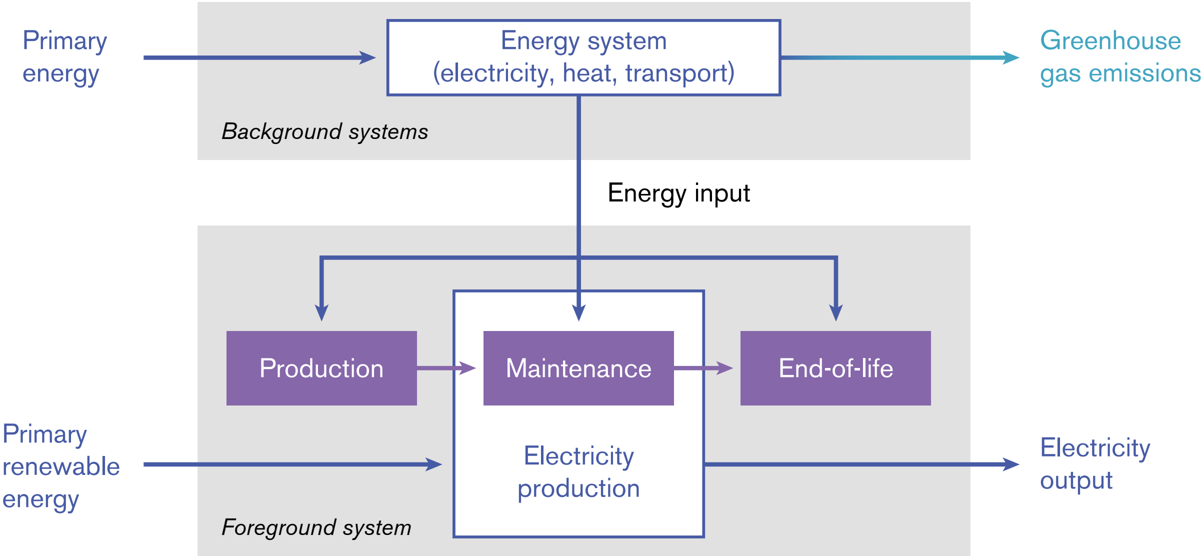

Figure 7.1 A simplified picture of the life cycle of a renewable power plant (purple) with associated energy flows (blue) and greenhouse gas emissions (teal). The system is subdivided into a foreground system and background energy systems.

An alternative indicator that conveys almost the same information is the *energy return on energy investment* (EROI). It compares the cumulative electricity output over the lifetime of the power plant to all energy input in production, maintenance and end-of-life treatment. In more complex systems with many parts with different lifetimes or when maintenance makes up a larger share of the energy input the EROI indicator may be preferable to the EPBT.

The direct primary renewable energy input in the power plant (low left corner in Figure 7.1) is not taken into account in the EPBT and EROI measures.[3] In contrast, a measure of *total system energy efficiency* would include both the direct energy input in power production as well as the more indirect life cycle energy inputs. Total energy efficiency would be a relevant measure in comparisons of different ways to convert a given resource.[4] One example could be a comparison between different means to convert a limited hydropower resource, and another could be

3 Similarly, the energy content of fuels directly combusted in fossil fuel-fired power plants are not included. See for example discussion in Raugei M, Fullana-i-Palmer P, Fthenakis V (2012) The energy return on energy investment (EROI) of photovoltaics: Methodology and comparisons with fossil fuel life cycles. *Energy Policy* 45:576-582.

4 Kushnir, D. and Sandén, B.A., (2011) Multi-level energy analysis of emerging technologies: a case study in new materials for lithium ion batteries. *J. of Cleaner Production*, 19(13):1405-1416; Rydh, C. J. and Sandén, B. A. (2005) Energy analysis of batteries in photovoltaic systems Part II. Energy return factors and overall battery efficiencies. *Energy conversion and management*, 46(11-12):1980-2000.

a comparison between solar cells and bioenergy systems that convert the solar energy hitting an area to electricity.

A generic problem in all energy analyses is to handle the fact that energy comes in different forms, mainly electricity, heat and various forms of chemical energy, e.g. gas, oil and coal. The value of different energy forms varies with application, e.g. liquid fuels are convenient in transport while computers are designed to run on electricity. Moreover, the conversion between forms entails different conversion efficiencies. It can be helpful to view the different energy forms as currencies. In the literature on EPBT, it is common to recalculate all currencies into one currency, most often something called 'primary energy'. In calculations of EROI, the conversion to a common currency is not always done, which creates some confusion.

