EN EntroNova

Report EN-R2021:01 rev3

ENERGY AND POLITICS IN THE WAKE OF THE CLIMATE DEBATE

Per Fahlén
prof. em. Energy & Environment

Resele
July 2021

EntroNova
ÖSTERRÅ 327, SE-880 31 RESELE, SWEDEN

ENERGY OCH POLITICS IN THE WAKE OF THE CLIMATE DEBATE

Per Fahlén

Report EN-R2021:01 rev3
EntroNova
Österrå 327
SE-880 31 RESELE
Sweden

Telephone +46 (0)722-25 11 42
e-mail per.fahlen@telia.com

R2021-01-Energy systems-Klimatkarusellen-Rev4
2021-10-21

Energy och politics in the wake of the climate debate

PER FAHLÉN

Entro Nova

Abstract

This report provides input to a textbook on the infected debate regarding climate change and the science behind it. The book, “The climate carousel”, is authored and edited by Elsa Widding.

Fear of the consequences of a climate change possibly caused by emissions of carbon dioxide has fuelled a rapid change in energy policies in many countries. It has triggered a massive expansion of so called renewable sources of energy branded as “climate smart”, “green”, “renewable”, “sustainable” etc. This input discusses the hard facts behind these buzzwords and in particular how nuclear and wind power compare, the hottest contenders in low-carbon electricity generation.

Keywords: climate smart, cost, economy, electricity, energy, environment, environmentally friendly, fossil free, hydro power, nuclear power, solar, sustainable, wind power.

Energi och politik I klimatdebattens spår

PER FAHLÉN

Entro Nova

Sammanfattning

Denna rapport är ett bidrag till en bok om den infekterade debatten om klimatförändring och den bakomliggande vetenskapen. Boken, ”Klimatkarusellen”, författas och editeras av Elsa Widding.

Rädsla för konsekvenserna av en klimatförändring, som möjligen orsakas av koldioxidutsläpp, har drivit på en snabb förändring av energipolitiken i många länder. Den har satt igång en enorm utbyggnad av så kallade förnybara energikällor, vilka marknadsförs med termer som ”klimatsmart”, ”grön”, ”förnybar”, ”hållbar” etc. Detta inlägg diskuterar vilka hårda fakta som finns bakom dessa slagord och i synnerhet jämförs de båda koldioxidsnåla alternativen kärnkraft och vindkraft.

Nyckelord: ekonomi, elektricitet, energi, fossilfri, hållbar, klimatsmart, kostnad, kärnkraft, miljö, miljövänlig, sol, vattenkraft, vindkraft.

.

Contents

Energy politics in the wake of the climate debate

Energy and politics in the wake of the climate debate

In the wake of the climate debate, politics have attained a decisive influence on the choice of energy sources, technologies for energy conversion and the attitude to environmental issues. Of course, politics have always been present when it comes to the energy supply of a nation as it is an item of national importance for development, prosperity and security. Some countries have subsidized a national coal-mining industry, others have made large public investments in e.g. hydro power or the extraction of oil and gas.

Now, however, we have entered a new era, to some extent less national and more global, where the focus is on mitigating perceived causes of climate change and creating a more sustainable supply of energy. This situation also changes major political and commercial influences on the preferred type of energy supply from a purely local/national level to an international level. Furthermore, the influence of global environmental activist groups such as World Wildlife Fund and Greenpeace has become increasingly more important. The efforts to minimize emissions of carbon dioxide and the use on non-sustainable resources have fuelled a surge of investment in "renewable" sources of energy, mainly solar and wind power.

This section will briefly dwell on some general issues regarding energy concepts, energy systems and the importance of knowing the purpose and the consequences of operating these systems. As much of the interest now lies on electrification of many types of operations and services, most of the discussion will concern alternative systems for generation of electricity, their environmental consequences and cost plus some comments on safety and health issues. The focus is on large-scale electric supply systems and I realise that conditions for renewable energy may be more favourable in specific local circumstances. The purpose of this input is to show that:

- There is more to the issue of energy supply than the number of kWh
- Consumer cost of alternatives must be evaluated at the system level, including all external costs such as distribution, stabilization, balance power etc.
- Simple labels such as "green", "free", "climate smart", "renewable", "sustainable" etc. do not provide factual information on the environmental consequences of energy supply.
- Issues of environment, safety, health etc. have local as well global repercussions.
- Social aspects such as quality of life, property values, health etc. are not covered in economic evaluations of alternatives of energy supply.

1 Energy systems

Energy systems are built for a purpose and the primary purpose may be of many different kinds (see 1.2) but it is never to be "climate smart", "sustainable" etc. Secondary, environmental requirements should not take priority over the primary purpose. Hence it is important to clarify the primary, functional purpose, to express secondary environmental requirements in explicit, preferably quantifiable, terms and to analyze the available opportunities of energy supply and the necessary technical systems for conversion and distribution. As often, the devil hides in the details and to understand the challenges it is necessary to have a basic grasp of issues concerning energy supply and demand. Figure 1.1 provides examples of practical considerations in the selection of technical systems that require an energy supply.

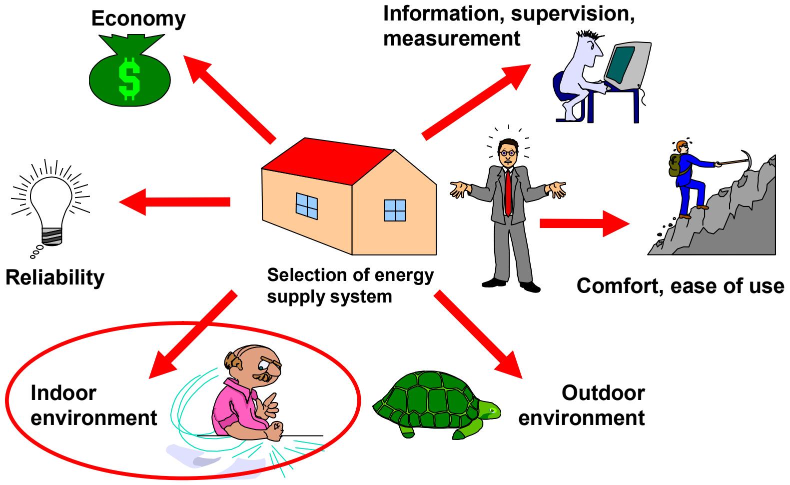


Figure 1.1 There are many considerations[20] in selecting a suitable technical system and its supply of energy. “Green” is not a sufficient answer.

1.1 Energy alternatives

In the discussion of alternative sources of energy a number of trendy concepts have been introduced such as ”green”, ”renewable”, ”sustainable”, ”climate smart” etc. These concepts, however, are usually undefined and often lack a scientific foundation. They tend to obfuscate a factual discussion and cannot be used for commissioning of technical energy-supply systems.

The energy balance of the earth is based on nuclear power; solar irradiation from nuclear fusion in the sun and geothermal energy from nuclear fission inside the earth. Whether you call these energy flows renewable or not is to a large extent a subjective position. Renewable energy is an oxymoron; it is a fundamental postulate in physics that energy cannot be created or consumed, only converted from one form to another. Instead of the value-based terms “renewables” and “non-renewables” it is better to use the main functional categories of **stored energy** and **flowing energy**. These terms categorize sources of energy according to whether they are **dispatchable**, i.e. under the control of the user, or **non-dispatchable**, i.e. at the mercy of uncontrollable factors such as the weather.

1.1.1 Stored energy

Stored energy in this context is internal energy that is bound to materia in terms of chemical bonds or atomic nuclei. Such forms of energy are available as **fuels**. Fuels may be converted to heat in processes that are controlled by the power producer. Also, the heat may be subsequently converted to mechanical energy, which can drive a generator or the propulsion system of e.g. a vehicle. Irrespective of its origin, stored energy tends to be classified as non-renewable or conditionally renewable, bio-energy being a notable exception (see 1.1.3 and 5.2).

1.1.2 Flowing energy

Flowing energy is kinetic (mechanical) energy, radiation or heat that originates from sources outside the control of the power supplier. They are usually weather dependent, e.g. hydro power, wind power and solar power, but may also be independent of weather such as geothermal energy. **Flowing energy** sources are characterized by the fact that energy flows independently of whether it is being used in a power supply system or not. Of course, such energy may be converted and subsequently stored as e.g. potential mechanical or chemical energy (see 0).

Sources of flowing mechanical energy are driven by solar irradiation and hence by nuclear fusion in the sun. This, of course, also applies to direct use of solar radiation. As already noted, geothermal energy originates from nuclear fission in the earth. Flowing energy is generally promoted as “renewable”, “free” energy etc.; the implication being that “there is nothing better than a free lunch”! More careful consideration (see 4), however, will show the relevance of the old saying that “there is no such thing as a free lunch”.

1.1.3 Political taxonomy of energy sources

As already indicated above, a subjective nomenclature in the discussion of energy alternatives is of little use in the analysis and takes the focus away from the desired functionality of a system and the actual consequences of its operation. In the aftermath of the nuclear disasters at Harrisburg (1979) and Chernobyl (1986) there was a growing concern regarding the safety and environmental aspects of nuclear power. Phasing out of the reactors and introducing “green” alternatives became a growing movement and thus of political interest. In Sweden, for instance, a referendum in 1980 decided that all 12 nuclear reactors should be successively decommissioned. Politicians more or less provided the outcome in advance as voters had three “no” alternatives but no “yes” alternative. The touted replacement was “green” energy, mainly wind and solar energy but also bio fuels. What the term “green” involved was not defined or explained to the voters.

Decades later, a sudden concern for the effects of a postulated global warming turned the focus to emissions of carbon dioxide and the importance of “climate smart” solutions. Still, however, the anti-nuclear position is a much stronger driving force in the current change of the energy supply system than is the concern for climate change. It is rather ironic that the Swedish concerted effort to phase out all fossil-fuelled power production in the 1970s, for reasons of security of supply (the oil crisis), also reduced the emissions of carbon dioxide drastically. These reactors are now being decommissioned and carbon dioxide emissions from electricity generation are on the rise (see 5.1).

Currently, the EU is developing an official European taxonomy[18] of energy sources. This political classification is at loggerheads with the national political classifications of e.g. Sweden and Finland. Suddenly, hydro power and biomass from forests are no longer considered as “sustainable” whereas conversion from coal to natural gas is conditionally “sustainable”. Obviously, the nature of these sources of energy has not changed, only the politically based labels are new. These labels have very significant repercussions for the economy of alternative sources of energy (see 4.4 on economic revenues).

1.1.4 Advertising and marketing

Vendors of equipment and energy supplying utilities often advertize their products and services as ”green”, ”renewable”, ”sustainable”, ”climate smart” etc. However, as already noted, these concepts are generally value-based and undefined and they are prone to misleading the customer in the choice of product. In many countries, this is contrary to the requirements of consumer legislation but it is often overlooked by responsible authorities due to the political pressure of “going green”. As an example, a number of electric utilities in Sweden were reported[24] to the Swedish Consumer Agency in 2016 for misleading advertisements incorporating the undefined concepts mentioned above. But the agency was instructed by government to support “renewables” and refused to act in accordance with the law on consumer protection. In 2020, however, after the agency had been reported to the judicial ombudsman, the agency is finally acting in accordance with the international regulations stipulated by the ICC advertising and marketing communications code[29] (ICC = International Chamber of Commerce).

The Swedish Consumer Agency now claims, exactly as pointed out in the report of 2016[19], that according to the rules of ICC ”green”, ”climate smart” etc. are vague and unspecified claims. The claims imply that a product or service has no or only a positive environmental impact. The buzz words may imply different things to different receivers of the message and the claims may give rise to many different interpretations. In order not to mislead the consumer the environmental claims must be both qualified and verified.

1.2 Energy demand and energy use

The choice of energy supply must be subordinate to the type of demand that needs to be satisfied! The purpose of a technical system that uses energy is not to use as little energy as possible or to cause a minimum of environmental impact; the system is commissioned to provide a specific service that there is a demand for in society. Of course, if the cost and consequences become too high then society may decide against it.

In the discussion of alternative solutions to cover a specific demand there is often a misconception of terminology. The distinction between demand, use and supply must be fully understood and that there is no such thing as “free” energy. For instance, the sun might be free in the sense that it is not paid for directly. But if it is to be used to cover e.g. a demand for sanitary hot water, then one has to pay for the equipment to convert insolation to heat. Furthermore, one must realize that this investment has not changed the demand for hot water, nor has it improved the efficiency of the hot water system per se.

Reducing purchased energy is not per se an improvement of efficiency (see also 1.3). Improved efficiency must reduce the use of energy while at the same time maintaining the quality of the service in question. It may be achieved e.g. by reducing heat losses, more efficient pumps, taps etc. Figure 1.2 illustrates some basic concepts and their relation in the case of the energy balance of a building.

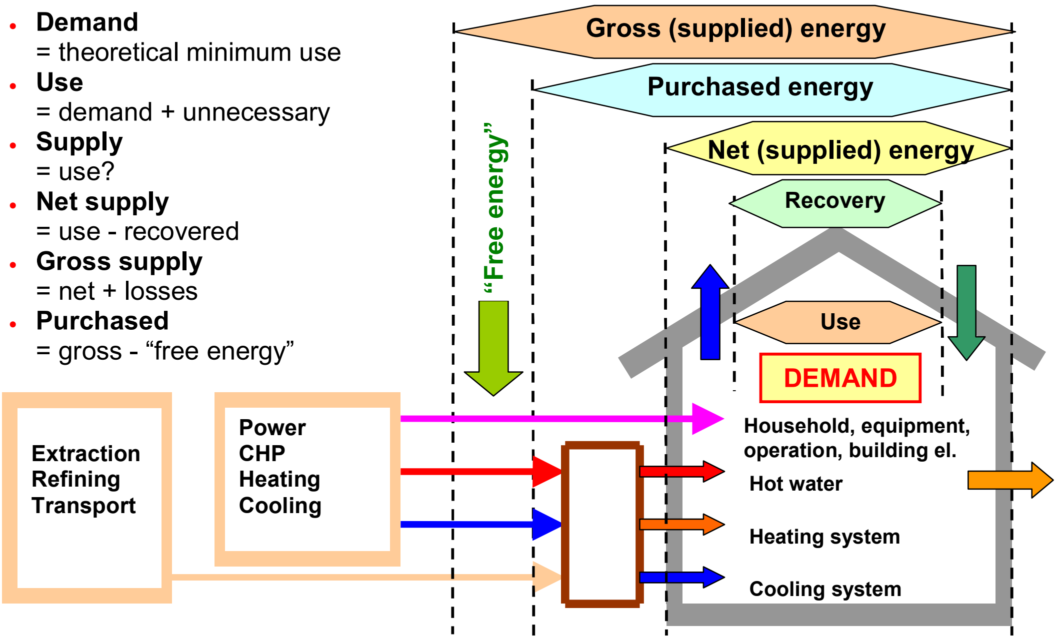


Figure 1.2 Energy balance of a building according to Fahlén[21]. Demand for electricity, hot water, heating and cooling. Note that energy use as well as purchased energy may be different from the demand.

1.2.1 Energy demand

Energy demand is an idealized concept that represents the energy demand of the actual service. For instance, in the case of hot water, how much hot water does one need for the purpose of personal hygiene, washing up etc.? What is the minimum temperature to manage this service? Demand is the energy input to an idealized system that can perfectly match the functional requirements.

1.2.2 Energy use and supply

Energy use typically exceeds the actual demand due to a mismatch between supply and demand as well as miscellaneous losses. Hence, a part of the supplied energy is unnecessary for the required function. There are, however, possibilities to reduce the energy purchased to cover the energy use. For instance, in a building one may recover part of the heat used for ventilating air flows or hot water. The required **net energy supply** then becomes the actual energy use minus the recovered energy. On the other hand, there are external losses, e.g. from efficiency losses in the supply system, so the required **gross energy supply** will be the net energy supply plus these losses.

1.2.3 Energy purchase

Finally, part of the gross energy supply may be covered by so called "free energy". This is energy that is not paid for on the utility bills. "Free energy" may be low temperature thermal energy that has been upgraded by a heat pump (see Figure 1.7), solar-thermal or solar-electric energy etc. The **purchased energy** then becomes the gross energy supply minus the "free energy".

This discussion demonstrates the difference between energy use that one pays for, i.e. purchased energy, and the use one does not pay for on the utility bill. However, one must realize that the free energy may not appear on the utility bill but it still has to be paid for in terms of investment for equipment such as heat pumps, solar collectors etc.

1.2.4 Examples

Improvement of efficiency can be achieved by one or a combination of measures such as:

1. **System change** (e.g. going from direct-acting electric heat to heat pump or district heating).
2. **Equipment change** (e.g. changing a heat pump to a more efficient unit).
3. **Component change** (e.g. changing pumps to more efficient units).

The various levels of energy demand, use and purchase as well as the possibilities of improving efficiency (see 1.3) may be illustrated by an example of an electrically heated Swedish home built in 1977.

Original use of energy: 25 MWh/annum for heating, hot water and household electricity.

New supply system[22]: Installation of a small ground-source heat pump reduced purchased energy to 16 MWh/annum while 9 MWh was “free” energy from the ground.

Improved supply system[22]: Heat recovery from ventilation exhaust air, a new design of an integrated heating and hot water storage tank plus a smart control system reduced purchased energy to 9 MWh/annum.

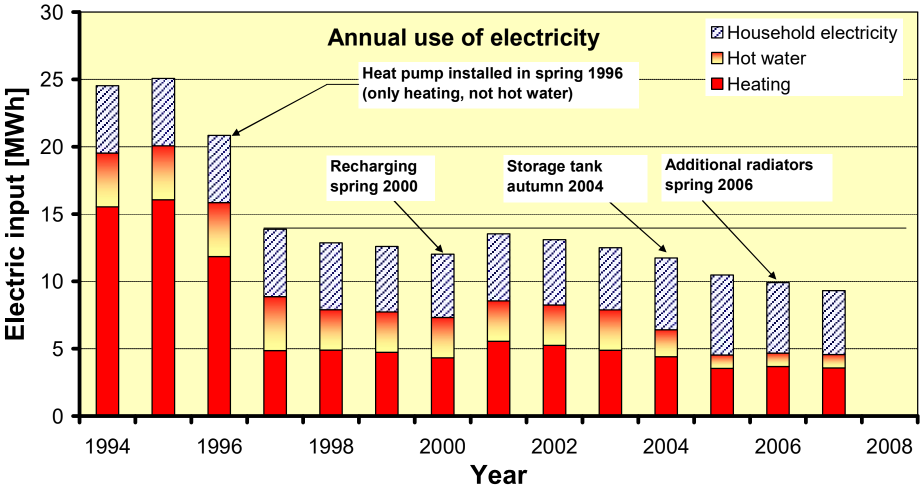


Figure 1.3: Measured values of electricity for heating, hot water and household purposes[22].

The heat pump seasonal Coefficient Of Performance (*COP*; see Figure 1.7), i.e. the ratio of thermal output to the required electric drive power input, was improved from 2.7 to 3.7 by means of the system improvements. But this result can be further improved by more efficient components in the heat pump and better load-matching.

Improved equipment: Research[23] has shown that the heat pump *COP* can be doubled by means of better load-matching by smart variable-capacity control and new electric-motor design.

More examples of improved equipment: The EU-directives on efficiency of white goods, lighting, electric motors etc. have significantly reduced the demand for energy in the respective sectors.

Conclusion: These examples show that large reductions of purchased energy, notably electric energy, are possible. These reductions are usually less expensive than building new supplies of e.g. solar or wind-based electric power. Reductions have the further benefit of not requiring increased grid capacity. On the contrary, reductions provide room for new capacity in the existing grid. Next we take a look at the fundamentals of the efficiency of equipment for the supply of energy.

1.3 Energy efficiency

The International Energy Agency, IEA, has pointed out that the most important field of action for future energy solutions concerns energy efficiency. Irrespective of the nature of the source of energy supply, just increasing the amount is not a sustainable solution. The bulk of future changes must involve improvement of efficiency. In this discussion, it is important to distinguish between improved efficiency and energy savings in general. Savings may be achieved simply by reducing the quality of a commodity, e.g. by providing less thermal comfort or limiting the amount or temperature of hot water. Improved efficiency, however, means less use of energy with retained quality of service.

Total efficiency will depend on the overall system design, the efficiency of supply equipment and the efficiency of user equipment.

1.3.1 Energy system aspects

The main types of demand call for supply and removal of heat (i.e. heating and cooling) and supply of electricity (power). The types of demand affect both the relation between power and energy and the relation between heat and power. Note that there will be significant losses along the path from supply to actual use in conversion, distribution and use, see Figure 1.4.

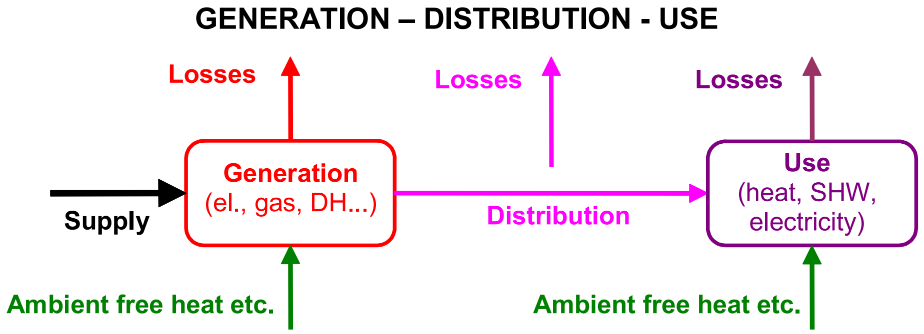


Figure 1.4 Losses along the path from supply to use depend on system design and the efficiency of equipment[20].

