ENERGY EFFICIENCY LIMITATIONS

by

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There is a global consensus relevant to consequences of inactivity on the mitigation of negative effects of the climate change. Clear tasks with measurable results that should be implemented in the specified time are also well known. The preparation of an energy policy is faced with strict constraints that require innovative approach throughout the whole cycle of policy making process, whereas particular attention has to be given to its implementation. Globally observed, energy efficiency is the best and the fastest way to reduce GHG emissions in the medium term.

Energy efficiency should be observed as the means for curbing the exploitation of natural resources. The increase of energy efficiency towards the point of theoretical maximum requires new technical improvements and the establishment of economic environments that stimulate such a trend. In this paper, technical and economic potentials of energy efficiency are evaluated. Also, activities for the correction of energy policies are specified in order to achieve faster and better effects on lowering exhaustion of natural resources and reducing GHG emissions.

Key words: *energy efficiency, energy policy, GHG emissions*

Introduction

The preparation and implementation of energy efficiency programs is not one-time and static job but a continuous and dynamic work that should enable conditions at the energy efficiency market for permanent reduction of energy consumption and GHG emissions. Therefore, the access to markets and to complex systems and the effects of the interaction between supply and demand should be changed and directed towards efficiency, environmental improvements and general social benefits. There are several barriers that prevent the development of the energy efficiency market in the desired direction. The analysis of these barriers should be used for the selection of appropriate instruments of the energy efficiency policy for their elimination. Due to rapid changes of market conditions, energy efficiency programs should be in line with these changes and the assessment of the effects of the energy efficiency policy should become permanent and common practice. The energy efficiency policy should also include mechanisms that will enable qualitative and quantitative evaluation of efficiency and cost-effectiveness of instruments of the energy efficiency policy and the selection of the best program depending on the potential of the energy efficiency market.

There are no doubts that such an approach also requires the knowledge of energy efficiency limitations that are primarily determined not only by natural laws but also by the

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development of technologies and by the capacity of the market to accept measures for the energy efficiency increase.

The Energy Roadmap 2050 [1] is the most integral strategic document that is related to the long-term design of the EU energy sector and it can also be used for national or local energy policies in other countries. The integrity of this document that is accompanied by numerous directives, for example [2], is reflected not only in detailed planning but also in dynamic and adaptable processes of its implementation.

The choice of measures for the energy efficiency increase depends on specified objectives. For example, if the objective is conditioned by market parameters, the economic potential will be defined and if it is conditioned by technical parameters, the technical potential will determine which measure will be applied. In both cases, the theoretical potential is an unattainable maximum [3-6] but a good orientation for assessing the validity of a concrete practical solution for the increase of energy efficiency. These estimates are numerous and very different [5, 7-17].

Energy efficiency has become an inevitable part of every energy policy. Striving to achieve high energy efficiency is an imperative as it directly affects national and regional economies. Energy efficiency is a very complex concept that depends on technical, economic, social, geopolitical and other factors.

The main purpose of this paper is to study possible quantification of energy efficiency limits. Due to its complexity, the context of the energy efficiency and all factors that have affected and still affect its present form are examined in details.

Context of energy efficiency

Energy efficiency is certainly one of the ways out of accumulated energy problems. The future will be certainly based on increasing the efficiency of energy production and on the use of clean energy technologies. However, great responsibility will also be on the side of consumers.

The availability of some of RES is not continuous. Since the growth of the use of RES is undeniable, energy networks will have to be adapted to constant fluctuations in the power of energy sources in the future, which will increase the importance of energy efficiency at the point of final energy consumption. Energy efficiency does not mean inefficiency in the production or the decrease of the comfort of living. The main point is to reduce energy use in order to achieve the same goal but not to disturb the basic process.

There are two different approaches to energy efficiency. However, they are not independent and they should be applied simultaneously. Therefore, there is:

– *Passive energy efficiency*. This approach involves the use or installation of devices and/or materials that actually use less energy or, if the use of some materials reduces energy consumption due to the use of these materials. For example, the replacement of conventional light bulbs with LED lamps that consume considerably less energy for the same effect, or the elimination of unwanted steam leakage from steam pipes, or the installation of insulation on the walls of a building and heat losses decrease, *etc*. Such measures are called passive because once they are applied they will continuously have the effect of reducing energy consumption throughout their whole lifetime. However, it is important that they are properly implemented and maintained in an adequate manner.

  Passive energy efficiency can generate the reduction of energy consumption from 10% to 15% on the average. However, if it is applied in an *active* way, the effect will be even higher. For example, one energy efficient light bulb will continue to consume energy if it is turned on in the period when it is not needed. The insulation of walls of the building will not reduce energy consumption for heating if desired room temperature is maintained by opening windows, *etc*. It is necessary to have an active attitude towards energy efficiency in order to use the potential provided by passive energy efficiency to the maximum.

