Chapter 13
Energy Conservation and Efficiency

Abstract In a strict sense, the term "energy conservation" is a misnomer. As demonstrated in Chap. 3 with the First Law of Thermodynamics, energy is conserved by nature. "Energy conservation" does not require any action by engineers or by the general population. What is usually meant by this colloquial term is the eventual conservation of natural primary energy resources, when we perform tasks that are necessary for the functioning of the human society. The colloquial "energy conservation" may be more scientifically expressed as *exergy conservation*, *minimum exergy destruction* or *minimum entropy production* while the societal tasks are being performed. The use of the exergy concept and exergetic calculations ultimately lead to the minimum consumption of primary energy resources and, finally, to the conservation of natural resources. While most of the other chapters in this book pertain to the supply side of the energy equation, conservation and improved efficiency are directly related to the demand side. By "conserving energy" and forgoing the use of a fraction of primary energy sources for the performance of societal tasks, the human society demands less primary sources that supply the global energy demand. As a result, less primary energy is demanded and consumed and the *natural resources* that supply this energy are conserved. In this chapter we distinguish between conservation and higher efficiency, we apply the concept of exergy in order to perform tasks with the minimum possible exergy destruction and we present several examples of methods that lead to the lesser consumption of natural resources in the areas of transportation and comfort in buildings. These methods include the use of fluorescent or LED devices for lighting, geothermal heat pumps for heating and air-conditioning, evaporative cooling, and electric cars.

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13.1 Societal Tasks, Energy Consumption, Conservation and Higher Efficiency

Energy conservation and *energy efficiency* appear to be synonymous concepts and are often used interchangeably in the energy field. However, there are subtle differences between the two. The best way to perceive these differences is to start with the concept of a *societal task* that needs to be fulfilled with the use of energy. The task in this case is any function of individuals, groups or the entire society, which is normally accomplished by the use of energy resources. Examples of such tasks are as follows:

- Maintaining a warm and comfortable temperature for the residents of a building in Berlin, Germany, during the winter months.
- Maintaining a cool and comfortable temperature for the residents of the households of Houston, Texas during the summer months.
- Providing adequate lighting in the classrooms of a High School so that students may read their books comfortably.
- Cooking 0.4 kg of pasta to produce a meal.
- Producing 10 gallons of gasoline from crude oil.
- Producing one ton of cement.
- Transporting three hundred passengers from London to Oxford.
- Manufacturing 1,500 m of 8-gauge copper wire.

From the beginning, it is important to realize that the human society does not demand energy *per se*. Humans use energy in order to accomplish several simple or complex tasks that are similar to the ones listed in the last eight bullets. When one looks at these tasks, one realizes quickly that energy use is not an end by itself, but the means to accomplish these and other similar tasks. If the tasks are accomplished, humans are satisfied, the economy moves along and the society functions well. How much energy is consumed for the accomplishment of these tasks is entirely irrelevant to the society and to human comfort, satisfaction and happiness. Simply put, if the societal tasks are accomplished, the human society is progressing and humans are happy, regardless of the amount of energy consumed. The actual amount of energy consumed is immaterial to the human society as long as "business is done." It is only when humans are unable to fulfill such tasks, because of the lack of sufficient energy supply or because energy has become too costly, that discontent and occasionally frustration and wrath manifest themselves in the societies and the nations. This discontent was demonstrated in several examples of violence during the energy crisis of the 1970s in the USA and Britain.

Similarly, when it is said that "energy demand" increases or will increase in the future, what is actually meant is that either humans will perform a larger number of societal tasks, which will require the use of more energy, or that more humans will perform the same number of individual tasks, which will require the use of more energy. Based on the statistical information of Chap. 1, increased affluence in a society typically implies that more such tasks will be required to be accomplished. For example, when a society becomes more affluent and the "standard of living" rises, a society typically requires more air-conditioning for the summer months, which increases significantly the use of electric energy. Similarly, when the population increases, the energy use also increases because more humans desire such tasks to be accomplished. Therefore, if one writes the total consumption of energy, E, as a function of the total number of tasks performed, TSK, one obtains the following expression for the rate of increase of the energy demand as a function of time:

$$\frac{dE}{dt} = \left[\frac{\partial E}{\partial(TSK)}\right]\frac{d(TSK)}{dt} + \frac{\partial E}{\partial E_T}\frac{\partial E_T}{\partial t}, \qquad (13.1)$$

where E_T is a measure of the average energy consumed per task. This simple and very general equation points to the fact that energy consumption may decrease if the average amount of energy consumed per task decreased or if the total number of tasks decreased. The first is related to what is commonly called "energy conservation" and to the increased efficiency of processes. The second is related to the total population on the planet that uses energy.

The accomplishment of the societal tasks may be done in more than one ways, methods or processes, which use different amounts of energy. Let us consider the first task in the previous list: to maintain a comfortable temperature for the residents of a building in Berlin during the winter months. This task may be accomplished in a variety of ways including the following:

1. Use the existing natural gas burner of the building and maintain the interior temperature at 24°C, as it was done in the last twenty years.
2. Use the existing natural gas burner of the building, maintain the temperature at 20°C and ask the residents to wear an extra sweater to keep warmer. Less energy will be used for the heating of the building.
3. Replace the existing natural gas burner with a heat pump, which consumes electricity instead of natural gas and maintains the temperature at 24°C. Because of the higher coefficient of performance of the heat pump, even if we account for the natural gas energy conversion to electric energy, less overall energy will be consumed for the fulfillment of the task, which is to maintain a comfortable temperature for the inhabitants of a building.

Obviously, the first alternative is the *status quo* of accomplishing the task: do nothing and continue with the same method the task was accomplished in the past. The second alternative necessitates that the residents of the building will have to change their behavior by putting on an extra sweater or another piece of clothing. This alternative implies that the residents will have to cooperate or to assist in the accomplishment of the task. In this case there is *conservation of energy* because an action of cooperation is required by the residents for less energy to be used. The third alternative is typical of an increased *energy efficiency* project. With the replacement of the hot-water burner by a heat pump, the temperature of the

Table 13.1 Several actions that lead to energy conservation and energy efficiency. All actions lead ultimately to natural resource conservation, which is the minimization of natural resource consumption

Energy conservation action	Energy efficiency action
Switch off lights when out of a room	Replace incandescent bulbs with fluorescent ones
Use carpooling for the daily commute	Replace the *BMW-381i* with a *Ford Escort* for the daily commute
Increase the thermostat temperature from 21 to 24°C in the summer. Do the opposite in the winter	Use a geothermal heat pump to replace the old air-conditioning and heating systems
Implement the daylight energy savings time	Install thermal insulation in the roof of buildings
Mandate a maximum speed on the highways	Install an additional feed-water heater in the electric power plant

building is maintained at the same level of 24°C and no cooperation is required of the residents of the building. The use of less energy is accomplished by the higher efficiency of the heat pump without any discomfort to the residents of the building.

Thus, *energy conservation* implies an action or a “sacrifice” from the society, such as: to switch off lights; to drive less miles; to use more bicycles rather than cars for transportation; to reduce the building thermostat in the winter and raise it in the summer, etc. On the other hand, *energy efficiency* is typically accomplished by the replacement of machinery, equipment or processes, with all other conditions remaining the same and does not require any “sacrifice” of comfort from humans. The lesser consumption of natural resources may be accomplished by either *energy conservation* or improved *energy efficiency* or a combination of both.

It must be noted that, occasionally, and especially when laymen are speaking, the terms *energy conservation* and *energy efficiency* are used interchangeably to denote the substitution of one energy form that consumes natural resources with an alternative energy form. For example, the substitution of a gas water heater with a solar heater, and the production of electric power from a wind turbine may be claimed as “energy conservation measures.” For the correct accounting of energy resources and optimized results, the scientist or engineer must be able to differentiate between substitution, efficiency and conservation. Table 13.1 gives several examples of *energy conservation* and *energy efficiency* actions as used in everyday life.

The common characteristic of both energy conservation and energy efficiency efforts is that societal tasks are performed with a lesser use of primary energy resources. In the case of the second and third alternatives for the heating of the building in Berlin, either one uses a heat pump or raises the thermostat, the net effect will be a lesser use of heating fuel. Both alternatives and, by extent, both energy conservation measures and energy efficiency measures result in the lesser consumption of primary energy sources. When the engineer or the entire society strive to consume less energy primary sources for the accomplishment of the societal tasks it is useful to know what is the *minimum amount of energy* the accomplishment of a certain task requires. For example, what is the minimum amount of energy one will have to use for the production of one ton of cement or for cooking 0.4 kg of pasta? This minimum for a given task may become a *benchmark* for the energy consumption and the task of the engineers will be to design processes and equipment that would more closely approach the minimum. As explained in Chap. 3, this benchmark may be formulated using the concept of exergy.

13.2 The Use of the Exergy Concept to Reduce Energy Resource Consumption

The concept of exergy may be used by engineers and scientists to make decisions on the choice of processes and equipment that best utilize the energy resources. In the following sections we will demonstrate with practical examples how the concept of exergy may be used in choosing or improving the engineering processes and systems that perform a given task by utilizing the minimum amount of primary energy resources.

13.2.1 Utilization of Fossil Fuel Resources

Let us assume that we have a certain amount of a natural resource, e.g. a mass of methane, CH_4, equal to one kmol, or 16 kg, and we wish to design an energy conversion system that would maximize the amount of electric work we produce. Since methane is a hydrocarbon, a common way to convert its chemical energy into work is to combine the resource with oxygen from the atmosphere and burn it to release its chemical energy in the form of heat. Accordingly, methane and oxygen undergo a chemical reaction and produce water and carbon dioxide.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O. \tag{13.2}$$

The reaction also releases a large quantity of heat. When one kmol of methane combines with oxygen in a conventional burner, it produces $\Delta H^o = 800{,}320$ kJ of heat. In a very commonly used process, methane is fed in the combustion chamber of a gas turbine, which utilizes a Brayton cycle and releases the heat of reaction to the working fluid. The turbine produces power and work as shown schematically in Fig. 3.9. In a well-designed power cycle, which has an overall thermal efficiency approximately equal to 40%, this process will produce an amount of electric work: W = 320,128 kJ/kmol. This amount of work may vary a little, depending on the efficiency of the gas cycle, which for most conventional gas power plants would be in the range 45–30%.