As the generation of electricity is often closely linked to a conversion of the internal energy of fuels into heat and subsequently into electric power there are possibilities of making use of both the heat and the power in an integrated system, polygeneration (see Figure 1.5 plus the thermodynamic basics in 1.3.2). Systems based on polygeneration may be building-specific, block-sized or large-scale community systems such as district heating and district cooling. They may also include exchange of heat between areas of surplus and deficit.

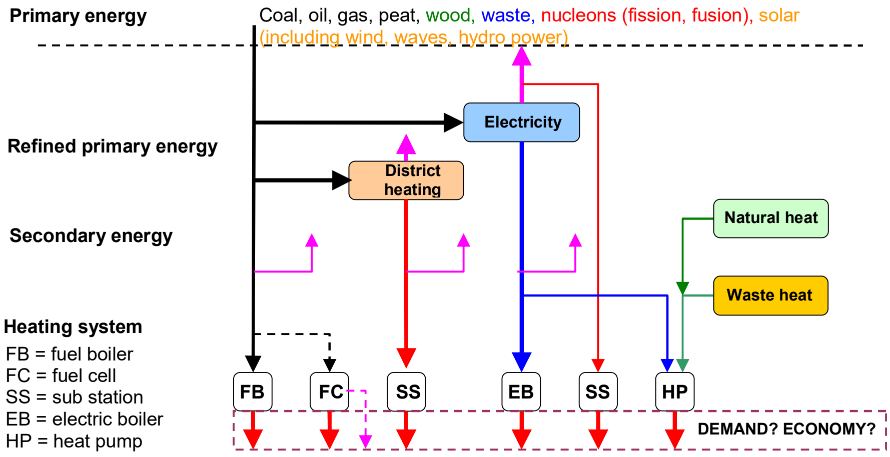
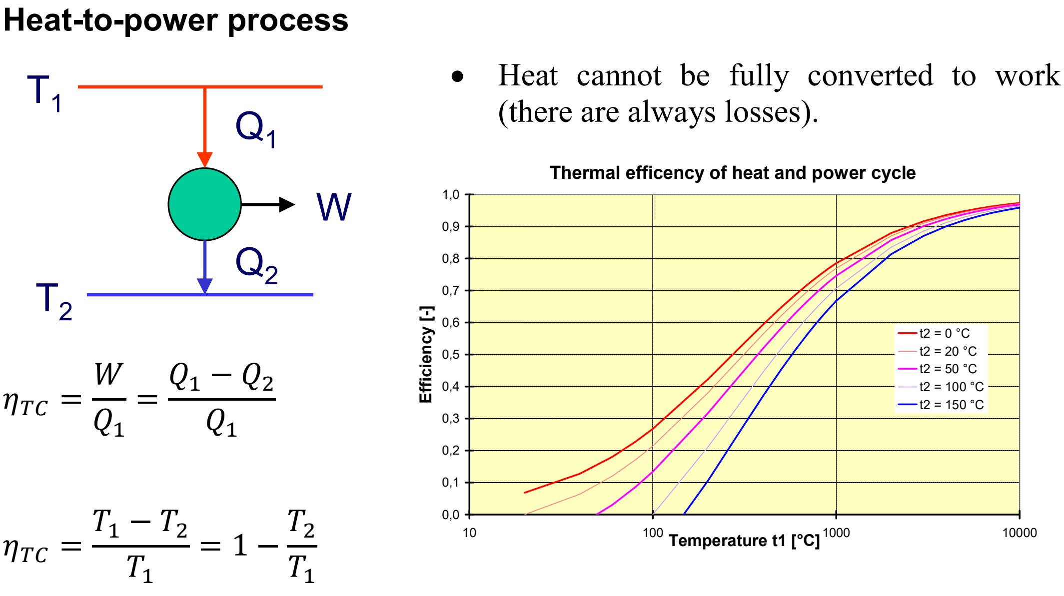


Figure 1.5 Possibilities of polygeneration[20].

1.3.2 Relations between heat and work

The subject of thermodynamics looks at the relation between heat and work. In particular, the problem of losses is much studied regarding where and how they appear in the process. This is at the heart of creating more efficient equipment for the supply of electric power and heat.

The power process: Conversion of heat to mechanical power. Most of the electric power is currently produced in thermal power plants. According to fundamental thermodynamics heat cannot be fully converted to work; there will always be losses. An ideal power process, without losses, is known as the Carnot process with an ideal thermal efficiency η_{TC} (see Figure 1.6).



Heat-to-power process

- Heat cannot be fully converted to work (there are always losses).

$$\eta_{TC} = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$$

$$\eta_{TC} = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}$$

Figure 1.6 The influence[20] of temperature on the efficiency of the conversion of heat to mechanical work for the ideal Carnot cycle.

Figure 1.6 illustrates how a supply of high-temperature heat, Q_1, is partly converted to mechanical work, W, e.g. in a turbine. As already stated, all heat cannot be converted to work and the waste heat, Q_2, is disposed of to the ambience or to some other heat sink. In polygeneration this waste heat is partly used for heating applications or for heat driven cooling equipment. Q_1 is typically supplied from a gas burner, a bio-fuelled boiler, a nuclear reactor or some other high-temperature source.

There are two major alternative uses of the heat to power process:

- **The power process:** The high temperature heat Q_1 is converted to work W (electricity) and the rest of the heat Q_2 is wasted.
- **The combined heat and power (CHP) process:** The high temperature heat Q_1 is converted to work W (electricity) and a part of the heat Q_2 is used for heating purposes.

As indicated in Figure 1.6, the temperatures are extremely important for the efficiency of the power process. This efficiency, η_T, is defined as the output of useful work or electricity divided by the input of thermal energy. The thermal efficiency of the ideal Carnot cycle, η_{TC}, comes closer to 1 with increasing high temperature input T_1 (absolute temperature in kelvin) and decreasing low temperature output T_2. This is the reason why bio-fuelled and nuclear plants do not have the same high power efficiency as e.g. a gas power station. The larger the fraction of heat input that becomes waste heat, the more important it is to find a use for this waste heat. A typical application is district heating but in such an application one must decide on which use that takes priority. Does the plant deliver waste heat from an electric power production or does it provide a bonus electric output from a heating duty?

In Sweden, the original plans were to build nuclear power as combined heat and power plants but parliament later passed a law to stop this (in order to simplify a move to leave nuclear power altogether). In the case of bio fuel or waste incineration, the efficiency is so low that typically the plants may be considered as district-heating plants with electricity as a by-product.

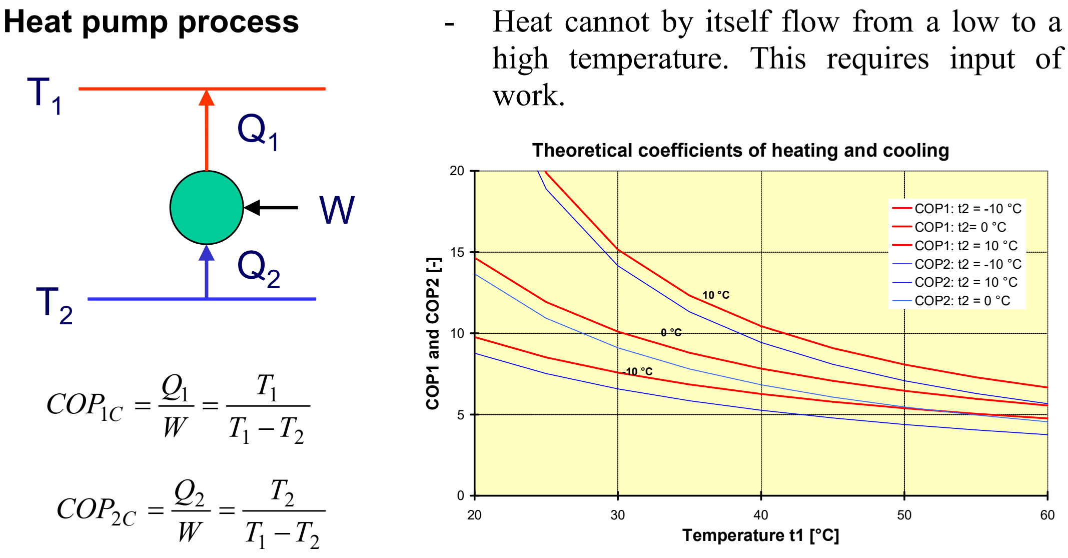
As an example, with a high temperature of 1000 °C and a low temperature of 100 °C the Carnot efficiency becomes 0.71. Reducing the high temperature to 300 °C decreases the efficiency to 0.35. Remember that a real process will always be less efficient than the ideal Carnot process.

The heat pump process: Conversion of low-temperature heat to high-temperature heat by means of mechanical power. Ambient sources of heat usually have too low a temperature to be used directly. For instance, an ice berg may contain much more heat than a pot of boiling water but it still cannot provide a decent cup of coffee. So the temperature of heat is important and the technology to efficiently change temperature of a medium is the heat pump process.

According to fundamental thermodynamics heat cannot by itself flow from a low to a high temperature; this requires input of work. Just as there is an ideal power process there is also an ideal heat pump process, which is known as the Carnot heat pump process. The actual performance of a heat pump is characterized by its coefficient of performance for heating, COP_1, or its coefficient of performance for cooling, COP_2. As indicated in Figure 1.7, the higher the COP the larger the amount of heat a given input of work can move. Note that COP is not an efficiency, it is a goodness number (efficiencies by definition are always less than or equal to 1). Figure 1.7 also indicates that the heat pump is a rather unique contraption as it provides both heating and cooling at the same time (ample opportunities for polygeneration).

The heat pump cycle, in a way, is the reverse of the power cycle. Instead of achieving an output of work by converting a flow of heat from a high to a low temperature, the heat pump, by means of an input of work, provides a heat flow from a low to a high temperature. From the definitions in Figure 1.7 it is obvious that the temperature difference between the high and the low level is extremely important. For typical applications, COP_1 will increase by 2-3 % per °C of reduced difference. For instance, if the supply temperature of an upgraded heating system can be reduced from 55 °C to 45 °C the COP of an existing heat pump may be increased by 20-30 %. This efficiency measure thus reduces the purchased electric energy by a similar amount.

As a rapidly increasing share of heating and cooling applications is served by heat pumps, their efficiency and in particular the overall system efficiency is important for the electric-supply system. This applies to both power and energy supply. In China, for instance, the market for air-conditioning heat pumps expanded rapidly in the 1990s and a new coal-fired power station had to be commissioned monthly to keep up with market requirements.



Heat pump process

- Heat cannot by itself flow from a low to a high temperature. This requires input of work.

$$COP_{1C} = \frac{Q_1}{W} = \frac{T_1}{T_1 - T_2}$$

$$COP_{2C} = \frac{Q_2}{W} = \frac{T_2}{T_1 - T_2}$$

Figure 1.7 The influence[20] of temperature on the ideal Carnot coefficients of performance for heating (COP_{1C}) and cooling (COP_{2C}) for the ideal Carnot cycle.

1.3.3 Efficiency of equipment

Most industrialized countries have research programs aiming at improving efficiency. There are also various labelling systems to promote the use of more efficient equipment. For instance, EU has a number of efficiency directives, which include labelling, e.g. for lighting, white goods, pumps, fans and electric motors. Similarly the US Environmental Protection Agency has its Energy Star program etc.

Some decades ago, there was a general rule of thumb saying that 80 % of the energy use and the environmental consequences occurred during the operation of a technical system and 20 % derived from its production and decommissioning. In many areas, improved efficiencies have reversed these figures so that the bulk of energy use and environmental consequences occur during manufacture and disposal and not during operation. Hence, there is no point in prematurely exchanging a modern, efficient refrigerator for an even more efficient unit; most of the energy cost and environmental impact comes from the change, not from the operation. This also has a bearing on various alternatives of power supply. As will be pointed out in sections 4 and 5, manufacture and disposal cannot be neglected in the discussion of cost and sustainability as they are dominant factors for many of the viable future alternatives.

Load matching is an important factor for the efficiency at system level as well as at equipment level of supply and use. Fahlén has shown the important relation between the factors[21] of demand and load at system level as well as the possibilities of large improvements of efficiency of equipment[23]. The trend in the heat pump market is towards rising energy coverage. Higher electricity prices, the possibility of hourly tariffs and new power rates as well as new requirements in the building code affect the possibility of using electricity for peak heating (the standard alternative so far). Thus it comes natural to size all types of heat pump, ground-source systems in particular, as close to full coverage as possible by overrevving the compressor on the coldest days. However, irrespective of application Figure 1.8 shows the importance of adapted electric motors, drives and control when much of the operation is at part load. E.g. at 20 % load ($f = 0.2$) a good unit may be more than twice as efficient as a standard unit.

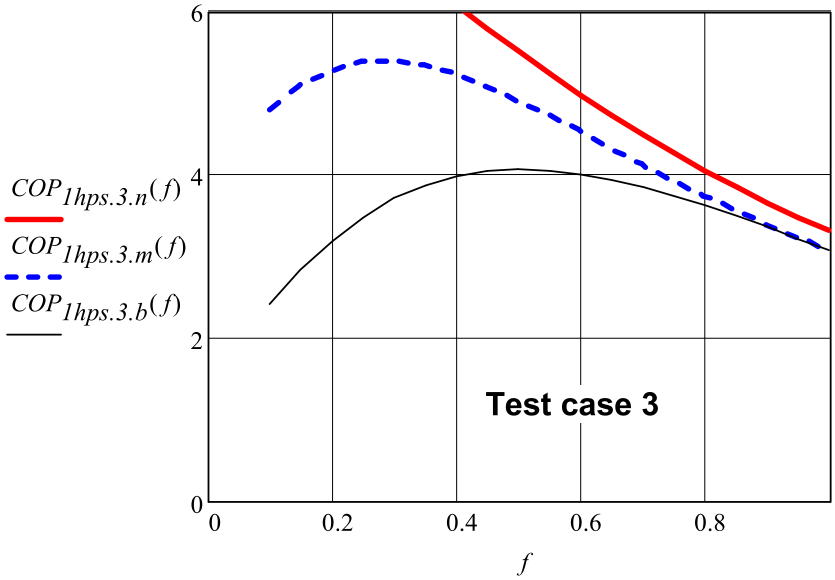


Figure 1.8 Coefficient of performance of a heat pump system (COP_{hps}) as function of the fractional capacity ($0 \le f \le 1$) for three levels of development. Evaporator and condenser fan powers vary in relation to the relative thermal capacity.

1.3.4 National use and supply of electricity in Sweden

To illustrate how electricity is used, an example from Sweden is given in Figure 1.9. The dominant sectors are housing/service and industry. Housing is the largest despite Sweden having a substantial electricity-intensive industrial production (steel works, paper and pulp etc.). It is noteworthy that the industrial sector is decreasing. This is largely due to the fact that industries such as paper and pulp are changing their processes and are now using waste products as fuels for in-house production of heat and power. Thus they often become net producers of electricity instead of large purchasers. Another interesting point from the diagram is the relatively large transmission loss. This is several times larger than the total amount of electricity that is used for transport (so far mainly for trains, trams and underground purposes but increasingly also for cars). As will be repeatedly pointed out in this contribution, the transmission losses will increase drastically in a system based largely on so called renewable energy.

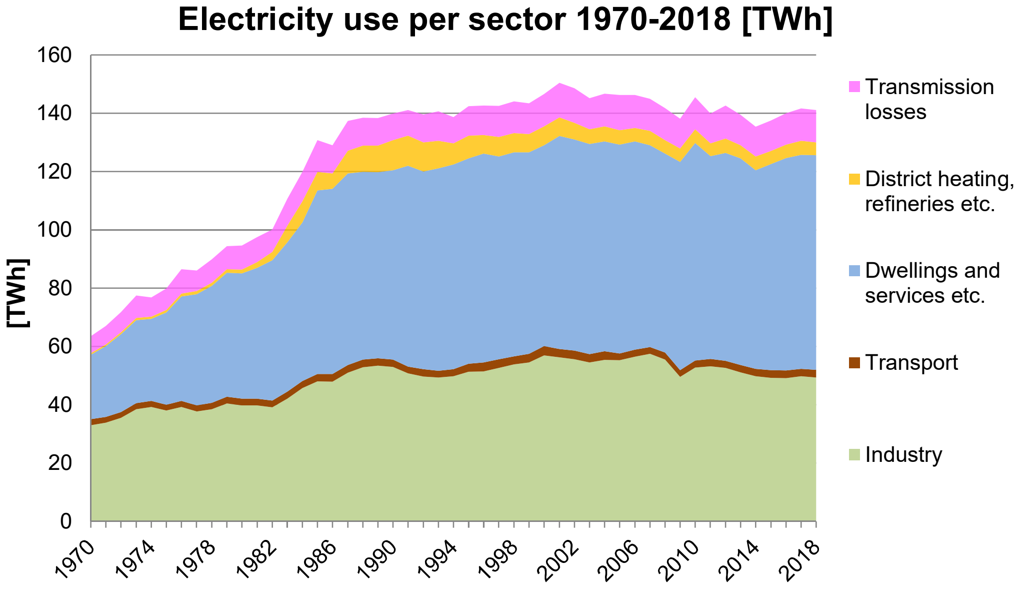


Figure 1.9 Use of electricity in Sweden by sectors[56].

Figure 1.10 shows the ongoing change in the origins of supply power. From 1970 until 2012 the generating capacity was almost totally based on low-carbon hydro and nuclear power; nuclear has the lowest value of carbon-dioxide emission per kWh and hydro the second lowest of currently viable alternatives of supply. Hence, replacing primarily nuclear power by wind and solar power will substantially increase the carbon-dioxide emissions from Swedish generation of electricity (not to mention all other negative impacts on the environment, see 5). Prior to the establishment of nuclear power, there were some other types of thermal power, mainly coal or oil. Solar power is still quite insignificant; it is not even visible in the diagram. Wind power, however, is rapidly expanding whereas nuclear power is being phased out due to political decisions.

Another interesting point from the comparison of Figure 1.9and Figure 1.10 is that use has diminished slightly despite a large growth in population, 25 % between 1970-2018. During this period a number of efficiency regulations have had effect. On the other hand, at the same time supply has gone up, mainly due to a large expansion of wind power. This power has so far had little use in Sweden and has had to be exported, often at a loss.

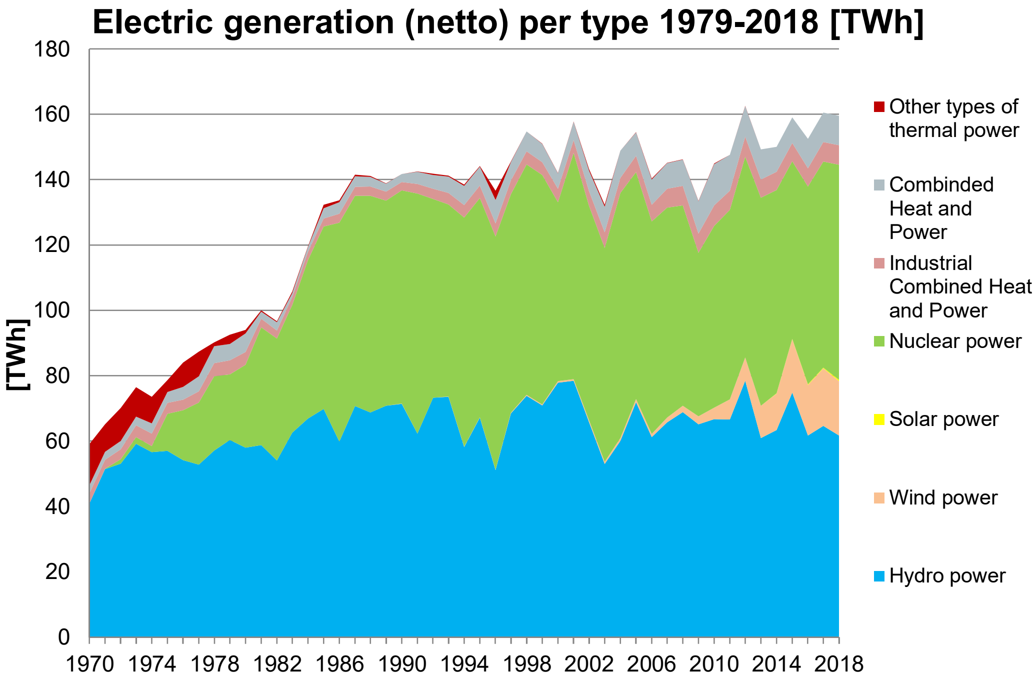


Figure 1.10 Electric power supply in Sweden by types of generation[56].

