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ARE RENEWABLE ENERGY RESOURCES LARGE ENOUGH TO REPLACE NON-RENEWABLE ENERGY?

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INTRODUCTION

While the very large potential of renewable energy has been known to some scholars at least since the end of the 19th century, the potential is still today commonly underrated in public debate. To get the physical proportions right is a necessary first step in a sensible discussion on possible and desirable development paths.

The primary purpose of this chapter is to answer the question if the resources of renewable energy flows are large enough to completely replace fossil fuels and nuclear energy, and to indefinitely support a world population of 9-10 billion people at a living standard equivalent to present day industrialised societies. A second purpose is to outline what expectations we may have on each of the different renewable flow resources.

The potential of the conversion route via bioenergy is excluded from this discussion but is treated more extensively in in another book in this e-book series.[1] Our scope is limited to potentials of electricity production, but since electricity is an energy form of high quality (see Chapter 2) its use is versatile. It is not unlikely

1 See Chapter 4 in *Systems Perspectives on Biorefineries*. (2014) 3rd edition. Chalmers Univeristy of Technology, Göteborg, Sweden.

Systems Perspectives on Renewable Power 2014, ISBN 978-91-980974-0-5

that many applications that today are powered by the chemical energy in fuels will switch to electricity in the coming decades[2]. Electricity can also, at a cost, be converted to chemical energy stored in hydrogen or even hydrocarbons (see Chapter 12). Hence, a comparison makes sense not only to the global electricity demand, but also to the total energy demand.

RESOURCE ASSESSMENT

The renewable energy flows have three different origins. Most renewable energy can be traced back to the influx of solar energy at the top of the atmosphere, an energy flow about 10 000 times larger than society's current use of primary energy (Table 3.1). The solar energy inflow is converted to a range of secondary energy flows, including winds, waves and water streams and currents. The geothermal energy flow derived from the hot interior of the Earth and the tidal energy originating from kinetic and gravitational energy in the Earth, moon and sun system are several orders of magnitude smaller.[3]

Table 3.1 Three primary energy inflows are the origins of all renewable energy sources.

Primary renewable energy influx	Annual flow (10^3 TWh/yr)
Solar energy - entering the Earth's atmosphere	1 500 000
Geothermal energy - transported to the surface of the Earth	400
Gravitational energy - converted to tides at the surface of the Earth	32

The objective of this chapter is to estimate somewhat realistic resource potentials; how much of the energy flows in Table 3.1 can be converted to electricity? Here we must admit that "resource potential" is an elusive concept and numerous attempts have been made in the literature to define and assess different types of potentials. An important starting point is to free the imagination from 'the prison of the present' and avoid confusing a realistic future potential with what is currently technically realised or what is believed to be economically competitive in the near term. A commonly used logic is then to start with some kind of ultimate physical potential and then add different kinds of limitations. In this chapter we will follow this route and try to identify what we here term physical potentials, technical potentials and socio-economic potentials. In this way, we will proceed from the hard facts of natural science to more socially constructed constraints, and thereby indicate different levels of flexibility.

The measure we here term *physical potential* tries to capture the part of the physical energy flow that theoretically could be converted to electricity. In some cases this is fairly straightforward, in other cases we need to rely on recently published

2 See for example *Systems Perspectives on Electromobility*. (2014) 2nd edition. Chalmers Univeristy of Technology, Göteborg, Sweden

3 To be more precise, also the exchange of heat radiation with the cold universe is a source of exergy ('useful energy', Chapter 2) that contributes to the geophysical processes on Earth. To some extent the kinetic or gravitational energy of the Earth also contribute to ocean currents and waves, wind energy and rainfall, and a minor part of the tidal energy from gravitational interaction is dissipated as friction heat in the solid Earth contributing to geothermal energy, see Hermann, W. A. (2006). Quantifying global exergy resources, *Energy* 31(12):1685–1702.

results based of advanced models. In almost all cases we exclude parts of the resource that we find highly unlikely as a basis for electricity production at any significant scale, for example, solar energy captured in the atmosphere, wind energy in high altitude jet streams and wave energy dissipated over the deep oceans.

In the *technical potential* we try to exclude parts of the resource that has not yet been conceived for electricity production. For example, solar and wind power over the deep oceans are excluded. Furthermore, we apply demonstrated conversion efficiencies instead of theoretical maxima. In most cases we rely on thorough assessments conducted by others that comply with these criteria.

It is not reasonable to view the technical potentials as feasible targets. There will be numerous economic, environmental and social concerns that will limit the amount of energy we ever would like exploit. To give a hunch of the order of magnitudes of electricity that we could expect from the different sources we have tried to derive *socio-economic potentials.* These are not based on current technology costs and electricity prices, but on the assumption that the conversion technologies will be able to compete in favourable locations, but will have to share the surfaces and landscapes of the Earth with other social activities and undisturbed nature.

This chapter does not explicitly take energy system integration into account. Obviously, utilisation of renewable flow resources on a very large scale will require storage and transmission technology and maybe changed temporal patterns of demand. We return to spatial and temporal characteristics of the different resources towards the end of the chapter (see also Chapter 5 and 9-12). Furthermore, the assessment lacks a time dimension. Developing the huge technical systems required will at least take several decades (see Chapters 15-16).

The numerical estimates are provided in the Table 3.2. With the exception of hydro power, only a minor fraction of the potentials have been utilised. The potential of solar power is large compared to current electricity and energy use; also the wind power potential is significant.

World energy demand, however, is expected to increase. If 9-10 billion people used as much energy as an average Swede use today, the primary energy supply would almost quadruple.[4] Nevertheless, demand would still not exceed the estimated socio-economic potential of solar power.