A moment's reflection will show that methane is a chemical substance, where the available energy is stored in the form of chemical energy. The maximum work that may be extracted from one kmol of any substance is given by the negative Gibbs free energy change during the reaction, $-\Delta G^o$, as expressed in Eq. (3.36). A glance at Thermodynamics Tables shows that for methane, $\Delta G^o = -816{,}650$ kJ/kmol and, hence, the maximum amount of work, which may be extracted from 1 kmol of methane would be $W_{max} = 816{,}650$ kJ. [1] Since this quantity of work is more than 2.5 times the work from the Brayton cycle mentioned above, it becomes apparent that there must be an alternative way to utilize methane and obtain an amount of work that is significantly higher than the amount of 320,128 kJ, which is produced by the original Brayton cycle power plant.

It is apparent that the combustion of methane in a conventional work-producing cycle would only supply a fraction of the maximum work. The combustion of all fossil fuels yields significantly less than the maximum work, which might be obtained from them, primarily because the chemical energy of the fuels is first converted to heat. The subsequent conversion of heat into work is subjected to the Carnot limitations, which were explained in Chap. 3. The discrepancy in the actual work obtained and the *ideal* or maximum work that might be obtained from the natural resource of the 1 kmol of methane, may lead the scientists and engineers to devise an alternative method, a process or a combination of processes that would potentially produce the maximum amount of work, $-\Delta G^o$, from these fuels.

When searching for a better alternative method than the combustion of fossil fuels, it becomes apparent that the maximum work from fossil fuels may be recovered by Fuel Cells, which were described in detail in Sect. 12.6. Fuel Cells convert directly the chemical energy to electricity, are not subjected to the Carnot limitations and may potentially convert the full amount of $-\Delta G^o$ into electric work. The proper use of the concept of exergy and the knowledge of the maximum work that may be obtained from this resource, points to the use of a Fuel Cell rather than a thermal power plant. Fuel cells in principle may convert the entire amount of the reaction's Gibbs free energy, $-\Delta G^o$, into electric energy. However, the thermal efficiency of fuel cells, which are now at a developing stage, is approximately 70–75%. This implies that only 70–75% of $-\Delta G^o$ will be converted to electric energy. Even this fraction is significantly higher than the thermal efficiency of a typical thermal power plant. Instead of using a burner/boiler with fossil fuels, the fossil fuel resources would produce significantly more electric work if they were used in a direct energy conversion device, such as a fuel cell.

It must be noted that, this example leads us to use an entirely different method for the conversion of the chemical energy of methane into work and it does not merely lead to small-scale improvements of the original method. While the exergy analysis determines the maximum work that may be produced from a natural resource it does not reveal directly the method, the system, or the equipment that will produce this maximum work. This is the assignment of the engineer or the scientist who is tasked with the production of the maximum work and who has to

[1] Methane combustion is one of the reactions with negative entropy change, $\Delta S < 0$. The maximum work, $-\Delta G^o$, that may be obtained from a given mass of methane is slightly higher than the heat obtained upon combustion, $-\Delta H^o$.

interpret the exergy calculations and to design the appropriate processes and equipment that would produce the maximum work. Also, the indication of a certain type of equipment, as with the fuel cell, does not necessarily imply that the maximum work will be produced, because the efficiency of all equipment will be less than 1. The invaluable contribution of the exergy concept to engineering is to furnish the amount of the maximum work that can be obtained from a resource or supply the value of the limit, which the engineers may strive to achieve. The knowledgeable engineer or scientist will then determine the method and will design the equipment and the systems to achieve a performance as close as it is feasible to obtain this optimum, within the economic, social, and environmental constraints of the design process.

13.2.2 Minimization of Energy or Power Used for a Task

In addition to helping determine the maximum work an energy resource may produce, the concept of exergy may also be used for the determination of processes or equipment when work or power is consumed. In such cases, exergy will help determine the minimum work, or power, that may accomplish a given task or a given process, where work or power must be used.

We use work or power in our everyday activities in order to accomplish certain tasks. For example, we use electric power in a refrigerator in order to keep food at a temperature below 5°C, or we use gasoline in a car in order to transport ourselves from home to work. The tasks here are the preservation of food and our transportation from home to work, not the consumption of electricity and gasoline, respectively. It must be emphasized that these tasks are not the consumption of a certain amount of energy or power. Since, power or work is necessary for the accomplishment of the tasks and since both have a cost, it is evident that rational consumers will try to accomplish all these societal tasks by using the minimum possible amount of work or power.

From the beginning we must recall that, according to thermodynamic convention, work produced by a system is positive, while work consumed by a system is negative. From the thermodynamic point of view, the work consumed by a refrigerator for the preservation of food during a day will be a negative number. Let us assume that we have three types of refrigerators, which during a year fulfill the task of keeping the food below 5°C, that consume 1,356 kWh, 1,672 kWh, and 2,198 kWh.[2] A rational consumer and environmentally conscious citizen would choose the refrigerator that consumes 1,356 kWh per year, which is the appliance that consumes the *minimum* work during a year. However, according to the thermodynamic convention, which is depicted in Fig. 3.4, the actual numerical values of the work required to run the three

[2] In many countries, refrigerators and other household appliances are sold by the manufacturer with an estimate on their annual consumption of energy.

refrigerators are respectively −1,356 kWh; −1,672 kWh; and −2,198 kWh. Of these, the value −1,356 is, actually, the *maximum*. Therefore, in order to conserve energy resources, we have chosen the *maximum* numerical value that represents the work. What is colloquially called the *minimum amount of work consumed*, is actually a *maximum* in the thermodynamic convention, which may be interpreted as the maximum work produced. Since exergy always determines the maximum absolute value of work involved with a process, the concept of exergy may be used for the determination of the best way to utilize the energy resources, not only in work-producing processes, where the value of the work is positive, but also in work-consuming processes, where the value of the work is algebraically negative. The following example of air compression will illustrate how one may use the concept of exergy in decision making processes involving the consumption of lesser work or power.

Let us assume that the task of a given process is to compress a mass of 1 kg of air at atmospheric pressure and temperature, which is 300 K,[3] to 20 atm. This process could be the compression process in a gas power cycle or in a process of energy storage via compressed air as described in Chap. 12. A typical compressor, with an 80% isentropic efficiency would consume approximately 506 kJ (actually,−506 kJ, according to thermodynamic convention). This compressor would compress the air to the required 20 atm, and by doing so, would also increase its temperature from 300 K to approximately 780 K. Since the task is solely the increase of the pressure, a moment's reflection proves that the increase of the air temperature is not necessary for the accomplishment of the given task. The significant temperature increase is a consequence of the type of equipment that was used for the accomplishment of the task, the almost isentropic compressor. Indeed, this rise in temperature is responsible for a good part of the 506 kJ of work required for this compression. Even if we had a perfectly isentropic compressor (and such devices do not exist) the amount of work spent would have been 405 kJ and the exit temperature approximately 693 K, which is, still, significantly high.

Now, let us employ the concept of exergy to determine if the task of pressurizing the air from 1 to 20 atm may be accomplished using a lesser amount of work. Since air is a compressible substance, we may determine the *maximum work* that is required by the physical principles, the Laws of Thermodynamics, for this process. The initial state of this process corresponds to the environmental state, which will be denoted by the subscript *0*, and the final state, denoted by the subscript *1*. Thus, $P_0 = 1$ atm, $T_0 = 300$ K and $P_1 = 20$ atm. Re-writing Eq. (3.31) for the compression process *0–1* and using the assumption that air is an ideal gas[4] with constant specific heats we obtain the maximum specific work for this process as follows:

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[3] In the absence of other information, the ambient temperature is usually taken to be 25°C (298 K). Also, most of the data on chemical reactions pertain to a reference temperature 25°C.

[4] The ideal gas assumption is not essential in the use of exergy for better efficiency. Any other equation of state or tables for the gas may be used. In such cases a closed algebraic form for the maximum work may not be feasible and one may need to obtain a numerical solution.

$$w_{max} = e_0 - e_1 = h_0 - h_1 - T_0(s_0 - s_1) = c_P(T_0 - T_1) - c_P T_0 ln\frac{T_0}{T_1} + RT_0 ln\frac{P_0}{P_1}. \tag{13.3}$$

Of the three terms in the last part of this equation, only the term $RT_0ln(P_0/P_1)$ is directly relevant to the task of air pressurization. As expected, this term has a negative value since $P_0 < P_1$, signifying that work must be spent for the process to occur. The other two parts of Eq. (13.3), which pertain to the initial and final temperature of the system, $c_P(T_0 - T_1) - c_P T_0 ln(T_0/T_1)$, are irrelevant to the original task, which is to provide pressurized air and does not necessarily ask for the air to be at a higher temperature.