1.4 Factors in the planning of energy systems

Irrespective of the energy demanding service under consideration, a logical sequence of decision-making should be applied, e.g. regarding the supply of electricity:

- **Specification of all required primary functional aspects** of the service in question. E.g. for generation of electricity: Quality of supply (voltage, frequency, interference and harmonic emissions), security of supply (acceptable annual hours of downtime).
- **Identification and quantification of the demand** in terms of user patterns and ranges of variation. E.g. power and energy and its temporal and regional variations. Always look carefully at the *possibilities of reducing demand by improvements in efficiency*.
- **Specification of all required secondary functional aspects.** E.g. environmental aspects in terms of specified emissions, use of non-renewable materials, noise, land-use, wildlife etc. Also specify the methods used for LCI/LCA, noise criteria etc. including any priorities in the evaluation and ranking of results.
- **Specification of any external/societal aspects** such as effects on local businesses, landscape, tourism, leisure activities etc.
- **Identification of which system alternatives, i.e. total fulfilment of demand, are viable.** E.g. systems that cover baseload, peak load, distribution, stability and security of supply.

- **Specification of the economic criteria** to be used and comparison of all viable alternatives. The economic evaluation depends greatly on the handling of investment costs and the assumed lifespan of the system. External costs of the viable alternatives should be internalized to make a fair comparison.

Unfortunately, this is normally not the case, in particular not in the politically driven conversion to “green” technologies. The German “Energiewende” is a sad example costing German society up to a thousand milliard Euros. The overriding goal to phase out nuclear power has resulted in a functionally and environmentally degraded system with the highest cost of electricity in Europe. The environmental results are totally opposite of the “green” aims. Sweden, as well as many other countries, is going the same route. The estimated extra cost in Sweden is around 200 milliard Euros.

In conclusion of this section, it should be obvious that the path of energy efficiency is equally, if not more, important than the path of new supply alternatives.

2 Electrical supply systems

As already noticed, much of the politically driven changes of energy supply have focused on “green” electricity. Thus, it is important to have a basic understanding of the functional prerequisites of an electrical supply system. Each single moment the supply power must exactly match the demand in all parts of the electric system. The following section provides some aspects that must be covered to understand the discussion of the economics and environmental consequences of alternative technical solutions. There is more to electricity supply than the mere question of kilowatt-hours!

2.1 Functionality

The fundamental task of the electrical supply system is to provide to users of electricity **the right quality at the right time in the right location**. These general functional requirements need detailed specification. Some of the specifications derive from national legislation but the rapid integration of national grids, e.g. in Europe, requires system harmonization.

- **The right quality** may concern for instance:
  - stability of voltage and frequency, distortion
  - rotor angle deviation, rotary inertia, handling of reactive power
  - reliability of supply
  - capability of handling faults and restarts after a fault
  - possibility of island operation (independent operation of a part of the system)
- **The right time** implies that supply is available when the user so desires.
- **The right location**, finally, infers that there is a difference between the location of users and the location of generation facilities.

In Europe, *the EU Commission Regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators*[17] specifies the technical requirements of power generating facilities to be connected to the electric system. This applies irrespective of the type of generation. As we shall see, the fundamental properties of the two main alternatives, fuel-based and flowing-energy electric supplies, lead to quite different requirements for grid admission.

In most supply systems, there are dedicated units for the following functions:

- **Base power:** Units of high first cost but with low operating cost. They operate with more or less constant capacity during most of the year. Nuclear plants are typically base-power units although France uses nuclear power also as control power.
- **Control power**: Units that can easily follow changes in demand. Hydro power and gas turbines are well suited for such purposes.
- **Balance power**: Units that are required to rapidly compensate for changes in supply, e.g. to compensate for the variability of wind and sun. Typical examples are gas turbines, which have a low first cost but a high operating cost. Note that this task is more complex and much less predictable than the task of a control-power unit.
- **Backup power**: All systems need a backup for situations when there is a major fault. Fuel-based power plants have a high operational reliability but even so one must always plan for the possibility of a disruption of supply. For this purpose there are standards and directives for the required margin of backup. Weather-dependent sources such as wind and solar power are a different cup of tea. The intermittency of operation is unplannable and for practical purposes they suffer major faults occurring daily or weekly even though the equipment is not at fault.

Other important concepts for the system operation are:

- **Rotating mass**: A measure of the mechanical inertia of large synchronous generators that provides stability of operation.
- **Rotor angle stability**: The ability of interconnected synchronous machines running in the power system to remain in a state of synchronism.
- **Capacity factor**: Ratio between the mean annual power delivery and the nominal installed power. A value of 1, i.e. 100 %, means that the plant can operate at full power all year round.
- **Rationing**: Electricity systems with a large share of intermittent sources such as solar and wind often have legislation and/or commercial incentives to disconnect users at times of shortage. A common euphemism for rationing is "flexible demand" which involves some compensation for an impaired function.

2.1.1 Fuel-based electric supply

A fuel-based generating facility has a large energy storage inherently built into the fuel. Thus it is in full control of the energy source and can control supply in direct relation to demand. The operator controls the supply of fuel and hence the supply of power and these plants are therefore often called **dispatchable**.

Fossil-fuelled, bio-fuelled and nuclear power stations operate large, synchronous generators that provide large rotary inertia and hence an output with inherently stable voltage and frequency. These generators also have the capacity for producing and absorbing reactive power, which are important qualities for the stability of the grid. Such units can be directly connected to the grid with no requirements of additional equipment, see Figure 2.1. In some cases, e.g. large nuclear power plants, the high first cost motivates operation as pure baseload but fuel-based units may be designed to include also the control function.

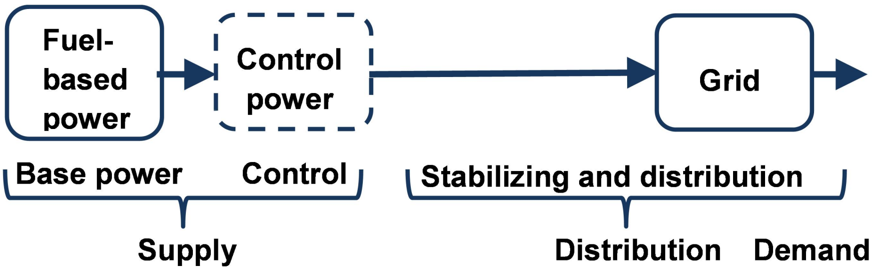


Figure 2.1 Example of a dispatchable, fuel-based power supply. Typical examples are fossil fuel, bio fuel and nuclear power plants.

Among low-carbon fuel-based technologies, nuclear power is the most viable option from a system perspective but also from environmental and economic aspects (see 4 and 5). Nuclear power can act as base power and control power, it can contribute to the handling of reactive power, stabilization of voltage and frequency, rotor angle stability etc. and it has a very high capacity factor. Furthermore, it provides ample opportunities for the application of combined heat and power.

2.1.2 Flowing-energy electric supply

As already noted, there are two kinds of flowing energy sources, weather-dependent and weather-independent sources. The former are also known as **VRE** = Variable Renewable Energy or **iRES** = intermittent Renewable Energy Source. Contrary to the case of a weather-independent generating facility, weather-dependent flowing-energy supplies cannot control supply in direct relation to demand and hence they are classified as **non-dispatchable**. The most prevalent VRE sources are wind power and photovoltaic solar cells. Currently, these types of supply are not synchronously connected to the grid and thus do not contribute to system stability.

VRE plants such as solar and wind power can neither provide base power, nor control power or balance power. Hence, to provide the same functionality as a fuel-based plant a VRE plant must be complemented with plants for balance power and/or storage, control power and stabilizing equipment (see Figure 2.2). This will add to the complexity and cost of the system.

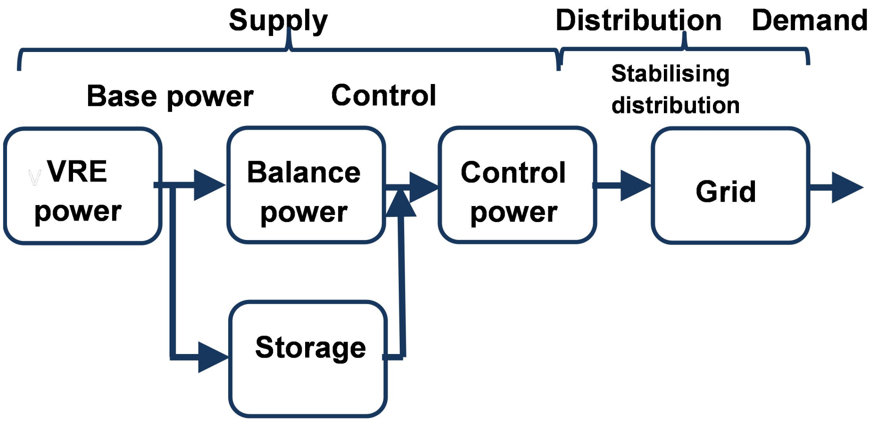


Figure 2.2 Example of a non-dispatchable, flowing energy power supply (VRE = Variable Renewable Energy). Typical examples are solar and wind power.

2.1.3 Some relevant supply alternatives

Low-carbon supply alternatives are fuel-based nuclear and bio power and flowing-energy by hydro, solar and wind power. As backup, balance or control power, natural gas is commonly used. For motivation of the comments below on economy and environment, see 4 and 5.

Nuclear power

- Dispatchable, i.e. weather-independent, supply.
- No shortage of fuel; uranium and thorium are abundantly available and have no current alternative use. Generation IV of reactor technology can operate on waste fuel. Hence countries with a previous fleet of reactors can satisfy their demand for electricity for 500-1000 years using only their current radioactive waste.
- Provides base power, control power and large energy storage in the reactor fuel. Can operate as a combined heat and power supply and provides system support in all important sectors.
- Lowest environmental impact and highest sustainability of all currently viable alternatives but also requires a long term perspective and stable regulations to be of economic interest. In most countries it is not a favoured alternative among politicians and hence not a favoured alternative in the taxonomy.

Bio power and waste incineration

- Dispatchable, i.e. weather-independent, supply.
- In most countries, bio fuel is a very limited and relatively expensive resource. Waste is currently plentiful and plant operators are actually paid to use waste as fuel. It is, however, at odds with sustainability issues and will probably not be politically acceptable in future taxonomies.
- Provides base power and intermediate energy storage in the plant fuel. Can operate as a combined heat and power supply and provides system support in all important sectors.

- A costly alternative which mostly relies on subsidies or, in the case of waste incineration, an abundance of waste that has a negative price.
- Questionable from environmental and sustainability points of view. Politically, its position is declining and it may not fare so well in upcoming taxonomies.

Hydro power

- Conditionally dispatchable; note that hydro power basically is a flowing-energy source with substantial variations between “wet” and “dry” years. It is made dispatchable by means of mechanical storage in dams. Available resources are already nearly fully exploited.
- Provides base power, control power and large energy storage in the dams. Provides system support in all important sectors.
- Little global environmental impact but has large local consequences. Requires a long term perspective and stable requirements to be of economic interest.
- Has been considered one of the major sustainable alternatives but is currently under critical scrutiny. May not be promoted in the upcoming European taxonomy.

Solar power

- Non-dispatchable; largely weather dependent.
- Provides neither base power nor control or balance power. Requires additional support systems on a major scale. Provides no system support in any important sector.
- Frequently touted as the environmental alternative of choice although its actual performance in terms of carbon dioxide emissions, use of renewable materials or sustainability is quite poor compared to nuclear or hydro power. Extremely expensive.

Wind power

- Non-dispatchable; largely weather dependent.
- Provides neither base power nor control or balance power. Requires additional support systems on a major scale. Provides no system support in any important sector.
- Currently the most expanding VRE alternative. It performs better than solar in terms of carbon dioxide, use of renewable materials or sustainability but is quite poor compared to nuclear or hydro power. It has very large local environmental consequences.

2.1.4 Energy storage

Flowing-energy sources will always need system support by means of balance power or storage to cover periods of low output. Storage is frequently promoted as the future solution for the low capacity factors and variability of wind and solar.

The purpose is to make VREs dispatchable at the system level. It must, however, be kept in mind that storage will always introduce substantial investment costs, loss of efficiency and considerable negative environmental consequences.

There are a few important aspects to consider before opting for storage and, if storage is the choice, what kind of storage is the most appropriate. One must for instance look at:

- Purpose: Minimizing cost, energy use, carbon foot print etc. or optimizing the supply network and minimizing power demand? There are many aspects and they are not all compatible; one must make a calculated decision.
- End-use: Is it thermal or electric energy?
- Location: Is the optimal location on the supply side or the demand side?
- Safety: Many types of battery impose a fire-and-health hazard that requires special measures.
- Space: Thermal storage requires space. Batteries need specially prepared and ventilated space.

Torcellini et al[61] discuss these aspects and provide a number of examples to illustrate the importance of an informed choice. The incentive for users to invest in storage is that it may reduce cost. Currently, this is based on a utility perspective to minimize investment costs and it aims at a demand shift to off-peak hours. These are usually at night when there is no solar power available which requires increased storage and cost in systems with a lot of solar power. The composition of the supply-power production will also affect how a demand shift will influence e.g. energy use or carbon optimization.

The end-use should decide whether to opt for thermal or electric storage. For instance, thermal storage is much cheaper than is electrical storage. It is only a fifth of the cost of battery storage and thus it makes little sense to store electricity for an end-use that is thermal. Why invest in solar PV and battery storage to operate an electric water heater instead of using thermal solar panels and a water-storage heater? The message is clear; use thermal storage for thermal loads and electric storage for electric loads.

Regarding location, scale economy usually makes utility-based storage cheaper than small-scale user storage. On the other hand, storage close to the end-use makes it easier to optimize individual control to match supply and demand. From a utility perspective, a user-side battery is a load that is controlled by the user and the user can suddenly create a new peak in the supply system. How can one ascertain that local storage will permanently reduce the supply load? Storage location also has a bearing on the reliability of supply. If storage is on the supply-side of the electric grid it is of little use if a power line goes down.

2.1.5 Storage alternatives in electric systems

In this report I will only deal with storage in electric systems. Some of the major alternatives are[10, 45]:

Mechanical storage: Most well-known *are hydroelectric storage*, i.e. conventional dams, and *pumped hydroelectric storage*. The first alternative stores mechanical kinetic energy as potential energy with little loss of efficiency. The second alternative stores electric energy as mechanical potential energy by pumping water from a lower level to a higher level. The four efficiencies of pump, pump motor, turbine and generator means a total efficiency loss of 25-30 %. There is a geographic shortage of suitable sites for pumped storage.

Not so common is the use of *compressed air storage*. The round-trip efficiency is rather modest, only 40-50 %. Another, so far little used, technology is storage by fly wheels. A costly alternative with limited capacity but with excellent efficiency, around 90 %, and a long lifespan.

Electromagnetic storage: Viable options are *capacitors*, *super-capacitors* and *superconductive magnetic energy storage*. Currently, the most promising technique is perhaps the super-capacitor. It has an almost unlimited number of charging/discharging cycles and a very high efficiency. Still, however, the low energy density and high cost are limiting factors.

Chemical and electrochemical storage: *Chemical storage* is typically imagined as using surplus VRE electricity to produce a combustible gas, either for subsequent use in a fuel-based electric power station or for direct use as a fuel for propulsion or industrial processes. Currently, much focus is on hydrogen as the saviour of future VRE systems. But the process of extracting hydrogen from water has an efficiency of around 60 % and the reverse process of producing electricity in gas-fired power station or a fuel cell has at best also an efficiency of 60 %. This means that the overall storage efficiency is less than 40 %. At present, this is not an economically viable alternative without large subsidies.

Electrochemical storage in batteries is a field of great political and hence commercial interest. Massive investments are made in new large-scale production plants, mainly for lithium-ion batteries. Batteries have a functional advantage in terms of fast response and thus for voltage and frequency control. Unfortunately, they are costly, have moderate energy density and a large weight as well as a fairly short lifespan. Lithium-ion batteries last around 5-7 years and have an efficiency of around 85-90 %. There is also a sustainability problem since lithium is a very limited resource in comparison with the envisaged future demand.

Note that storage is not only a possibility for VRE alternatives. A nuclear power station could for instance operate at full capacity as a combined heat and power unit and in times of excess electricity production store the surplus electricity. The question of storage is superficially treated in public debate. Whatever the selected alternative, it will always add cost, complexity and negative environmental consequences.

2.1.6 Grid aspects

The electric grid has three major tasks:

- Transmission and distribution to satisfy demand in the right place at the right time.
- Compensating and stabilizing supply to provide electricity of the right quality.
- Ascertaining security of supply by means of backup power, alternative pathways, island operation etc.

Svenska Kraftnät (the Swedish National Power grid) has studied[58] the consequences of introducing a large fraction of VRE, primarily wind power, into the Swedish national grid. The following challenges are pointed out as potentially problematic and costly:

- **Power availability:** Wind power is weather dependent and unplannable and will impair the power balance on numerous occasions and not only at times of maximum demand.
- **Power balancing**: So far, only relatively predictable and moderate changes in demand have been necessary to balance by means of control power (in Sweden by hydro power). With the introduction of VRE, unpredictable and very large variations in supply also have to be balanced (in Sweden the existing balancing hydro-power capacity is already fully spoken for).
- **Unplannable power:** Wind power introduces large stochastic variations in supply in both the short-term and long-term perspective. This has not been experienced before and the variations do not follow any known pattern.
- **Voltage control:** Historically, grid design has been coordinated in a way that all connected generators have served an important part of maintaining a balance of reactive power and thus a possibility of controlling the supply voltage. At times of disruption in the net, the capacity of supplying reactive power is even more important. Reactive power must be produced locally; it cannot in practice be transmitted via power lines or transformers as it will take space from active power and increase losses.
- **Generator characteristics:** Most of the wind-turbine generators and solar cells do not have the capability of supporting voltage control. This implies a deterioration of the security of supply unless special measures are taken.
- **System inertia**: Nuclear power stations contribute to grid stability by means of synchronous generators with large rotary mass (system inertia; the Swedish nuclear reactors have been important for the stability of the entire Nordic grid). Wind and solar power are currently not using synchronous generating equipment.
- **Siting:** Wind power is decentralized and mostly localized far from places of demand. It is usually connected to grids at lower voltage levels and will replace large scale generators connected to the high-voltage national grid and thus the support for voltage control will go down. This will have negative consequences for both the transmission capacity and the security of supply of the grid. Furthermore, siting is based on the best generating conditions or finding places where there is little local opposition to the negative local environmental consequences of e.g. wind power. These sites are usually very poor choices from a grid point of view regarding the efficiency and stability of supply.

2.1.7 Deterring national examples

Countries such as Germany and Sweden have been used to well-planned and well-functioning electric grids based on technical requirements. Power stations have been built in optimal locations based on considerations of grid stability and minimal need for transmission. Nowadays, however, with the politically driven expansion of solar and wind power, the entire system design must be adapted to satisfy the needs of suppliers and not the needs of users. In both countries wind power is mainly located in the north whereas users primarily live in the south, i.e. far away from demand. This means that a great deal of new transmission capacity must be built. Instead of traditional design aims, to minimize the need for transmission, VRE-dominated grids will maximize transmission requirements and hence the cost, transmission losses and negative environmental impact of such installations. To further aggravate the situation, long distance transmission requires new compensating and stabilizing equipment.

New transmission capacity is required but recent premature, politically motivated, decommissioning of two nuclear reactors at Ringhals in the south of Sweden actually reduced the capacity of the existing national grid by around 1000 MW. This is due to the loss of reactive-power capacity and its effect on grid stability and corresponds to the mean capacity of 1000 large wind turbines which will lose their current transmission possibilities. The cost of new transmission capacity for the wind turbines is of the same magnitude as building new nuclear power at the existing site.

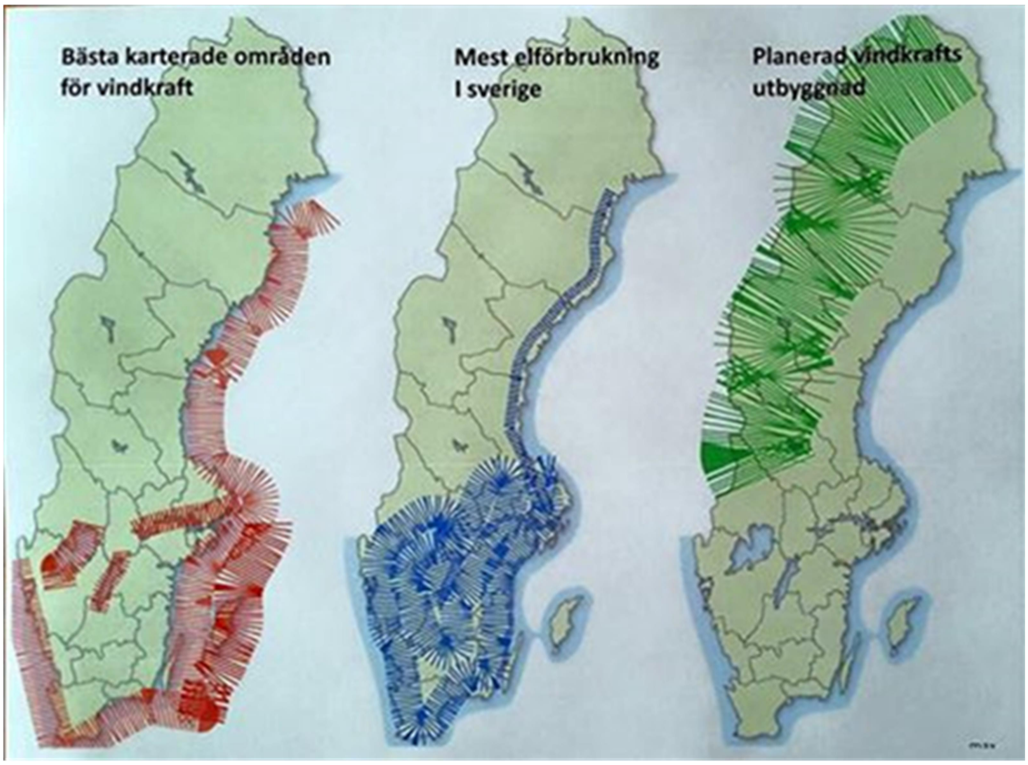


Figure 2.3 Sites for demand and wind power supply in Sweden. Red = the best wind sites, blue = the sites of highest demand and green = sites where most of the wind power is built (Göran Widén).