– *Active energy efficiency*. This approach enables intelligent use of energy and it ensures the same results with lower energy consumption. The control and automation can provide optimum use of energy equipment. Such measures for the increase of energy efficiency are relatively easy to use and the payback period is, as a rule, less than two years.

Numerous programs for energy efficiency increase consist of raising awareness and changing behavior of users of energy systems. For example, switch off lights when they are not needed. Such an active measure is free of charge but it can fundamentally change the behavior of a user and his attitude towards all energy consumers. However, such a measure is subject to a human error. Automation reduces such a risk. It enables turning off devices when they are not needed, controls electric engine operations according to the actual need or maintains heating capacity at the optimum level. The permanent monitoring and maintenance program (M&M) ensures effective and reliable implementation of applied measures, both passive and active ones, throughout their lifetime.

The fig. 1 shows the effect of simultaneous action of passive and active energy efficiency. At the beginning of the implementation of measures for the increase of energy efficiency, the consumption of energy of the energy system was 100%. In the first stage, passive measures were applied and, for example, the savings of 15% were achieved in the period of time that was necessary to replace and install the equipment. After that stage, the process of automation started, which is the active approach. This measure led to additional savings of 10% relevant to the initial energy consumption. The aggregate effect of passive and active measures is now 25%. The application of active measures in the considered case shown in fig. 1 lasted shorter than the application of passive measures. However, this is not always a rule.

The lifetime cycle of measures for the increase of energy efficiency starts practically after the implementation of active and passive measures. It is very important to develop effective

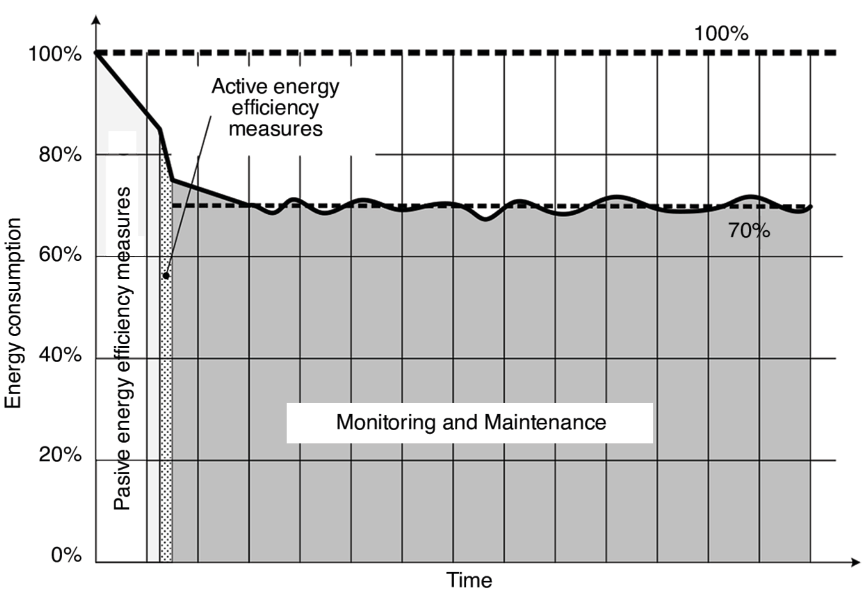

Figure 1. Simultaneous action of passive and active energy efficiency measures

and efficient M&M program immediately and to implement this program on a permanent basis during the implementation of these measures. Well-designed M&M program can lead to additional energy savings from 2 to 8%.

In the lifetime of measures applied in order to increase energy efficiency, deviations from target savings are quite possible. These deviations can occur due to the failure of equipment and due to inconsistent monitoring and maintenance, which is the responsibility of employees. These deviations can be small in amplitude and they should be maintained at the level of target savings during the lifetime. In the given example, fig. 1, expected energy consumption after the implementation of measures planned for energy efficiency increase is on the average 70% relevant to previous consumption. Therefore, complete and permanent effect of the implementation of measures aimed at energy efficiency increase has been achieved.

The term energy efficiency that is an essential element of this paper implies optimization of energy consumption in any energy transformation. In these transformations, there are different technologies that have been changed and improved over time. The initiator of these transformations, a man, has done that for the purpose of satisfying his own needs. The availability of energy resources and their value have determined the technology to be used in accordance with some economic criteria or social conditions.

Energy efficiency has become more important because of the *revolutionary* growth of prices of fossil fuels and energy (1973), which has somehow coincided with the creation of conditions for the start of the Third Industrial Revolution. However, sudden and significant changes that have occurred in the field of technology have also influenced the development of the energy sector and energy efficiency as the means for reducing energy consumption and improving environmental protection but they have no influence on its essence.