It may be easily proven by elementary calculus that, for all values of T_0 and T_1, except for $T_0 = T_1$:

$$c_P(T_0 - T_1) - c_P T_0 \ln(T_0/T_1) < 0, \tag{13.4}$$

The fact that this expression is negative implies that additional work must be spent for the air to increase its temperature during the pressurization process. Hence, the part of Eq. (13.3) that contains the temperature terms always adds to the work required for the completion of the task, even though it does not pertain directly to the given task. One may also observe that this part of the equation becomes equal to zero if $T_0 = T_1$. Therefore, if the condition $T_0 = T_1$ is satisfied in the compressor, that is we have an isothermal compression of the gas, the absolute value of the specific work required would always be less than that required by an isentropic compressor. It is seen again that the exergy analysis of the air pressurization process points to the best alternative process, the isothermal compression. The "*minimum work*" required for this isothermal compression is actually an algebraic and thermodynamic *maximum*, and in this case it is given by the expression:

$$w_{max} = RT_0 ln\frac{P_0}{P_1} = -258 \text{ kJ/kg}. \tag{13.5}$$

This may be interpreted that *at least* −258 kJ of work must be performed for the pressurization of 1 kg of gas, or that *at least* 258 kJ/kg of work must be consumed for the task to be performed.

One may observe that this amount of work is significantly lower than that required for even the idealized isentropic compression, which is 405 kJ/kg in absolute value. Ironically, although the value −258 kJ/kg is a maximum, in practice we call this "minimum work," because we typically consider only the absolute value of the work consumed, not its algebraic value. It is apparent in this example that the correct use of thermodynamic theory, and especially of the concept of exergy, provides only the numerical value of this "minimum work," and only gives scant indications on the process, equipment or the engineering system to be used. It is up to the ingenuity of the good scientist or engineer to design the engineering system that best approximates this optimum.

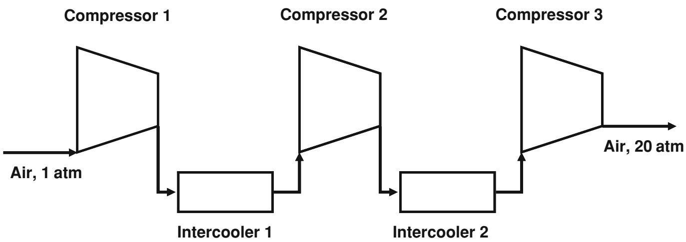

Fig. 13.1 A series of three compressors with intercoolers

Table 13.2 Compressor input work, in kJ/kg, for the compression of air from 1 to 20 atm

Isentropic compression, no intercooler, η = 80%	506
Isentropic compression, no intercooler, η = 100%	405
Isentropic compressions, one intercooler, η = 80%	400
Isentropic compressions, two intercoolers, η = 80%	371
Isentropic compressions, many intercoolers, η = 80%	323
Isothermal compression, η = 100%	258

It must be noted that, because isothermal processes require a significant amount of heat transfer from the compressed gas, such processes are very slow and rather difficult to achieve in practice, if a significant quantity of gas is to be compressed. In engineering practice a number of smaller, isentropic compressors with intercoolers, which were mentioned in Sect. 3.6.2, are used for the reduction of the gas exit temperature. The intercoolers are essentially heat exchangers that admit fluid from a compressor, cool the fluid to a lower temperature and supply it to the next compressor for further pressurization as it is shown in Fig. 13.1. This is repeated until the fluid is pressurized to the desired level. In the example of the pressurization of 1 kg of air, when only one intercooler is used with two 80% efficient compressors, the work required is 400 kJ; when two intercoolers are used, the work required is reduced to 371. An almost isothermal process may be achieved by using a large number of intercoolers with almost isentropic compressors. If a very large number of compressors and intercoolers are used with 80% efficient compressors, then the amount of required work is 258/0.8 = 323 kJ/kg. Table 13.2 gives a summary of the absolute value of the work required during these processes of the compression of atmospheric air to 20 atm. It is apparent that a good engineer will use the exergy method and design the compression process with a couple of intercooling stages to achieve significant "energy savings" for the performance of the given task.

13.2.3 Combination of Tasks: Cogeneration

More than one task needs to be accomplished simultaneously in several industrial applications. For example, a refinery uses a high amount of heat at moderate temperatures (110–130°C) as well as a significant amount of electric power for the operation of its turbomachinery. A typical commercial supermarket in the winter uses a significant amount of heat for space heating as well as electric power to run the refrigerators and freezers. The two tasks in this case are the production of an amount of electric power $\dot{W}$ as well as a rate of heat $\dot{Q}$. The tasks may be accomplished separately, e.g. by means of a vapor cycle, which uses the chemical energy of a fossil fuel at a rate $\dot{m}_w$, for the production of the power and a separate burner for the production of heat using a similar fossil fuel at a rate, $\dot{m}_q$. An exergy analysis of the two processes would prove immediately that the two separate systems would destroy a great deal more exergy and, thus, would consume a great deal more fuel (natural resources) than a single *cogeneration* system, which generates both power and heat. The cogeneration of electric power and heat satisfies both tasks by producing simultaneously the required amounts of heat and electric power using a single cycle, which may be a vapor or a gas cycle.

Cogeneration of heat from a vapor cycle may be achieved in one of the following two methods:

a) Using a condenser at higher temperature than the temperature at which heat is required and,
b) Extracting a fraction of the steam from the turbine (bleeding) at suitable pressure and temperature.

The schematic diagram of the first method is identical to the one depicted in the typical Rankine vapor cycle of Fig. 3.8, with the condensate extracted at higher pressure and the condenser being used as the heat exchanger that transfers the heat for the accomplishment of the heat addition task. The second method is depicted in Fig. 13.2. Steam is extracted from the turbine at state 5 and is diverted to a heat exchanger which delivers the heat of condensation for the fulfillment of the heating task. The condensate at state 6 is pumped to the boiler and, thus, returns to the original power cycle. If the mass flow rate of the extracted steam is denoted by $\dot{m}_1$, the rate of heat extracted from the cogeneration cycle is given by the following expression:

$$\dot{Q} = \dot{m}_1(h_5 - h_6). \tag{13.6}$$

Cogeneration may also be achieved by a gas cycle, using the turbine exhaust gas.

Of course, the extraction of the steam fraction from the power cycle implies that a higher amount of steam must be heated in the cogeneration cycle for the production of the power $\dot{W}$ and that the amount of fuel used in the co-generation

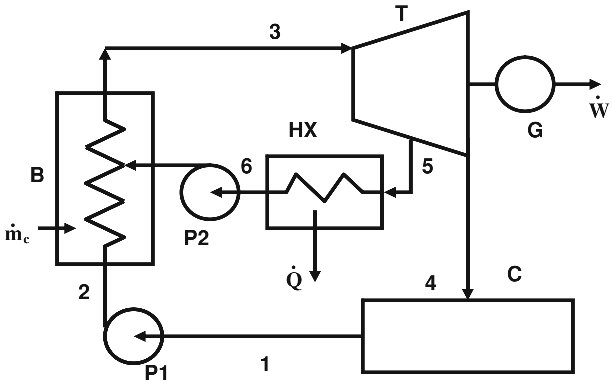

Fig. 13.2 Cogeneration of heat and electric power from a single cycle

process, $\dot{m}_c$, is higher than the original amount of fuel, $\dot{m}_w$, which produced the original power, $\dot{W}$, in the conventional power plant. However, it may be easily proven that the rate of fuel, which must be spent for the separate production of heat and power, $\dot{W}$ and $\dot{Q}$, is always greater than the rate of fuel used in the cogeneration process:

$$\dot{m}_w + \dot{m}_q < \dot{m}_c. \tag{13.7}$$

The last inequality indicates that the cogeneration method always results in the conservation of primary energy resources. The examples of methane combustion, air pressurization, and cogeneration show how the concept of exergy and *exergy analysis* may be used to determine the maximum work and power that may be extracted from a natural resource; the minimum work required for the completion of a task; and the minimum amount of energy resources to be used for the completion of two tasks. The analysis of engineering systems using the exergy concept reveals the optimum value and points to the method that should be used for optimum results. The analysis also assists the scientist or the engineer to choose equipment and processes that lead to an optimum design of the pertinent system. An exergy analysis is a valuable scientific tool that should be used in the design of energy conservation projects as well as projects that are used for the harnessing of natural energy resources.

13.2.4 Waste Heat Utilization

All power plants reject very large quantities of heat, the so-called *waste heat,* to the environment. A typical 400 MW coal-fired power plant has thermal efficiency approximately 40% and rejects approximately 600 MW to its surroundings. Even though this is an enormous amount of heat power, it is not used in practice

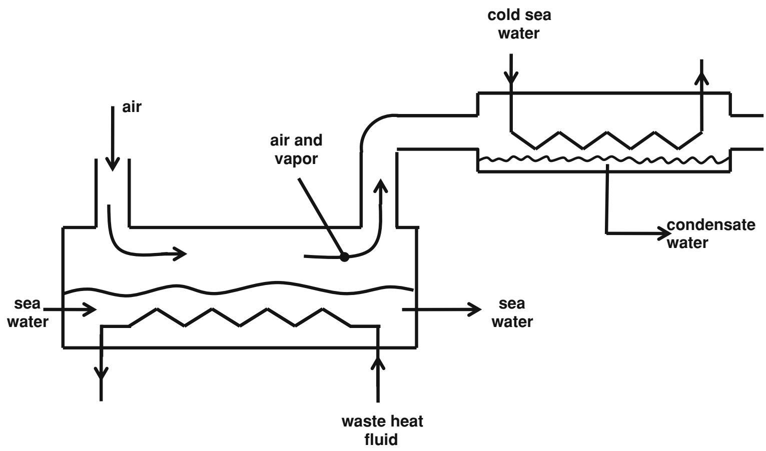

Fig. 13.3 Use of waste heat in desalination

because it is rejected from the condenser at low temperatures, which are typically close to 40°C. Very few practical applications may use such low temperature heat. Because there is a great deal of such low temperature heat available near all the steam power plants, including fossil-fueled and nuclear power plants, substantial energy savings may be generated if users of low temperature heat would collocate with power plants. Among the applications that may use such low temperature heat are the following:

1. *Sea-water desalination*, which is very important in arid regions that are close to the sea, such as the Texas part of the Gulf of Mexico, the countries of the Persian Gulf and the countries that border the Red Sea. A schematic diagram of this desalination process is shown in Fig. 13.3. The colder sea water on the left enters a vessel where it is heated by the waste heat water to a higher temperature (35–42°C). A constant stream of air from the top extracts water vapor and produces an air stream with higher humidity. This stream of air is then directed to another vessel/condenser, where the additional humidity is condensed by the ambient sea water. The condensate is fresh water, which is collected at the bottom of this vessel and sent for consumption. For more fresh water condensate, the warmer saline water output of the condenser may be mixed with the sea water input of the evaporator at the left.
2. *Soil heating for agriculture*. In general, a small increase of the soil temperature causes higher crop yield and, oftentimes, multiple crops per season. The waste heat from a power plant may be transferred by warm water in underground piping to increase the soil temperature in neighboring fields and greenhouses. In temperate climates, the crop yield often doubles when the soil temperature is maintained between 30 and 34°C.
3. *Aquaculture*. Similar to agriculture, heated ponds have a significantly higher yield of fish. The water of the ponds may be controlled and, when necessary,

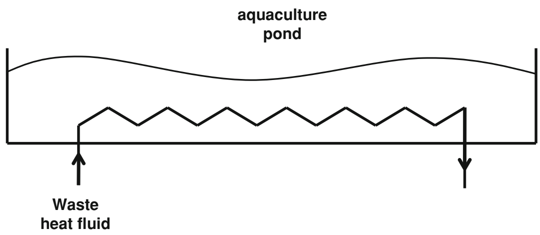

Fig. 13.4 Use of waste heat in aquaculture

heated up by the waste heat to temperatures in the range 30–35°C where not only the fish protein yield is higher per unit surface of the pond, but also where different, more desirable aquatic species may grow to be harvested. Figure 13.4 shows a schematic diagram for the use of the waste heat from a nearby power plant to aquaculture.

4. *District heating* is the heating of a large number of buildings by a single heat source. Geothermal water may be used for district heating systems as was seen in Sect. 9.5. The large quantities of heat produced by power plants may be similarly used for the heating of nearby buildings. When the electric power plant is located close to a district of a city, this district may satisfy a great deal of its space heating needs using the waste heat of the plant. Again, water may be the heat transfer medium that transports the heat from the condenser of the power plant to the building interior.[5]

It is apparent that, when the distance of the heat source to the consumption of waste heat is long, e.g. more than a few kilometers, the use of the waste heat becomes more difficult, primarily for three reasons:

a) The temperature of the heat carrying medium, usually water, drops by heat transfer to the surroundings;
b) The pumping power for the transport of the water becomes significant; and
c) The capital cost in piping and pumps required for the transfer of heat becomes high enough to render the project uneconomical.

13.3 Conservation and Efficiency Measures in Buildings

Approximately one third of the energy consumption in the OECD countries is spent in private and public buildings. The temperature of the buildings is maintained within a narrow range throughout the year, for the comfort of their

[5] Apart from waste heat utilization, other sources of hot water, such as water from hot springs and aquifers, have been used for district heating. Oftentimes such district heating systems are classified as *geothermal district heating*.

inhabitants. Since the ambient temperature varies significantly and the inside temperature remains almost constant, heat enters the buildings during the hot summer months and leaves the buildings during the cold winter months. In order to compensate for these natural heat transfer processes and maintain the almost constant temperature in the buildings, significant amounts of heat must be supplied to the buildings during winter and removed during the summer. Heating during the winter; air-conditioning during the summer; lighting throughout the year; and the supply of hot water throughout the year are tasks that consume most of the energy required in the buildings. In addition, appliances, such as refrigerators, microwave ovens, television systems, computer, and communication systems consume significant amounts of energy in the form of electric power. It is apparent that any reduction in the amount of work and heat required for the performance of these tasks would result in the conservation of energy resources. The following subsections describe some of the methods that may be implemented or are currently used for the minimization of the total primary energy use in buildings.

13.3.1 Use of Fluorescent Bulbs or Light Emitting Diodes

The typical incandescent bulb provides very low amount of light energy in comparison to the electric energy input. Typical efficiencies of incandescent bulbs—defined as visible radiation energy divided by the electric energy input—are in the range 2–4%. Typical efficiencies of florescent bulbs are in the range 10–12% and those of sodium lamps approach 20%. The efficiency of Light Emitting Diodes (LED) is close to 60%. It is apparent that the substitution of an incandescent bulb with a fluorescent bulb or, better, a LED would increase significantly the lighting efficiency of a building. For example, the amount of lighting produced by a 100 W incandescent bulb may be provided by a 25 W fluorescent bulb or by a LED that consumes only 5 W. In a typical multi-use commercial building where lighting is provided for 50% of the time during the year, that is for 4,380 hrs/yr, the mere substitution of a single incandescent bulb with its fluorescent equivalent would save $60*60*4{,}380*(100 - 25)$ J $= 1{,}183$ MJ of electricity, or 328.5 kWh per year.

This is not the final number of the energy savings. The energy used by all the lighting devices dissipates in the building and heats up the air. Since a building requires cooling during the summer and heating during the winter, the lighting energy saved does not need to be removed by the air-conditioning system during the summer and must be supplied by the heating system during the winter. In calculating the total energy savings, the location of the building makes a significant difference. For example, if the building where the 1,183 MJ of lighting energy are saved is located in Fort Worth, Texas, USA where air-conditioning is required 65% of the days during a year (2,847 hrs/yr at the 50% utilization rate of the building) and heating 15% of the year (657 hrs/yr) and if heating and cooling are accomplished with a heat pump system that has coefficients of performance 2.8

Table 13.3 Summary of annual energy savings, in kWh, in a large building where 10,000 W of incandescent light bulbs are substituted with fluorescent lights that consume 2,500 W and produce the same luminescence

Source of savings	Location: Fort Worth, TX	Location: Berlin
Electricity to lights	32,850	32,850
From air-conditioning	7,630	2,350
Additional heating	(1,300)	(5,190)
Total	39,180	30,010

for cooling and 3.8 for heating, then an additional 2,847*60*60*(100 − 75)/2.8 J = 275 MJ or 76.3 kWh of electricity is saved from the cooling requirements of the building and an additional 657*60*60*(100 − 25)/3.8 J = 46.7 MJ or 13.0 kWh must be supplied for the heating requirements of the building during winter. The total annual savings for this building would be (328.5 + 76.3 − 13.0) = 391.8 kWh.

If this building were in Berlin, Germany, where heating is required for 60% of the year (2,628 hrs/yr at the 50% utilization rate) and cooling for 20% (876 hrs/yr) the cooling savings amount to 23.5 kWh/yr and the heating supplement by the heat pump system is 51.9 kWh/yr for total savings (328.5 + 23.5 − 51.9) = 300.1 kWh/yr.

It is also apparent that, if the substitution of the 100 W incandescent bulbs were achieved by LEDs, which would consume only 5 W, the corresponding electric energy savings would be significantly higher in both locations. Based on this simple example for the substitution of a single incandescent bulb, Table 13.3 gives a summary of the energy savings in a large building resulting by the substitution of the equivalent of 10,000 W of incandescent bulbs with fluorescent ones that consume only 2,500 W and provide the same amount of luminescence. All numbers are in kWh per year. Throughout the calculations, it is assumed that lighting is required in the building for an average of 12 hours per day of the year.

Because commercial and residential buildings utilize several kW of electric power for lighting, it is apparent that significant energy savings are realized with the mere substitution of traditional lighting devices by more efficient ones, such as fluorescent bulbs or LED's. The energy savings also result in significant cost reduction for the operation of buildings. It is also apparent that energy savings are higher in buildings that are air-conditioned for longer fractions of the year. The substitution of incandescent bulbs with fluorescent lights or LED's produces higher savings in hotter climates, where the air-conditioning season is longer.

While the substitution of incandescent bulbs with more efficient lighting devices is a measure that falls under the energy efficiency category, energy conservation measures pertinent to lighting uses may be also implemented in residential or commercial buildings. Among these measures are switching off lights when they are not needed and switching off light emitting appliances, such as televisions and computer screens, when they are not in use.

13.3.2 Use of Heat Pump Cycles for Heating and Cooling

The refrigeration or heat-pump cycle, which was described in Sect. 3.6.3 and depicted schematically in Fig. 3.12, essentially creates two heat sources: the first at a low temperature, T_L, and the second at a higher temperature, T_H. When in the heat pump mode of the cycle, a quantity of heat, Q_H, is dissipated during the condensation process (process 2–3) of the cycle to the interior of a building at temperature T_H. Simultaneously, the cycle absorbs heat, Q_L, from the environment, which is at temperature T_L during the evaporation process (process 3–4) and consumes work W during the compression process (process 1–2). The coefficient of performance of the heat pump, $\beta_{hp} = Q_H/W$, is a measure of the work consumed and the heat transferred to the building.

The coefficient of performance of well-designed heat pumps may reach significantly high values, typically 4 to 5. This implies that for every unit of work that the heat pump consumes, four to five units of heat are transferred to the building. Therefore, the heat pump becomes a very efficient way for space heating, especially if it replaces electric heating. A heat pump is also a good alternative to gas heating if the coefficient of performance is sufficiently high. The following example illustrates an efficient use of a heat pump for space heating.

Consider a large building that has a heating need of $23*10^6$ kJ during a cold winter day. If the building is heated by a burner that uses natural gas with heating value 43,000 kJ/kg and the combustion efficiency of the burner is 92%, then $23*10^6/43{,}000/0.92$ kg = 581 kg of gas would be needed to heat up the building. Now let us consider an alternative heating method with a heat pump system that has a coefficient of performance 4.8. In this case, the heating requirement of $23*10^6$ kJ may be supplied to the building with the consumption of $23*10^6/4.8$ kJ = $4.79*10^6$ kJ of electric work by the heat pump.