Figure 2.3 figure illustrates the discrepancy between the location of sites for demand and wind power supply in Sweden. Red indicates the location of the best wind sites, blue represents the sites of highest demand and green shows where most of the wind power is built. The long distances of transmission result in substantial energy losses: approximately 10 % from north to south in Sweden and 20 % for exports. Furthermore, the northern location will decrease annual generation by circa 10 % due to frosting (see Figure 2.4).

Figure 2.4

Frosting of a wind-turbine rotor. The rough frost adversely affects the rotor efficiency and hence the energy production and maintenance costs. The frost also increases noise generation and affects the frequency spectrum of the noise.

In Germany, replacing nuclear power by solar and wind has resulted in the building of new coal-fired power plants for reasons of balance power and grid stability. This is in stark contrast to the goals of the much touted “Energie Wende” (Energy transformation).

2.2 Energy and power

As already noted, electric power must be generated and distributed instantaneously in perfect balance with demand. It is of little consequence if the annual demand for electricity can be generated on an annual basis if the power is not there the very instant it is needed. Energy can be stored (see 0) but power must always be there continuously. In many countries the choice for the future supply of electricity is between the low-carbon alternatives nuclear or wind power. Two practical examples are Germany and Sweden.

2.2.1 The German “Energiewende”

After the tsunami in Japan in 2011 and the subsequent breakdown of the nuclear power plant at Fukushima, Germany decided to decommission all its nuclear power plants even though not a single person was killed in the nuclear incident. A total transformation of the energy supply, “Energiewende”, based on VRE in the form of solar and wind power is the planned replacement. This was also going to save the climate in the process. So far, this has not fared very well. After subsidies of up to a thousand milliard euros and building a number of new coal-fired power plants to balance the VRE supply, Germany has among the highest CO2 emissions in Europe and the highest cost of electricity. The country has also been forced to build a number of costly phase-shift transformers to protect the electricity grids of neighbouring countries from the variability problems of the VRE supply.

Figure 2.5 clearly shows that the bulk of German wind power operating hours are at a relatively low capacity. The peak is at a measly 4 % of the installed wind power capacity and generation at more than 50 % capacity is only during 40 h of the annual 8760 h.

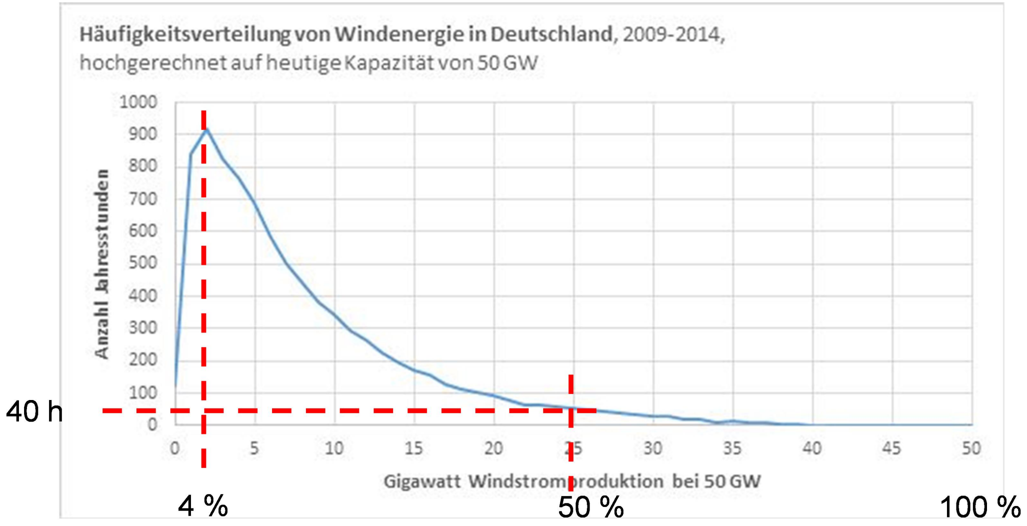


Figure 2.5 Distribution of the hours of generating a given wind power capacity for the German grid over the 5 year period 2009-2014.

Schuster[45, 51] has followed the expansion of solar and wind power in Germany for many years.

Figure 2.6 shows for the period 2011-2017 the electric power supply in GW by wind (blue) and the sum of wind plus solar (red) compared with maximum and minimum grid loads.

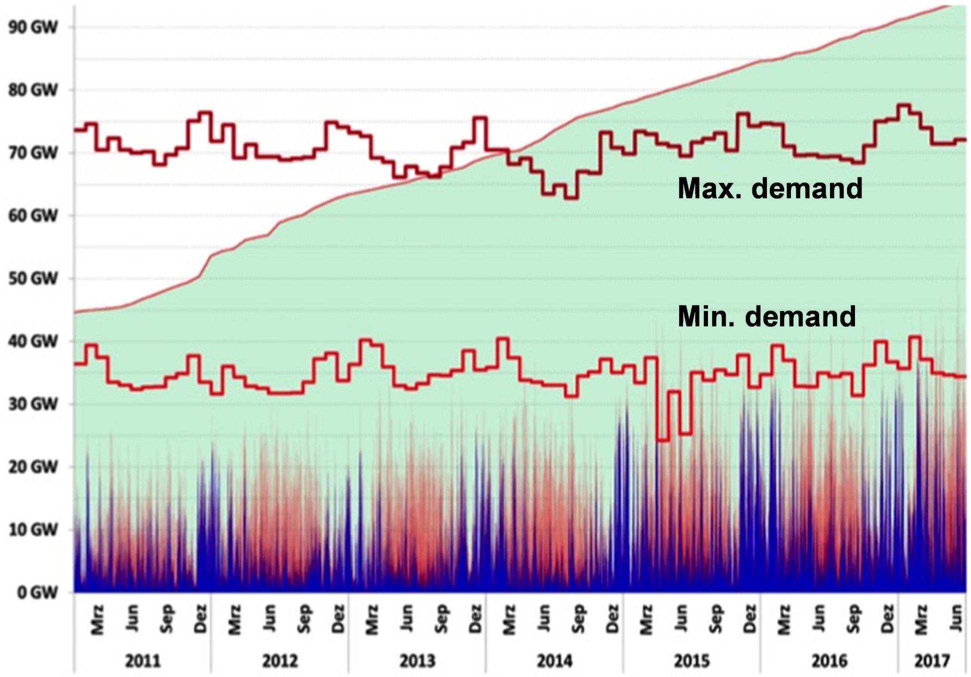
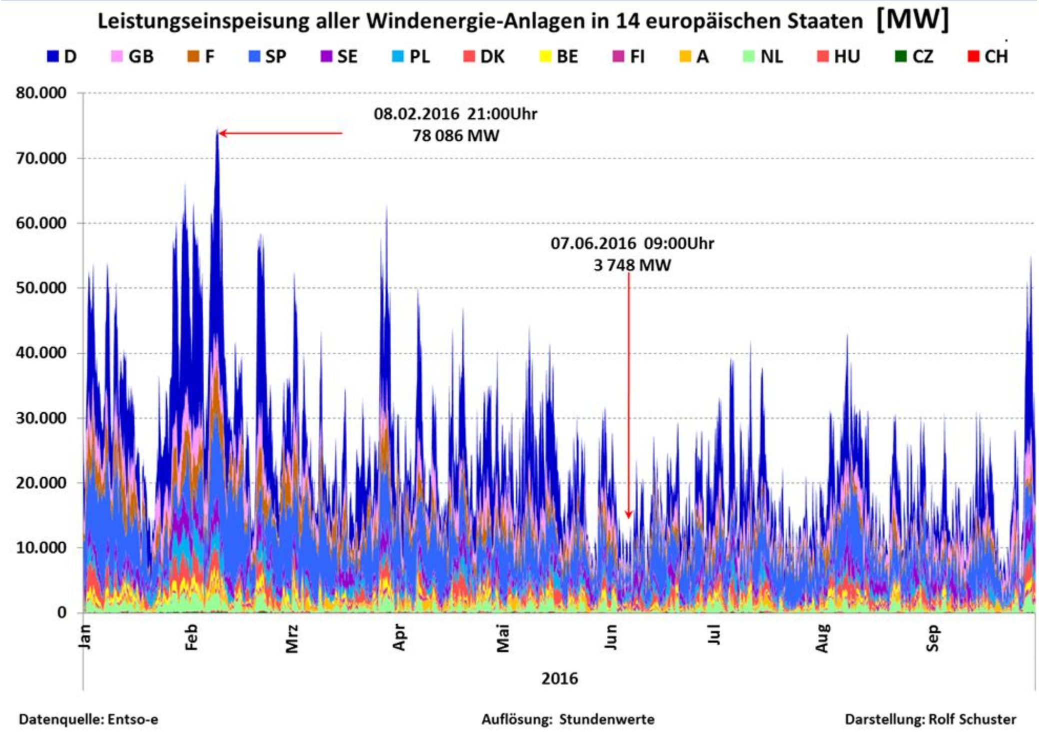


Figure 2.6 Electrical power production (in GW) by wind (blue) and the sum of solar PV and wind (red) compared with maximum and minimum grid load. Installed renewable capacity is indicated by the green area.

Grid loads vary somewhat between years but have not substantially changed over the period. Also shown is the increase of installed renewable power (light green area). As the installed renewable capacity goes up, the minimum grid load is increasingly exceeded, leading to overcapacity and export of surplus energy, often at negative prices. Noteworthy is also that despite the large increase of installed power over the years, there is very little increase in actual output. This is partly due to a substantial variation of wind between years but also that the capacity factor will drop as less suitable sites have to be used and more capping of output results from increased overproduction.

In the discussion of the variability of wind, a common claim is that it always blows somewhere and that by increased transmission capacity between countries there is a possibility of levelling the generation at an international scale. Practical experience tells us otherwise. There is a strong correlation of wind speed between countries and Figure 2.7 clearly shows that the collective output from 14 European countries in 2016 has more or less the same variability as that of individual countries. This means that when wind-power output is high in one country and this country tries to export its surplus this wind power will be competing not with fossil fuels but rather with the excess wind power from another country. The large dips in the output will still have to be covered by some other type of balance power and/or storage.


Leistungseinspeisung aller Windenergie-Anlagen in 14 europäischen Staaten [MW]

Datenquelle: Entso-e Auflösung: Stundenwerte Darstellung: Rolf Schuster

Figure 2.7 Variation of the supply of wind power by 14 different European countries, individual values as well as the total (Rolf Schuster[45, 51]).

2.2.2 The Swedish bid for 100 % renewable energy

In 2016 a Swedish political majority agreed that Swedish electricity should be 100 % renewable by 2040. No study was made as to the feasibility, cost or environmental consequences of this decision. The agreement was also at odds with the position regarding nuclear power. It was claimed that there was no ban on nuclear power but nuclear power is still not considered renewable! Going 100 % renewable is of great concern for the authority responsible for the national grid. Svenska Kraftnät[40, 58, 60] (SVK, the Swedish National Power grid) has investigated for many years the future functionality of the grid and the deteriorating power balance due to increased use of VRE. As the fraction of wind power goes up so does the number of serious incidents regarding system stability and the power-sufficiency margin goes down.

The Swedish electric supply system, which is now being transformed, was extremely well engineered and running basically on nuclear and hydro power (see

Figure 2.8). It was originally divided into six separate supply regions, each with a good power balance. The two most northern regions, solely based on hydro power, had a limited surplus which was exported to the south. The southern regions had a nuclear power station in each region as a node for the balance of power and grid stability. This minimized the need for transmission and hence the cost and losses.

Balanced supply regions

- Northern surplus (hydro)
- Minimized need for transmission capacity
- Minimized cost and transmission losses

Demand and supply

- Rather predictable demand
- Predictable supply
- Storage in fuel depots and dams

Control

- Base power: Nuclear
- Base and control power: Hydro
- Stability and reactive balance by rotary mass in nuclear and hydro power stations

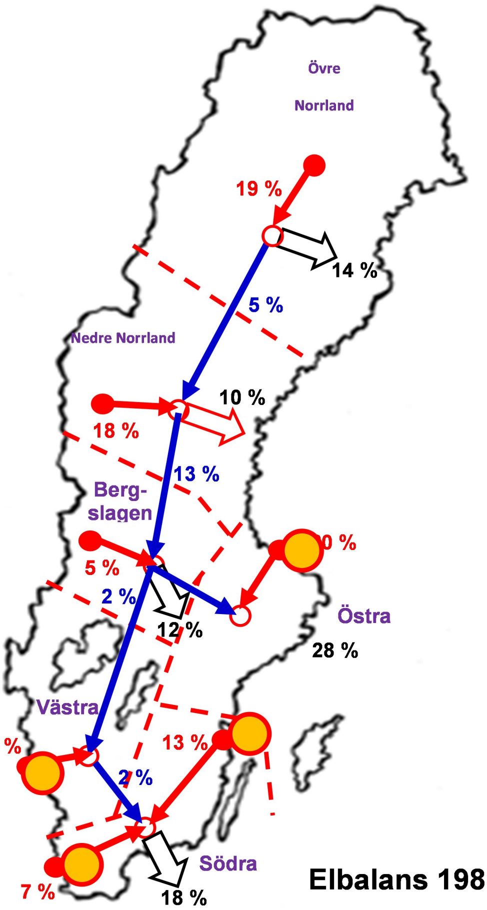


Figure 2.8 Electric balance of the Swedish grid in 1986. Yellow circles indicate the 4 nuclear plants with altogether 12 reactors.

As the southern nuclear reactors are decommissioned, this region will experience a severe shortage of both power and energy. Building wind power in the north is no sustainable solution. It will require an enormous expansion of transmission capacity but in no way ameliorate the lack of generating capacity. The variability of wind power is clearly shown in Figure 2.9, which presents the hourly capacity of the total Swedish wind power in 2018. Obviously, it is impossible to foresee the large weather-related variations and time and again, the total supply is close to zero. The large variations will also lead to poor utilization of the transmission capacity. Should the grid be sized for the mean capacity, the maximum capacity or some other value?

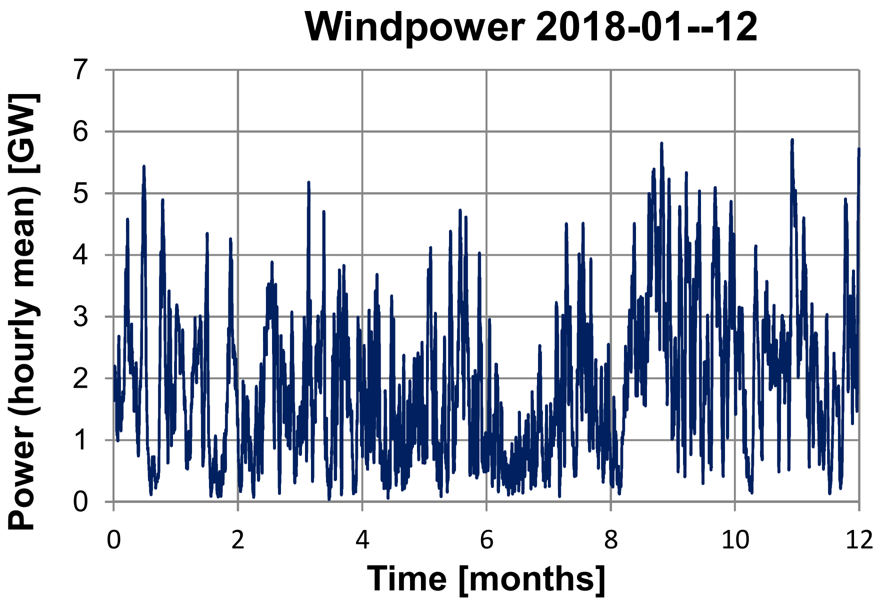


Figure 2.9 Swedish wind power in 2018 (data by Svenska Kraftnät).

Figure 2.9 gives the same impression of variability as the German examples. Enlarging the data for January, a cold month when it is likely to have a period of maximum demand,

Figure 2.**10** indicates that the total wind-power output is close to zero for several days. This must be solved by means of new systems for supply and/or storage plus equipment for stability and control. Already SVK has noted a large increase of the number of serious incidents regarding grid stability and a deteriorated quality of supply. Note that as there are periods of almost zero supply a balance power equal to the total wind-power capacity must be available at all times.

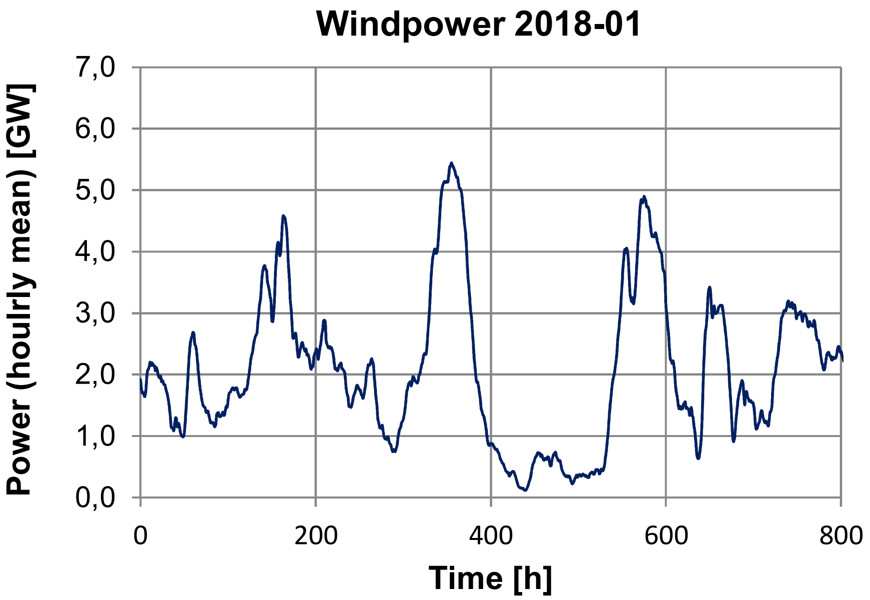


Figure 2.10 Swedish wind power in January2018 (data by Svenska Kraftnät).

3 Analysis of economic and environmental consequences

Prior to discussions of economy and environmental consequences of alternative energy supply systems it is important to clarify certain fundamental principles of the analysis. Life cycle analysis is the weapon of choice when studying specified long-term effects of technical systems. Often a classification/levelling of the system boundaries is made to clarify where and why the effects arise. It is, however, important to understand the difference between Life Cycle Inventory, LCI, and Life Cycle Analysis, LCA. LCI is related to the cause and LCA to the effect.

LCI provides factual data of the amounts of specific materials used in specified processes, the quantities of specified emissions etc.; i.e. objective data. Life cycle assessment (LCA), on the other hand, aims to give a measure of the potential environmental impacts associated with a given product, service, or decision. LCA may have a certain amount of subjective input in terms of which effects one chooses to evaluate and how these effects are prioritized.

3.1 Life cycle analysis (LCI, LCA, EPD and LCC)

The basis of a Life Cycle Analysis, LCA, is the factual Life Cycle Inventory, LCI[38]. Results regarding energy conversion processes are compiled by various organizations such as the IEA, NEA, US Department of Energy etc. Using LCI data in LCA applications is a selective process that depends on the purpose of the LCA. It is important to consider for instance:

- **Purpose:** Environmental or economic consequences?
- **System boundaries:** Which parts of the process are included in the analysis? Where in the process does the analysis begin and finish?
- **Input data:** Quality of input data? Based on assumptions or measured data? Technical or economic lifespan?
- **Modelling:** Quality and validation of models?

3.1.1 Principles of LCA

The LCA should be based on international standards such as ISO 14040[30] and 14044[31]. This is mostly not the case in public debate and certainly not in the undefined buzzwords “green”, “climate smart”, “renewable”, “sustainable” etc. (see the discussion in 1.1 and 5).

According to the standards, the environmental impact is based on LCA estimates comprising building and dismantling of power stations, fuel extraction and processing, and the operation and handling of waste products. The LCA provides information on emissions under normal operation, which implies that breakdowns or accidents are not included.

The main environmental impact is not necessarily at the location of operation; this is typically the case for alternatives with low operational cost such as nuclear, wind and solar energy. Some technologies are more affected by the building phase while fuel production and use are more important factors for others.