Here we apply a common currency in calculations of both EPBT and EROI. We use electricity as this this common currency, since we believe electricity is a more well-defined currency than 'primary energy'.[5] In particular, it is straightforward to use in assessments of electrical power production technologies. To be clear we here use $EROI_{el\text{-}eq}$, as the ratio of the life-cycle electricity *output* to the sum of life-cycle energy *inputs* expressed in electrical energy equivalents.[6]

In life cycle assessments (LCA), which try to evaluate the environmental impact (e.g. contribution to climate change) of a product, service or technology, it is common to subdivide the system in foreground and background systems (Figure 7.1). The foreground system consists of the industrial processes that are defined and described specifically for the LCA study. These processes are usually directly linked to the assessed technology. The background systems comprise all other industrial processes, which would exist also without the assessed technology. Distinguishing the energy background system is of particular importance in assessments of climate impact of energy technologies since most of the impact stems from the background system, and this may vary between regions and change over time.

In particular it might seem unfair, or illogical, to allocate emissions from coal and natural gas to renewable power since these are the technologies the renewable power seek to replace. It has been suggested that when a technology in general, in contrast to particular plants, is to be evaluated, a 'net-output approach' can be used where the electrical input is deduced from the electricity output. However, when one seeks to estimate the side effects of building and operating renewable power plants in a specific year and location, emissions from the observed or forecasted energy background system need to be included in the assessment

5 While electric energy is the flow of electric charge, easily transferrable to many other energy forms (Chapter 2), 'primary energy' typically denotes naturally occurring energy sources. These may come in many different forms, ranging from solar radiation and the mechanical energy in winds, waves, streams and dams (Chapter 3), to the nuclear energy in uranium atoms and the chemical energy stored in coal, oil and natural gas. Since these forms of energy require different technologies for conversion into more well-defined energy carriers demanded in society, such as electricity and heat, with widely different conversion efficiencies (different exchange rates), 'primary energy' does not serve well as a common currency. In a system dominated by fossil fuels as primary energy, it makes some sense, but becomes less suitable in a system with high shares of different renewables.

6 Kushnir, D. and Sandén, B.A., (2011) Multi-level energy analysis of emerging technologies: a case study in new materials for lithium ion batteries. *J. of Cleaner Production*, 19(13):1405-1416; Rydh, C. J. and Sandén, B. A. (2005) Energy analysis of batteries in photovoltaic systems Part II. Energy return factors and overall battery efficiencies. *Energy conversion and management*, 46(11-12):1980-2000.

(see also Chapter 6 on the importance of differentiating between assessments of individual installations and generic technologies).[7]

In the LCA literature, a distinction is made between process LCA and input-output LCA. In the former type of study physical flows that can be allocated to the functional unit, in this context a kilowatt hour of renewable electricity, are defined and described bottom-up with process-specific information. One then needs to apply some cut-off rules, since if the machine that produced the machine and the electricity that powered the computer used by the executive officer in the factory that produced that machine etc. are to be included, the supply chains can become infinitely long. By using an economic input-output matrix this problem can be circumvented, as the input-output matrix covers the entire economy and include processes that are difficult to capture in physical terms such as services. On the other hand, one typically loses some detail with input-output LCA in comparison to process LCA. Hence, hybrid LCAs try to combine the best of both methodologies. In general, energy input and emissions tend to be higher in studies that apply input-output or hybrid LCA methodologies, as compared to those only applying process LCA.

ENERGY BALANCES AND CLIMATE IMPACT: CURRENT STATE-OF-THE-ART

Keeping in mind the theoretical background presented in the previous section, let us now move on to explore empirical evidence: What do state-of-the-art life-cycle assessments tell us about the energy balance and climate impact of renewable power?

There are numerous estimates of climate impact and energy balances in the literature. To be up to date, the results presented in this section are mainly based on life-cycle analyses from a recent study by the International Resource Panel.[8] The Resource Panel study presents comprehensive life-cycle assessments of power generation technologies that are either important causes of climate change or relevant for large-scale mitigation of climate change. Ocean energy results, here including tidal and wave power, are not available from the Resource Panel study and are adapted from other sources.[9]

Figure 7.2 compares estimated $EROI_{el\text{-}eq}$ and climate impact of different technologies. The ranges in results indicate variation among technological designs and regions defined in the Resource Panel study. Looking at the $EROI_{el\text{-}eq}$ results, one overall impression is that over their lifetime as producers of electricity, renewable

7 The net output approach was suggested by Hillman, K. M. and Sandén, B. A. (2008) Time and scale in life cycle assessment: The case of fuel choice in the transport sector. *International Journal of Alternative Propulsion* 2(1):1-12.
A scenario approach with changing background systems over time was used in Arvesen, A. and Hertwich, E. G. (2011) Environmental implications of large-scale adoption of wind power: a scenario-based life cycle assessment, *Environmental Research Letters* 6:045102.

8 Hertwich E.G. et al. (2014) *The benefits, risks, and trade-offs of low-carbon technologies for electricity production.* International Resource Panel, United Nations Environment Programme. In preparation.