It must be recognized in this example that the electric work must be produced in a power plant at the expense of a significantly higher amount of heat. Since typical efficiencies of electric power plants are approximately 35%, the heat requirement at the power plant would be $4.79*10^6/0.35$ kJ = $13.69*10^6$ kJ. If the power plant used natural gas for the production of electricity at the same efficiency as the burner of the building, this amount of heat would be produced from $13.69*10^6/43{,}000/0.92$ kg = 346 kg of natural gas. Therefore the substitution of the old burner with a heat pump system results in overall savings of 235 kg of natural gas per day. The savings are the consequence of the significantly higher coefficient of performance, β_{hp}, of the heat pump. In general, if the overall thermal efficiency of the power plant is η_t, and the transmission efficiency for the electric energy is η_{tr}, the substitution of the burner heating system with a heat pump system results in savings if the following inequality is satisfied:

$$\beta_{hp}\eta_t\eta_{tr} > 1. \tag{13.8}$$

An additional advantage of utilizing a heat pump cycle for buildings is that, during the summer, the operation of the heat pump system may be reversed to become an air-conditioning system: since the refrigeration cycle creates a cold and a hot heat source, the colder heat source may be utilized in the summer to supply the same building with cooler air. In practice this is achieved by reversing the air streams in the building, which remove heat from the evaporator of the cycle (process 4–1 of Fig. 3.12) and add heat to the condenser of the cycle (process 2–3 of Fig. 3.12) respectively. Because the same equipment are utilized as heating and cooling equipment, the use of the heat pumps/air-conditioners has become widespread, both in large buildings, such as schools, hospitals, office complexes, and manufacturing plants as well as for smaller residential buildings.

A further advantage for the use of heat pump systems for cooling is that these systems have the capability to supply hot water to a building at no additional expense. A glance at the refrigeration cycle of Fig. 3.12 proves that the heat removal process from the cycle, process 2–3, occurs at relatively high temperatures, especially at the superheat part of this process. A fraction of the heat rejected during this process may be used to raise the temperature of water in a closed tank and use it as the hot water supply of the building, where the heat pump operates. Since typical upper refrigeration cycle temperatures are in the range 60–70°C and typical hot water temperatures are in the range 45–50°C, it is apparent that the refrigeration cycle may be used for the entire supply of hot water in a building, or at least a fraction of this supply. In practice this is accomplished with a heat exchanger coil that passes through the hot water tank. The immediate result of this heating process is that the hot water heater consumes less natural gas or electricity for the heating of hot water. For example, in the case of the gas heater, if the heat pump cycle provides a quantity of heat Q_{hw} to the water tank of the heater, and the lower heating value of the gas is $(\mathrm{LHV})_g$, then the mass of gas that has been saved and not burned for the production of domestic hot water is:

$$m_g = \frac{Q_{hw}}{(LHV)_g}. \tag{13.9}$$

A schematic diagram of the hot water production process is shown in Fig. 13.5, where the heat exchanger coil supplies the heat to the bulk of the water in the heater. The subscript r pertains to the refrigerant and the subscript w to the water. When the refrigeration cycle operates in the heating mode, the heat pump must operate at longer times to supply the additional heat to the water heater. When the refrigeration cycle works in the cooling mode all the heat in the condensation process 2r–3r must be dissipated and the heating of water does not add to the energy consumption of the building. Therefore, the application of this method for domestic water heating is particularly advantageous in hot climates where the refrigeration cycle operates in the cooling mode for extended periods of the year and heat needs to be dissipated somewhere. It has been documented that heat pump cycles have provided 100% of the hot water needs of households in the

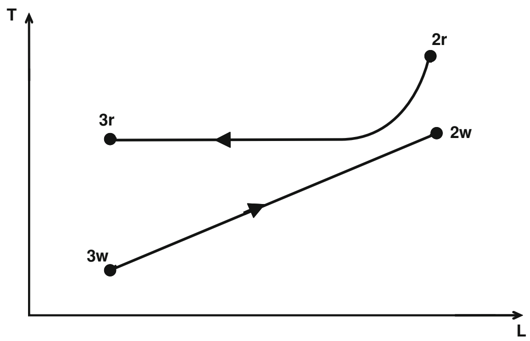

Fig. 13.5 Hot water supply from the condenser of a refrigeration cycle

southwestern part of the U.S.A. during the months April to October and from 30 to 100% in the winter months, without any additional cost of operation.

13.3.3 Geothermal Heat Pumps

One of the major drawbacks for the use of heat pumps for the heating or cooling of buildings is that they exchange heat with the atmospheric air, whose temperature is variable. During the heating season, the evaporator of the cycle removes heat, Q_L, from the atmospheric air. During the cooling season, the condenser of the cycle dissipates heat, Q_H, also to the atmosphere. However, the atmospheric temperature is highly variable and ranges in some regions from −20°C during the colder winter months to more than 40°C during the summer months. The ambient temperature variability makes the design of the refrigeration cycle difficult to optimize. Elementary calculations on the refrigeration cycle show that the coefficient of performance of a heat pump drops significantly when the outside air temperature is very low. Similarly, the coefficient of performance of the air-conditioning cycle drops significantly when the atmospheric air temperature is at its extreme highs. The c.o.p. of an air-conditioner is significantly lower when the outside temperature is 42°C than when the outside temperature is 30°C. As a consequence, the thermodynamic performance of a heat pump or an air-conditioning system deteriorates significantly when the system is needed more, that is during the coldest (as heat pump) and during the hottest (as air-conditioner) days of the year. In some cases a supplemental source or system for the cooling or heating of the building is required because of this performance deterioration.

Since the reason for this performance deterioration is the variability of the atmospheric temperature, which reaches extremes during a year, it is apparent that, if another heat reservoir with almost constant temperature were available, where heat could be absorbed during the heating season and dissipated during the cooling season, the refrigeration cycle used for the heating and cooling of the buildings would operate with higher c.o.p. throughout the year and would not be affected by seasonal temperature extremes. Moreover, this system would operate more

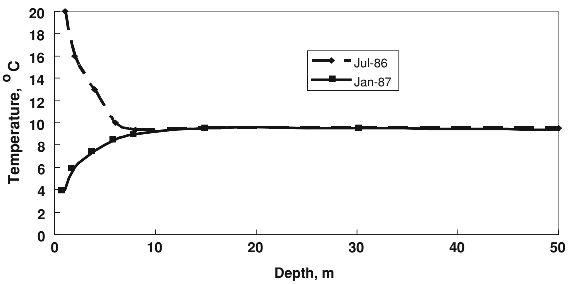

Fig. 13.6 Temperature variation of the ground temperature for Giessen, Germany

reliably, because it would not be affected by large temperature variations. The ground is such a heat reservoir: while the surface of the ground is variable and follows the atmospheric temperature, the ground temperature deeper than 6 m (20 ft) is almost constant, down to depths of 100 m (330 ft). Actually, the annual variability of the ground temperature reduces by a factor of 2 at a depth of 1.2 m (4 ft). The constant ground temperature depends on the latitude of the region and is approximately 6°C (42°F) in Scandinavia; 10°C (50°F) in Germany and England; 15°C (59°F) in Southern Italy; 18°C (65°F) in Dallas, Texas; and close to 20°C (69°F) in San Antonio, Texas. Figure 13.6 shows the ground temperature variation for the city of Giessen, Germany [1] for the months of July and January. It is observed that the ground temperature below 8 m is almost constant in both winter and summer, at 9.5°C. Also, it is observed that, even close to the surface of the ground, e.g. at 3 m, the temperature remains almost constant throughout the year.

A geothermal heat pump (GHP) utilizes a refrigeration cycle with the ground as the medium to dissipate heat from its condenser during the summer as well as to absorb heat by its evaporator during the winter months. The heat exchange to the ground is accomplished by a system of tubes that carry the cooling or heating fluid. Three main types of heat exchangers are used in the design of GHP's: two of them use a horizontal configuration and one uses a vertical configuration.

1. The horizontal ground piping system, which consists of a series of horizontal trenches with pipes at depths between 2 to 5 m. The heat exchange fluid, typically water, is forced by a pump to circulate in the system of tubes and, thus, dissipates the heat to the level of the pipes during the cooling operation and absorbs heat during the heating operation. Given that the depth of the trenches is shallow, the heat is dissipated close to the ground, where, nevertheless, the temperature is almost constant throughout the year.
2. The trench, spiral collector system, for which the trenches dug are at a similar depth, 2–5 m, but wider. The heat exchanger tubing is placed in the trenches in circular loops, in a configuration that is similar to the toy *slinky*. A large number of loops in the "slinky" facilitate the heat transfer from the circulating fluid to the ground.
3. The vertical loop system, which is essentially a long vertical U-tube heat exchanger placed in the ground. This system requires the least amount of

surface area, but typically extends to depths between 50 and 100 m. The piping of the tubes is of plastic material and a special bonding agent (bentonite or another heat-conducting gel) is used to fill the entire well and to provide structural stability to the U-tube.

The first two types of GHP systems exchange heat close to the surface of the ground and are suited for regions where more heating than cooling is required during the year. These systems are not suitable for climates where the cooling season is much more extended than the heating season, such as the southern part of USA, where significant amounts of heat power need to be dissipated in the ground. The third system, with wells extending to 120 m, is more suitable to be used in hot and arid climates. The deep wells dissipate the heat deeper into the ground and, typically, do not raise the ground temperature appreciably. However, it has been observed that, even with the deep wells, the ground temperature rises by 3–6°C. The ground temperature rise occurs when the air-conditioning use is highest during the summer and very large quantities of heat are dissipated.