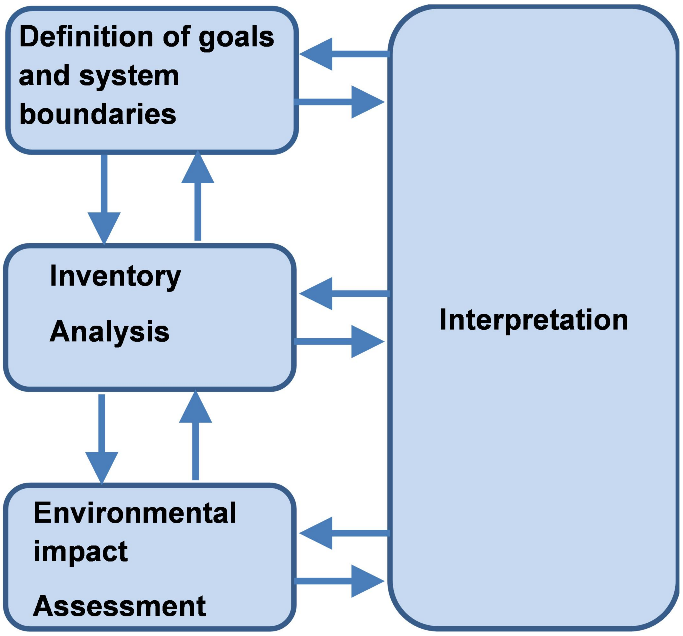


Figure 3.1 The various steps of a life cycle analysis according to the international standards ISO 14040[30] and 14044[31].

Figure 3.1 describes the principle steps of the LCA. The arrows indicate that it is an iterative process, where results are continuously used to improve the process. Results may be given directly, without any qualitative qualifications, or after specified prioritization according to the aims of the assessment.

3.1.2 Environmental Product Declaration (EPD)

Results are preferably presented in accordance with the methodology of the international EPD®-system (Environmental Product Declaration[43, 48]). Results for specified factors such as carbon dioxide, sulphur dioxide, non-renewable materials etc. are commonly divided by the electricity production and stated e.g. in grams/kWh. For each category of product, e.g. electricity generation, there is a set of Product Category Rules (PCR). These rules describe the necessary contents of a declaration of environmental performance regarding a specific product. The performance declaration should include not only the LCA but also the effect on biological diversity as well as any potential environmental hazards.

In order to make the results of an LCI/LCA comprehensible from a general environmental perspective, the environmental effects of emissions and use of materials are often estimated. Such environmental effects are for instance climate change, acidification, depletion of resources etc. These effects are normally calculated by means of predetermined conversion factors. Note that these conversion factors may have very different factual background. Presumed effects on climate change may be highly disputable whereas the effect of for instance sulphur dioxide on acidification may be rather well understood.

Many substances may contribute to the same type of environmental effect whereas one substance may simultaneously contribute to several different effects. Translating detailed data from an LCI into a compressed LCA declaration makes the information not only more comprehensible but also more debatable. A qualitative sorting of the results from an inventory in various categories of environmental effect is known as classification. A quantitative calculation, on the other hand, is called categorization. There are various ways of comparing different environmental effects, e.g. to decide between alternative technical solutions, but these methods will always be more or less subjective. For instance, how does one prioritize between e.g. climate change and depletion of resources?

3.2 System boundaries

As already stated, the focus regarding life cycle analysis will be on alternatives for generation of electricity, in particular between low-carbon alternatives such as nuclear, solar and wind energy. An electric supply system is typically[34, 62] classified according to three levels of increasing complexity (see Figure 3.2):

- Plant level
- Grid level
- External and social level

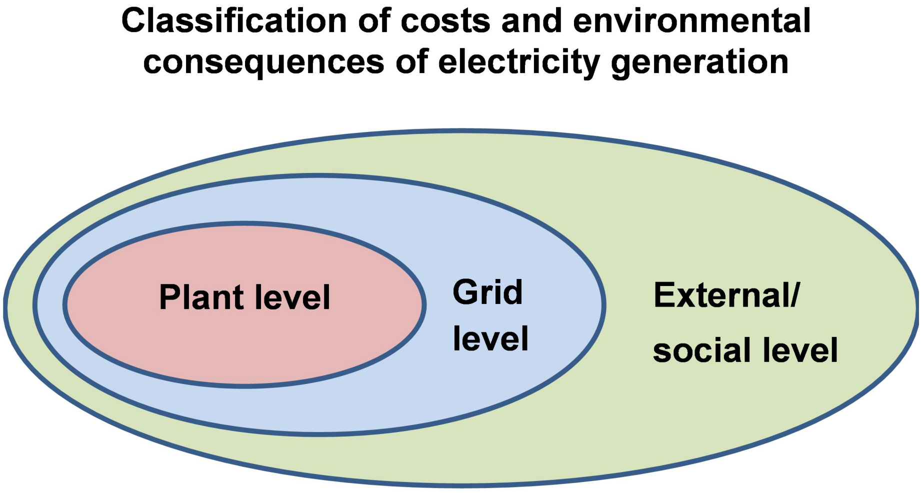


Figure 3.2 Classification and allocation of costs and environmental consequences of electricity generation based on inputs from OECD, IEA and NEA[34].

3.2.1 Plant level

The first category[34] comprises plant-level factors, which include the materials and the manpower used to build, operate and decommission the plant. Construction materials typically include concrete, steel and aluminium but also composite plastics, rare-earth metals etc. During the operating phase, fuel is typically the dominating factor in fuel-based systems. The NEA and the IEA publish a survey of the plant-level costs in OECD countries every five years in the Projected Costs of Generating Electricity series (see IEA/NEA, 2010 and IEA/NEA, 2015; IEA/NEA, 2020 is currently in preparation).

3.2.2 Grid level

The second category[34] involves the costs and use of resources at the grid level of the electricity system. This includes the transmission and distribution network with the necessary stabilizing and safety equipment. It also includes the costs that plants impose on the system in terms of extending, reinforcing or connecting to the grid, but also the costs for maintaining spinning reserves or additional dispatchable capacity when the output of some technologies, typically wind and solar photovoltaic (PV), is uncertain or variable.

3.2.3 External and social level

The third, even broader, category[34] includes items that impact the well-being of individuals and communities outside the electricity sector. Known as external or social costs, such costs include the impacts of local and regional air pollution, climate change, the costs of major, frequently not fully insurable, accidents, and land use or resource depletion. Social costs also include the impacts of different power-technology choices on the security of energy and electricity supply, employment and regional cohesion, innovation and economic development, natural beauty, tourism, property values etc. If these impacts are negative, they add to the full costs of a technology; if they are positive, in principle, they need to be deducted as a social benefit.

4 Economy of electric supply alternatives

The economy of electric supply alternatives is a more complex issue than the mere question of the cost of the actual power station. The previous discussion in 1to 3 makes it abundantly clear that a system perspective must be adopted to find a system design that is economically optimal not only for the power utility but also for users, grid operators, the environment and society as a whole. Unfortunately, politically influenced market conditions do not favour such considerations. It is appropriate to look at three different system levels[34] where costs appear:

- Plant level, i.e. the power station
- System level, i.e. including the entire grid
- External and social costs

It must also be kept in mind that the economy of a supply system not only depends on cost but also on income. Hence, we must also take a look at the available alternative revenues.

4.1 Plant level costs

LCOE, the Levelised Cost of Electricity, is the most common metric for plant level costs. According to the OECD report[34] "The full costs of electricity provision" LCOE indicates the discounted life-time costs for different baseload technologies, averaged over the electricity generated. The purpose is to provide informed investment choices to electric utilities in regulated electricity systems. It is, however, less pertinent in deregulated electricity systems where revenues vary from period to period over the life-time of an electricity generator. LCOE is also unable to capture the system costs of certain technologies. Despite these limitations, it often remains an attractive first reference because of its simplicity and transparency.

The economic figures quoted in this section will be given in the currency of the reference and then converted to euros (€). The following exchange rates are used (July 2021): 1 CNY = 0.24 €, 1 GBP = 1.17 €, 1 KRW = 0.00074 €, 1 USD = 0.85 €, and 1 SEK = 0.098 €. Sometimes the reference provides cost related to the installed capacity (total or annual) and sometimes related to the annual electricity production. One alternative may be derived from the other by means of the following relation:

$$C_E \left[\frac{€}{\text{MWh}}\right] = \frac{C_P\ [€/\text{MW}]}{\tau_{LT} \cdot \tau_{a,h} \cdot f_C} \quad \text{or} \qquad C_E \left[\frac{€}{\text{MWh}}\right] = \frac{C_{P,a}\ \left[\frac{€}{\text{MWh}}/\text{year}\right]}{\tau_{a,h} \cdot f_C}$$

where C_E = cost per MWh, C_P = cost per MW, $C_{P,a}$ = annual cost per MW, τ_{LT} = expected life-time in years, $\tau_{a,h}$ = annual hours (8760 h/annum) and f_C = the capacity factor. In the conversion, the expected life-time/capacity factors are for hydro power 60/0.5, nuclear 60/0.9, onshore wind 15/0.3, offshore wind 12/0.4, solar 25/0.2 and bio 40/0.5.

4.1.1 Investment

Investment costs will depend on the country and how large the market is; there are potential benefits from replication and series production of identical or similar units. Nuclear plants, for instance, have not been frequently built in western countries for decades[11, 34, 39]. The policy in many countries has been to phase out nuclear power and hence to introduce various regulations that make this alternative more costly and less attractive to build. The odd plants[11] now being built therefore tend to be more than twice as expensive as those of a country such as Korea[69], which has built 24 reactors between 1983-2019 with a median building time of 4.8 years and an overnight investment cost in the range 1.5 to 3 €/MW. The Korean reactors have exceptionally high capacity factors with a mean value of 96.5 %.

Hydro power: This probably carries the highest first cost of the low-carbon alternatives. In Sweden, for instance, the specific cost of building dams required to make hydro power dispatchable was much higher than building the fleet of nuclear reactors. Sweco et al[59] provides a figure of 125 SEK/MWh (12.2 €/MWh and 3.2 €/MW). Most sites available in Europe have already been exploited so the potential for new construction is virtually nil.

Nuclear power: The range of values for nuclear-plant costs is large: It varies both in time and by country as accounted for in several studies[11, 34, 39, 68]. In Europe, construction costs of the few units that are currently under way is quite high, up to 5 M€/MW, whereas those of South Korea[1] only cost around 2 M€/MW of electric power output. This is less than half the cost of current European projects and demonstrates the influence of practical experience from continuous construction. Figure 4.1 shows the specific cost of energy from a report compiled by OECD/WNA[34].

Compared to wind power, with much lower cost per MW, nuclear will still have a much more favourable cost per MWh as indicated by Figure 4.1, around 5 USD/MWh (4.2 €/MWh). NEI[46] gives a value of 5.72 USD/MWh (4.86 €/MWh) and SWECO et al[59] reports 49.0 SEK/MWh (4.80 €/MWh). With a capacity factor 3 times higher and a lifespan that is 4 times longer, nuclear will produce 12 times the energy of wind power for an investment that is less than 3 times higher.

Wind power: Hughes[13] has investigated a large number of installations and he finds that onshore wind power is built at a planned cost of around £1.30 million/MW (1.52 M€/MW and 38.5 €/MWh) and offshore wind £2.16 million/MW (2.53 M€/MW and 60.1 €/MWh). Subsequent evaluation shows that the mean of the actual figures are rather like £1.61 million/MW (1.88 M€/MW and 47.7 €/MWh) and £3.99 million/MW (4.67 M€/MW and 111 €/MWh) respectively! Contrary to the common view that costs are going down, the experience by Hughes[13] is that costs are not decreasing, rather the opposite. According to Sweco et al[59], the investment cost for wind power is 490 SEK/MWh (48.0 €/MWh and 1.89 M€/MW)

Solar power: The cost for installed capacity is around 1 M€/MW. On the other hand, taking into account the low capacity factor of solar power, this is by far the most expensive alternative per kWh.

Bio power: Bio power has a very high cost for generation of electricity, around 17 €/MWh. It relies heavily on CHP and/or subsidies for anything close to economic balance.

4.1.2 Operation and maintenance

Hydro power: SWECO et al[59] gives a value for the operating cost of hydro power of 184 SEK/MWh (18.0 €/MWh).

Nuclear power: According to OECD/WNA[34], the cost of operation and maintenance is 11-36 USD/MWh with a mean value of 22 (18.7 €/MWh). NEI[46] provides a value of 24.7 USD/MWh (21.0 €/MWh) and Sweco et al[59] 245 SEK/MWh (24.0 €/MWh).

Wind power: Hughes[13] finds that operating costs for new onshore installations are around £77000 per MW (0.090 M€/MW or 34.28 €/MWh) and they will increase steadily by circa 3-4 % per annum. Offshore operating costs typically start at £184000 per MW (0.215 M€/MW or 61.44 €/MWh) and will go up by 8-9 % per annum. Sweco et al[59] states 160 SEK/MWh (15.7 €/MWh). Much of the operational cost is linked to the problem of leading edge erosion, which lowers efficiency and lifespan of the turbines (see also 5.2 and 7.1) but gear-box trouble has also been a persistent problem.

Solar power: Annual operating costs according Hughes[13] are £19000 per MW for large scale solar power (around 0.022 M€/MW or 12.7 €/MWh).

Bio power: Sweco et al[59] gives a value of 243 SEK/MWh (23.8 €/MWh).

4.1.3 Decommissioning

Nuclear power: The cost of decommissioning is generally included in the operating cost of nuclear. Payments are made to a fund that is sized to fully cover the cost of decommissioning and long-term storage of radioactive waste.

Wind power: Usually only a minor part of the decommissioning costs is paid up front. The full cost can be around 100 – 400 kSEK/MW[4] (0.1-0.4 M€/MW), i.e. quite considerable in relation to the investment. The enormous concrete foundations are too expensive to remove and are currently just covered with earth.

Solar power: Solar installations do not in general pay up front for decommissioning. At present, there are no good ways of recovering scrapped equipment.

4.1.4 Plant level costs of alternative sources of supply

Comparison of plant level cost is neither a simple nor a straightforward task. There are numerous figures around, many of questionable quality. In particular, figures for the low-carbon options of nuclear, solar and wind power are elusive. They vary greatly between countries and time periods.

Figure 4.1 provides estimates from an OECD-report[34] of plant-level costs for dispatchable and renewable power generation technologies at a capital cost of 3 % (7 % and 10 % are also provided), assuming region-specific fuel prices, an 85 % load factor for nuclear, coal and gas, as well as a carbon price of 30 USD per tonne of CO2. The latter presumes that the social costs of climate change due to carbon emissions are at least partially internalized in the policy provisions of OECD countries.

Sweco[36, 59] provides the following values: nuclear 32, hydro 31, wind 65, bio 43 and solar 170 USD/MWh. NEI[46] has a value of 30.42 USD/MWh for nuclear power.

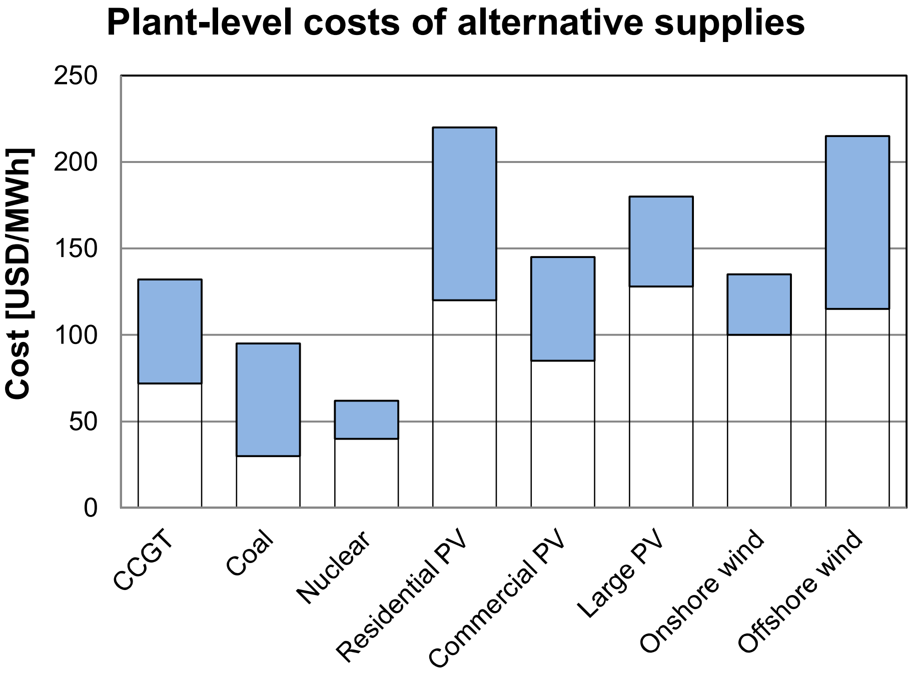


Figure 4.1 Plant-level costs[34] for dispatchable and renewable power technologies at 3 % capital cost. Blue bars indicate the range of cost for investigated plants.

Contrary to the currently ubiquitous claim that wind power has the lowest cost, at least at plant level, the diagram indicates that nuclear power has by far the lowest cost per MWh (1 USD is approximately 1 EUR). There seems to be a wide gap between offered costs of wind power and the actual costs of investment, operation and decommissioning. Professor Hughes of Edinburgh University has investigated[13, 28] the economy of around 1000 wind-power installations in Britain and Denmark. In his evaluation, the mean life-time of on-shore wind power was 15 years and that of off-shore wind power was 12 years. Typical values of the lifetime used in LCC analysis are given in Table 4.1.

It is obvious that using a projected life-time of e.g. 20 years instead of an actual value of 15 years will underestimate in LCOE by 33 % (20/15). Also, current economic models are unfavourable to long-term investments such as nuclear and hydro power. Typically, a plant with a lifespan of 60 years will benefit from only a third of its future revenues whereas a lifespan of 20 years will benefit from all its projected earnings.

Table 4.1 LCOE for alternative supply sources given by Martikainen[41]

Parameter	**Nuclear Korea**	**Nuclear Finland**	**Wind EU Onshore**	**Wind EU Offshore**	**Solar PV Germany**
Investment [M€/MWh]	2.0	3.4	1.6	3.3	1.4
Capacity factor [-]	0.90	0.90	0.25	0.40	0.10
Life-time [years]	60	60	20	20	25
Cost [cents/kWh]	0.4	0.7	3.7	4.7	6.2

4.2 System-level costs

Hirth et al[62] characterize the system-level costs by means of the categories *profile costs*, *balancing costs* and *grid costs*. This classification is also used by OECD[34]. Figure 4.2, based on Hirth et al, illustrates the composition of system-level costs.

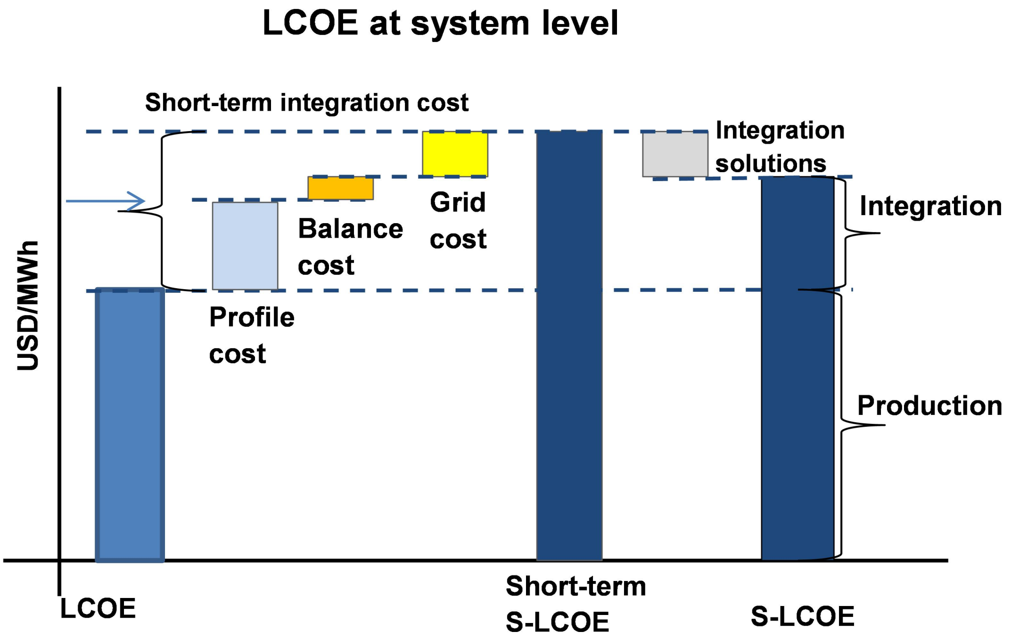


Figure 4.2 Integration costs are divided into three components: profile, balancing and grid-related costs (Hirth et al). To some extent integration costs that occur in the short term can be reduced by integration options in the long term.

4.2.1 Profile costs

Profile costs are related to the variability of VRE output. In particular at higher shares this leads to increasingly inappropriate load-matching properties and the need for backup capacity; VRE has a low capacity credit. The full-load hours of capital-intensive dispatchable power plants decrease while these plants need to ramp up and down more often. Moreover, VRE supply might exceed demand and thus be overproduced. The overall system hence becomes more expensive even if the plant-level costs of VRE would be comparable to or even less than those of dispatchable technologies (which they currently are not).