9 Kelly K.A. et al. (2012) An energy and carbon life cycle assessment of tidal power case study: The proposed Cardiff–Weston severn barrage scheme. *Energy* 44(1):692–701; Parker, R.P.M. et al. (2008) Energy and carbon audit of an offshore wave energy converter. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 221(8):1119-1130; Thomson, R.C. et al. (2011) Full life cycle assessment of a wave energy converter. *IET Conference on Renewable Power Generation (RPG 2011),* Edinburgh, UK, Sep 6-8; Woollcombe-Adams, C., Watson, C.M., Shaw, T. (2009) Severn Barrage tidal power project: Implications for carbon emissions. *Water and Environment Journal* 23(1):63-68.

power plants 'pay back' tens of times the energy costs of building and operating the plants. Further, according to these results, the $EROI_{el\text{-}eq}$ of renewable power is generally comparable to or greater than that of gas and coal power. Hydropower stands out in Figure 7.2 by exhibiting a much wider interquartile range and total range than the other technologies. The lower end of the spectrum for hydropower reflects that one of the included power plants is situated in a remote area and has large transport infrastructure requirements associated with it.

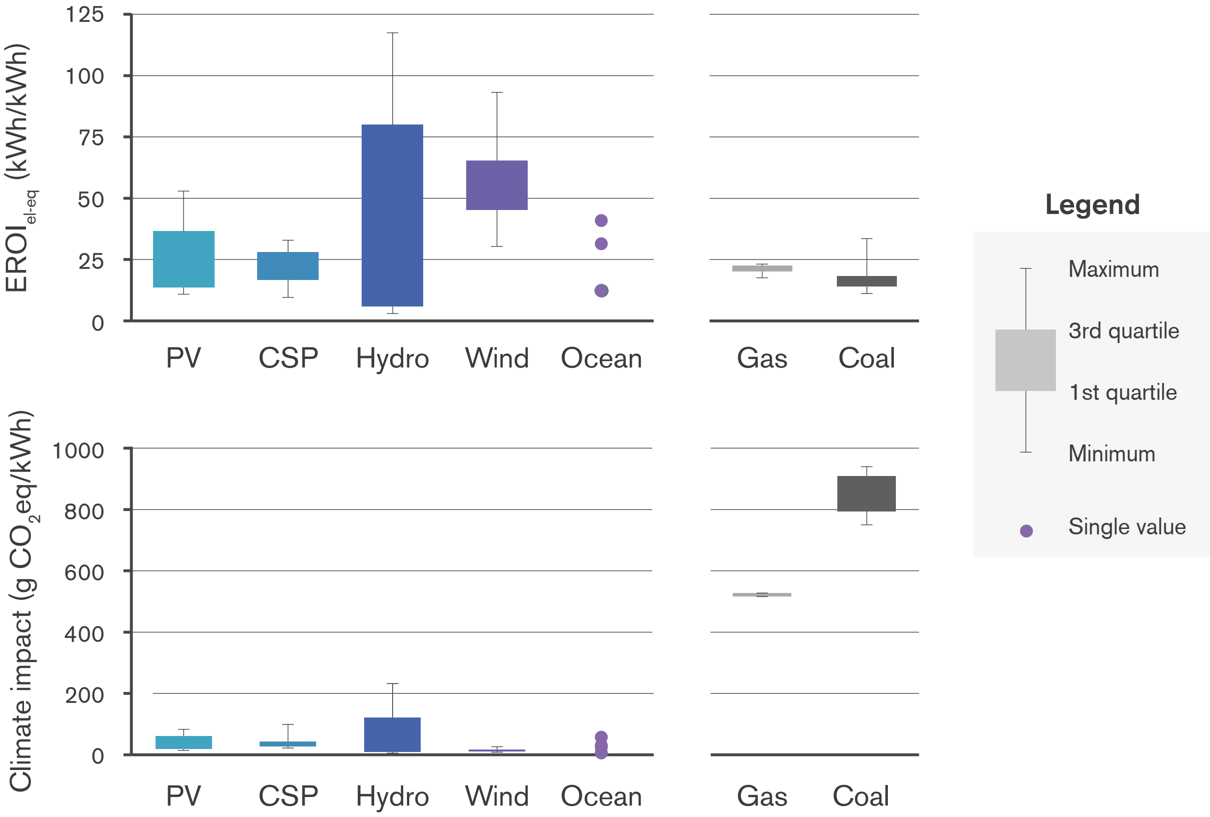

Figure 7.2 Energy return on investment (EROIel-eq) (upper panel) and climate impact (lower panel) for renewable and conventional fossil fuel power production. PV: solar photovoltaics. CSP: concentrated (thermal) solar power. Ocean comprises wave and tidal power. The fossil fuel systems are without carbon capture. A conversion factor 0.3 is used to convert energy contained in combustible fuels to electrical energy equivalent. Data sources: Hertwich E.G. et al.[10] and (for ocean energy) Kelly K.A. et al. as well as Parker, R.P.M. et al. [11]

As mentioned in the previous section, when we want to compare how efficiently a given resource is converted, the total energy system efficiency is a suitable measure. The large EROI values in Figure 7.2 indicate that the indirect life cycle energy input is small compared to the output and thus also to the direct energy input of primary renewable energy. Hence, for the total energy system efficiency, the direct conversion efficiency is in most cases a more important parameter than indirect life cycle energy requirement.