A figure of merit for refrigerators, heat pumps and air-conditioners is the Seasonal Energy Efficiency Ratio (SEER) defined as the ratio of the Btu's of refrigeration, or heat removal, to the electric energy input in Watt-hours. The relationship between the SEER and the c.o.p. of a refrigeration cycle is:

$$\beta_{ref} = \frac{Q_L}{W} = (SEER)\frac{1055}{3600} = 0.293(SEER). \qquad (13.10)$$

Because of the almost constant ground temperatures, the substitution of a conventional air-conditioning system with a GHP is usually accompanied by a significant increase in the SEER of the equipment. As a result of such a substitution, the air-conditioning system performs the same cooling task while consuming less electric power. This has the obvious beneficial effects of less spending for cooling by the owner of the building; and less pollution associated with the electricity consumed for the environment. It also has a rather unexpected advantage for the utility (power generation company): in many regions, where the climate is warm, the peak power demand occurs in the summer as a result of the use of high air-conditioning demand. For regions, such as the Southwest of the USA, the summer power demand by far exceeds the winter demand as it is demonstrated in Figs. 12.1 and 12.2. As a consequence, the peak power demand occurs in the summer and is highly dependent on the need for cooling. The growth of population in these regions implies significant growth of the peak electric power and significant capital expenditure for the power generation corporation in new power plants and maintenance for older ones. Oftentimes, it is financially advantageous for such a corporation to invest in energy efficiency measures, such as higher SEER for air-conditioning systems, than in new power plants. Several power generation corporations offer a rebate to consumers that install GHP's. This trend is more apparent with the publicly owned utilities, which do not derive a significant financial advantage from selling more power to consumers. For

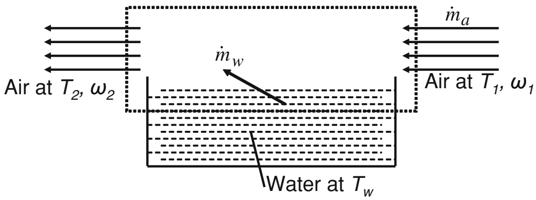

Fig. 13.7 Evaporative cooling

example, since 2009 the San Antonio, Texas, utility (CPS) has offered a rebate to its customers for the installation of GHP's with higher SEER than conventional air-conditioning systems.

13.3.4 Adiabatic Evaporation

Adiabatic evaporation in hot and arid climates may reduce significantly the cooling needs of a building. When a stream of warm and dry air passes on top of a water body, a fraction of the water evaporates. The warm air stream provides the latent heat for the vaporization of the liquid water and, hence the temperature of the air stream decreases, oftentimes significantly. The specific humidity of the air stream increases simultaneously. Figure 13.7 depicts a schematic diagram of the evaporative cooling process. The mass balance in the control volume denoted by the dashed-line rectangle is as follows:

$$\dot{m}_w = \dot{m}_a(\omega_2 - \omega_1), \tag{13.11}$$

where $\dot{m}_a$ is the mass flow rate of the air; $\dot{m}_w$ is the mass flow rate of the water that evaporates and enters the air stream; and ω is the specific humidity of the air. Similarly the energy balance—first law of thermodynamics—may be written as follows for this control volume:

$$\dot{m}_a(h_{a1} + \omega_1 h_{v1}) + \dot{m}_w h_w = \dot{m}_a(h_{a2} + \omega_2 h_{v2}). \tag{13.12}$$

The subscripts v and a denote the water vapor and air respectively. Because the temperature difference $T_2 - T_1$ is small, the enthalpy difference of the air is equal to the product of the specific heat and the temperature difference. Hence the cooling effect, or temperature reduction, $T_2 - T_1$, is:

$$T_2 - T_1 = \frac{1}{c_P}(\omega_1 h_{v1} - \omega_2 h_{v2} + \omega_2 h_w - \omega_1 h_w) \tag{13.13}$$

or approximately, in terms of the latent heat of vaporization of water, h_{fg}:

$$T_2 - T_1 \approx \frac{h_{fg}}{c_P}(\omega_1 - \omega_2). \tag{13.14}$$

Table 13.4 Outlet temperature drop in evaporative cooling

T_1 (°C)	φ_1 (%)	φ_2 (%)	T_2 (°C)
35	10	60	21
35	20	70	23
40	20	70	26
40	20	50	30
35	30	60	23

The evaporative cooling effect can be significant in dry weather and may be used to partially or totally cool the air of a building. In addition, evaporative cooling may be achieved with rudimentary and inexpensive equipment and this makes it very attractive from the economic point of view. For example blowing air with a fan over a small open water container or injecting small water droplets in front of an air fan will result in significant evaporative cooling. Locating residences at the shores of the sea or a lake, where local, natural breezes bring cooler air has the same cooling effect. Table 13.4 shows the evaporative cooling effect, in terms of the relative humidity, φ, for several inlet and outlet conditions. It is observed that 10–18°C cooling of the ambient air may be achieved by merely increasing its relative humidity from the range 10–30 to 50–70%. In most cases, this temperature drop cools the ambient air sufficiently for additional air-conditioning not to be needed. This type of natural cooling has been used for centuries in the Mediterranean countries and especially in the islands, where artificial air-conditioning was almost unknown until the beginning of the twenty-first century.

13.3.5 District Cooling

The idea of *district cooling* is similar to that of *district heating* but is not based on the use of waste heat. District cooling is based on the higher efficiency of larger and better maintained air-conditioning installations in comparison to smaller and less efficient installations. The typical household air-conditioning plant is a smaller 2–10 kW engine. Affordability and low-price (not highest efficiency) is the primary design consideration of these smaller units. As a result, the coefficient of performance of typical small building air-conditioners is between 2.0 and 3.0. A much larger refrigeration unit, which might supply chilled water to a district of several buildings, may be designed with a significantly higher coefficient of performance. Water cooling of the system's condenser alone would increase the coefficient of performance of the unit by 1 to 1.5 units. A larger compressor, frequent maintenance and continuously controlled operation would further increase the coefficient of performance of the refrigeration system.

A schematic diagram of district cooling is shown in Fig. 13.8. A large refrigeration plant cools water and maintains it at low (8–15°C) temperature in the *chiller,* which is a large, well-insulated tank. The cold water is pumped by

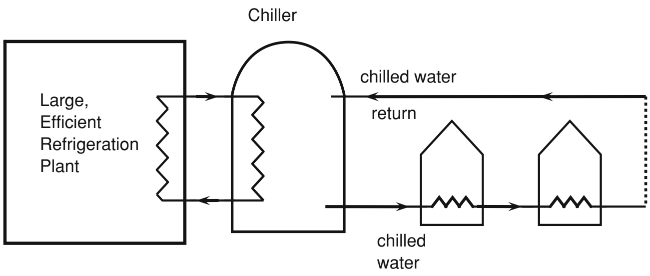

Fig. 13.8 Schematic diagram of the district cooling concept

underground ducts to nearby buildings, where it absorbs heat from the interior air and thus, supplies the cooling effect. The returned, warmer water is cooled in the chiller by the refrigeration unit.

District cooling operates at best when the buildings are close enough for the water of the chiller not to be heated significantly by heat transfer with the ambient air or the ground. For this reason, district cooling works best with larger buildings in high density areas, such as high rise buildings, commercial centers, large hotels, municipal centers or a combination of them. Several districts in city centers of the USA and southern Europe have adopted this concept of cooling with significant energy savings. Use of district cooling in suburban areas, where the building density is low, the distances long and there is significant heat transfer to the chilled water from the environment, does not result in appreciable energy savings and sometimes may even add to the energy consumption.

13.3.6 Other Energy Conservation Measures for Buildings

In addition to space heating and cooling, the hot water use in buildings consumes high amounts of thermal energy. Gas-heated hot water heaters are by far better to be used than electric hot water heaters. This happens because the electricity used in the latter emanates from an electric power plant with efficiency typically in the range 30–40%. A higher quantity of heat ($Q = W/\eta_t$) has been used for the production of the electric energy that is converted back into thermal energy in the electric water heater. In contrast, a burner has 90–98% thermal energy conversion efficiency.

Let us consider that the task at hand is the temperature rise of 200 kg of water (approximately 56 gallons) from 20 to 50°C, which requires 25.14 MJ of thermal energy [$H_2-H_1 = m*c_p(T_2-T_1)$]. The best way to supply hot water is by the use of heat pump systems, which were described in Sect. 13.3.2 and Fig. 13.5. However, the installation of heat pump systems requires a significant capital outlay, which most homeowners do not wish to spend. For this reason, there are currently two common water heater systems that supply hot water in most OECD countries, gas and electric heaters.

In order to evaluate the gas and electric heater systems used in domestic applications, we will assume that the thermal energy to the water may be supplied by one of the following two methods in the two types of heaters:

a. Burning natural gas in a burner with 95% efficiency, or
b. Using electricity from a plant with an overall efficiency 35%, which uses natural gas as its fuel.

Bearing in mind that 1 scf (standard cubic foot) of natural gas typically provides 1.072 MJ, using alternative (a) would consume 24.7 scf of natural gas. Using alternative (b) would consume 67.0 scf of natural gas. Therefore, switching from alternative (b) to alternative (a) would save 42.3 scf of the primary energy source, the natural gas. As a rule, and because electricity is generated to a large extend from thermal energy with 30–40% efficiency, the final conversion of electric energy into heat always wastes a high amount of primary energy resources. The simple conversion of the chemical energy of the primary energy resource into thermal energy, e.g. in a burner, is a much better, and most often a more economical way to produce thermal energy, whenever the latter is needed.