A chip, a miniature ceramic piece on which electric components and contacts are placed by photo-imaging is an electric circuit that can perform specified function in an integrated circuit. This chip is practically the symbol of the Third or Digital Industrial Revolution. The explosive development of the chip industry has led to the rapid and enormous development of digital technology and the suppression of analog electronics and mechanical devices. The sudden commercialization of chips began in the sixties of the previous century.

The Fourth Industrial Revolution is creating and altering ranges in the field of artificial intelligence, robotics, Internet of Things and intelligent devices, big data technologies, car industry, 3-D printing, quantum computers, nanotechnologies, *etc*.

The time necessary for new technologies to become mature and commercialized has been shortened. According to some estimates, some 75 years passed before an *electric voice machine* by Alexander Graham Bell was commercially used under the name *telephone*. For the breakthrough of a radio, a lot of money and efforts were invested in the period of 38 years, the time needed for its commercial use, for a television, some 13 years were necessary but, for the Internet, only four years were quite enough.

Today, these new technologies, which have replaced up to that time dominant ones, are called disruptive technologies. They beat traditional technologies or products by enabling conditions for the creation of completely new industries. There are, in fact, two categories of technology [18]: Sustaining and Disruptive. The first category gradually improves existing technologies while the second category completely blocks previously used technologies and offers totally different solution compared to previously valid ones.

The new technology, regardless of its advantages, provokes momentary resistance of the one that is jeopardized. The reaction is quite normal because in the development of the old technology a lot of money has been invested, the supporting industry has been developed, and the market has already accepted it, *etc*. Users are a special problem because people do not accept changes easily as they do not know what consequences these changes will cause even if they lead to better living. For example, the explosive development of mobile telephony has fundamentally changed the significance of communication. With a mobile phone, a man gets full freedom of movement and remains permanently the part of a communication system regardless of his position. That telephone patented by Bell is now a victim of a disruptive technology although it was a disruptive technology itself at the time it was invented.

Large corporations are designed to work with sustaining technologies. Since they are large, they are also sluggish because they employ a lot of people, they serve a large market and they have a mechanism for maintaining and developing traditional technologies. As a result, these corporations have a problem with disruptive technologies that offer new marketing challenges to this inert system by using potentially more efficient solutions, reduction of costs, *etc*. It is therefore not uncommon for large corporations to either reject or purchase disruptive technologies without the intention to use them soon because they are not on the road of their current objectives.

In parallel with the establishment of conditions for the emergence of the Third and the Fourth Industrial Revolution, energy efficiency has appeared in the today's terms. Energy efficiency has been caused by the increase of fossil fuel prices, but it is quite natural and logical that new technologies have influenced the development of technologies that are used in all energy sectors.

Boilers for the production of steam, steam turbines, air compressors, or cooling devices, *etc*. are still used today in industry and in other areas in which some energy transformation is carried out or some services are performed that use energy. Energy efficiency of these devices has been increased primarily by the use of new materials, as well as by the use of numerous technologies in the domain of intelligent devices. Here, we refer to intelligent devices, sensor networks, network protocols, communication between machines, cloud computing, big data, *etc*.

If we understand a steam boiler as a device for the production of steam with desired pressure and temperature, it is assumed that we will use chemical energy of some fuel for the formation of flame and that within the boiler there will be transfer of heat generated by combustion to water that will absorb adequate amount of heat and evaporate and thus reach desired parameters. The use of new materials has not changed the concept of the boiler itself, but it has changed the boiler's performances because new materials enable higher levels of efficiency to be achieved, boilers are lighter due to lower material consumption, their lifetime is extended, *etc*. This is a typical process for upgrading and improving traditional technologies. In addition, some technical solutions for boiler elements have also been developed, so that the efficiency of some modern boiler design has reached values of 95% and more. This result is not the consequence only of the use of new materials and design improvements but also of the use of new sensors, new actuators and new digital devices for automatic process management and its control. The boiler has become an intelligent device that achieves full connection between the flow of produced steam and its parameters and fuel consumption whereas optimum efficiency is always achieved in given conditions. Yes, but steam is used somewhere in the factory for driving a machine or for performing some process of heating. By means of appropriate sensors, these devices or apparatuses can perform optimally their production activities with the use of steam. With the establishment of wire or wireless data transfer, it is possible to enable communication of these devices with a global network and communication between machines via the Internet protocol. The basis for every machine to machine (M2M) communication is a process: data collection, data transmission through communication network, data processing, and execution of the control function based on generated information.

Or, if there are two or three boilers that should, according to production requirements, produce steam of the same temperature and pressure but of different total flow in order to satisfy variable process requirements by means of communication between intelligent devices, it is possible to automatically manage steam production in real time with the satisfaction of some predetermined criteria, for example, minimum energy consumption.