10 Hertwich E.G. et al. (2014) *The benefits, risks, and trade-offs of low-carbon technologies for electricity production.* International Resource Panel, United Nations Environment Programme. In preparation.

11 Kelly K.A. et al. (2012) An energy and carbon life cycle assessment of tidal power case study: The proposed Cardiff–Weston severn barrage scheme. *Energy* 44(1):692–701; Parker, R.P.M. et al. (2008) Energy and carbon audit of an offshore wave energy converter. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 221(8):1119-1130

The most apparent example might be the comparison between direct solar and bio electricity. The direct conversion efficiency from solar energy to electricity is typically about hundred times higher in solar cells than in systems based on energy crops and combustion. For the total energy balance, it therefore does not matter much if the EROI is somewhat lower for the solar cells. If the bioenergy, hypothetically, would be produced without any energy input other than the solar influx on the field and if the solar cells would have an $EROI_{el\text{-}eq}$ in the lower end (say 10) the solar cell system would still be about 90 times more efficient and thus require a fraction of the land needed for the bioenergy system[12] The climate impact results in Figure 7.2 also place renewable power in a favourable light, with the interquartile ranges for solar, hydro and wind power being barely visible when plotted on the same scale as the climate impact of fossil fuel power. This indicates substantial mitigation potential if renewable energy sources replace fossil fuels in power generation. It may be noted that biogenic methane emissions from hydro power reservoirs is a concern for some regions of the world, especially when large areas are flooded.[13]

CHANGING BACKGROUND SYSTEMS

In the previous section we saw that greenhouse gas emissions of solar, hydro, wind and ocean power are low, but they are not zero. So, why are they not zero? It is because we need to rely on current industries to for example process materials, manufacture components and transport goods. How much fuel industries burn per unit of output differs appreciably between regions. Hence, background system characteristics can have significant bearing on LCA results. This is illustrated by the hypothetical example of polycrystalline silicon PV in Figure 7.3, where the variability in results is entirely due to regional differences in background systems.

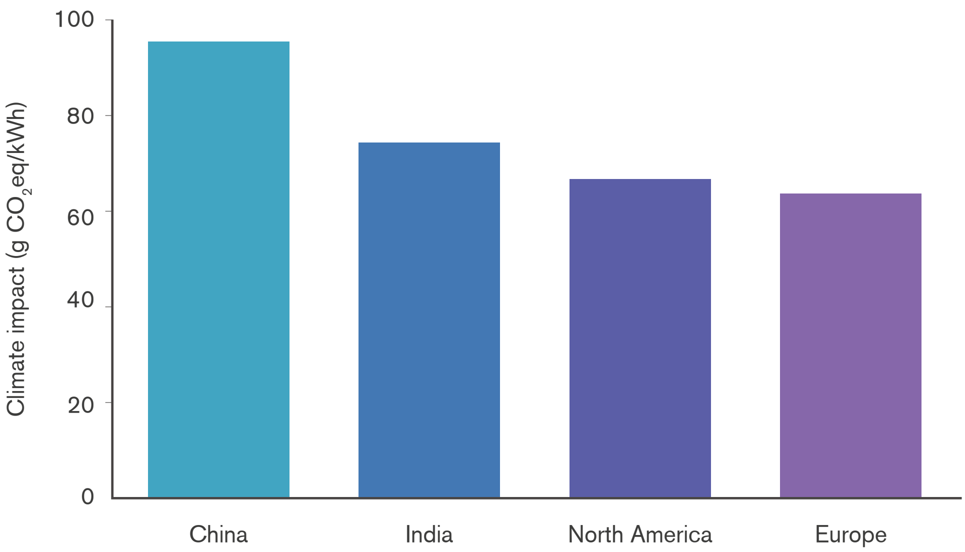

Figure 7.3 Climate impact of electricity from ground-mounted polycrystalline silicon photovoltaics, assuming identical foreground system and solar insolation value (2000 kWh/m²/year on tilted modules) for all regions. Data source: Bergesen J. et al. [14]

12 See also Chapter 3 and *Systems Perspectives on Electromobility.* (2014) 2nd edition. Chalmers Univeristy of Technology, Göteborg, Sweden

13 Hertwich, EG (2013) Addressing Biogenic Greenhouse Gas Emissions from Hydropower in LCA. *Environmental Science & Technology* 47(17):9604-9611. See also Chapter 6.

