

Why thermal power plants have a relatively low efficiency ¹

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Summary

Thermal power plants are the backbone of our electricity system. They convert heat energy into mechanical work, and work into electricity. Their efficiency is typically between 30 and 50%. This means that only half or even less of the heat energy generated in the plant is available as electricity - the remaining heat is dissipated to the environment. As a result, these power plants are judged inefficient and to be replaced as soon as possible by 'better ones'.

But this conclusion is a bit rash. Upon closer examination, one can see that the numerical value for efficiency is based on a combination of the laws of physics with definitions made by man. Special attention should be given to 2 issues: First, according to physics, only a fraction of the energy necessary to produce electricity can be converted into electricity. This fraction depends on the type of the power plant. Secondly, the remaining rest of the energy, that fraction that cannot be converted into electricity, is treated differently in efficiency calculations for different types of power plants. Sometimes, it is taken into account in the calculation, and sometimes it isn't. This is mostly due to historic reasons - frequently, the method for determining efficiency was defined to make calculations easy. This simplifies labour with a specific plant, but makes comparisons between different types of power stations difficult. For thermal power stations, this arbitrary agreement is particularly relevant. Their relatively low efficiency is mainly a consequence of the definitions used, and based on these definitions, it is governed by the laws of physics.

Based on these different definitions, it is impossible to determine by that single value which is 'better': a hydro power station with 85% efficiency, a coal-fired thermal power plant with 45% efficiency, or a solar power plant with 15% efficiency. Which power plant is 'better' depends on how it fulfils its role to produce reliable, cheap and environmentally sustainable power in the best way. This could very well be a plant with a relatively low efficiency.

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1 Introduction

Thermal power plants convert heat (via mechanical energy) into electrical energy. The most important types are coal, gas and nuclear power stations, or, outside Germany, also oil-based power stations. Thermal power plants are the backbone of our electricity system. Their efficiency is typically between 30 and 50%. Based on this, it is often concluded that thermal power stations are inadequate, waste energy, and need to be replaced by 'better' facilities. To evaluate this conclusion, one needs to look at the physical properties of heat energy, as well as at the fine-print in efficiency calculations, defined by man.

2 Definition of efficiency

The efficiency of a power station is indicated with the Greek character η , and is defined as follows:

$$\eta = \frac{\textit{electricity produced}}{\textit{energy input}}$$

Efficiency is mostly indicated as a percentage, and hence needs to be multiplied by a factor of 100.

This definition applies to any power plant. It seems to be straightforward, but in practice, a few problems arise with it. First, power plants themselves use electricity for their operation (lighting, pumps, etc.). Using the total amount of electricity generated yields the 'gross efficiency', while subtracting the power plants own use gives 'net efficiency'. Comparisons are only meaningful based on net efficiency.

Secondly, one must be carefully what to take as 'energy input' in the equation for the efficiency. For example, in a coal-fired power station, one could use the chemical energy content of the coal, i.e. the energy that could be converted to heat in a combustion process, and subsequently to electricity. However, what to do, if the coal has a high content of humidity, and consumes a lot of energy for drying (vaporising water)? In such a case, the amount of heat energy available for generating electricity is significantly lower than the chemical energy content in the coal. The same applies when the combustion is incomplete and part of the coal remains in ashes, or escapes as dust with exhaust gasses. Also the heat that escapes with the flue gasses is not available for generating electricity. Finally, for conventional power plants, experts agreed upon using the chemical energy content of coal (or gas or oil), as it would be delivered in case of complete combustion, but subtracting the vaporisation energy of water vapour in the flue gasses (since this heat escapes usually through the chimney, and cannot be used). For nuclear power plants, the convention is to use the thermal energy of the reactor (i.e. thermal power) to calculate efficiency.

This settles the issue for thermal power plants. But how about other types of power stations? For hydro power stations, the convention is to use the potential energy of the water with respect to the height of drop of the hydro station (i.e. not the altitude of the lake reservoir above the sea level, nor its distance to the middle of earth). For a solar (photovoltaic) power station, one takes the solar energy received - directly or indirectly - on the surface area of the power station. But one does not take into account the entire area covered by the plant, but just the active area of the solar cells. The energy received on intermediate surface areas (necessary for example to avoid mutual shading between solar cells) is left out of consideration. For a wind plant, only the kinetic energy of the wind on the active rotor area is taken into account, ignoring for example the necessary spacing between wind power stations. For each type of power plant, conventions are in place. These conventions have been selected pragmatically. This smoothes calculation for all types of power stations, but makes it very difficult to make statements comparing different types of power stations.