Explosive development of the Internet of Things has greatly influenced the development of energy efficiency as the means for achieving global goal relevant to the reduction of energy consumption and reduction of environmental pollution.

These are only some examples of the development of energy technologies and energy efficiency technologies and shifting efficiency limitations enabled by the development of technologies in general.

Energy efficiency in details

The reasons for the use of and insisting on energy efficiency are very clear and they assume mitigation of pressures on scarce energy resources, reduction of energy costs and, probably the most important reason is the reduction of GHG emissions generated in energy processes. The reduction of the impact of GHG emissions on climate change also requires significant technical changes in the manner of energy production and in its use. By means of a simple eq. (1), it is possible to clearly identify basic factors of influence [19]:

$$Carbon\ Emission = Population \cdot \frac{GDP}{Population} \cdot \frac{Energy}{GDP} \cdot \frac{Carbon\ Emission}{Energy} \tag{1}$$

Carbon emission in this equation implies the amount of carbon and/or adequate amount of CO_2 and other GHG. This refers to the equivalent amount of carbon (kg C_e) or the equivalent amount of CO_2 (kg CO_2e), which is the amount that produces the identical greenhouse effect as the mixture of all GHG.

The first two members of this equation, to the right of the equals sign, depend on demographic, social and economic factors. They directly affect carbon emissions but limiting these members is a very sensitive and complex issue. Namely, the reduction of the number of inhabitants goes far beyond the very issue of energy consumption and, therefore, the actual number of inhabitants is often used in analyses. The national economic success is measured by gross domestic product (GDP) and it is certainly related to energy consumption. Energy consumption is more or less related to the GDP and depends on the structure of the national economy. Some developed countries change the structure of their economies with the intention and in order to reduce the impact of energy consumption onto the GDP by abandoning industries with high energy consumption and by moving these industries to other countries, as a rule, developing countries. The GDP/population indicator is one of indicators that will be used in the following analyses. This is the measure of the national economy and it is an excellent indicator of the standard of living.

The third and the fourth member are yet two indicators very often used in analyses. The indicator energy/GDP [kWh per $] is called Energy Intensity and the indicator carbon/energy [kgCe/kWh] is the indicator of carbon emissions. The relationship between the equivalent carbon and equivalent CO_2 emissions is direct and uniform. The impact on these indicators is closely related to technical options that use energy. The energy intensity depends on the efficiency of energy transformations. Therefore, energy efficiency as a means for reducing energy

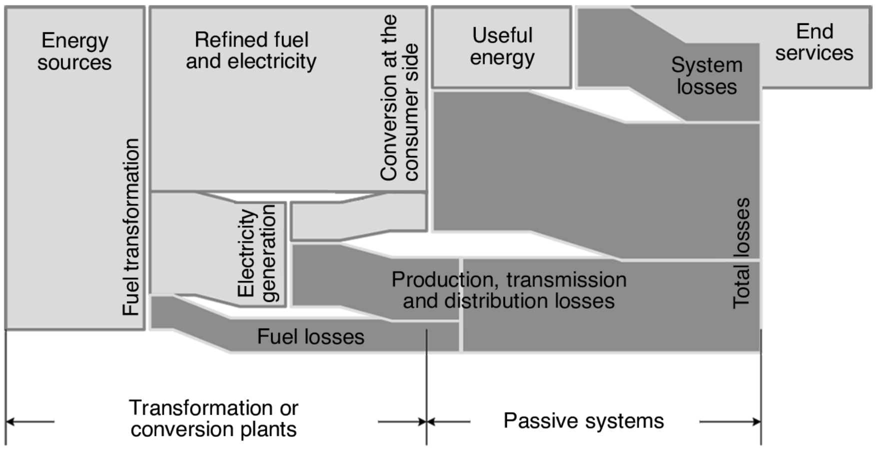

Figure 2. Energy costs

consumption is one of the most important factors affecting its reduction. The last indicator, the carbon emission indicator, shows the level of gas emissions that have occurred because of the use of the unit value of energy. And, it depends on applied technical solution and used fuel.

In the simple eq. (1), the main influencing factors are recognized and their control enables the reduction of carbon emissions, restricts very unfavorable climate change and reduces the consumption of scarce energy resources.

Figure 2 shows the energy flow from raw fuel to final service or services. The presented flow allows identification of technical areas in which energy transformations are performed (fuel production, electricity generation and final services).

It is necessary to distinguish transformation or conversion devices (power plants, engines, lighting bulbs, *etc.*) in which energy is transformed into more useful and more suitable energy form and passive systems (for example, buildings, vehicles, *etc.*) where the part of energy is finally released as low quality heat in the environment in exchange for final services (for example, transportation, comfort, *etc.*).