While the global potentials of the other power sources are of a different order of magnitude, they may be of local importance. The sections below elaborate on the derivation of the numbers and include a discussion on geographical and temporal variation of the different energy flows.[5]

4 The energy scenarios in IPCC (2000) *Special report on emission scenarios*, Cambridge, UK and New York, NY, USA: Cambridge University Press approximately span a range from 150 000 – 600 000 TWh/yr of primary energy supply in 2100, with the high end thus corresponding to a quadrupling of primary energy supply.

5 The subdivision in sections happens to bear some resemblance to the classical ‘four elements’: fire, air, water and earth.

Table 3.2 Physical, technical and socio-economic potentials of electricity production from renewable energy flow resources compared to the realised production in 2012 as well as to total world supply of electricity and primary energy in the same year. See text for references, calculations and explanations.

	Potential			World Supply
(10^3 TWh/yr)	**Physical**	**Technical**	**Socio-economic**	**2012****
RENEWABLE ELECTRICITY				
Solar (at surface)	730 000	20 000	1000	0.09
Wind (near surface)	2 000	700	100	0.5
Water				
Hydro	50	16	8	3.7
Osmotic	30	2	0.4	-
Wave (near coast)	32	2	0.4	-
Tidal	22	1	0.2	0.001
Ocean current	40	*	*	-
Ocean thermal (OTEC)	120	*	*	-
Geothermal	60	2	1	0.06
WORLD ENERGY				
Electricity				23
Primary energy				150

* Could not be assessed (see text).
** Source: PB statistical review of energy (2013).

SOLAR POWER

The solar constant, i.e. the irradiance at the top of the atmosphere, is measured to about 1360 kW/m^2.[6] Multiplying with the cross section of the Earth this amounts to a total inflow of about 1500 million TWh/yr (Table 3.1). For space-based solar power this constitutes the ultimate resource limit. However, solar satellites that harness the solar energy outside of the atmosphere and beam it down to Earth are still only at the drawing table.

Averaged out over the surface of the Earth, the irradiation at the top of the atmosphere corresponds to 340 W/m^2. Earth bound solar power plants need to let go with the 55%, or about 190 W/m^2, that reaches the Earth surface, summing up to 840 million TWh/yr.[7] The rest is absorbed in the atmosphere or reflected out in space before it reaches the ground. The irradiation at ground level has two components, direct and diffuse light. While conventional flat plate solar cells can harness the energy in both components, technologies that concentrate the light beams such as concentrated solar thermal power or concentrated photovoltaics can only make use of direct radiation (Chapter 4).

6 In a sense, this is 'the mother of all energy constants'. Nevertheless, new knowledge has revised also this number. Recent measurements indicate a value of about 1362 W/m^2 and a slight downward correction of the earlier estimate of 1366 W/m^2, see Kopp, G. and Lean, J.L. (2011) A new, lower value of total solar irradiance: Evidence and climate significance. *Geophysical Research Letters*. 38(1), L01706.

7 188±6 W/m^2 according to Stephens, G.L., et al. (2012) An update on Earth's energy balance in light of the latest global observations. *Nature Geoscience,* 5:691-696. Our estimate is 189 W/m^2 based on insolation data from NASA (2013). *NASA Surface meteorology and Solar Energy: Global Data Sets* [accessed 2014-07-03].

The theoretical limit for conversion of direct and diffuse light to electricity at the surface of the Earth has been estimated at 93% and 75%, respectively.[8] About two thirds of the energy at ground level is direct radiation. Hence we can identify a physical potential of 700 million TWh/yr (Table 3.2).

The solar cell modules and solar thermal power plants that are commercially available today typically have conversion efficiencies between 10 and 20%, while the highest recorded efficiency of a small cell in 2013 was 44%.[9] In, principle solar cell modules can be put side by side, e.g. on roof-tops, but on large solar farms, some additional spacing is normally required. Current large solar electricity plants in the US have a module area to land area ratio of 20-50%.[10] Where land is scarce, a packing density in the upper end of the range is more likely. In conclusion, with current technology an overall conversion efficiency of 10% is feasible over large areas, implying an average production potential of about 20 W/m².[11]