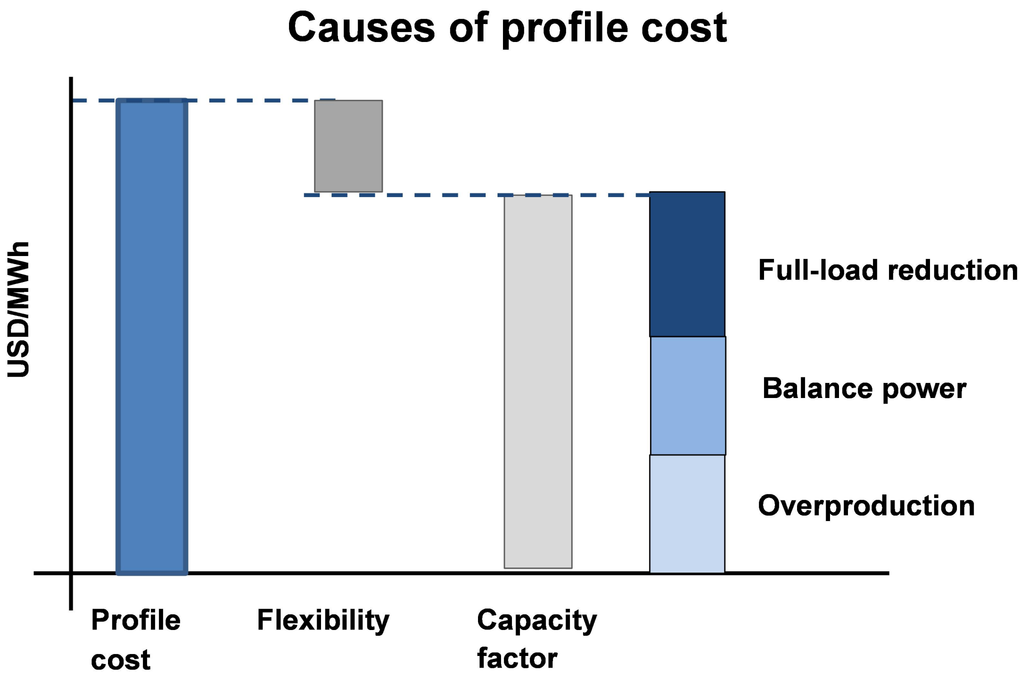


Figure 4.3 Profile costs based on Hirth et al[62].

4.2.2 Balancing costs

Balancing costs are related to the uncertainty of power production due to unforeseen plant outages or to forecasting errors in relation to production. Such events require that a higher amount of spinning reserves be available. Day-ahead forecast errors of wind or solar PV generation cause unplanned intra-day adjustments of dispatchable power plants and require operating reserves that respond within minutes to seconds. Uncertainties in VRE power production may also lead to an increase in ramping and cycling of conventional power plants, to inefficiencies in plant scheduling and, overall, to higher costs for the system.

4.2.3 Grid-related integration costs

Grid and connection costs reflect the effects on the transmission and distribution grid infrastructure due to the locational constraint of generation plants. While all generation plants may have some siting restrictions, the impacts are more significant for VRE. Because of their geographic location constraint, it is generally necessary to build new transmission lines or to increase the capacity of existing infrastructure (grid reinforcement) in order to transport the electricity from centres of production to load. Also, high shares of distributed VRE resources may require sizeable investment into the distribution network, in particular to allow the inflow of electricity from the producer to the grid when the electricity generated exceeds demand. Connection costs, i.e. the costs of connecting the power plant to the nearest connecting point of the transmission grid, can also be significant. This is especially the case if distant resources have to be connected as is often the case for offshore wind. Also, if grid constraints are enhanced by VRE the costs for congestion management like re-dispatch of power plants increase.

4.2.4 System-level cost of alternative technologies

Figure 4.4 provides an illustration to the importance of taking system-level costs into account when comparing the overall cost of alternative sources of supply. The diagram clearly shows that whilst dispatchable, fuel-based sources are little affected by system costs, for flowing-energy VRE sources these costs are very much larger than the cost of the power plant per se. Hirth et al[62] found that already at a market share of 20 % wind power, the grid integration cost was equal to the plant cost. The authors also found that above 20 % share the integration cost increased very rapidly.

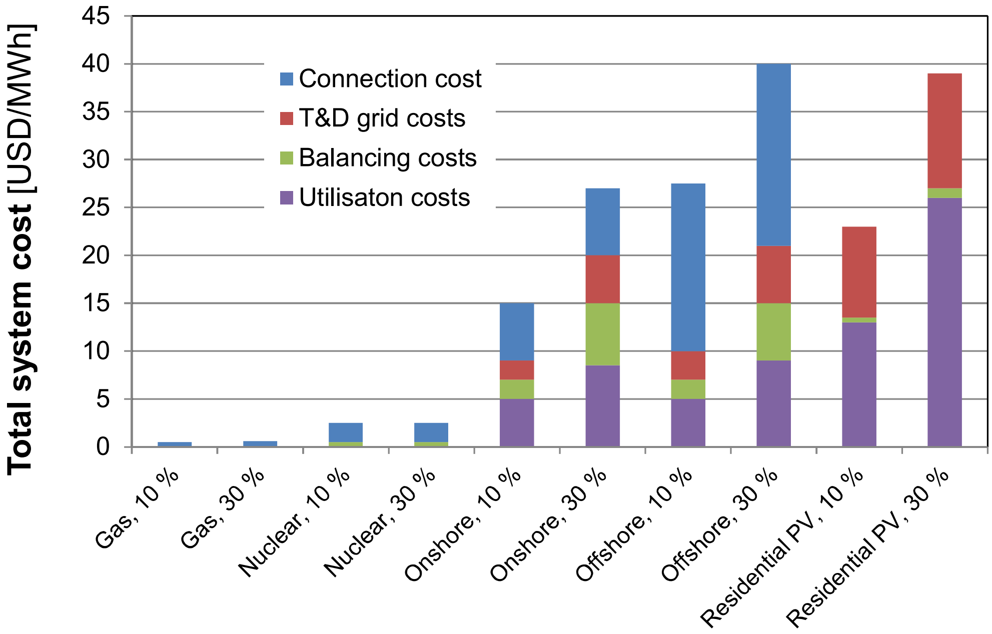


Figure 4.4 Grid-level system costs of selected generation technologies for shares of 10 % and 30 % of VRE generation (based on OECD[34]). T&D = Transmission and Distribution.

Currently, the system cost will in most markets not be carried over to the plant operator but instead will be addressed directly to consumers via the grid bill. This constitutes a direct subsidy to operators of VRE plants and an unfair competitive edge unless the system costs are internalized for each operator. Governments and policy makers should therefore introduce policies aimed as much as possible at the internalisation of system costs. One possibility is to enforce the European regulation on requirements for grid connection of generators[17]. In principle, this requires of connected generators that they must contribute to the system operation by means of supporting actions such as voltage and frequency control, island operation etc. VRE suppliers thus would have to build such equipment or show signed contracts with operators that can provide system support.

4.3 External/social costs

Examples of external costs other than those related to the grid are rarely considered as they are difficult to assess. Examples of such costs are:

- **Climate change impacts**: Is there an anthropogenic climate change and if so, are the effects negative, positive or negligible? This is discussed elsewhere.
- **Air pollution**: This is by far the biggest uninternalized cost of electricity generation. Although figures are uncertain it is obvious that combustion of waste, wood, coal, peat, gas etc. are the main culprits.
- **Major accidents**: Costs related to accidents are many orders of magnitude lower than those of air pollution (see section 7).
- **Land-use change and natural resource depletion**: Most electricity sources have significant land requirements when the whole fuel cycle is considered, including fuel extraction, generation and waste disposal. The fuel that has the highest land-use requirement by far is biomass but wind power is also quite area-intensive. Almost everywhere, when wind farms are planned, there is local opposition (also see 5). Such industries are generally built in rural areas, often of high scenic and ecological value. Noisy and obtrusive towers of more than 250 m height will affect property values and possibilities of tourism.
- **Security of energy and electricity supply**: The continuous availability and affordability of energy, in particular of electricity, is an indispensable condition for modern societies. Hence it is important to understand the factors influencing the security of supply and to implement directives to ascertain that this is actually achieved in practice. Grid-supervising authorities have been concerned for many years of the negative impact in this regard by the growing share of VRE.
- **Employment**: Increased employment per kWh has a negative influence on the private cost of electricity. On the other hand, it has a positive influence on external/social cost as it provides opportunities for work. Not only the numbers but also the educational requirements are important to consider. “Green” alternatives, e.g. solar and wind, are claimed to boost employment in rural areas but several studies indicate that such industries may actually cause a larger loss of job opportunities in other sectors (tourism, rising cost of electricity etc.).
- **Impact of energy supply on economic growth**: The rapid growth of welfare since the days of the industrial revolution is largely due to the introduction of new and abundant sources of energy. In this respect, one might say that coal saved what was left of European forests. Sweden had its first energy crisis in the 18th century when forests around cities and towns were depleted of fire wood. Introduction of a new and more efficient type of storage fireplace saved the day.

One study that has looked into the question of external and social costs is the EU-project Cases[47]. This report provides estimates of the full costs of electricity generation in Europe. Results are obtained by summing external costs due to impacts on human health, environment, crops, materials and climate change to private generation costs. Some examples of results are (results in Ecents/kWh):

- **Hydro**: External cost 0.09, private cost 11.04, total cost 11.13
- **Nuclear**: External cost 0.14, private cost 2.62, total cost 2.76
- **Wind,** onshore: External cost 0.07, private cost 6.02, total cost 6.09
- **Wind,** offshore: External cost 0.07, private cost 6.14, total cost 6.21
- **Solar PV**: External cost 0.80, private cost 25.14, total cost 25.94

According to this study, nuclear power has the lowest cost by a wide margin whereas solar photovoltaic has by far the highest cost when external and social costs are included.

4.4 Revenues

There are two sides to the economy of production, cost and income. In most countries, VREs still depend on various types of subsidies to be competitive even though they do not bear their system costs. The subsidies vary between countries but two examples are green certificates and certificates of origin. Green certificates force all utilities to supply a specific fraction of their electricity mix from sources that have been politically classified as renewable. Hence, irrespective of cost, renewables have a secured market. Certificates of origin, on the other hand, means that utilities can add an extra tariff on electricity produced by sources classified as sustainable in the EU taxonomy.

A new source of extra income for VREs is the introduction of PPA[3] or Power Purchase Agreements. Such agreements involve long-term contracts of renewables at a fixed price, often substantially above market price. This is contrary to the conventional situation where one gets a discount by signing for a long term. It is also quite problematic, in particular with wind power, and of great concern for the grid-responsible authority. The high variability of VRE causes large fluctuations of the market price, at times prices become negative, but the source is not affected; the price feedback signal is disconnected. The PPA supplier keeps feeding in power even though there is no demand and this disrupts the normal function of the grid.

4.5 Examples

A few examples regarding the cost of replacing nuclear power by means of wind power, currently the most touted alternative, is rather depressing reading. How is it possible that politicians decide on restructuring the entire electricity system without due consequence analysis regarding functionality, cost and environmental consequences?

A study by professor H W Sinn[52] at the university of Munich indicates that the cost of replacing 3 reactors by wind and pumped-storage hydro power will cost as much 32 new reactors. Going for battery storage instead is even worse; the cost will equal that of 85 new reactors and the battery storage must be replaced perhaps every ten years.

SWECO [35] has made an estimate of the cost of Sweden going 100 % renewable and came up with the figure 160 000 M€. Many of the required solutions are not available at present and, as is the case with many long-term, large-scale infrastructure projects, it would not be surprising if the real cost were much higher.

Hong et al[27] made a detailed study of the economic and environmental consequences of phasing out the Swedish nuclear power. Replacement would be wind power with gas power as balance. The study shows that the cost of electricity would increase by a factor 2-10; the larger the share of wind power the higher would be the cost. Emissions of carbon dioxide would also increase. Other consequences would be reduced efficiency and increased wear of hydro plants.

Proponents of solar and wind power often purport that their costs have rapidly gone down and that wind power is the lowest-cost low-carbon alternative. However, there is little evidence that this is true even at plant level and certainly not at system level. Figure 4.5 indicates a clear correlation between cost of electricity and the share of solar and wind power.

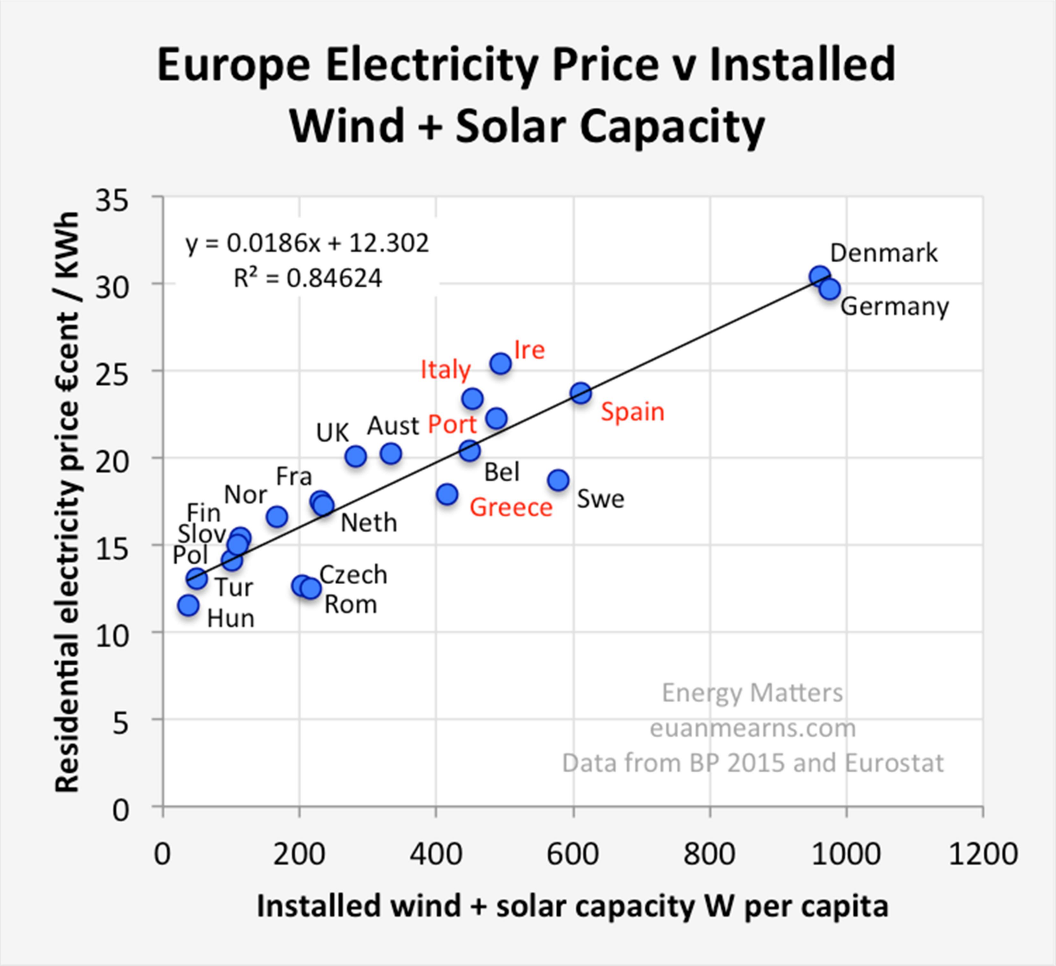


Figure 4.5 Relation[42] between the cost of electricity and the fraction of solar and wind power in the electricity systems of different countries.

Professor Gordon Hughes[13] has made detailed studies of the economy of real-world wind and solar plants. His findings are complex but sobering:

- "The actual costs of onshore and offshore wind generation have not fallen significantly over the last two decades and there is little prospect that they will fall significantly in the next five or even ten years.

- While some of the components which feed into the calculation of costs have fallen, the overall costs have not. For example, the weighted return for investors and lenders has declined sharply, especially for offshore wind, because of a fall in perceived risk. In addition, the average output per MW of new capacity may have increased, particularly for offshore turbines. However, these gains have been offset by higher operating and maintenance costs.

- Far from falling, the actual capital costs per MW of capacity to build new wind farms increased substantially from 2002 to about 2015 and have, at best, remained constant since then. Reports discussing the construction of new offshore wind farms in the early 2020s imply that their costs may fall by 2025, but such reports are consistently unreliable as well as being incomplete. Final costs tend to be significantly higher, so little weight can be attached to forecasts of future costs.

- Far from falling, the operating costs per MW of new capacity have increased significantly for both onshore and offshore wind farms over the last two decades. In addition, operating costs for existing wind farms tend to increase even more rapidly as they age. The cost increase for new capacity seems to be due to the shift to sites that are more remote or difficult to service. Much of the increase with age is due to the frequency of equipment failures and the need for preventative maintenance, both of which are strongly associated with the adoption of new generations of larger turbines – both onshore and offshore.

- Turbine manufacturers and wind operators appear to be relying on an increase in load factors via (i) an increase in hub heights to take advantage of higher wind speeds, and (ii) changes in the engineering balance between blade area and generator capacity. However, the inferior reliability of new turbine generations leads to a more rapid decline in performance with age, so that the ultimate effect on average performance over the life-time of new turbines is unclear.

- The combination of increasing operating and maintenance costs with lower yields with ageing means that at current market prices the expected revenues from electricity generation will be less than expected operating costs after the expiry of contracts guaranteeing above-market prices. The length of these contracts has been reduced, implying a need to recover capital costs over a shorter economic life, which pushes up the effective capital charge."

5 Environment

For decades, politicians, environmental activists and media have presented bio, solar and wind power as environmentally "benign", "renewable", "sustainable", "climate smart" etc. without clear definitions of the concepts. The sources may in some sense be considered renewable but transforming this energy to electricity involves equipment that requires large amounts of non-renewable materials for its construction. The ubiquitous misuse in marketing of unsubstantiated environmental claims regarding renewables was reported[24] to the Swedish Consumer Agency in 2016. As this practice is against current marketing laws, the Agency has decided to watch this issue more closely in the future and to apply the international guidelines by ICC[29].

In this section I will discuss some environmental impacts of electricity generation starting with global aspects such as emission of green-house gases, use of non-renewable materials and sustainability ending up with local aspects such as biological diversity, acoustic environment, scenic landscapes etc.

5.1 Green-house gases and global warming

The fear of anthropogenic climate change is a major driver for investment in renewable sources of energy. The main focus is on emissions of carbon dioxide and hence it is of interest to look at the figures for some of the low-carbon alternatives. One of the best accounts comes from the EPD[63, 64] (Environmental Product Declaration) certificates of Vattenfall (the former Swedish state power board). The data are based on the international standards ISO 14001[55] and 45001[32] and have been certified by external auditors.

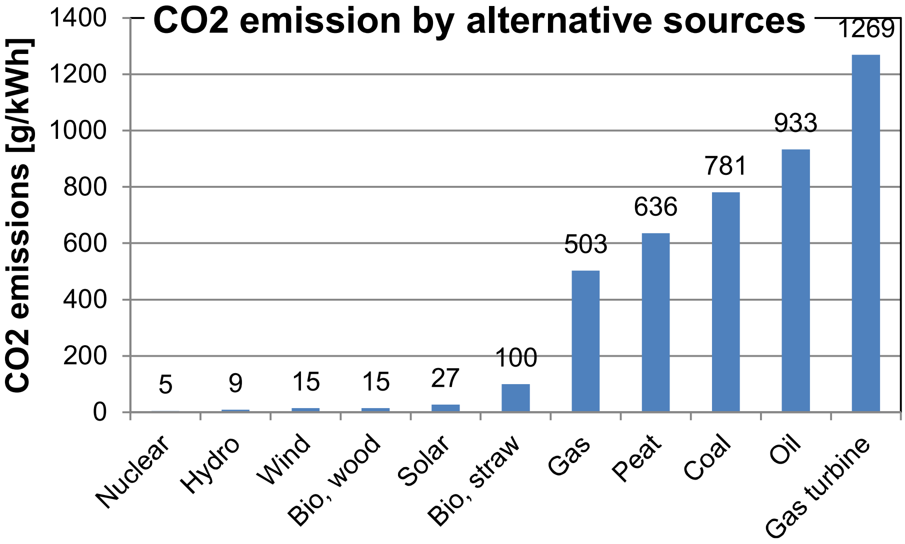


Figure 5.1 Carbon dioxide emissions by alternative sources.

Figure 5.1 shows that contrary to common perception, nuclear power has the lowest specific emission of carbon dioxide. Hydro power has almost twice, wind and bio (wood chips) three and solar five times the value of nuclear. Note that these are values at plant level. At system level, which is the level that really matters, the value of nuclear is unchanged whereas the values of wind and solar may more than double.

There may be other aspects also regarding global temperature changes. A 2018 study conducted by scientists from Harvard, published in the academic journal Joule, found that wind turbines cause significant local increase in surface temperature in the areas where they are located by mixing of air between strata of the atmosphere. The study looks at what would happen if the United States tried to obtain all of its energy from wind turbines. It found that the mixing of warmer air and cooler air results in a temperature increase of 0.54 °C in the areas where the wind turbines would be located. According to the study, surface temperatures in the United States would increase more due to wind turbines mixing air in the atmosphere than would be offset by reducing emissions.

This study is based on the same type of models as used to predict global warming by carbon dioxide and hence liable to the same criticism but still, it is difficult to see why believers in an upcoming climate disaster are so eager to replace the factually best alternative by something that is more of a problem than a solution. How can wind, bio and solar power be "climate smart"?

5.2 Use of non-renewable materials

As already noted (1.1), the concept of renewable energy is an oxymoron but has become an institutional conceptualization in the public debate. Harjanne and Korhonen[26] discuss in some detail this problematic terminology and the linked concept of sustainability (see 5.3; renewable does not equal sustainable and vice versa). The concepts are usually not defined and they include sources of energy of very different kinds, e.g. solar, wind, geothermal, hydro, wave and tidal power as well as various types of bio fuels.