In passive systems, there is no energy transformation in a standard sense. Therefore, it is very difficult to define efficiency. For example, the purpose of energy used for heating a room in which people live or where a process is performed is to maintain previously specified temperature in this room. If this room is not insulated from the surroundings, heat losses will be greater than in case when this room is well insulated. But, the temperature in it will be the same (provided the heating device has sufficient capacity). If the room is perfectly insulated, heating is practically not necessary and temperature is again the same as the specified one. Defining the efficiency of such a passive system does not have any practical meaning because it depends on practical limitations of engineering practice (whether it is possible to place insulation, how tick it should be, *etc.*).

We are going to discuss here available potentials, fig. 3, individually. The theoretical potential is determined by the laws of thermodynamics. Any desired efficiency is limited by market conditions that define economic potential, while technical potential takes into account practical technical and technological limitations for the application of available measures. Basically, the most important thing is to choose a realistic goal so that it is objective, technically feasible and economically justified.

In fig. 3, current energy consumption is assumed to be 100% in some energy system. For example, this can be heat that is used in a plant for the production of electricity. The plant

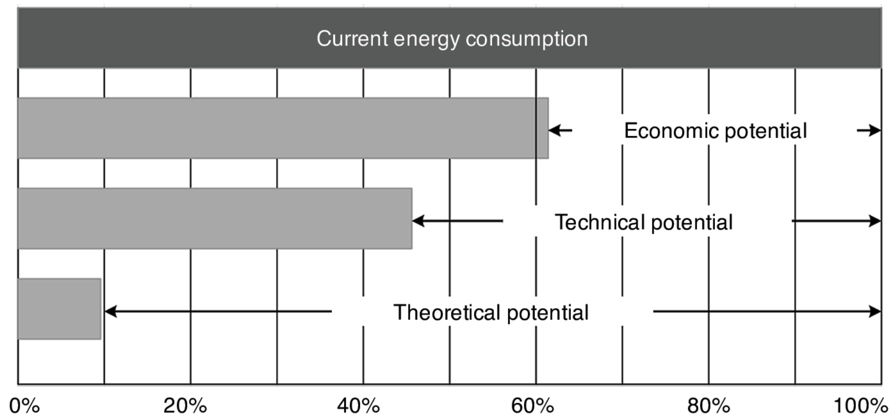

Figure 3. Potential gains from energy efficiency

operates with some total efficiency η_{TOT} and consumes some energy Q_{TOT}. This is 100% energy consumption. If this plant operated according to the Carnot cycle (ideal cycle), at the same maximum and minimum temperatures then, the same amount of electricity, for the example given in fig. 3, could be produced with only 19% of the current energy consumption. This means that the theoretical potential of energy efficiency improvement is as much as 81%. Unfortunately, there is no plant that operates according to the Carnot cycle and without any losses.

With available technologies, it is possible to increase energy efficiency of the observed plant. For example, by installing a device for thermal energy recuperation, by replacing the turbine with a new and more efficient one, by automatic control of fuel and air ratio in the burner according to oxygen content in combustion products, *etc*. This means that there are technological improvements of the existing energy system that can reduce energy consumption by 50% in relation to the consumption before their implementation.

Theoretical models define absolute goal by calculating the upper limit of efficiency on the basis of the laws of thermodynamics. The use of the theoretical model for determining potentials for energy efficiency increase will be considered on the example of two cycles: Carnot's and Joule's.

The Carnot process is very important for theoretical comparisons although its practical realization is impossible. It consists of four reverse processes as shown in fig. 4. By means of isentropic (reversible and adiabatic) compression (compressor A), working gas (data in the figure next to individual points are valid for air, ideal gas) changes the state from the point 1 to the point 2. In the point 2, maximum temperature and pressure are reached in the observed Carnot cycle. Figure 5 gives the scheme of a plant satisfying the conditions of this cycle.

After compression, air enters the turbine A where isothermal expansion is performed up to the pressure, p_3. In order to maintain constant temperature during expansion, it is necessary to supply heat. From the state 3, the air expands isentropically in the turbine B to the pressure, p_4, at which the lowest temperature in the cycle ($T_4 = T_{min}$) is reached. Finally, from the pressure, p_4, the air is compressed isothermally to the starting point 1. Here, for the purpose of maintaining constant process temperature, it is necessary to release heat into the environment. The cycle is performed along two isentropes (1-2 and 3-4) and two isotherms (2-3 and 4-1). Technical work is the sum of technical works of these four processes and it is shown in the area limited by these changes.