14 Bergesen J. et al. (2014) Photovoltaic power. In *The benefits, risks, and trade-offs of low-carbon technologies for electricity production*. International Resource Panel, United Nations Environment Programme. In preparation

A significant share of the climate impact of renewable electricity is caused by fossil-fuel burning in power stations; that is, exactly the power stations that renewable power plants are meant to replace. Of course, emissions from power stations are real and need to be included in life-cycle assessments of *individual installations*, but at the same time one could argue that they are not an inherent property of renewable power as such, and should therefore not be included in assessments of the *technology in general*.

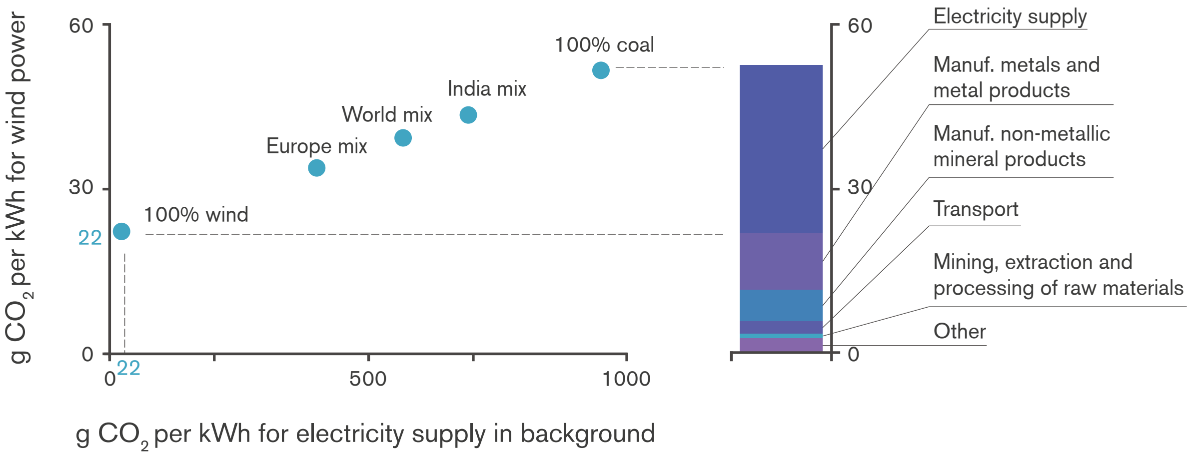

Figure 7.4 An illustrative example of the impact of background systems. The CO_2 intensity of offshore wind power (vertical axis) is plotted as a function of CO_2 intensity of background system electricity (horizontal axis). The stacked column shows the breakdown of CO_2 emissions by industries in a scenario where the background system uses coal as the only source of electricity. Source: Adapted from Arvesen et al.[15]

To illustrate the role of the background electricity, we run an input-output-based LCA model for offshore wind power with different electricity mixes. This includes a scenario where, hypothetically, coal is the only source of electricity in the world, and one where offshore wind is the only source. In the latter case, a loop is created in the model so that the wind power that we study in the foreground system and the electricity that we model in the background system are essentially the same, hence corresponding to a net-output approach.[16]

As is evident from Figure 7.4, the CO_2 impact in the 100% offshore wind case is less than half of that in the 100% coal case. However, eliminating all direct emissions from electricity does not make offshore wind power CO_2-free, as 22 g CO_2/kWh is emitted in manufacturing, transport and other sectors (see the stacked column in Figure 7.4). In a prospective study of possible future systems the carbon intensity of these sectors may of course also decrease. In general, there may also be cases where the carbon intensity (or at least the energy intensity) of background activities increases in the future, for example as a result of generally declining metal ore grades and shift towards more remote ore deposits.[17]

15 Arvesen A. et al. (2013) The importance of ships and spare parts in LCAs of offshore wind power. *Environmental Science & Technology* 47(6):2948-2956.

16 The model is adapted from Arvesen A. et al. (2013) The importance of ships and spare parts in LCAs of offshore wind power. *Environmental Science & Technology* 47(6):2948-2956. A hybrid life-cycle analysis model is used in the reference, but for the sake of simplicity we here use a purely input-output-based model version with a one-region representation of the world economy. The approach taken in the all-wind case has been termed a 'net-output approach', since the electricity output that is required to produce wind power is deducted from the gross output, see Hillman, K. M. and Sandén, B. A. (2008) Time and scale in Life Cycle Assessment: the case of fuel choice in the transport sector. *Int. J. of Alternative Propulsion*, 2008, 2(1):1-12.

17 See, e.g., Norgate, T. and N. Haque. (2010) Energy and greenhouse gas impacts of mining and mineral processing operations. *Journal of Cleaner Production* 18(3):266-274; Mudd, G. M. (2010) The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. *Resources Policy* 35(2):98-115.