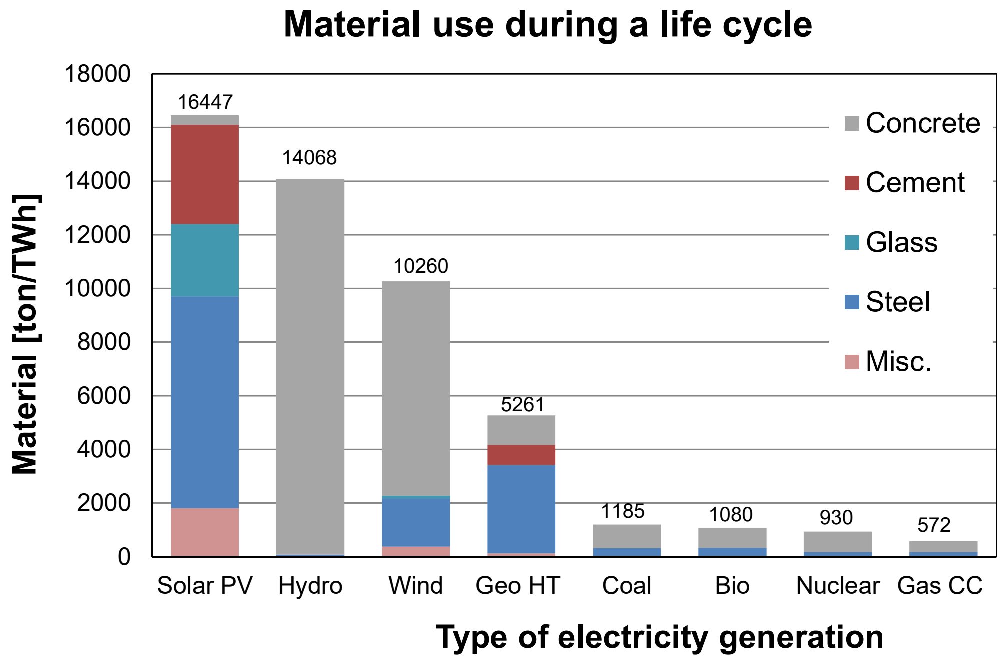


Figure 5.2 Specific use of materials for alternative ways of generating electricity (source: Quadrennial Technology Review[14], September 2015, U.S. Department of Energy, table 10.4).

How do the so called renewable alternatives fare in a comparison? Figure 5.2 provides a compilation of data from a report[14] by the US Department of Energy. The following designations are used: gas CC = natural gas with a combined cycle; nuclear = a pressurized water reactor (PWR); Solar PV = a silicon photovoltaic solar cell, silicon; Geo HT = a high temperature geothermal plant. Misc. = miscellaneous materials used in small quantities such as aluminium, lead, iron, silicon, copper and plastics. Data apply to the generating plants per se, i.e. required system-level installations are not included.

Clearly “renewables” have the highest demand for non-renewable materials! The poorest performer is solar power followed by hydro and wind power. Solar requires 15 times the value of nuclear power and wind 10 times. These alternatives use very little material for their operation whereas gas, with low specific demand for plant construction, uses a lot of non-renewable gas during operation. The challenge of most flowing-energy alternatives (renewables) is the low energy density of the energy flows plus their variability. Low energy density results in high material and land area requirements for the harvesting process.

Steel and concrete are two of the most prevalent construction materials. Steel may be recycled but not so concrete. For wind power installations the massive concrete foundations will simply be covered and left in the ground at decommissioning. However, there are important non-renewables that do not carry a lot of physical but rather more of a functional weight. Examples are rare-earth metals, cobalt etc. used in wind turbine generators and solar panels. These materials go into the category miscellaneous and are already in short supply. For some, the full capacity of all known sources is already more or less spoken for.

Another problematic material is the reinforced plastic used for wind turbine rotor blades. It is a toxic waste and there is currently no good method for its recycling; mountains of scrapped blades are rapidly rising. According to WINDEUROPE there are at present (2020) around 130,000 wind turbines in operation in Europe comprising around 2.5 million tons of plastic composite material. 12,000 wind turbines, i.e. 36,000 rotor blades, are expected to reach their End-of-Life within 5 years. A 2 MW turbine has 3 rotor blades of 50 m length weighing 7 tonnes each and thus each rotor consists of around 3x7 = 21 tons of GFRP =Glass Fibre Reinforced Plastic.

Not only is the GFRP an end-of-use problem, it is also a serious operational problem. Sandöy[50] and Solberg et al[54], summarize findings from the report[49] “Rain Erosion Maps for Wind Turbines” and other studies. They conclude that a wind farm of 20 units will spread more than one ton of micro plastics per year in its vicinity. Over the expected life-time, this will amount to 25 tons of which 30-40 % is the highly toxic Bisphenol A[44] (see also 6.1 and 7.1). The industry outwards treats this problem lightly and provides unreasonably low values of emission while at the same time spend a lot of resources to minimize the severe production loss that the erosion causes. According to NMF[44], the wind industry is one of the largest sources of epoxy-based micro plastics emissions.

5.3 Sustainability

No energy supply comes without some societal and environmental impact. Harjanne and Korhonen address the common misconception of a direct connection between the concepts renewable and sustainable and the lack of clear definitions. The Brundtland Report in 1987 defined sustainable development as *development that meets the needs of the present without compromising the ability of future generations to meet their own needs* (United Nations 1987). The authors propose their own, slightly more pragmatic definition of sustainability: *Sustainable energy enables societal development that is largely, even if not entirely, decoupled from increasing environmental degradation for the foreseeable future*.

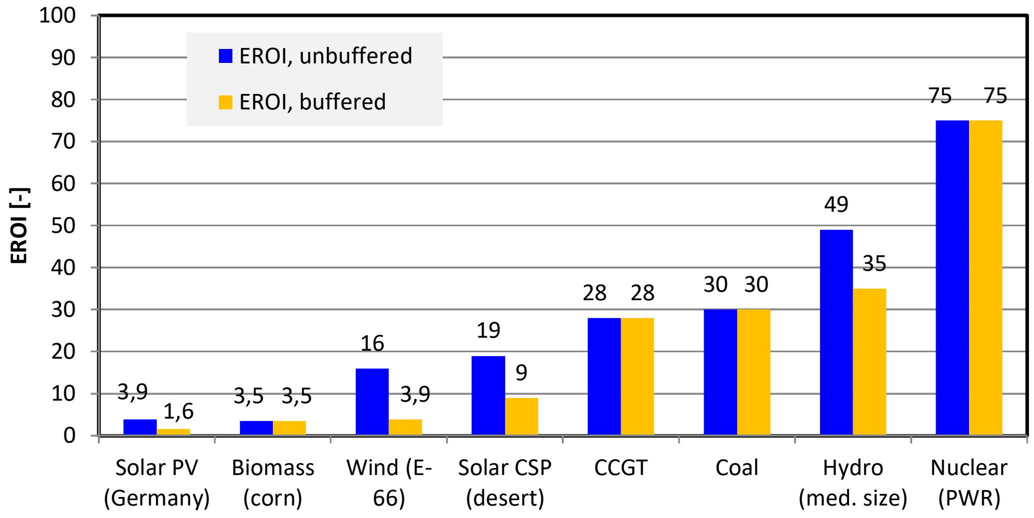


Figure 5.3 EROI based on data from Weissbach[33, 65] and presented by Kelly[33]. Blue (left hand) bars apply to plant-level data (no storage) while yellow bars (right hand) bars represent system-level data, i.e. including demand for storage.

To be sustainable, it is obvious that a generating facility for electricity must have an output over a life cycle that is larger than the energy required for building, operating and decommissioning the plant (all types of energy converted to the equivalent amount of electrical energy). The ratio between output and input is known as EROI[33, 65], Energy Return On Investment. Figure 5.3 clearly shows that in this respect nuclear power is by far the best alternative. At system level solar power struggles even to produce a net surplus. Biomass and wind fare better but are still below 4 whereas nuclear power has a value of 75. Fuel-based sources such as biomass, coal and nuclear have their storage intrinsically in the fuel and thus do not require external storages whereas this is an important factor for weather-dependent sources such as solar, wind and hydro power.

Note that wind and large-scale solar power are usually located far away from users. At system level this means that not only will the power required for grid expansion and balance affect EROI but also the transmission losses. For instance, Swedish exports involve 20 % losses and these will both reduce net delivery and increase the required system input by 20 %; a total reduction of EROI by 40 %.

5.4 Land use

The location of energy facilities is likely to affect the aesthetic value of the land. For instance, wind (both onshore and offshore), rooftop solar, hydro and tidal electricity generation are very location-dependent and may thus impinge on the views of valued natural landscapes and affect the utility of residents and visitors.

Onshore wind power, in particular, will initiate organized protests wherever it is planned. Currently, the height of wind turbines exceeds 250 m with rotor diameters of 150 m. Figure 5.4 eminently illustrates the size of the towers and the large areas required by the open-cast mining for wind power. The industrial sites are usually located in sensitive rural landscapes and the steel-tower forest often has a much larger negative effect on local environment than e.g. open-cast coal mines. They and their blinking lights may be visible for more than a hundred kilometres.

Figure 5.4 Wind power greatly affects local environment. The ”turf” below the towers is a fully grown forest with 30 m high trees and one may just discern the power line among the tree tops in the foreground (Kalahatten at Piteå; archive photo by Helena Landstedt/TT).

Table 5.1, based on data from Harjanne and Korhonen[26], underlines the large difference in land-use requirement between “renewable” sources of energy and dispatchable sources such as coal and nuclear power. Compared to nuclear, biomass requires a specific area use which is 5000 times larger, solar photovoltaic and hydro require 100 times more and wind power 10 times more. Note that regarding wind power, the figure does not include the rather extensive areas required by new power lines.

Table 5.1 Land-use requirement[26] of some “renewable” sources of energy compared to the dispatchable sources of coal and nuclear power.

Energy Source	**Energy form**	**Specific land use** [m^2/MWh]	**Capacity factor** [-]	**Variability**
Solar PV	Electric; solar-to-elec.	10	0.16-0.30	Diurnal, seasonal
Hydro	Kinetic mechanical	10	0.12-0.62	Seasonal, between years
Wind	Kinetic mechanical	1	0.26-0.52	Stochastic, seasonal, between years
Biomass	Chemical	500	0.70-0.90	Depends on fuel properties
Coal	Chemical	0.2 -5	0.75-0.93	Fully controllable
Nuclear	Nuclear fission	0.1	0.85-0.90	Depends on fuel and plant

The negative effect of industrial wind power on the scenery is not only of aesthetic concern for local residents. It directly affects tourism and the local work opportunities provided by related business activities. It will also have a negative effect on property values.

Aesthetic concerns are not limited to renewable electricity sources. However, electricity generation that is not location-dependent, like fossil fuels and nuclear power, is sited in areas where they will not impinge too heavily on property values or natural views. Also, siting is mostly in close proximity to users and hence there is little need for long and area-requiring power lines.

5.5 Biological diversity

The most invasive of the renewable technologies regarding biological diversity are probably biomass and wind power. Modern harvesting and plantation-type forestry has transformed the environment in large areas of global forests. Wind power adds to the problem as much of it is built on high ridges, with low accessibility and low priority for traditional forestry. These ridges provide much of what is left of old trees and are important habitats for wood fowl, birds and animals of prey, lichen, moss etc. Research indicates that many aspects of wind power are negative for humans, birds and animals. Birds and bats are killed in large numbers and medical studies show that animals living in the proximity of wind turbines experience large stress levels in the brain. The fact that inventories of birdlife and wildlife are done by the exploiter’s own consultants is problematic from a credibility point of view.

- **Aquatic life:** In regions with hydro power, the wind-power-induced large and frequent control of water flow and water table is detrimental to the aquatic life in rivers.

- **Insects:** According to estimates by Krueger, German wind industries kill around 1200 tons of insects per year. This is also a problem for the wind turbines as a film of dead insects on the rotor blades reduces their efficiency.

- **Birdlife:** The Spanish Society of Ornithology estimated in 2012 that yearly Spain’s 18,000 wind turbines might be killing 6 to 18 million birds and bats. In a summary[15] of avian impacts at wind turbines by Benner et al., bird deaths per turbine per year were as high as 309 in Germany and 895 in Sweden. Studies[8] in Sweden show that the prevalence of wildfowl such as wood grouse, capercaillie etc. goes down by 60 % in wind industrial areas. This is supported by other studies in Austria and Norway. The capercaillie is considered to be an ”umbrella species”, i.e. results for the capercaillie are also valid for other rare birds. The negative consequences for raptors are well-known. Just one site at Smöla in Norway has registered hundreds of white-tailed eagles killed by the wind turbines. For the golden eagle, it is recommended to have an undisturbed area of 10 km around a nest. In areas of large exploitation this will not be possible as disturbance areas from adjacent industries overlap. Contrary to the requirements of the European directive on species and habitats, this is not considered in the judicial process.

- **Wildlife:** Disturbing factors are noise, fluttering shadows and a fragmentation of habitats, not least by large stretches of new roads. Wind industries are often built in remote areas which have been sanctuaries to large predators as well as to their prey. A paucity of data exists with which to assess the effects of wind-turbine noise on terrestrial wildlife, despite growing concern about the impact of infrasound from wind farms on human health and well-being. Agnew et al[2] have measured chronic stress in the brains of badgers in the proximity of wind turbines. Badgers are suitable mammals to further assess physiologic changes as a result of wind farm developments because they often reside in habitats in which turbines are constructed. Importantly, badgers also have a hearing range which is similar to humans.

- **Reindeer herding:** The Sami Parliament is very critical of the neglect of cumulative effects of multiple wind industries in areas of reindeer herding, i.e. most of northern Finland, Norway and Sweden. Studies by SLU[53], the Swedish University of Agriculture, clearly show that reindeer avoid areas of wind power. The ongoing exploitation risks a total annihilation of reindeer herding and thus the Sami culture.

6 Health

Burning of fossil fuels, coal in particular, is by far the largest source of health problems caused by electricity generation. In this text, however, I will only look at the low-carbon alternatives nuclear, wind and bio power regarding matters of health.

6.1 Radiation, gas emissions and particles

The risks of nuclear power are rather well-known. In this context, however, it is important to stress the difference between risk and an actual health problem. The only occasion, so far, when the risk of nuclear power has turned into an actual health problem is the severe accident at Chernobyl. WHO[66] assessed that less than 50 people died as a direct consequence of the accident, an estimated 2,200 of the 200,000 involved in rescue operations may have a radiation-related shortened lifespan and around 4000 people were inflicted by thyroid cancer but have a survival rate of 99 %.

This reactor was half military and used for large-scale experiments, one of which resulted in the disaster. As a comparison, Swedish authorities estimate that the number on annual deaths due to natural radioactive radiation in dwellings is around 500. This means that since the referendum in 1980, when it was decided to phase out nuclear power in Sweden, an estimated 20,000 people have their lifetimes shortened by natural radiation but none due to Swedish nuclear power.

Burning of biomass is a major source of particle and hydrocarbon emissions. Ultrafine particles from wood stoves have been identified as a health hazard in areas where their use is prevalent. Unburned hydrocarbons have been known to cause biomass-related smog in the USA and in Sweden it is estimated small-scale wood stoves cause larger emissions of hydrocarbons than those of all industries and traffic put together. Finally, burning of biomass causes acidification to an even higher degree than e.g. oil (in this case by NOx emissions resulting in precipitation of nitric acid). In large-scale plants for generation of electricity these problems can be dealt with but they must be handled and they come at a cost.

Wind power is identified as one of the largest emission sources of epoxy-based micro plastics due to leading edge erosion (see Figure 6.1). Over their 20-year lifespan, emissions from just one site of 20 wind power units may amount to 25 tonnes, a third of which is the highly toxic substance bisphenol A (BPA; high on the EU-list of hazardous substances). Just 1 kg of BPA may contaminate 10 thousand million litres of water[54]. According to WHO, drinking water should contain less than 0.1 microgram of BPA per litre.

Figure 6.1 Leading edge erosion of a wind-turbine rotor blade (@MarkELacey).

6.2 Noise

When it comes to wind power by far the worst health-related problem due to its operation is noise. WHO and other health organizations have long argued the case of reducing noise levels in the environment; an environment free of noise and with nightly skies undisturbed by artificial lighting is a commodity in short supply in modern society. As the countryside is turned into large-scale industrial areas, the scenery and the acoustic environment is totally transformed. All over the world people complain of serious noise disturbances from enormous rotor blades plus light disturbances by fluttering shadows and blinking lights at night. ”Wind power syndrome” has become an established medical term for noise-related symptoms, which include disturbance of sleep, headaches, dizziness, nausea, tinnitus as well as heart and vascular conditions.

The Environmental Noise Directive (2002/49/EC) recognizes that community noise is potentially harmful and so requires that all EU member states map the noise exposure of their populations. Despite this, wind turbines are often erected in quiet rural areas, where sleep disturbance due to wind-turbine noise is reported more frequently. In particular, low-frequency and infra-sound are very problematic due to their range of disturbance; infra sound more than tens of kilometres. The low frequencies are also very difficult to insulate against in buildings; indeed, one may at times experience amplification inside buildings.

There are many studies to support the complaints of seriously negative effects of wind-turbine noise. For instance, Germany’s Max Planck Institute has identified sub-audible infrasound as the cause of stress, sleep disruption etc. and a Swedish group has shown that it is the pulsating nature of low-frequency wind turbine noise, “amplitude modulation”, that is responsible for sleep problems among those forced to live with it. A Finnish study claims that the safe setback distance for dwellings is of the order of 15 km; this is quite different from current permissible distances of sometimes less than 1 km.

Stelling[57] observes that "Complaints from citizens, including reports of adverse health impacts have persisted and increased as more turbines have been installed. The reported symptoms conform to those described internationally by many people living near wind turbines. With the proliferation of recent research and the rediscovery of earlier, until now largely ignored studies, infrasound and low frequency noise (LFN) can no longer be dismissed as irrelevant."

It is therefore incomprehensible that this situation is still not quite accepted by authorities in the granting-of-permission process. Acoustic experts have for decades objected to the unscientific and rather nonsensical application of dB_A as the unit of choice in the characterization of wind-turbine noise. This is measured with a filter that virtually eliminates the low frequencies, which are the most problematic regarding range of disturbance, penetration in buildings and adverse health effects. Furthermore, the dB-values do not at all consider the tonal and repetitive aspects of wind-turbine noise; these factors make wind-turbine noise much more aggravating than virtually any other source of noise.

Many acoustic experts[7, 37] opine that the computational models and acceptance criteria used for wind power evaluations are inadequate and not fit-for-purpose. Reports[19] on serious noise problems abound but authorities and courts prefer a simple measure to ascertain transparency and rule of law and to simplify the judicial process. But if this measure is irrelevant for the purpose of environmental legislation, i.e. to protect the health and living conditions of people, the measurement is totally pointless. Why should legal rights only apply to exploiters and not to private citizens? It is after all the common man who will pay the bills of the exploiters and suffer a ruined living environment. Some of the serious problems of current practice in the judicial process regarding building permission of wind turbines are:

Computational models are typically not validated for the specific application. They do not consider the topography of the landscape, thermal refraction in northern climates and other weather-related phenomena such as frosting of rotor blades etc. Research by Larsson at the university of Uppsala[37] shows that the models used greatly underestimate the noise. He also claims that diurnal differences in weather may cause noise-level changes up to 20-25 dB_A. The acceptance value in Sweden is 40 dB_A for the total noise level. Practical studies[5, 6] of the influence of frost on rotor surfaces indicate large noise variations with a mean increase of the sound power of 7 dB L_{wA} (1-2 weeks) and a maximum of 10-20 dB_{LwA}. Note that this refers to the emission power of the source and not the sound pressure at the exposed location as indicated by dB_A.

Acceptance levels for wind-turbine noise are not up to the task. It is difficult to understand why the level for wind-turbine noise is generally set to 40 dB_A. This is a value that was designed for quite different types of noise and environment. Wind-turbine noise has a large share of infrasound and low-frequency noise with both tonal and modulated properties. Also, the large industries are generally built in extremely quiet rural areas. Even for less problematic types of noise, the Swedish Environmental Protection Agency prescribes a maximum value of 35 dB_A in such locations, but this is hardly ever implemented in practice (the Agency has been instructed by the government to facilitate the expansion of wind power).

Research in e.g. Great Britain[9] and Canada[25] show that one important reason for the obnoxious nature of wind-turbine noise is a specific type of amplitude modulation known as OAM[9]. This is not at all reflected in a measure such as dB_A; it may annoy over large distances and it penetrates into buildings. Also the infrasound part of the noise is affected by the modulation and has a different character from other types of infrasound and a documented negative health effect[16].

Experience from wind turbines in operation indicate that people perceive great discomfort even at measured levels much lower than 40 dB_A. As early as 2011 Canadian research [67] raised this issue and recommended changes in the related directives. The recommendations by the Public Health Agency of Sweden regarding low frequency noise, which are now beginning to be applied, give no clue as to how these recommendations should be of relevance for wind-turbine noise.