Even a gas-heated hot water heater dissipates a significant amount of energy to its surroundings. The heater maintains a constant water temperature in the range 45–50°C, and is typically located in an attic or a basement, where the air temperature is significantly lower. As a result, the heater looses constantly heat by conduction and convection. The heat loss is higher during the night hours when the ambient temperature is lower. Ironically, hot water is not needed during the night. Water heaters in the USA consume an average of 12% of the annual energy consumption of the average household and most of it is dissipated in the environment. Better insulation of the water heater is a good conservation measure that reduces the average heat losses of the heater.

A water heater design that supplies hot water only when it is demanded is another way to reduce the energy spent on hot water. This heater is smaller and is located close to the demand of the hot water, which is the bathroom or the kitchen sink. The heater is equipped with a sensor that ignites the gas when water flows in its pipe. When there is water flow, gas combustion in the heater supplies heat to the coils inside the heater and, thus, increases the temperature of the water that exits to the desired temperature. When water is not needed, the gas valve is closed by the flow sensor and the combustion stops. The main advantage of this self-igniting heater is that it almost does not store any hot water. It only supplies hot water on demand. When the demand ceases there are no large quantities of hot water in the heater, which cool later with a large loss of energy. The technology for these heaters is well-known and such heaters have been used in several European countries since the 1950s. Because 56% of the thermal energy supplied to the typical water heaters of the USA households is lost to their surroundings, the wider application of these smaller self-igniting heaters would reduce significantly the average household energy demand.

A natural method that reduces the heating and cooling needs of buildings is the use of awnings at windows that predominantly face the Sun, that is the southern side of buildings in the northern hemisphere or the northern side in the southern hemisphere. Well-designed awnings reduce significantly the sunlight that enters a window during the hot season, when the sun is at the highest and would allow the Sun rays to enter during the cold season when the Sun is at the lowest in the horizon. More solar energy enters the building during the heating season and less during the cooling season. This combination reduces both the heating and the cooling requirements of the building. Use of simple awnings in the south-facing windows may reduce by 15–25% the cooling needs of a household in the southern part of the USA and of most Mediterranean countries at similar latitudes.

Other conservation methods that would decrease the energy consumption in buildings are as follows:

1. Use of double-glazed windows. They increase significantly the insulation of the buildings.
2. Use of better fitting doors and windows that reduce the air draft in buildings. Similarly, in older buildings, use insulating adhesive strips to better seal doors and windows.
3. Wider use of fans for the circulation of air, which improves human comfort and reduces the need for air-conditioning.
4. Placing the heating and air-conditioning vents on the floor rather than the ceiling. This keeps the supply of hot and cold air where it is mostly needed by the occupants.
5. Use of diffuse natural lighting rather than artificial lighting. In addition to conserving the electric energy needed for the lights, this measure also reduces the cooling needs of the buildings.
6. At the time of planning and construction, optimize the orientation of the buildings and fenestration (windows) placement for less energy consumption.
7. Use retractable awnings outside the windows.
8. Use screens and thin films to reduce the insolation during the summer.
9. Better insulate attics, basements and other exposed parts of the buildings.
10. Use programmable thermostats that allow the internal temperature to be outside the human comfort zone, when the buildings are not occupied.

In all these cases, the reduction of energy consumption would also reduce the cost of maintaining the building. Older buildings, which were built in an era of cheaper energy and are very costly to maintain may be *retrofitted* to reduce their annual energy consumption. The retrofitting results in significant savings for the owners, who are able to amortize the cost of retrofitting in a short time, typically 2–6 years. Buildings that were constructed before the 1970s and especially ones where air-conditioning has been added after the original construction are prime candidates for significant monetary savings from energy retrofits. In most OECD countries local governments and local utilities provide loans and rebates to assist with the capital expenditures of building retrofitting.

13.4 Conservation and Improved Efficiency in Transportation

The transportation sector consumes approximately 30% of the net energy demand in most OECD countries and encompasses both the transportation of individuals and of goods. The wider recreational use of the automobile after the 1950s and the exponentially increasing trade among nations have contributed significantly to the consumption of energy, especially to the consumption of liquid fuels such as gasoline, diesel oil, and kerosene. In trying to devise methods for the reduction of the energy consumption in this sector of the economy, one must always keep in mind that the societal task, which needs to be fulfilled is the transport of persons or goods from one location to another and that several alternative methods are usually available. For example: 100 tons of potatoes need to be transported from Idaho to New York City; or 35 passengers need to travel from Marseille, France to Barcelona, Spain. The societal task of the transport of potatoes is fulfilled when the potatoes are transported by truck, by train, by airplane, or by a fleet of passenger cars. The societal task of the passenger transportation may be accomplished by ship, airplane, train, bus, or, by individual cars. It becomes immediately apparent that, of the available methods to accomplish the transportation task, one would use the least amount of energy or fuel. For example, transportation of goods and persons by train consumes always less energy than other land forms of transportation. Transportation by car is most often the most energy consuming method.

Given all the available means of transportation, public transportation in cities, and especially the metro/train transportation is the least energy consuming method, when it is used by a high percentage of the citizenry. However, personal convenience, societal values or status, and long-time habits play an important role in the way our society uses energy for transportation. For example, residents of most cities in the USA (with the exception of New York City) consider that it is more convenient for them to drive to their work rather than use public transport, while the vast majority of Parisians would never drive to work and would take the bus/metro combination, where they also read their daily paper or a book. In addition, for several individuals it is a status symbol to drive a larger, more expensive and, typically, higher energy consuming car than a smaller compact car. Occasionally, the short-life of some goods dictates that these goods be transported faster at the expense of higher amounts of energy. For example, tulips from Holland delivered to flower shops in Philadelphia must be transported by airplane instead of the more economical and less energy consuming ship.

A great deal may be accomplished in the reduction of the energy consumption in the transportation sector, both for the transport of goods and for individuals. At first, it must be recalled that bulk transport of goods in trains or ships is by far less energy consuming (in kJ per kg of goods transported) than the transport by trucks or by airplanes. Therefore, whenever there is no *a priori* reason to do otherwise—e.g. the goods have a short life and may be damaged—transportation by train or boat should be preferred. At the same time, it makes sense both economically and from the energy point of view, to pool resources and fill the entire transportation medium during a trip: A filled to capacity train, truck, airplane, or ship transports goods cheaper and with less specific energy consumption (kJ/kg transported) than a partially filled vehicle. For a long time, nautical companies have been using several methods, including visits to a number of ports, to fill their ships with cargo. Commercial airlines are increasingly using similar strategies to fill the aircrafts in most trips by using several methods, such as differential pricing, shared codes and offering flights at periods of high demand.

Human transportation is different than goods transportation because safety and convenience play more important roles than energy savings. While safety is paramount and should not be compromised, a certain amount of convenience may be often sacrificed for energy efficiency. For example, commuting by bus for a suburban community, while less convenient than individual cars would save a significant amount of fuel. In addition, it will contribute to the reduction of traffic congestion, to lesser emissions and to better environmental quality. Among the ways individuals and communities may reduced their energy consumption for transportation are the following:

1. Car-pooling, where several individuals from the same suburban area share a ride to the workplace. This reduces the number of cars on the road, gasoline consumption and congestion. Several municipalities encourage this practice by designating fast-moving High-Occupancy Vehicle (HOV) lanes on the highways and by assisting in the formation and coordination of car-pooling groups.
2. Establishment or wider use of bus routes and, if possible, of light rail systems.
3. Substitution of older vehicles that have low mileage with others of high mileage, especially those vehicles used for daily commute. It includes the wider use of hybrid cars, which store and re-use some of the energy that is typically wasted in stops by converting it to electric energy. This also entails the purchase of newer cars with smaller, more efficient engines.
4. Development of close-to-work communities, which are advocated by several urban planners and are designed to reduce the daily commute to work.
5. Traffic light synchronization. Frequent stops, which entail decelerations and accelerations, increase significantly the energy consumption of a vehicle. Optimized traffic patterns with average constant vehicle speeds between 35 and 45 miles per hour are desirable in urban and suburban environments for the minimization of energy consumption as well as pollution mitigation.
6. Smooth connection of highways by the use of dedicated entrances and exits without traffic lights and delays that slow down the traffic and induce higher gasoline consumption.

7. Avoidance of peak hours of traffic by the adoption of staggered work hours in large municipalities. For example, in the U.S.A. cities the working day for most businesses is rigid, starts between 8:00 am and 9:00 am and ends between 5:00 and 6:00 pm. This creates peak hour "traffic jams" in most municipalities, which slow the traffic significantly, increase the total fuel consumption and most often, contribute significantly to air pollution. The adoption of more flexible working hours (e.g. start between 7:00 am and 10:00 am and end between 4:00 and 7:00 pm) would alleviate the peak hour "traffic jams," and would reduce congestion and the commuting time of the workers.
8. Wider use of the hybrid cars, which through a system of an electric motor/generator and batteries, recover and store for later use some of the mechanical energy that is typically dissipated by the brakes.
9. Wider use of smaller cars or electric cars for commuting to work.

13.4.1 Electric Cars

When in motion, vehicles counteract ground friction and air friction forces and need power to do so. A vehicle may also need to spend additional work in order to counteract the gravity force and move up a hill.[6] This work is produced by the engine, which in the large majority of the vehicles is an internal combustion (IC) engine. It is well known that the internal combustion engine is rather inefficient with an overall thermal efficiency, η_{tv}, between 8 and 15%. This overall efficiency is for the entire system of the vehicle and covers the IC engine, incomplete combustion, emissions, transmission, etc. It is also well known that the existing electric power plants produce electric power at a significantly higher overall efficiency, η_t, between 32 and 38% or even higher. An electric battery may be charged with efficiency, η_B, approximately equal to 97%. Electric cars use motors that convert the electric energy in a battery to work with efficiencies, η_M, close to 90%.[7]

Typical vehicles are fitted with an IC engine, which has an average overall efficiency, $\eta_{tv} = 12.5\%$ and needs a quantity of work, W, in order to travel a distance L with specific driving patterns (instantaneous and average speed, number of stops, etc.). Traveling this distance is the required task. For the performance of this task, the vehicle will consume an amount of gasoline that would be equivalent to $Q_{IC} = W/\eta_{tv}$, or $Q_{IC} = 8\ W$.