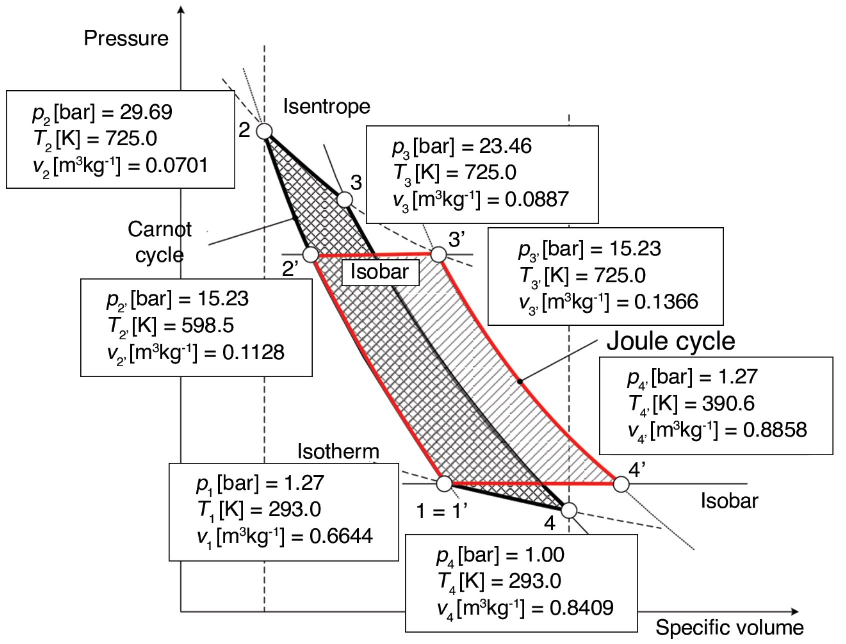

Figure 4. Scheme of the Carnot and Joule Cycle in a P-V Diagram

Basic energy parameters of this cycle are: heat source = 49.01 kJ/kg, heat sink = 19.81 kJ/kg, and technical work = 29.20 kJ/kg. The efficiency of the Carnot cycle is η_C = 59.59%.

The Carnot process can hardly be realized technically because it is necessary to achieve large pressure ratio ($p_{max}/p_{min} = p_2/p_4$) in order to obtain sufficiently high efficiency. This ratio reaches values that are sometimes practically impossible to achieve. Attempts to practically realize the Carnot plant have failed and it only has theoretical meaning. Therefore, it is used for the purpose of comparisons with technically feasible processes.

The efficiency of the Carnot cycle depends only on temperatures between which the process is performed, that is, between temperatures of the heat source and of the heat sink. Since the Carnot process is completely reversible, it has the highest efficiency between specified temperatures and it, in fact, shows the theoretical potential of energy efficiency.

The summary of presented analysis shows that maximum efficiency is 59.59% between temperatures 725 and 290 K regardless of which working fluid is used.

In practice, other cycles are used because they are technically feasible unlike the Carnot cycle. The Carnot cycle will be compared with the Joule cycle, which is often successfully used in practice. The Joule cycle is also shown in figs. 4 and 6 shows the scheme of the plant that operates according to this cycle. It consists of two isobars and two isentropes. The air is heated in a heater at constant pressure. This increases the volume and air temperature (change 2' to 3'). In the heater, heat from combustion products or from a nuclear reactor or in some other way is transferred. Air heated in this way is led into a turbine where it expands isentropically from pressure p_3' to pressure p_4' whereby mechanical energy is transferred to the joint turbine and compressor shaft. After expansion, air is cooled in a cooler at the constant pressure. Cooling is done with water or air. After cooling, air is compressed isentropically to the pressure p_2' whereby the cycle is closed. Basic parameters of this cycle are: heat source = 127.77 kJ/kg, heat sink = 98.57 kJ/kg, and technical work = 29.20 kJ/kg. The efficiency of the Joule cycle is η_J = 22.86%.

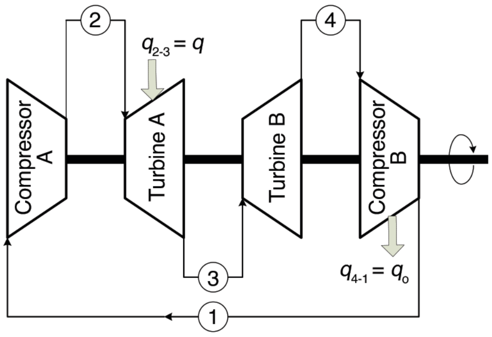

Figure 5. Drawing of the Carnot Cycle Plant

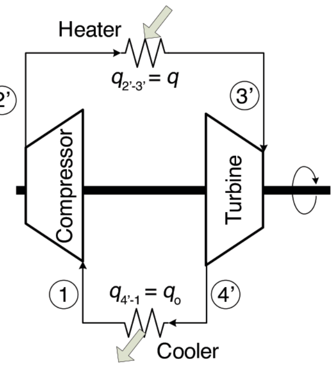

Figure 6. Drawing of the Joule Cycle Plant

It should be noted that the work in the Carnot's and in the Joule's cycle is the same. Namely, the calculation is done with the intention to compare these two cycles between the same temperatures of the heat source and the heat sink (T_{max} = 725 K and T_{min} = 293 K) and to produce the same useful technical work with that. Losses are not mentioned. The advantage of the Carnot cycle in relation to the Joule cycle is obvious although this cycle is used in practice because it can be technically realized in an acceptable economic way and its scheme is simpler compared to the Carnot's one and the plant is cheaper.