CHANGING FOREGROUND SYSTEMS

As seen above, the choice of background systems for the production of electricity, transport and input materials is of critical importance for how much carbon dioxide emissions that are allocated to renewable power production. But not only technology background systems vary. Every class of technology (such as 'wind power' or 'PV') contains a wide span of different designs and every design might be produced in several ways and installed in areas with different conditions. This is less of a problem when a unique power plant is assessed, while it is a challenge when one aims at making claims about 'a technology' in general.

To capture the variation and a representative mean value of current systems one would ideally collect data from every producer in the world in a consistent manner. This is however not possible (partly due to trade secrets), and maybe not even worth the effort. What might be more interesting from a strategic point of view is to capture systematic variation within technology groups. Figure 7.5 provides one such example of the effect of scale on the carbon dioxide intensity of on-shore wind power. In the lower end of the turbine size spectrum, the carbon dioxide intensity decreases markedly with scale. The evidence in Figure 7.5 is inconclusive for the megawatt turbine size range however (there are too few data points).

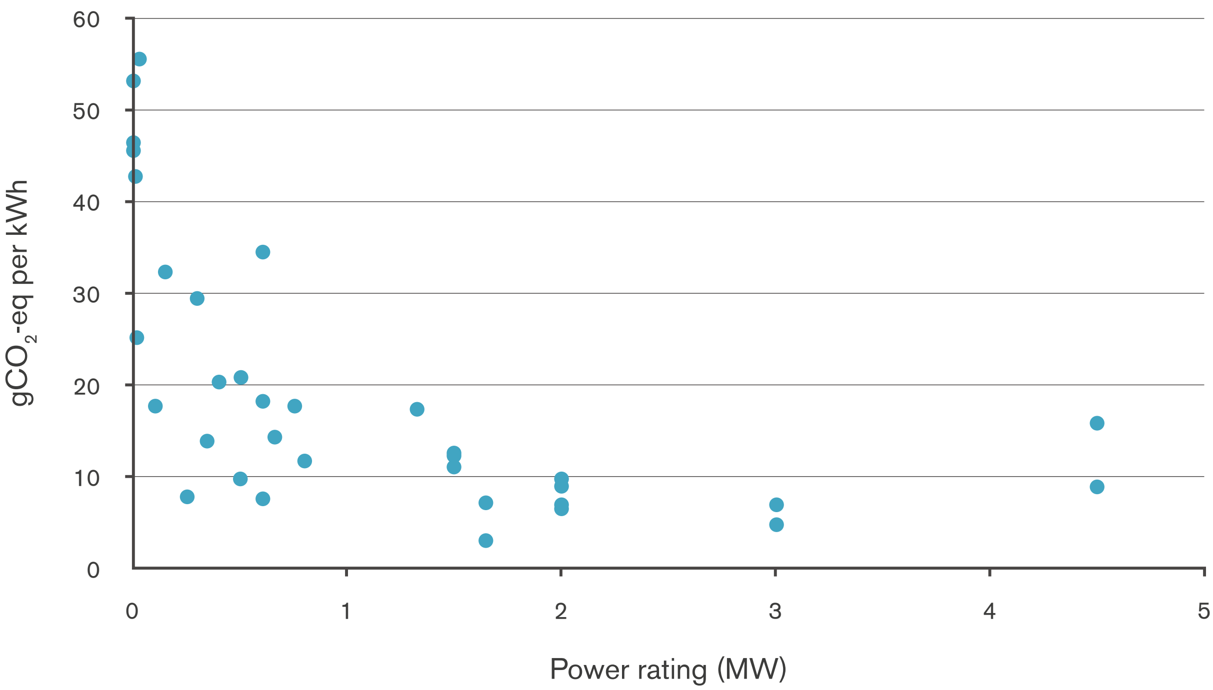

Figure 7.5 Climate impact of on-shore wind power related to power rating of the turbine (process LCA). Source: adapted from Arvesen and Hertwich[18].

Another important observation is that the required energy input (and thus also the related climate impact) may change over time. An example of a drastic reduction of EPBT and the related increase of EROI is provided in Figure 7.6. The EPBT of PV systems decreased from 20-40 years in the early 1970s to about one year in 2011. This implies that the EROI over the same period increased from about one to 20-40. While the quality of data and assessment methodology clearly has improved over time, the trend can mainly be attributed to the growing production

18 Arvesen, A., Hertwich, E.G. (2012) Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs, *Renewable and Sustainable Energy Reviews*, 6(8):5994-6006

volumes that have allowed for efficiency improvements due to the accumulation of experience and knowledge and realisation of economies of scale in production. In 2011, the market for PV was more than 100 000 times larger than in 1975.