3 What's special about thermal power stations

The heat so-called 'thermal energy' – generated through the combustion of coal, oil, biomass, waste, etc. is transferred with an efficiency of over 90% to water in the boiler of a power plant. This water subsequently becomes steam. In the steam of the plant's water-steam circuit, we can find back almost the full combustion heat.

Next, it is important to recognise that thermal energy consists of 2 fractions. The first fraction has the potential for performing work and therefore, it can be converted into mechanical energy and subsequently into electricity. The second fraction cannot be converted into work due to physical reasons. This second fraction is not available for generating electricity. In the language of physics, the first fraction is labelled 'exergy', the second 'anergy'. The subdivision into these 2 fractions is not a fixed property of heat energy, rather it depends on thermodynamic process parameters (pressure and temperature of the steam, respectively of the heat storing medium in general), and on environmental factors (mainly outside temperature). The exergy content increases with higher steam temperature and decreasing ambient temperature.

The exergy content can be calculated through following equation:

$$Ex = \frac{T_m - T_e}{T_m}$$

with

Ex Exergy content

T_m Temperature of the medium storing thermal energy, i.e. hot steam

T_e Outside temperature

(all temperatures are expressed as absolute temperatures in degrees Kelvin; absolute zero-point is around $-273^\circ C$. To obtain the exergy content as a percentage, one must multiply by a factor of 100).

The equation explains the increase in exergy content with increasing T_m and decreasing T_e . For this reason, constructors of thermal power plants strive for the highest possible temperature. But with increasing steam temperature, pressure also increases strongly. The limits are determined by the (boiler) material's capability to withstand high pressures at high temperatures. Hence, the development of power stations has largely been the development of heat resistant materials. Present state-of-the-art for power plants are $540^\circ C$ and 260 bar, and the evolution is by far not finished.

The second factor influencing the exergy content is the environment temperature T_e . If we could operate a power plant in an environment at absolute zero and cool down the steam to absolute zero, all anergy would disappear and the heat energy in the steam generated in the plant would be pure exergy. The entire heat energy could then be converted into electricity. In practice, though, environment temperatures are well above absolute zero, and heat energy will always have an exergy and anergy component, setting an upper limit for efficiency.

Let's come back to the power plant. Here, the steam makes the turbine rotate. While doing so, the exergy content of the steam is transferred into mechanical work with a very high efficiency (close to 100%). This work is taken from the heat energy, or 'extracted', hence the term 'exergy'. The mechanical work of the turbine is then transferred over the shaft to the generator, where it is converted to electricity, with again a very high efficiency. In this way, the exergy in the heat is almost entirely converted into electricity. In theory, exergy can be converted completely into electricity. In such a case, the efficiency of the power plant would be equal to the exergy content². How close one comes to this theoretical value is a measure for the technical quality of a power plant.

The anergy content of the heat remains in the steam. After leaving the turbine, at low temperature and pressure, the steam has lost its potential to perform work. Its temperature is hardly above that of the environment. Its thermal energy can no longer be exploited to perform work and generate electricity. It is waste heat, hence the term 'anergy'. It is dissipated to the atmosphere, usually through cooling towers. Above all, this unavoidable, but not usable fraction of the heat energy limits the maximum efficiency that can be achieved³. The actual efficiency of a power station is always just below the

²This theoretical maximum efficiency of a power plant is also referred to as 'Carnot efficiency', after the French physicist Nicolas Leonardo Sadi Carnot (1796 – 1832).

³Sometimes, in literature one finds references to the 'exergetic efficiency' of a power plant. This is different from the 'conventional efficiency' in the sense that for the term 'energy input' only the exergy content of the energy is taken into account. Theoretically, the exergetic efficiency can be one, and will in

exergy content. The closer it approaches the exergy content, the 'better' the power station. The distance between exergy content and plant efficiency says more about the technical quality of a power station than its efficiency.

4 Hydro power

Up to a certain extent, the situation is the same for a hydro power plant. Here as well, the water coming out of the power station still has some potential energy. This energy cannot be used within the given surroundings of the plant either (no adequate slope available). Rather, the remaining potential energy⁴ is dissipated to the environment with the water leaving the station. In other words, the potential energy of the water can be used only down to the level where it is in equilibrium with the environment, in this case expressed as altitude. The parallel to thermal power stations is obvious. In the latter case, we can use the heat in the steam only down to the level where it is in (or close to) equilibrium with the environment, this time expressed as temperature. In both cases, the remaining energy in the medium (water or steam) cannot be used and is dissipated to the environment. The difference is only in the man-made definition of efficiency. In the case of hydro power, efficiency is defined by taking as 'energy input' only that fraction of the energy, which can be used under the special conditions of the environment, leaving the not usable portion out of the equation. In thermal power stations, on the other hand, efficiency is defined referring to absolute zero, including into the 'energy input' the fraction of energy that cannot be used in practice.