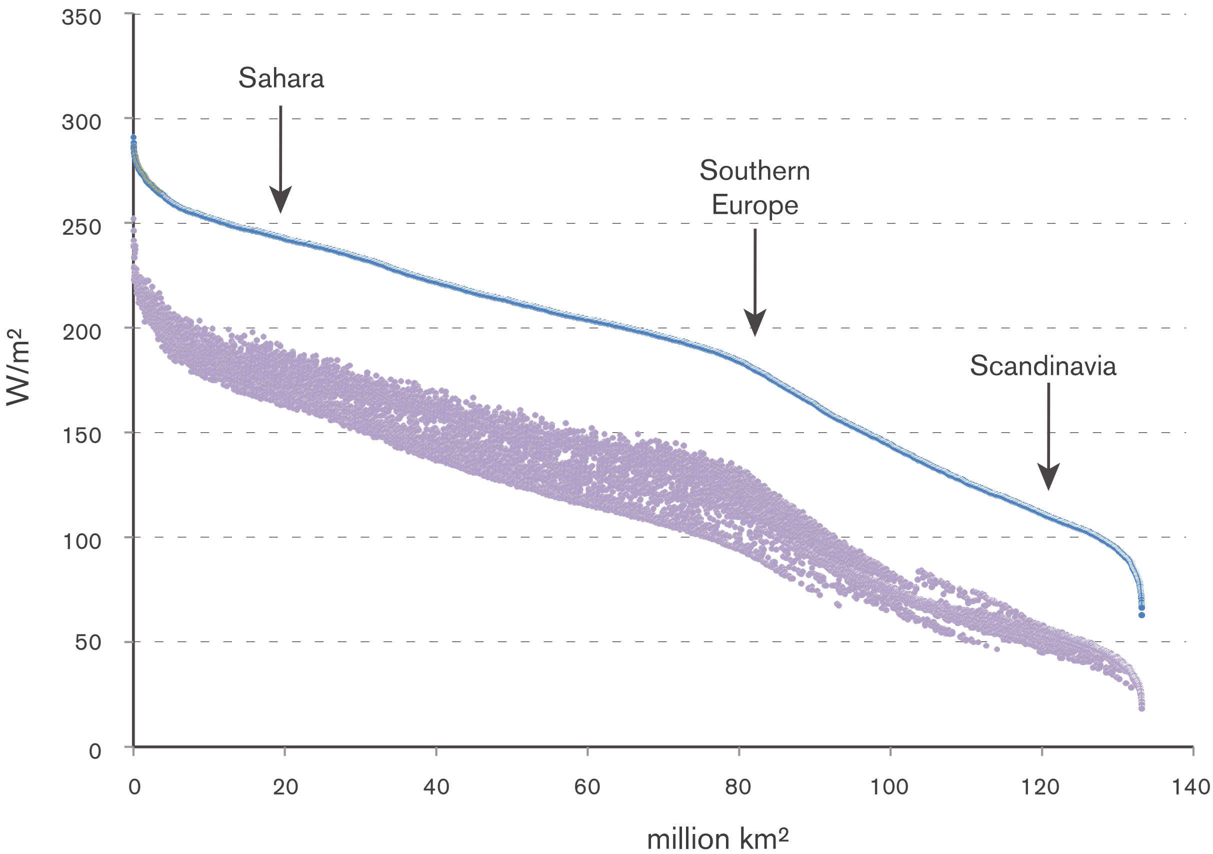

Figure 3.1 The distribution of total solar energy irradiance (blue line) and the part made up of direct light (purple dots) (in W/m²). The total land area of the Earth north of Antarctica is included and divided into 17346 grid points, 1x1 degrees in size. Source: Based on data from NASA (2013).

The physical potential implies a complete coverage of the globe. In principle, there is nothing hindering solar power at sea. There are prototypes and plans

8 Hermann, W. A. (2006). Quantifying global exergy resources. *Energy* 31(12):1685–1702.

9 Green, M.A. et al. (2013). Solar cell efficiency tables (version 42). *Progress in Photovoltaics: Research and Applications* 21(5):827-837.

10 Ong, S. et al. (2013). *Land-Use Requirements for Solar Power Plants in the United States.* (NREL/TP-6A20-56290) Golden, CO, USA: U.S. Department of Energy's National Renewable Energy Laboratory (NREL).

11 The 10% could e.g. correspond to a system with 10% efficiency and 100% packing density or one with 20% efficiency and 50% packing density.

for off-shore solar power and floating solar cells may prove to be less technically demanding than e.g. wave and off-shore wind power. However, besides small installations on boats and oilrigs and some systems attached to the shore, to date all solar power plants are located on land. Land (excluding Antarctica) covers 26% of the Earth and actually receives the same fraction of the energy inflow.[12] A conversion of 10% then results in an onshore technical potential of 20 million TWh/yr (Table 3.2).

The distribution of the solar energy resource is depicted in Figure 3.1. About 98% of the total irradiation is supplied at an annual intensity above 100 W/m^2. Since solar energy is currently harnessed even in Scandinavia in the far right of the graph (about 115 W/m^2), there are basically no land areas that can be excluded from the resource base. However, the figure also shows that the direct irradiance is typically 50-90 W/m^2 lower than the total energy inflow, implying that the share of direct radiation decreases with decreased irradiance. Hence, technologies that concentrate sunlight are likely to be relatively more competitive in sunny areas.

Given that solar electricity can be produced almost anywhere, including the surfaces of buildings, infrastructure and vehicles, as well as on land of low value, it is difficult to justify any particular limit to production below the technical potential. However, some comparisons could indicate a reasonable socio-economic potential. In 2012, 5% of the area of EU was covered by 'artificial land' (buildings, roads etc.);[13] a third of the global land area is covered by deserts; and it has been suggested that an area corresponding to 6% of all land north of Antarctica could be available for bioenergy production.[14] Covering 5% of the global land area of any type, including sunnier and less sunny areas, with solar power plants with an overall conversion efficiency of 10% would constitute a socio-economic potential of more than 1 million TWh/yr (Table 3.2).

WIND POWER

Wind energy is driven by pressure difference caused by uneven heating and cooling of the Earth atmosphere. Thus, it originates from solar energy, and around 1% of the solar energy inflow, or some 14 million TWh/yr, is estimated to be converted to wind energy.[15] This energy is ultimately dissipated through friction (or drag) in the moving air itself and between the moving air and land and water surfaces (see wave energy below). Extraction of wind power would effectively mean an increased drag. There are two ways to calculate the ultimate potential to convert wind energy to electricity: top-down and bottom-up approaches.

12 Based on data from NASA (2013) *NASA Surface meteorology and Solar Energy*: Global Data Sets.

13 See news release from Eurostat (2013) *Buildings, roads and other artificial areas cover 5% of the EU.* Oct. 25. In Sweden, suitable roof-tops could provide some 40 TWh/yr according to Kjellson, E., 2000, *Potentialstudie för byggnadsintegrerade solceller i Sverige*, Lund, Sweden: Lund University. Areas covered by railways and larger roads could supply another 100 TWh/yr. In energy terms, this would cover the Swedish electricity consumption. However, power supply will not match demand and therefore storage would be required to utilise this resource (see Chapter 5 and 9-12) One can also note that if all land had the same area coverage of solar cells as Germany had at the end of 2013, solar cells would produce about 20 000 TWh/year, almost corresponding to global electricity production in 2012 (Table 3.2).