Prospective numbers for 2020 (see Figure 7.6) indicate that the trend towards higher EROIs may continue. Figure 7.6 also shows that thin-film PV tends to have a higher EROI than traditional crystalline silicon PV. A technology shift towards thin-films could thus increase the overall EROI of PV.[19] A conclusion we may draw is that claims about the feasibility of a technology based on old data may be of little value, and even up-to-date data for current production might be of limited value when it comes to foresee the energy balance and climate impact of future systems.

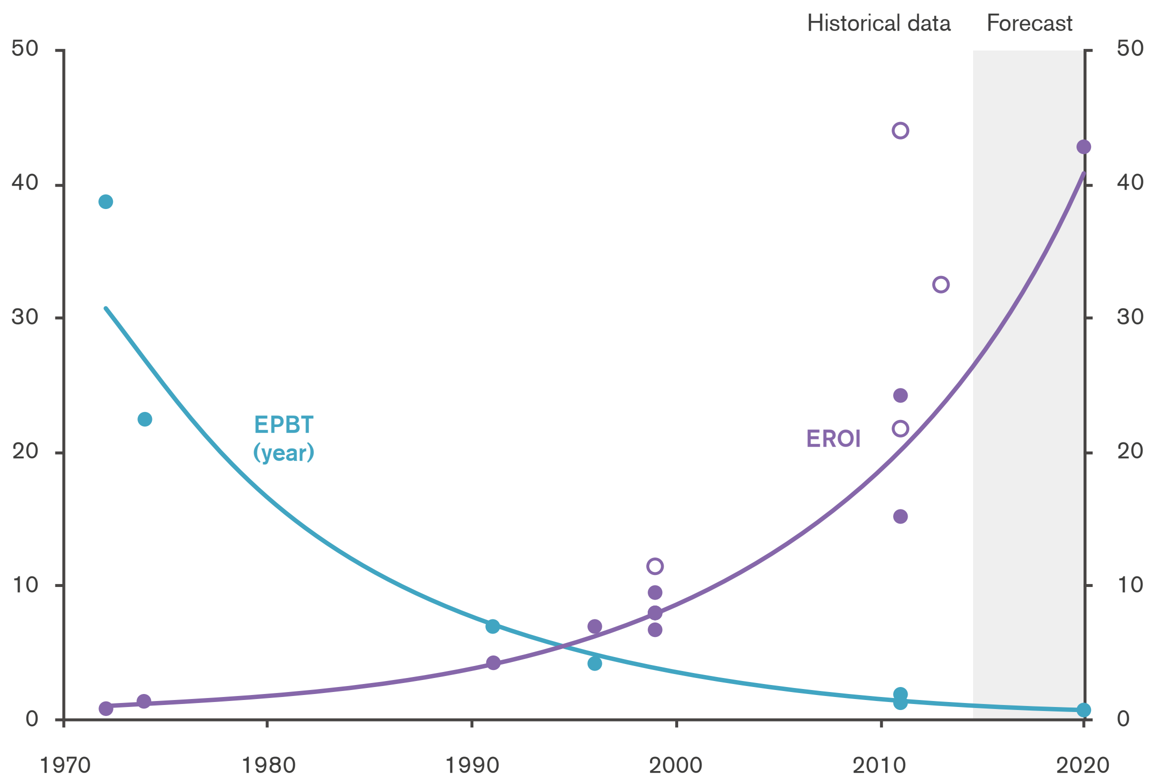

Figure 7.6 The development of energy payback time (EPBT) and energy return on energy investment (EROI) of PV systems over time. The solid and empty dots represent crystalline silicon and thin film technology, respectively. The value for 2020 is a forecast received from a design study. The trend lines are best fit exponential curves of historical data for crystalline silicon. A solar insolation of 1700 kWh/m^{2}yr is used for all values and a lifetime of 30 years is used to calculate EROI values.[20]

19 One study has daringly suggested that the EPBT for novel plastic PV technologies may need to be measured in days, instead of months or years. These may however have shorter lifetimes and thus the corresponding increase of EROI is lower. See Espinosa, N., et al. (2012) Solar cells with one-day energy payback for the factories of the future. *Energy & Environmental Science* 5(1):5117-5132). It may also be noted that potential future shortages of supply of certain metals (e.g., tellurium and indium) used in some (but not all) thin-film PV could place a limit on the future market uptake of such technologies or decrease EROI due extraction from low grade ores, see e.g. Andersson, B. A. (2000) Materials availability for large-scale thin-film photovoltaics. *Progress in Photovoltaics* 8:61-76; Graedel, T. E. and Erdmann, L. (2012) Will metal scarcity impede routine industrial use? *MRS Bulletin* 37(04):325-331.