The analysis of the Joule cycle is the part of the assessment of the technical potential. Numerous losses that occur in practical realization of this cycle have not been taken into account so that its efficiency is even less than the one that has been calculated. In addition to the Joule cycle, there are many other cycles that can do the same job between specified temperatures. By their analysis and calculation of individual efficiency, it is possible to obtain the best cycle, that is, one that offers the greatest technical potential for the increase of energy efficiency.

Economic potential is difficult to predict over longer periods of time, for example, by monitoring changes of energy efficiency indicators or based only on known technologies. Economically influential factors are susceptible to change, in particular, to changes resulting from the amendment of the government's policy. It depends on the process used for assessment.

Cost-benefit analysis is a method of economic analysis that compares and evaluates all advantages and disadvantages of some project by analyzing costs and benefits. Usual tools of this economic and social analysis are simple payback period and economic net present value. Here, the adjective *economic* indicates that the net present value is calculated only on the basis of economic indicators and not on the basis of financial ones.

Therefore, after technical analysis and consideration of technical potentials for the increase of energy efficiency, it is continued with the assessment of economic potentials. No matter which approach we opt for, economic analysis will identify economic benefits that individual technical solutions bring. It can happen sometimes that some technical solutions which are found after analysis that lead to the significant increase of energy efficiency are rejected after economic analysis because, for example, the price is too high and all economic parameters are unfavorable.

The choice of a consistent energy efficiency measure

Energy efficiency

Conventional energy efficiency is based on the first law of thermodynamics and for devices or plants for energy transformation, energy efficiency is defined in the following way:

$$\eta = \frac{\text{Useful energy}}{\text{System input energy}} \tag{2}$$

For example, typical energy efficiency values calculated according to the first law are about 38% for a power plant using natural gas, about 95% for electric motors, and for the air conditioner, the COP is about 1.8. The use of efficiencies calculated in the above manner is limited to the comparison of devices that perform the same energy transformations because it is possible that efficiency is even higher than 100% in some case and for certain energy transformations. This is because this kind of calculations does not take into account the *quality* of energy. For example, in the case of heating by means of natural gas fired stoves, possible efficiency is 95%, but if electric heating is used, the efficiency is 100%. Based on these values, it can be concluded that heating devices have already reached maximum efficiency. The COP of a typical heat pump is 3 (the efficiency equivalent is 300%), and it can be even higher. Electricity and mechanical work are more valuable energy carriers than low temperature heat, that is, they have different quality. Conventional energy efficiency based on the first law of thermodynamics does not take into account differences in quality. This is a shortcoming of efficiency defined in such a way and it should be kept in mind. In spite of shortcomings, efficiency defined in this way is still most often used in engineering practice.

Exergy efficiency

Exergy efficiency (based on the First and the Second law of thermodynamics) gives a more realistic measure for the efficiency of energy transformation. It uses mechanical work rather than energy as the basis for calculating efficiency and it is defined by the relation of useful work and operation of an ideal thermodynamic process. Exergy efficiency is defined as:

$$\varepsilon = \frac{\text{Output exergy}}{\text{Input exergy}} = \frac{\text{Useful work}}{\text{Maximum possible output work}} \tag{3}$$

By definition, the theoretical limitation of the efficiency of individual devices or any energy system made up of more transformation devices is always one.

Mechanical work is chosen as the basis for comparison because it is the form of energy of high quality and low entropy. Electricity, which can be very efficiently transformed into mechanical work, is another form of high quality energy. For the device that transforms one form of mechanical energy into another (for example, a gearbox), or electricity into mechanical energy (for example, an electric motor), exergy and energy efficiency are almost the same. But, when heat energy is at the device inlet (for example, heating device), the energy value of heat has to be converted into equivalent units of mechanical work.

The critics of this approach give the following example. They say that the replacement of incandescent light bulbs with much more efficient light emitting diode (LED) lamps does not save a lot of energy because after such a replacement, waste heat of incandescent light bulbs is not used for heating and as a result, the consumption of energy for heating purposes is increased. They neglect the fact that there are climate areas where heating is not even necessary, but on the contrary, space must be cooled further to eliminate waste heat of bulbs. According to the First law of thermodynamics, 100% of electricity input in an incandescent light bulb is converted into light and waste heat. From the perspective of the Second law, electricity is high quality energy (it can be converted into work almost completely), while waste heat of the incandescent light bulb is a form of low quality energy (it is difficult to convert low temperature energy into mechanical work). By replacing conventional light bulbs with LED ones, energy savings could be used to run high-efficiency devices, such as a heat pump that can deliver three times more low-quality thermal energy. Not all forms of energy are equal in quality or usefulness.