14 In the IPCC (2011) *Special report on renewable energy.* Cambridge, UK and New York, NY, USA: Cambridge University Press, p. 226. an area of 7.8 million km^2 (or 6% of all land north of Antarctica) is considered to be available for bioenergy production. On this area, 170 EJ/yr of bioenergy could be produced, which in turn could be converted to some 15 000 TWh/yr of electricity. With an area efficiency of 10%, direct conversion of solar energy would produce some 1.3 million TWh/yr on the same area.

15 Marvel et al. (2013). Geophysical limits to global wind power. *Nature Climate Change* 3:18–121.

Top-down approaches start with the observation that at some level of increased drag from wind power extraction, the climate system will not be able to replenish the kinetic energy. A recent top-down study estimated the physical wind power at the bottom 200 m of the atmosphere at 2 million TWh/yr (Table 3.2).[16] Currently there is no technology that can convert wind energy over the deep ocean to electricity.[17] The onshore (90%) and offshore near coast (10%) technical potential was estimated at 700 000 TWh/yr. Adding more turbines at this saturation level would only reduce the production of others.

There could also be other practical issues that would limit the technical potential. Bottom-up approaches starts with maps of average wind speeds in different regions. Every windmill based on the principle of a rotating turbine has a theoretical limit of 59% called the Betz factor (see Chapter 4). In reality, turbines may reach 40-50% under optimal conditions. To harness as much of the wind resource as possible, turbines can be packed in wind farms; however, when densely packed they also steal wind from each other and worsen the economics of each turbine. Hence, there is a trade-off between energy conversion per turbine and energy conversion per land area.

One study estimates the peak power production at 7 W per m^2 of farm area, based on an assumed optimal density of one 2.5 MW turbine per 0.28 km^2 and a farm loss of 20%. In most places, the average production would be much lower, since 7 W/m^2 of farm area corresponds to a wind speed of more than 10 m/s. The energy in the wind is proportional to the cube of the wind speed (see Figure 3.2 and Chapter 4, Box 4.1). Hence, the energy in the wind falls quickly with lower wind speeds. At 6 m/s, the power output the same farm would only reach 1.5 W/m^2 or about 20% of the rated capacity.[18]

An additional result of the relationship between wind speed and energy content is that, compared to solar energy (Figure 3.1), the wind energy resource is less evenly distributed. In areas with low average wind speed, the energy density is very low and economic extraction of wind power is not likely to be feasible. The bottom-up studies thus typically exclude areas in the world with low wind speeds.[19] However, when calculating the theoretical output of wind farm placed in reasonably good locations all over the world, one bottom-up study estimated a technical potential of 800 000 TWh/yr.[20]

16 Archer and Jacobson (2012). Saturation wind power potential and its implications for wind energy, *PNAS* 109(39):15679–15684. The physical potential to capture energy from high altitude jet streams was estimated at 3 million TWh/yr. Currently there are no available technology that can capture energy from high altitude jet streams (if lower energy use in airplanes is excluded).
17 There are several experiments with floating wind mills, still, there is a limit on the depth where these can be placed as well, as they are anchored to the sea floor and secondly there may be economical limitation on how far away they can be placed from the demand.
18 A study of land use of wind energy farms in the US found an average capacity density of 3 W/m^2. With a capacity factor of 30% the average production would be 1 W/m^2, 10 kWh per m^2 and year. Denholm et al. (2009). *Land-Use Requirements of Modern Wind Power Plants in the United States*. (NREL/TP-6A2-45834). Golden, CO, USA: U.S. Department of Energy's National Renewable Energy Laboratory (NREL).
19 Since winds speeds generally increase with height, more energy can be extracted with larger (and higher) turbines.
20 The study included onshore (80%) and offshore near cost (20%) areas with capacity factors above 20% but excluded onshore ice, forest and water covered areas. Lu, X., et al. (2009). Global Potential for Wind-Generated Electricity. *PNAS* 106:10933-10938. A similar estimate is provided by Archer and Jacobsson (2013). Geographical and seasonal variability of the global "practical" wind resources, *Applied Geography* 45:119-130.

According to the top-down studies cited above this should be an overestimation since it assumes extraction above the saturation limit when winds cannot be replenished at the global level. According to the top-down models, the huge wind farms imagined in the bottom-up study would interact and steal wind from each other. We therefore assume a technical potential of 700 000 TWh/yr (Table 3.2).

In practice there are mainly two aspects that limit the socio-economic potential of wind power. In populated areas there are conflicts about siting, while less populated windy areas are remote and require large infrastructure investments. The technical potential derived from the bottom-up study, in fact, requires that about 30% of the land area outside of the polar regions is used for wind power production. Even if wind turbines can co-exist with agriculture, forestry and solar electricity harvesting, such a high penetration is probably not desirable (see also discussion in Chapter 6). From this perspective a socio-economic potential in the order of 100 000 TWh/yr seems reasonable claiming a few percent of onshore and near-cost areas (Table 3.2).

WATER POWER – RIVERS AND OCEANS

Water is a liquid of relatively high density and is a good carrier of kinetic energy (Figure 3.2). Electric power can be produced from natural flows of moving water in several ways, including hydro, wave, tidal and ocean current power. Moreover, heat differences in the oceans can be converted to electric power in ocean thermal energy conversion (OTEC) plants and differences in salt concentrations between rivers and oceans can be used to produce electricity in osmotic power plants (see more on technologies in Chapter 4).