20 Historical data: Wolf M. (1972) Cost goals for silicon solar arrays for large terrestrial photovoltaics. *Proceedings of 9th IEEE PV specialist conference*:342–50, Silver Spring, MD, USA.; Wolf M. (1975) Cost goals for silicon solar arrays for large terrestrial photovoltaics – Update 1974. *Energy Conversion* 14(2):49-60; Baumann, A. E., et al. (1997) Environmental impacts of PV systems-ground-based vs. BIPV. *Twenty-Sixth IEEE Photovoltaic Specialists Conference*, pp 1361-1364. Anaheim, CA, USA, Sep-29 Oct 3; Alsema, E. A. (2000) Energy pay-back time and CO_2 emissions of PV systems. *Progress in Photovoltaics: Research and Applications* 8(1):17-25.; De Wild-Scholten, M. J. (2013) Energy payback time and carbon footprint of commercial photovoltaic systems. *Solar Energy Materials and Solar Cells* 119:296-305; Mann, S. A., et al. (2013) The energy payback time of advanced crystalline silicon PV modules in 2020: a prospective study. *Progress in Photovoltaics: Research and Applications*.

The trend in Figure 7.6 can mainly be attributed to falling energy requirements of the PV modules, and less to reduced requirement of other system components. A consequence of this is that substructures will be of increasing importance for ground mounted systems, and in small roof-top systems, components such as inverters will likely be responsible for an increasing share of the energy input.

This leads to the next important issue: location. Due to variation in natural conditions and availability of complementary technical infrastructure, the energy balance will differ between locations.

Differences in the density of renewable energy flows have a large impact on the EPBT and EROI of renewables. The solar energy influx varies by about a factor of two over most parts of the world (see Figure 3.1 in Chapter 3). Thus the EROI of a PV system in Sweden would be about half that of a system in northern Africa (the numbers in Figure 7.6 is calculated from an irradiance representative for southern Europe, close to the world average for horizontal surfaces). The wind energy resource is more variable than solar energy and all other renewable energy flows have an extreme geographical variability (Chapter 3 and 4). For example, trying to make use of a tidal resource where the tide hardly is noticeable or hydropower where the land is more or less flat would entail very low EROI values.[21]

It is not just the energy density which varies across locations, but also distance to existing infrastructure and other site characteristics influencing material and energy requirements. PV integrated in buildings requires no other substructures while ground mounted systems in open areas normally require some additional construction work. PV at sea might in turn require new types of substructures and maintenance. A comparison of on-shore and off-shore wind power shows that the higher electricity production at sea is more or less balanced with higher energy costs for construction and maintenance.

The fact that all locations are not equal should at some point in time start to have a negative effect on the energy balance. First the good spots are taken; then lower quality resources in more complicated environments will be used. Decreases in EROI can also conceivably occur as public resistance towards renewable power hinder exploitation of sites that are optimal from a resource or technical point of view. This effect should still be fairly small for most renewable energy sources since only a fraction of the potential is utilised (Chapter 3). Hydropower might be an exception, since most good sites and a large fraction of the technical potential is already used (Chapter 3 and 6). Another example might be the current development of offshore wind power in Europe; the average distance to shore for new projects was 14 km in 2009 and 29 km in 2012, and both distance to shore and water depth are on the whole expected to increase in coming years.[22] For solar power the argument might be of less relevance since the resource is so evenly distributed across the globe in abundant quantities (Chapter 3).

21 However, as stated in the introduction to this chapter there may be niche applications where the energy balance is of less importance, and the crucial thing is to produce some electricity from the resources that happen to be locally available.
22 EWEA (2013) *The European offshore wind industry - key trends and statistics 2012.* Brussels, Belgium: EWEA.

A related aspect, which goes beyond the scope of this chapter, is the varying need for enhanced grid infrastructure (Chapter 9), flexible operation of fossil fuel power plants (Chapter 11) or energy storage (Chapter 5 and 12) to accommodate intermittent renewables in the electric system, and the energy use and greenhouse gas emissions connected with such grid and balancing requirements.

CONCLUDING REMARKS

While historical data for some technologies indicate that worries might have been warranted in the past, we can conclude that there is now less cause for concern about greenhouse gas emissions and energy payback of renewable power technologies in general. Replacing conventional fossil fuel-based power plants with renewable power offers substantial reductions in greenhouse gas emissions. The energy return on energy investment is now at least as high for renewables as for conventional fossil fuel-based power plants. With lower greenhouse gas intensities of energy background systems and development of foreground system components and production processes, it is likely that the climate impact will decrease in the future. It is also likely that technology development will continue to improve the energy balance of most renewable power technologies.

However, it is possible to construct systems with low energy return on energy investment and high climate impact. With large scale implementation of the less abundant renewables, the energy return may decrease as lower quality resources in more complicated environments are used. Moreover, new requirements of electrical grids and energy storage systems are not considered in this assessment and, depending on system configuration, these components may add a significant energy burden. Hence, we consider it still worthwhile to assess individual projects and follow the general trends.