Exergy efficiency can be calculated directly by finding the coefficient between output and input exergy flows through a device but in practice, this is very difficult. Instead, if conventional energy efficiency, η, is known then, exergy efficiency, ε, can be estimated by means of the following equation:

$$\varepsilon = \eta \nu \tag{4}$$

where dimensionless quality factor, ν, is used to correct losses relevant to the quality of energy.

The creation of a global energy efficiency map requires allocation of average efficiencies to each energy conversion device, including fuel transformation, different ways of electricity generation and application with end-users. It is important to select efficiency values that are representative for global device average, calculated in a consistent way and on the basis of credible sources.

Average energy and exergy efficiencies for fuel transformation, production of electricity and thermal energy are shown in tab. 1.

Table 1. Energy and exergy efficiency of some devices [19]

Device	Description	η	ν	ε
		%	%	%
Electricity production by means of:				
Heavy fuel oil	Crude oil and oil products	37	94	35
Biomass	Combustible animal and plant products, communal and industrial waste	25	90	23
Natural gas	Natural gas	40	96	38
Coal	Hard coal, lignite and derived fuels (coke, furnace gas, *etc.*)	34	94	32
Nuclear energy	Nuclear fission (heat equivalent of electricity)	33	100	33
RES	Hydro, geothermal, solar, wind, tide and wave energy	80	100	80
Process fuels	In oil refineries, gas stations, coal preparation, liquefaction, *etc.*	93	100	93
CHP	Plants for combined production of heat and power (all fuels)	56	62	35
Heat	Thermal power plants (all fuels)	85	24	20

η = energy efficiency, ν = quality factor, ε = exergy efficiency

The values are obtained on the basis of top-down analysis but such a principle cannot be used for finding average values of devices that are used in final energy consumption because they are not determined by means of statistical studies of global energy flows. Instead, published values for energy and exergy efficiency are used.

Table 2 shows the overview of average energy efficiencies, η, quality factors, ν, and exergy efficiency, ε, for frequently used devices in final consumption.

Conclusion

Energy efficiency is an integral part of every energy policy because it is undoubtedly powerful mechanism for slowing down the consumption of depleted natural resources. The development of modern technologies has generally contributed to the development of energy efficiency and efficient technologies so that their importance continues to grow. At the same time, their technical potential is still far from the theoretical one which indicates opportunities for further improvement of energy efficiency in all energy sectors and at all levels of energy consumption.

The present level of scientific knowledge and technological readiness provide necessary requirements for entering into the Third and the Fourth Industrial Revolution. However, this is not enough and it is not possible to expect serious changes without a desire for these changes to actually happen. The development of energy efficiency technologies and the use of renewable energy sources make definitely an integral part of these changes and they are the part of economic development.

In this paper, the general context of energy efficiency has been analyzed and its limits have been assessed. The potentials of energy efficiency in the reduction of energy consumption are substantial and they will certainly play an important role in the development of the energy sector in the future.

Table 2. Energy and exergy efficiency of devices in final consumption [20]

Devices in final consumption	Description	η %	ν %	ε %
Average movement		26	90	24
Diesel engine	Diesel engine: trucks, automobiles, ships, trains and generators	22	95	21
Gasoline engine	Internal combustion engine : automobiles, generators, garden machines	13	99	12
Aircraft engine	Turbo and turboprop engine	28	99	27
Other engines	Gas or steam driven engines	47	53	25
Electric motor	AC/DC induction motors (without electric motors for refrigerators)	60	93	56
Average heat		58	24	14
Oil burner	Boilers, petrochemical cracking, chemical reactors	61	25	15
Biomass burner	Open fires, stoves and boilers	34	20	7
Gas burner	Open fires, stoves, boilers and chemical reactors	64	21	13
Coal burner	Open fires, stoves, boilers, furnaces and chemical reactors	59	31	19
Electric heater	Electric resistant heaters, electric arc furnaces	80	30	24
Heat exchanger	District heating, CHP heat	87	15	24
Other average values		60	14	8
Chillers	Cooling and air conditioning in industry, utility companies and buildings	104	6	7
Lighting devices	Wolfram, fluorescent, halogen and LED lamps	13	90	12
Electronic devices	Computers, TV sets, portable devices, etc.	20	30	6
All devices		51	50	25

Note: η = energy efficiency, ν = quality factor, ε = exergy efficiency

Acronyms

M&M – monitoring and maintenance
CHP – combined heat and power
RES – renewable energy source
LED – light emitting diode
GDP – gross domestic product

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