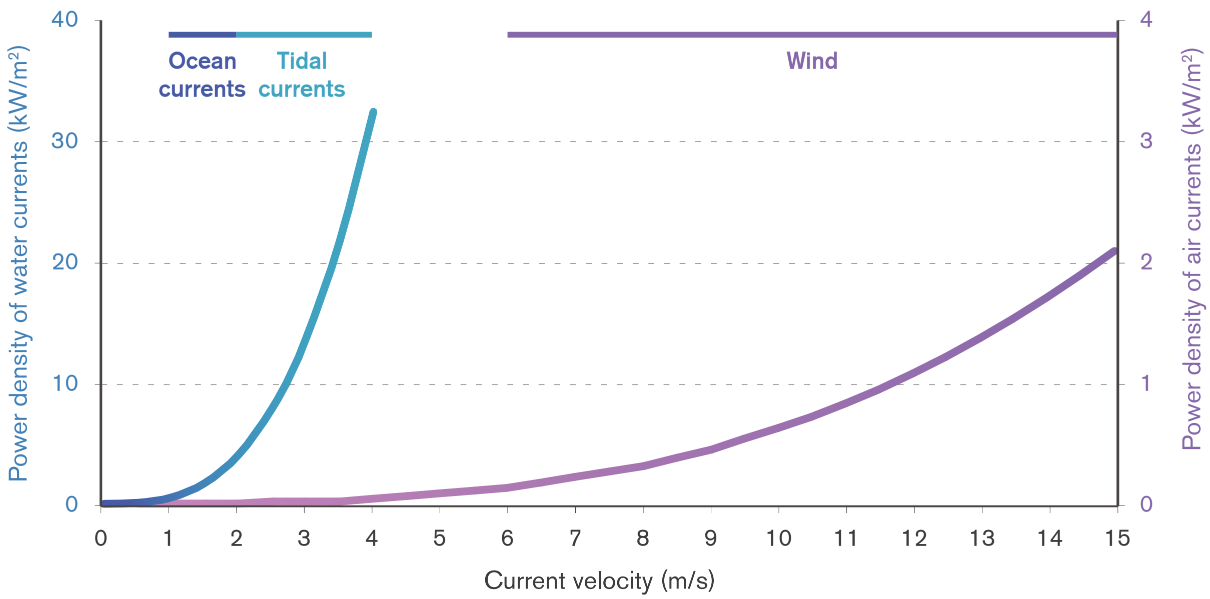

Figure 3.2 Power densities of currents of water and air as a function of current velocity. The power density is proportional to the density of the fluid and the cube of the current velocity (see also Box 4.1). The density of water is almost a thousand times larger than the density of air. Observe that the area in the figure is not the land area discussed in the text but the cross section area of the current.

Hydro power is currently by far the most common source of renewable power and relies ultimately on the solar energy that evaporates water from land and oceans. While almost a fourth of the solar energy influx to Earth is used in the water cycle, only a small fraction can be utilised as hydropower. A large share of the precipitation falls on the oceans, and of the annual precipitation on land of about 120 000 km^3 most is absorbed by soil or vegetation. About 40% remains as runoff water. When accounting for geographical variations in precipitation and altitude, the runoff water provides a physical potential corresponding to some 40 000-60 000 TWh/yr (to pick one number we use 50 000 TWh/yr in Table 3.2).[21]

The conversion efficiency of hydro power plants can exceed 90%, but several site specific factors limit exploitation. Hence, the technical potential has been estimated at 16 000 TWh/yr (Table 3.2). Hydro power is a mature technology and no technological breakthroughs with significant changes of the technical potential can be expected. Nonetheless, advances are being made within small-scale hydropower schemes, indicating that the access to the power source can spread. The global socio-economic potential of hydro power has been estimated at 8000 TWh/yr (Table 3.2).[22] However, this potential is dependent on a multitude of factors that vary in time and are difficult to predict. For instance, costs are influenced by the consideration of environmental impacts, the value of alternative land-use and other sectors' demand for the freshwater resource (Chapter 6). Rivers suitable for hydro power often cross national borders, thus being a source of political conflict. In 2012, 3600 TWh/yr or almost half of the socio-economic potential was utilised (Table 3.2).

Rivers also carry another potential power source. When rivers return freshwater to the salt oceans, the difference in salinity, i.e. the osmotic pressure gradient, can be utilised to generate power. Based on the total runoff water and the power that theoretically can be extracted a physical potential of 30 000 TWh/yr has been estimated. The technical potential has been estimated at 1600-1700 TWh/yr.[23] Continued development of membrane technology will improve the economics. Since osmotic power plants, in contrast to hydropower, need to be situated close to the mouth of the river, where many societal activities are located, we halve the ratio between technical and socio-economic potential used for hydropower to calculate a socio-economic potential of 400 TWh/yr (Table 3.2).

The total transfer of energy from winds to ocean waves is estimated at 500 000 TWh/yr (0.17 W/m^2 of ocean).[24] The physical potential in waves reaching the coastlines has been estimated at 32 000 TWh/yr, with a reduction to 26 000 TWh/yr when areas with very low wave power intensity or ice cover are excluded.[25]

21 Rogner, H.-H. et al. (2012). Energy Resources and Potentials, Chapter 7 in *Global Energy Assessment - Toward a Sustainable Future*, Cambridge, UK and New York, NY, USA and Laxenburg, Austria:Cambridge University Press and the International Institute for Applied Systems Analysis.; Hermann, W. A. (2006) Quantifying global exergy resources. *Energy* 31(12):1685-1702.

22 Rogner, H.-H. et al. (2012).

23 Rogner, H.-H. et al. (2012). Energy Resources and Potentials, Chapter 7 in *Global Energy Assessment - Toward a Sustainable Future*, Cambridge, UK and New York, NY, USA and Laxenburg, Austria:Cambridge University Press and the International Institute for Applied Systems Analysis.; Skilhagen, S.E. et al. (2008). Osmotic power – power production based on the osmotic pressure difference between waters with varying salt gradients. *Desalination*, 220(1-3):476-482.