Measurements are usually performed by the same company that does the calculations. It is quite unsatisfactory that a company that is subcontracted by the exploiter not only makes the calculations for approval but also conducts the measurements to verify its own calculations. The verifying measurements are normally done by single measurements in summer. This is like measuring the temperature in summer and then concluding that there will be no problems with icing. Conny Larsson of Uppsala University highlights the large diurnal variability, 20-25 dB_A, of wind-turbine noise. Hence sufficiently long periods of continuous measurement are required with sufficient frequency resolution during different seasons of the year to verify that the acceptance criteria are met.

Regulations relating to wind-turbine noise are in desperate need of reformation in response to the abundance of available information on its problematic character. Authorities and courts do not respect the negative consequences for local people struck by wind-power exploitation. Also, authorities and courts in general take a very one-sided stand and regularly violate laws and international regulations. Exploiters get their permission based on irrelevant information and once they have their permission it is extremely difficult for local people to repeal the decision even if subsequent inspection reveals that the operation is in violation of the requirements. The lack of knowledge and missing inspection and evaluation of accumulated experience has resulted in major shortcomings in noise regulations for wind turbines. People as well as wildlife are afflicted by wind-turbine noise to a much higher degree than commonly presented in the environmental-consequence documents established prior to an operational permit.

7 Safety

There are many aspects of energy-supply systems that may contribute to people being exposed to the risk of accidents or illness. The report by OECD[34] on the levelised cost of electricity also discusses the economic consequences of fatalities and health issues in some detail. The main reference is the ENSAD data base. The Energy-related Severe Accidents Database is continuously updated and is considered to be the most reliable and complete source of information regarding human-made severe accidents in the energy sector. Note that risk involves the probability of an accident to happen whereas statistics refer to actual incidents.

7.1 Risks

I will only dwell on a few categories regarding low-carbon technologies, mostly concerning wind power, as this is a technology that is rapidly expanding.

Nuclear power: The main risk of nuclear power is exposure to radioactive radiation. This risk is extremely low (see Table 7.1). There are also mechanical risks during construction and decommissioning but the very large output of a nuclear plant makes the risk per kWh very low.

Hydro power: The large dams required to make hydro power controllable present a hazard due to dam failure. The risk is low but the consequences dire (see Table 7.1). The risk during construction is similar to that of nuclear power.

Biomass: The main hazard of biomass is that of most combustive technologies. Emissions of particles and adverse gases will influence the respiratory air quality. In this respect biomass is no better than coal. In fact, the WHO has called biomass burning in developing countries a major global health issue.

Wind power: There are a number of risks related to wind power such as fire, mechanical and chemical risks.

Figure 7.1 Fire in a wind-turbine generator.

- *Fire:* It is not uncommon for wind turbines to catch fire and as they are sited in the best wind positions on top wooded ridges the risk of wildfire is high (see Figure 7.1.). Rural locations also mean that they are far from any fire brigade.

- *Mechanical risk:* Wind-turbine towers topple over, lose their rotor blades and may throw large chunks of ice up to half a kilometre (see Figure 7.2). Due to the danger of ice throws, hunting is no longer permitted during the winter season in some wind-turbine areas. Contrary to the EU machinery directive, fencing of the industrial site is not required in Sweden. Also, the required safety inspections before start of operation are often missing. Another mechanical risk is the increased risk of erosion and slides of river banks as hydro power must regulate the flow and water table much more frequently in order to support the intermittent wind power.

Figure 7.2 Collapsed wind-turbine tower.

- *Chemical risk*: The rotor blades of wind turbines usually contain Bisphenol A. Due to erosion of the blades, this substance is spread in nature and may affect the ground or surface water (see 5.2 and 496.1). Bisphenol A (BPA) is on the EU list of particularly toxic chemical substances. It is cancerous and affects the reproductivity of humans and animals. There is also a rapidly growing mountain of toxic waste from wind turbines and solar cells to which there is currently no acceptable solution. If, during decommissioning, the turbine towers are simply felled to save money, the spread of micro plastics will be considerable.

7.2 Statistics

Risk assessment and statistics are two different things. Even though common perception is that nuclear power is a high-risk source, statistics verify the scientific analysis that the actual risk is extremely low (see Table 7.1). On the other hand, hydro power is generally perceived as a low-risk source but again statistics tell a different story. However, it is important to understand that there are substantial differences between individual countries.

Conca[12] notes that the U.S. death rates for coal are much lower than those for China, which is strictly a result of regulation and the Clean Air Act. Hydro is dominated by a few rare large dam failures like Banqiao in China in 1976, which killed about 171,000 people. Workers still regularly fall off wind turbines during maintenance but since relatively little electricity production so far comes from wind, the total number of deaths is small. Nuclear has the lowest death print, even with the worst-case Chernobyl numbers and Fukushima projections, uranium mining deaths, and using the Linear No-Threshold Dose hypothesis. The reason that the nuclear number is small is nuclear power produces so much electricity per unit and that it must be able to withstand the worst case disaster, no matter how unlikely.

The table below lists the mortality rate of each energy source as deaths per billion kWhs produced. The numbers are a combination of actual direct deaths and epidemiological estimates and are rounded to two significant figures. For coal, oil and biomass, carbon particulates resulting from burning are the main cause of upper respiratory distress.

Table 7.1 Mortality rate for alternative sources of electricity according to Conca[12].

Energy Source	Mortality Rate [deaths per billion kWh]	Comments
Coal – global average	100,000	50 % of global electricity
Coal – China	170,000	75 % of China's electricity
Coal – U.S.	10,000	44 % of U.S. electricity
Oil	36,000	36 % of total energy, 8 % of electricity
Natural Gas	4,000	20 % global electricity
Biofuel/Biomass	24,000	21 % of global energy
Solar (rooftop)	440	< 1 % of global electricity
Wind	150	~ 1 % of global electricity
Hydro – global average	1,400	15 % of global electricity
Hydro – U.S	0.01	7 % of U.S. electricity
Nuclear – global average	90	17 % of global electricity (incl. Chern&Fukush)
Nuclear – U.S.	0.01	19 % of U.S. electricity

8 Discussion

In the wake of the climate debate, the politically driven transformation of the energy system is based more on belief than on fact. I have tried in this text to show that the choices made seem contradictory to the envisaged future. For instance, replacing nuclear power by wind power plus something that is still not clear, will result in an electricity system that:

- is more complex and less functional (laws for future rationing are already in place but this is called flexible demand),
- has a lower security of supply and a lower electric quality,
- increases the emissions of carbon dioxide by a factor 3-10,
- increases the use of non-renewable resources by a factor > 10,
- lowers the sustainability of electric-energy supply by a factor > 10,
- harms local environment, the living conditions of people and wildlife and is detrimental to biological diversity,
- is negative to aquatic life in rivers (due an increased variability in the operation of hydro power),
- reduces the efficiency and revenues of hydro power and largely increases the wear and operational costs of hydro power,
- puts democracy and human rights at risk for people living in the countryside,
- is much more costly.

The transformation of electric-supply systems in many countries, aiming for a large share of renewables, is motivated by climate and environmental considerations. Sadly, facts point in a different direction; nuclear power is superior functionally as well as environmentally and also more cost-effective. It is puzzling to see the stand of environmentalists in this matter. To cite L A Johansson, Kompass:

“The environmental movement has not only distanced itself from its original purpose in the sense that it is ready to sacrifice natural values for abstract ideas regarding climate, it has also made a U-turn from a grass root perspective caring for the local perspective to a top-down ideology that is forced upon people from above. It is a moralizing ideology which people with power in politics and business refer to in order to motivate unpopular ventures. It works in the sense that anyone who opposes renewable energy sources according to the ruling narrative is a despicable person.”

As concluding remark I would like to cite also the former CEO of ABB, Percy Barnevik. When the political drive for solar and wind power started in Sweden he summarized the situation as follows (at that time, the Swedish grid used approximately half nuclear and half hydro power):

”In Sweden we have low-cost electricity, we have ”clean” electricity, we have security of supply, in short we have an electricity supply that all other countries wish they had. And our main concern is how to get out of this situation as quickly as possible.”

9 Abbreviations and designations

B	Billion = one million millions (one thousand milliards)
BPA	Bisphenol A
CCGT	Combined-cycle gas turbine
COP	Coefficient of Performance
DOE	Department Of Energy (United States)
EPA	Environmental Protection Agency (United States)
EPD	Environmental Product Declaration
EU	European Union
ICC	International Chamber of Commerce
IEA	International Energy Agency
GW	gigawatt = 10^9 W = one thousand million watts
GWh	gigawatthour = 10^9 Wh = one thousand million watthours
iREN	intermittent Renewable Energy
kW	kilowatt = 10^3 W = one thousand watts
kWh	kilowatthour = 10^3 Wh = one thousand watthours
MW	megawatt = 10^6 W = one million watts
MWh	megawatthour = 10^6 Wh = one million watthours
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-operation and Development
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCOE	Levelised Cost Of Electricity
PV	Photovoltaic
T&D	Transmission and distribution
TW	terawatt = 10^{12} W = one million million watts
TWh	terawatthour = 10^{12} Wh = one million million watthours
VRE	Variable Renewable Energy
WHO	World Health Organization

Q	Heat	[W]
W	Work	[W]
COP	Coefficient Of Performance	[-]
η	Efficiency	[-]

10 References

1. 2017. Nuclear Energy Is the Fastest and Lowest-Cost Clean Energy Solution. (Thoughtscapism.).
2. Agnew, R C N, Smith, V J, Fowkes, R C, 2016. Wind turbines cause chronic stress in badgers (Meles meles) in Great Britain. Journal of Wildlife Diseases, 2016-05-17.
3. Akinci, E, 2020. PPA and the electricity market (in Swedish). pp. 29. (ELS Analysis.).
4. Aldén, L, 2013. Dismounting of wind turbines and finishing treatment of the site (in Swedish). Energimyndigheten dnr 2012-008255, (Uppsala University.) Visby.
5. Arbinge, P, 2012. The effect on noise emission from wind turbines due to ice accretion on rotor blades. Thesis for M.Sc. KTH report TRITA-AVE-2012:62, pp. 75. (KTH.) Stockholm.
6. Arbinge, P, Appelqvist, P, 2013. Investigation of the effect on noise emission from wind turbines due to ice accretion on rotor blades (in Swedish). Bygg & teknik, no. 3, 2013, pp. 59-62. Stockholm.
7. Bernström, R, 2014. Granliden/Järnstad/Ryket, Ödeshögs commune - statement on the noise from wind turbines (in Swedish). (Bernström akustik.).
8. Björklund, S, 2016. Negative consequences of windpower exploitation effects on courting places for caipercaille (in Swedish). Dalademokraten, 2016.
9. Cand, M, Bullmore, A, Wilson, B, 2013. Wind Turbine Amplitude Modulation: Research to Improve Understanding as to its Cause & Effect. (Renewable UK - The voice of wind & marine energy.) England.
10. Carbajales-Dale, M, Barnhart, C J, Benson, S M, 2014. Can we afford storage? A dynamic net energy analysis of renewable electricity generation supported by energy storage. Energy & Environmental Science, 2014-07, pp. 1538-1544.
11. Cohen, B L, 1990. Chapter 9 - The nuclear energy option - Costs of nuclear power plants - what went wrong? (University of Pittsburgh.) Plenum Press.
12. Conca, J, 2016. How Deadly Is Your Kilowatt? . Forbes, 2012-06-10.
13. Constable, J, Hughes, G, 2020. The Costs of Offshore Wind Power: Blindness and Insight. Briefings for Britain, 2020-09-21.
14. DOE, 2015. Quadrennial Technology Review - An assessment of energy technologies and research opportunities - Chapter 10: Concepts in Integrated Analysis. Quadrennial Technology Review 2015, (US Department of Energy.).
15. Duchamp , M, 2012. Spanish wind farms kill 6-18 million birds & bats a year Save the eagles international, 2012-01-14.

16. Enbom, H, Malcus-Enbom, I, al, e, 2013. Infra sound from wind turbines - a neglected health risk (in Swedish). Lälartidningen, 2013-08-06, pp. 32-33.

17. EU, 2016. Commission Regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators. pp. 68. (EU.) Paris, France.

18. EU, 2020. Taxonomy: Final report of the Technical Expert Group on Sustainable Finance. pp. 58. (International Chamber of Commerce (ICC).) Paris, France.

19. Fagerlind, L, 2016. We reject the sound measurements of SSVAB in Björkhöjden, Stamåsen och Ögonfägnaden(in Swedish). Fullsjön.

20. Fahlén, P, 2007. Heating, Ventilation and Air Conditioning (HVAC) Systems Engineering - Lecture notes on master's course ENM045. Compendium Compendium K2007:xx, (Chalmers University of Technology.) Göteborg.

21. Fahlén, P, 2008. Efficiency aspects of heat pump systems - Load matching and parasitic losses (keynote speech). 9th IEA Heat Pump Conference, Zürich, Switzerland, 2008-05-20 -- 22. vol. CD-proceedings,

22. Fahlén, P, 2011. Heat pump for heating and hot water - experience from and improvement of a retrofit, ground-coupled installation. 10th IEA Heat Pump Conference, Tokyo, Japan, 2011-06. vol. CD-proceedings,

23. Fahlén, P, 2012. Capacity control of heat pumps. REHVA Journal, 2012-10, pp. 28-31. (REHVA.) Brussels, Belgium.

24. Fahlén, P, 2018. The consumer agency and wind power (in Swedish). EN-R2018:02, (Entro Nova.) Resele, Sweden.

25. Guidotti, T L, 2014. Understanding The Evidence: Wind Turbine Noise. (The Expert Panel on Wind Turbine Noise and Human Health, Council of Canadian Academies.).

26. Harjanne, A, Korhonen, J, 2019. Abandoning the concept of renewable energy. Energy Policy, vol. 127, 2019-04, pp. 330-340.

27. Hong, S, Qvist, S A, Brook, B W, 2018. Economic and environmental costs of replacing nuclear fission with solar and wind energy in Sweden. Energy Policy, vol. 112, 2018, pp. 56-66.

28. Hughes, G, 2016. New research: Wind farms have just half the useful lifespan which has been claimed, according to new research which found they start to wear out after just 12 years. Daily Mail, 2016.

29. ICC, 2018. ICC advertising and marketing communications code. No. 240-46/745, pp. 58. (International Chamber of Commerce (ICC).) Paris, France.

30. ISO, 2006. ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework (ISO.) Switzerland.

31. ISO, 2006. ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines. (ISO.) Switzerland.

32. ISO, 2018. ISO 45001:2018 Occupational health and safety management systems. Requirements with guidance for use. (ISO.) Switzerland.

33. Kelly, M J, (referenced), 2016. Energy Return On Investment. MeteoLCD Weblog, 2016-05-29.

34. Keppler, J H, Aspelund, K, Rothwell, G, Cometto, M, Marc, D, Iracane, D, Ha, J, Paillère, H, 2018. The Full Costs of Electricity Provision NEA 7298, pp. 216. (OECD-NEA.).

35. Krönert, F, Bruce, J, Jakobsson, T, Badano, A, Helbrink, J, 2017. pp. 49. (SWECO.).

36. Krönert, F, Helbrink, J, Marklund, J, Edfeldt, E, Walsh, R, Bitar, F, Holtz, C, Bruce, J, 2017. Economic prerequisites for alternative power generators - A background report to the energy commission (in Swedish). pp. 94. (SWECO.).

37. Larsson, C, 2014. Noise from wind turbines, model validation - measurement - Final report (in Swedish). Slutrapport projekt 32437-1, pp. 27. (Uppsala University.).

38. Lesage, P, Muller, S, 2017. Life Cycle Inventory: An In-Depth Look at the Modeling, Data, and Available Tools. Encyclopedia of Sustainable Technologies, Elsevier, 2017, pp. 267-275.

39. Lovering, J R, Yip, A, Nordhaus, T, 2020. Historical constuction costs of global nuclear power reactors. Energy Policy, vol. 91, 2016-02-02, pp. 371-382.

40. Lundbäck, M, 2018. The roll of nuclear power in the Swdish power system - Possibilities and limitations by changes in the nuclear power generation (in Swedish). SVK 2017/3593, pp. 59. (Svenska Kraftnät.) Sundbyberg.

41. Martikainen, J-P, 2012. Response to ‘A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015–2030’. Journal of Cleaner Production, vol. 208, 2019-01-20, pp. 142-143. (Elsevier.).

42. Mearns, E, 2017. Energy Prices in Europe. 2017-01-02.

43. MSR1999:2, 2000. Regulations for certified environmental product declaration - Application in Sweden of ISO TR 14025 Type III environmental declaration (in Swedish). Ed. 1, 2000-03-27. (AB Svenska Miljöstyrningsrådet.) Stockholm, Sweden.

44. Oddekalv, R, 2021. NMF-ECHA-REACH-Bisphenol - comments and evidence. 2021-02-15, (NMF - green warriors of Norway.).

45. Ongen, J, Marko, I, Koch, R, Debeil, A, 2017. Hidden consequences of intermittent electricity production. Revue européenne de science, vol. 2, no. 2, 2017-06, pp. 399.

46. Patel, S, 2020. U.S. Nuclear Industry Shaved Generating Costs by 7.6% Compared to 2018. Power, 2020-04-16.

47. Porchia, R, Bigano, A, 2012. CASES Cost Assessment of Sustainable Energy Systems - Part 2 Full cost: levelised european estimates results and

assessment. Project No 518294 SES6 WP6, pp. 58. (FEEM – Fondazione Eni Enrico Mattei.).

48. PSR1998-1, 2000. Product specific rules for certified environmental product declaration for the generation of electricity and district heat (in Swedish). Ed. 1, 2000-05-25. Stockholm, Sweden.

49. Pugh, K, Stack, M M, 2021. Rain erosion maps for wind turbines based on geographical locations: A case study in Ireland and Britain. Journal of bio- and tribo-corrosion, no. 34, 2021-01-22, pp. 1-7.

50. Sandöy, R, 2021. Epoxy and bisfenol A - Alarming numbers of emissions from wind turbines (in Norwegian). pp. 3.

51. Schuster, R, 2018. Data from ENTSOE-e and the European Energy Exchange AG. Graphical display by R. Schuster, op. cit. Leipzig, Germany.

52. Sinn, H W, 2013. Energy system change into nothing (in German). public university lecture, http://www.ifo.de/de/w/45rLZDYv4, (ifo Institut.) ifo Institut – Leibniz-Institut für Wirtschaftsforschung an der Universität München e.V.

53. Skarin, A, Sandström, P, Alam, M, Buhot, Y, Nellemann, C, 2016. Reindeer and windpower II - Windpower in operation and effects on reindeer and reindeer keeping (in Swedish). Rapport 294, pp. 74. (SLU.) Uppsala.

54. Solberg, A, Rimereit, B-E, Weinbach, J E, 2021. Pollution from wind turbine blades (in Norwegian). pp. 20. ("The turbine group".).

55. SS-EN-ISO14001, 1996. Environmental management systems - Specification with guidance for use (ISO14001:1996). Ed. 1, September 27. (SIS/CEN/ISO.) Stockholm, Sweden.

56. Statens Energimyndighet, 2020. The energy situation. Website, (Statens Energimyndighet.).

57. Stelling, K, 2006. Infra sound - low frequency noise and industrial wind turbines. (The Multi-municipal Wind Turbine Working Group) Ontario.

58. SVK, 2015. Adapting the electric grid for a large quantity of renewable electricity production - A partial account from the Swedish Power Grid (in Swedish). 2015/929, pp. 59. (Svenska Kraftnät.) Stockholm.

59. Sweco, 2017. Cost of alternative ways of electric power production 2016 (in Swedish). (Sweco, IVA, Ernest & Young, Energimyndigheten.).

60. Sämfors, O, 2014. The Swedish electricity supply (in Swedish). Stockholm, 2014. (Svenska Kraftnät.)

61. Torcellini, P, MacCracken, M, Narayanamurthy, R, Deru, M, Lowe, B, 2021. Energy storage: Helping move toward a sustainable future. ASHRAE Journal, 2021-07, pp. 24-32. (ASHRAE.).

62. Ueckerdt, F, Hirth, L, Luderer, G, Edenhofer, O, 2013. System LCOE: What are the costs of variable renewables? Energy, Elsevier, vol. 63, 2013-12-15, pp. 61-75.

63. Vattenfall, 2018. Life Cycle Analysis - Nordic electricity generation by the Swedish State Power Board (in Swedish). (Vattenfall.) Stockholm.

64. Vattenfall, 2020. EPD Climate declaration for electricity from Vattenfall's nuclear power. pp. 1. (Vattenfall.) Stockholm.

65. Weissbach, D, Ruprecht, G, Huke, A, Czerski, K, Gottlieb, S, Hussein, A, 2013. Energy intensities, EROIs, and energy payback times of electricity generating power plants. Energy, 2013-04-08 (submitted), pp. 210-221.

66. WHO, 2005. Chernobyl: the true scale of the accident. 2005-09-05, (WHO/IAEA/UNDP.).

67. William, K G, Palmer, B A, 2009. Evidence Based Study of Noise Impacting Annoyance. Fourth International Meeting on Wind Turbine Noise, Rome, Italy, April 2011-04-11--14.

68. WNA, 2020. Economics of nuclear power. https://world-nuclear.org/, (World Nuclear Association Website.).

69. WNA, 2020. Nuclear Power in South Korea. https://world-nuclear.org/information-library/country-profiles/countries-o-s/south-korea.aspx, (World Nuclear Association Website.).