Hence, it should not come as a surprise that plant efficiencies for hydro power plants are much higher than for thermal power stations. But to conclude from that the latter to be technically inferior and wasteful, is not permissible. If one must compare power plants of different types, the efficiency of thermal plants should be calculated based on exergy content, and then compared with the 'conventional efficiency' of hydro power stations, or, one should calculate potential energy for hydro power plants referring to the middle of earth. Such a comparison would look quite differently. Technically, both types of power plants are approximately equivalent.

5 What is better: hydro power, or thermal power?

The main difference between these 2 types is that thermal power stations use up their primary energy (when fired with fossil fuels), whereas the energy source of hydro power plants is renewable. Thermal power plants cannot be operated for ever, but as long as fuel

practice always be higher than the 'conventional efficiency'.

⁴Theoretically, potential energy is zero in the middle of earth.

supplies last⁵, we can use them on a large scale, and practically everywhere. In contrast, hydro power plants can be constructed only in very limited sites, and can be used only to the extent the water runs.

Further distinctions can be made according to risks and environmental effects. It is important to realise that, due to the unresolved waste problem of thermal power stations (unavoidable emissions of climatically risky carbondioxide), environmental problems will limit the use of thermal power stations much earlier and more stringent than limited supplies of fuel.

6 Efficiency of other power plants

As for other power stations, there are physical limits of efficiency due to the agreed upon definitions too. In case of wind power plants, for example, one cannot reduce the wind speed to zero, since 'used' wind must be removed to make place for 'new' wind. The remaining kinetic energy in the wind is not used, but it is included in the definition of 'energy input'. According to this definition, the theoretical maximum efficiency of a wind power plant is 59.3%. In practice, values around 40% are realised.

Also in the case of solar energy (photovoltaic) there are physical limits, since photons (quanta of light) with insufficient energy cannot contribute to electricity generation, while those with too much energy convert their surplus energy into useless heat. To calculate efficiency, however, the 'energy input' is defined as the total photon energy being irradiated to the active surface area. For silicon as active material⁶, the maximum theoretical efficiency on the basis of this definition is some 28%. At present, values of 15% are achieved in real plants⁷.

In the table, typical efficiencies are given, as they can be achieved in modern power plants. It must be stressed once again that efficiency comparisons between different types of power plants have little meaning due to the arbitrary conventions in defining efficiencies. For the sake of completeness, efficiencies of vehicles and electric motors are included into the table.

In addition, it is important to realise that thermal power plants (hard coal, lignite, gas and nuclear) can produce electricity all over the day and all over the year, whenever we need it. Electricity from renewable energies, on the other hand, is only available when there is

⁵Fossil fuels will be available for at least another 100 years, only our children might condemn us for having used up irretrievably important raw materials for the chemical and pharmaceutical industry; nuclear fuel supplies are available for many thousands of years.

⁶Currently, by far, silicon is the most used material in solar cells.

⁷Single cells sometimes achieve more than 15%, but over the entire plant, 15% is rather strongly optimistic.

sufficient water, wind or sun. The third column of the table gives typical annual values for the energy availability of the different power plants (pertinent to German conditions). An energy availability of 50% means that operating the plant (theoretically) at full power for half a year would generate as much electricity as it generates realistically in a whole year. Or, in the example of a solar (photovoltaic) plant, 10% energy availability means that the plant on average operates only at 10% of its rated power. Even when one considers only daylight time as a basis, the average output is limited to 20% - there is simply not more sunshine in Germany.

Some of the energy availability values are disappointingly low. But it is even worse, as shown in the last column of the table: Power plants on the basis of renewable energies do not only have low energy availabilities, but they also do not fit into an operation schedule. They depend on weather conditions and can not be operated according to demand. They might stand still just when we need them most urgently. Energy availability and operability according to demand are more appropriate measures about the capability of a power technology to secure the electricity supply of a modern economy than efficiency.

Type of power plant	Efficiency %	Availability %	Dispatchability
Hard coal	47	95	Yes
Brown coal	45	95	Yes
Gas – STAG	58	95	Yes
Hydro	85	50	Partially
Wind	40	20	No
Solar PV	15	10	No
Solar thermal power	30	10	No
Nuclear	35	95	Yes
Gasolin car	20		
Diesel car	25		
Electric motor	95		

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