24 Hermann, W. A. (2006) Quantifying global exergy resources. *Energy* 31(12):1685-1702.

25 Mörk et al (2010). Assessing the Global Wave Energy Potential, ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering, 3:447-454, (Paper No. OMAE2010-20473), Shanghai, China, Jun. 6–11.
A slightly lower physical potential of 18 000 TWh/yr is reached in Gunn, K. and Stock-Williams, C. (2012). Quantifying the global wave power resource. Renewable Energy 44:296-304.

Currently, there are no large arrays of wave power converters installed in the world. The few estimates of how much of the total wave energy that reach a cost-line that might be converted to electricity in arrays of devices indicate an overall conversion efficiency of 5-6%.[26] This gives a technical potential of about 2 000 TWh/yr. Since the conversion efficiency of individual devices is much higher, higher packing densities may raise this number. Nevertheless, the socio-economic potential is likely much smaller. The economics of extracting power from waves with low power intensity is unfavourable and in areas with higher intensities, devices need to be sensitive enough to efficiently utilise normal waves and at the same time be robust enough to withstand extreme waves. In addition, competition for the use of coastlines adds another limitation. Applying a similar argument as for solar and wind and taking into account that the wave power resource is geographically more concentrated, a socio-economic potential of 20% of the technical potential, or 400 TWh/yr, might be feasible (Table 3.2).

As Earth rotates through the gravitational fields of the sun and the moon, the surface is set in motion. A total of 32 000 TWh/yr of gravitational origin is dissipated in the Earth-moon-sun system (Table 3.1). Out of this, 22 000 TWh/yr generate tidal waves over the continental shelves constituting the ultimate physical potential of tidal power.[27] Tidal power systems utilise either the potential energy of the tidal wave or the kinetic energy of fast-flowing tides, mainly realisable in bays and straits, respectively (Chapter 4). The technical potential in the UK and Western Europe has been estimated at about 5% of the mechanical energy lost over the shelves which may be extrapolated to a global technical potential of 1000 TWh/yr.[28] Only a fraction of the resource is likely to be economically and environmentally viable. Applying the same reduction as for wave power would yield a socio-economic potential of 200 TWh/yr (Table 3.2).

Ocean currents are driven by solar heating, wind, gravity and the rotation of Earth. The mass transport of ocean currents is immense and predictable but the energy density is low compared to tidal currents due to lower velocities (Figure 3.2).[29] The total energy of ocean currents has been estimated at about 40 000 TWh/yr although this is yet to be verified (Table 3.2).[30] There are no estimates of the technical potential of arrays of ocean current power converters. The slow speed of the ocean currents and the depths of the oceans present an economic challenge. Both costs and environmental feasibility of this power source remain very uncertain and its socio-economic potential cannot be assessed (see Chapter 4 and 8).

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26 Beels, C. et al. (2011). A methodology for production and cost assessment of a farm of wave energy converters. *Renewable Energy* 36:3402-3416; Gunn, K. and Stock-Williams, C. (2012).

27 The remaining fraction dissipates in the deep oceans and as friction in the solid Earth (providing a small contribution to geothermal energy), see Hermann, W. A. (2006) Quantifying global exergy resources. *Energy* 31(12):1685-1702. Energy in tidal waves over shallow water has been estimated at around 9 000 TWh/yr in for example Charlier, R. H. and Justus, J. R. (1993) *Ocean energies*. Amsterdam, The Netherlands: Elsevier Science Publishers.

28 Hammons, T.J. (1993). Tidal power. *Proceedings of the IEEE,* 81:419-433; Blunden, L.S. and Bahaj, A.S., (2007). Tidal energy resource assessment for tidal stream generators. *Proceedings of the Institution of Mechanical Engineers*, *Part A: Journal of Power and Energy* , 221:137-146.

29 The Florida Current (part of the Gulf Stream) has been reported to encompass a physical potential of about 120 TWh/yr, Hanson et al (2010). Power from the Florida Current: A New Perspective on an Old Vision. *Bulletin of American Meteorological Societty,* 91:861–866. Other fast-flowing ocean currents include the Agulhas Current in South East Africa, the Kuroshio Current in East Asia, and the East Australian Current, see Lewis et al. (2011). *Ocean Energy.* In *Special Report on Renewable Energy Sources and Climate Change Mitigation.* 497-534. Cambridge, UK and New York, NY, USA: Cambridge University Press.

30 Charlier, R. H. and Justus, J. R. (1993) *Ocean energies*. Amsterdam, The Netherlands: Elsevier Science Publishers.

It is not only the water movements in waves and currents that make the oceans a potential source of renewable power. It is also possible to make use of the temperature difference between warm surface water and cold deep water (ocean thermal energy conversion – OTEC). In the tropics, the sea surface is heated by the solar energy to around 25 degrees, whereas the temperature at 1000 meters depth is around 4 degrees. The theoretical maximum conversion efficiency (the Carnot efficiency) depends on the temperature difference, see Figure 3.3. The technical efficiency is in general less than half of the theoretical. A temperature difference of around 20 degrees would therefore imply an energy conversion efficiency of about 3%.

A recent study based on an ocean general circulation model find a physical potential of 120 000 TWh/yr.[31] Beyond this point, additional plants will reduce the production of other plants due altered water temperatures (compare top down assessments of wind power above). A production on this scale would have major global environmental impacts. At a production of 60 000 TWh/yr it is estimated that global ocean currents and temperatures will be only marginally affected. However, the socio-economic potential is likely to be constrained by local environmental concerns (Chapter 8). In addition, OTEC plants need to be quite close to the demand, to reduce the need for long distance cables in the oceans, and will still require a depth of 1000 meters.[32] The main economic potential is perceived to be in small islands in the Pacific that today rely on expensive energy import. Due to the very large uncertainties involved, we here refrain from trying to estimate technical and socio-economic potentials.

GEOTHERMAL POWER

Larger natural heat gradients than those found in the ocean are accessible for energy harvesting. The heat flow from the interior of the Earth due to radioactive decay (66%) and the slow cooling of the Earth (33%) creates a potential to extract geothermal energy.

The total heat flux through the surface of Earth crust is around 400 000 TWh/yr (Table 3.1), whereof 90 000 TWh/yr through terrestrial surfaces.[33] How much of this that theoretically could be converted to electricity depends on the temperature difference that can be utilised (Figure 3.3). In one assessment the difference between the temperature at the Earth's surface and the temperature of about 800 ˚C at the interface between the crust and the mantle was taken as a basis for estimating a theoretical efficiency of 70%. This would result in a theoretical potential of about 60 000 TWh/yr below the continents (Table 3.2).[34] None of these figures include the potential of 'mining' heat from dry rock. The heat content of the earth crust is in the order of 100 000 times larger than the annual heat flow through the crust. We are not aware of any assessment of the potential and effects of large scale extraction of the slowly replenished heat in dry rock.[35]

31 Rajagopalan, K. and Nihous, G.C. (2013). Estimates of global Ocean Thermal Energy Conversion (OTEC) resources using an ocean general circulation model. *Renewable Energy,* 50:532-540.

32 On site hydrogen production via electrolysis has been suggested as a means to circumvent limitations related to long distance cables.

33 Stefanson, V. (2005). World Geothermal Assessment, *Proceedings World Geothermal Congress,* Antalya, Turkey, Apr. 24-29.

34 Hermann, W. A. (2006). Quantifying global exergy resources, *Energy* 31(12):1685–1702.

35 Mining of stored heat that is not replenished is by definition not renewable. However, extraction could in principle shift the equilibrium and affect the cooling rate of the Earth, and thereby the rate at which the heat is replenished.

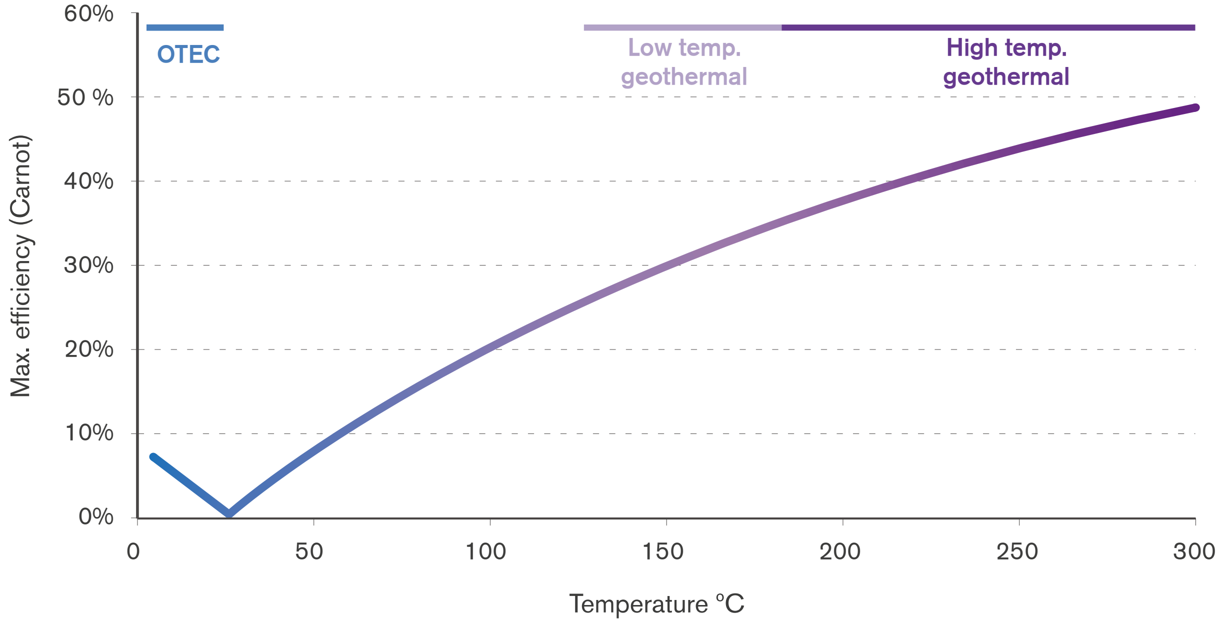

Figure 3.3 Theoretical maximum conversion efficiencies to electricity for different temperature differences (the Carnot efficiency).

Today, geothermal energy is harnessed in specific geological settings utilising geothermal fluids with temperatures of about 120-300°C (Figure 3.3). Based on a relation between the occurrences of volcanoes and identified geothermal resources a global technical potential has been estimated at about 2000 TWh/yr. This could be reduced to 400 TWh/yr with pessimistic assumptions and increased to 10 000 - 20 000 TWh/yr with optimistic assumptions.[36] A country by country estimate found a technical potential of 300 TWh/yr with the technology available in 1999 and 1000 TWh/yr with improved technology. The latter number was taken as an economic potential (until 2050) in the Global Energy Assessment report. [37] Where hydrothermal resources are available the environmental impact is likely to be modest, hence we here apply this number as the socio-economic potential (Table 3.2).

GEOGRAPHICAL AND TEMPORAL DISTRIBUTION

As is evident from Figure 3.1, the geographical variability of the solar power potential is relatively small. The sunnier regions of the world get only about twice as much irradiation as the less sunny regions. While the distribution of wind power is not as even, sufficient wind power resources are available over large areas of the world.

36 Stefanson, V. (2005). World Geothermal Assessment, *Proceedings World Geothermal Congress,* Antalya, Turkey, Apr. 24-29.
37 Gawell, K. et al. (1999). *Preliminary report: Geothermal energy, the potential for clean power from the earth*, Washington, USA: Geothermal energy association. Rogner, H.-H. et al. (2012). Energy Resources and Potentials, Chapter 7 in *Global Energy Assessment - Toward a Sustainable Future*, Cambridge, UK and New York, NY, USA and Laxenburg, Austria:Cambridge University Press and the International Institute for Applied Systems Analysis.).

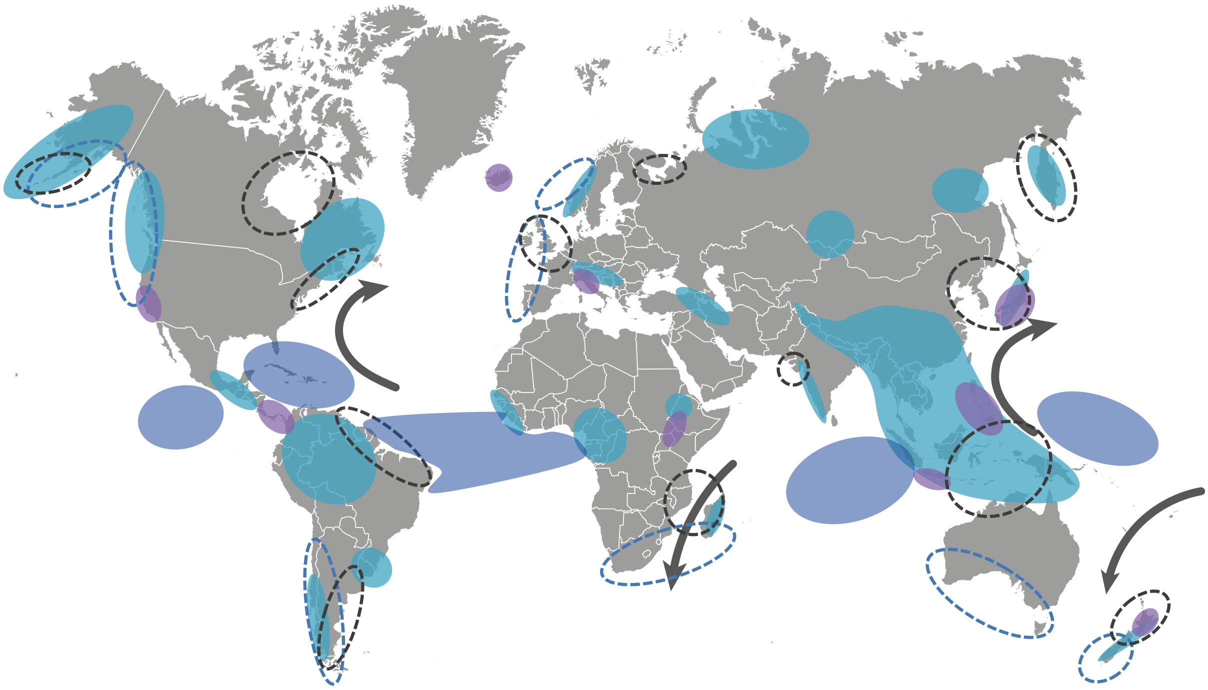

Figure 3.4 Global renewable power hotspots (solar and wind excluded): small-scale and large-scale hydropower (teal), geothermal energy (purple), ocean thermal energy (blue), tidal power (black broken line), wave power (blue broken line) and ocean current power (gray arrows).

In contrast, the geographical concentration of the geothermal resource and of the water power resources is very large. Zones where hot spots exist are depicted in Figure 3.4. While the OTEC resource is in principle is more wide spread over tropical seas, any socio-economic potential will likely be geographically concentrated as well. The implication of this is that even if the global potential of all these resources is relatively small they can all be of local importance.[38] One can view the water (and wind) energy resources ultimately derived from solar energy, as local concentrations of the solar energy influx, with a potential to deliver power at low cost with specific characteristics where available (compare the energy densities in Figure 3.1 and 3.2).

The concentration to specific locations implies that local environmental and social factors will be critical determinants of how much of the technical potentials that will be utilised in the future (Chapter 6 and 8). We can also note that very high percentage of the technical potential of hydro power is already utilised in some countries, e.g. about 70% in Sweden and Norway and almost 90% in Switzerland.

The solar energy inflow varies on different timescales. The night-and-day variation is present everywhere. The seasonal variation is prominent closer to the poles, but hardly noticeable in the sunnier regions closer to the equator. While these variations are fully predictable there is also whether dependent variation on shorter time scales. The wind resource is generally less predictable (see also Chapter 4, 9 and 11).

38 Maps of wave, ocean current and tidal energy intensities are provided in Lewis et al. (2011). *Ocean Energy*. In *Special Report on Renewable Energy Sources and Climate Change Mitigation*. 497-534. Cambridge, UK and New York, NY, USA: Cambridge University Press..

Hydropower with dams is very flexible and can deliver power on demand (see also Chapter 11). Geothermal power and OTEC can deliver a constant flow of electricity. Ocean current, run-of-river hydro and osmotic power will likely have a fairly constant output with some variations over seasons. Tidal power varies with the tidal cycle but is highly predictable. Wave power is variable and less predictable. However, it is less variable and more predicable than wind and some areas have a fairly constant inflow of ocean swell.

CONCLUSION

The answer to the question posed in the chapter heading is clearly yes. While the renewable energy flows currently supply only a fraction of global energy and electricity demand, the technical potential is two orders of magnitude larger than current and anticipated demand. Our attempt to estimate a realistic socio-economic potential indicates that an energy system that can be sustained as long as the sun shines can be several times larger than the current global energy system. It is also evident that a complete replacement of fossil fuels and nuclear energy will fundamentally rely on the direct conversion of solar energy, with wind and hydro power as important complements. While, all the other renewable energy flow resources, most likely, always will remain marginal at the global level, they can indeed be of great local importance due to geographical concentration. Due to differing characteristics in terms of temporal variability and control they may also serve to balance supply and demand of electrical power.