[6] Because of friction in the engine and transmission only a small fraction of the work spent during the ascent of a hill is recovered during the descent.

[7] Internal combustion engines and thermal power plants convert thermal energy/heat to work and are subject to Carnot limitations (Eq. 3.22). The charging of a battery and the operation of a motor are forms of direct energy conversion and they are not subject to Carnot limitations.

Now let us assume that we substitute the internal combustion engine in the car with an electric motor that is powered by a system of batteries, which are charged overnight. The efficiency of the battery charging, η_B, is 97%, the efficiency of the motor, η_M is 90%, and the efficiency of the thermal power plant that produces the electric power for the batteries is $\eta_T = 36\%$. The plant-to-wheels overall efficiency of the electric car is:

$$\eta_E = \eta_T * \eta_B * \eta_M = 0.36 * 0.97 * 0.90 \text{ or } 31.4\%. \tag{13.15}$$

Therefore, when the internal combustion engine is substituted with an electric motor, the heat needed at the power plant for the production of the work W is equal to $Q_E = W/0.314 = 3.2$ W. The required heat savings for this substitution are equal to (8–3.2)W = 4.8 W or 60% of the original value $Q_{IC} = 8$ W. If a similar fuel is used in the vehicle and the power plant, this substitution causes a 60% reduction of the fuel. Actually, most of the vehicles use gasoline or diesel, while electric power plants typically use coal or nuclear fuel, which are cheaper and more abundant. Hence, the fuel savings are more meaningful to national economies, which import oil or gasoline.

While wider use of electric vehicles has advantages from the energy efficiency point of view, as well as because electric vehicles are pollution free, electric vehicles have not been widely adopted because of the following disadvantages:

1. The overall electric car engine system costs significantly more than that of the internal combustion engine.
2. The typical distance traveled with one charge—the range of the electric vehicle—is limited to approximately 80 miles (130 km).[8]
3. The typical time for the recharge of the batteries is significant, usually more than two hours. This prevents the use of electric vehicles in long trips that may require battery recharging. The few "fast-recharge" batteries that have been invented, and which claim recharge cycles of the order of 10 minutes, are costly, may create problems with the local electricity grid, and have not been convincingly tested for reliability and long-term endurance.
4. Typical battery life is currently limited to a few hundred recharges, beyond which the performance of the battery deteriorates. New materials and technological advances in this area may alleviate this problem in the near future, when it is anticipated that battery lives will extend to thousands of recharges.

[8] The daily range of several city buses is less than this figure. Several municipalities in the USA and Europe have adopted the use of electric buses. In addition to the significant energy savings, these buses do not have gas emissions and do not contribute to environmental pollution and noise pollution in the cities.

13.4.2 Fuel Cell Powered Vehicles

An electric vehicle powered by a *fuel cell* does not suffer from the last three limitations associated with the battery charging and discharging of an electric car. The fuel cell is an open thermodynamic system operating continuously and consumes hydrogen or another fuel. The fuel may be stored in a tank in a way similar to the gasoline or diesel tanks, which all current vehicles with internal combustion engines use. The fuel cell converts the stored hydrogen directly to electricity, which is used in the electric motor that provides the power for the vehicle. Figure 13.9 shows the energy conversion processes associated with an electric car powered by a fuel cell. Hydrogen is produced by electrolysis. The chemical energy in the hydrogen fuel is directly converted to direct current electricity, which is used by the motor to propel the vehicle. Typical efficiencies of fuel cells, η_{FC}, are approximately 70%. With a motor efficiency of 90% as in the example of the electric car, the hydrogen-to-wheels efficiency of a fuel cell powered vehicle would be 67.5%.

However, it must be recalled that hydrogen is not an abundant fuel and must be produced artificially, usually by the decomposition of water. Assuming that hydrogen is produced by the process of electrolysis, which has typical conversion efficiency, $\eta_{EL} = 70\%$, and that the electric energy for this process is produced at a thermal power plant with thermal efficiency $\eta_T = 36\%$, then the overall plant-to-wheels efficiency of this vehicle would be: 0.36*0.7*0.7*0.9 = 15.9%. Even this lower number is higher than the efficiency of most internal combustion cars. It is also anticipated that, with the wider use of hydrogen as a fuel, hydrogen production efficiencies and fuel cell efficiencies will improve significantly to deliver plant-to-wheels efficiencies close to 25%, or almost twice as much as those of the typical IC engines that are currently used for transportation. An additional advantage of the fuel cell powered cars is the significant reduction of pollution that is currently caused by the IC engines.

Because the technology of the electric vehicles is known, it is expected that a higher number of such vehicles will be in the roads in the next two decades, especially public buses, vans, school buses, and short-haul trucks. The substitution of internal combustion engines with electric motors will have the overall effect of lesser liquid fuel consumption, primarily of gasoline and diesel; lesser primary energy consumption; and lesser air pollution in cities.

From the point of view of the electric power supply, because the battery charging will be primarily accomplished during the night hours, when electric utilities have ample capacity to produce more power, the additional electric power consumed will not impose a strain on the peak power demand of the electric grid. On the contrary, the wider use of electric vehicles would make smoother the daily demand fluctuations (Figs. 12.1 and 12.2) of electricity and will save a significant amount of primary liquid hydrocarbon resources, mainly crude oil.

Whether or not electric cars will be widely adopted by the public as private cars depends to a large extend on the *range* of the electric cars—the maximum driving

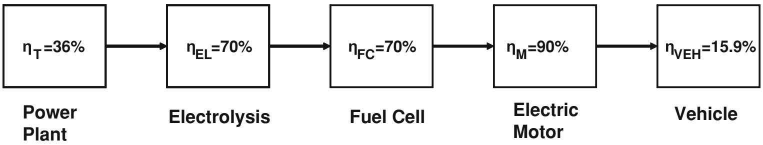

Fig. 13.9 Energy conversion diagram for a fuel cell powered vehicle. Typical efficiencies of the individual processes are shown in the boxes of the diagram

distance before charging—that will be achieved in the near future. Private cars are used for commuting as well as for vacation and other long-distance travels. Having to stop for extended periods of time for battery recharging is an inconvenience that the public is not willing to endure. It follows from the processes in Fig. 13.9, that the improvement in the efficiency of fuel cells and in the production of hydrogen, or of another suitable fuel, as well as the wider availability of hydrogen will have a profound effect in the wider adoption of fuel-cell powered cars. These cars will only need to refuel with hydrogen or another suitable fuel, a rather fast process that can be quickly accomplished in appropriate hydrogen fuel stations. The wider adoption of fuel cell powered private cars and trucks will almost eliminate the need for liquid hydrocarbons in the society and will signal the advent of the *Hydrogen Economy*, which was mentioned in Sect. 12.5.

Problems

1. For each of the following three societal tasks provide details on the methods and engineering systems they are currently met/accomplished.

   - Maintaining a comfortable temperature for the residents of the households of Houston, Texas during the summer months.
   - Provide adequate lighting in the classrooms of a High School so that students may learn comfortably.
   - Cook 0.4 kg of pasta.
     For each one of these tasks provide an alterative method to accomplish it and state if primary energy resource savings would result from the alternative method.

2. Consider the heating and cooling needs of your household. What improvements can be made to reduce the overall energy resource consumption? Separate these improvements into conservation and improved efficiency measures.
3. One of the reasons the transportation sector consumes a great deal more energy in the USA is the commute to work by individuals. The average, one-way commuting trip in Houston, Texas is 21.5 miles. Because of traffic jams the average mileage of the cars in the same area is 12 miles per gallon. Consider that four neighbors driving daily the average commuting distance decide to carpool. What is the amount of gasoline saved weekly and annually? What

would be the annual gasoline savings if 500,000 persons carpooled in a similar manner? Consider that, in the latter case, the driving conditions will get better to the point that the average mileage will improve from 12 to 16 miles per gallon. How many tons of CO_2 are not emitted to the atmosphere annually because of the carpooling activity? The week in Houston has five working days and the year 52 weeks. Also, you may consider that gasoline is composed solely of octane.

4. A tank of 0.7 m^3 is to be filled with air at 12 bar. What is the minimum electric work needed? How much electric work is used by a reciprocating compressor with an isentropic efficiency 72%?
5. 150 kg/hr of steam are needed for an industrial process. The steam is produced by an electric heater. The local power plant uses natural gas for the production of electricity with an overall efficiency 38% (this includes the transportation losses). What would be the percent reduction of the natural gas consumption if the electric heater were to be substituted with a gas heater?
6. A large oil refinery uses 40 MW of heat, which is supplied by steam at 120°C and 1 bar. The refinery also uses 18 MW of electric power. Design a Rankine cycle and a small power plant that satisfies the heating and electric needs of this refinery.
7. A large food processing plant uses 10 kg/s of steam at 140°C, 1 bar. The plant also needs 5 MW of electric power to run its electric components and sells another 10 MW to the local utility. Design a Rankine cycle to accomplish these tasks.
8. A five-ton[9] air-conditioning unit for a household is to be replaced with a GHP system. As a result, the c.o.p. of the system is expected to improve from 2.8 to 3.9. The air-conditioning system is used in this household 2,350 hours per year. What are the annual energy savings due to this improvement? If all this energy came from a coal power plant of 37% overall efficiency, how many less kg of CO_2 are emitted because of this improvement every year?
9. What does the SEER number mean for an air-conditioner? The total rated power for the local utility is 5,000 MW, of which 95% is used during peak demand hours and the power generating factor for the utility is 52%. The air-conditioning of the customers account for 60% of the peak demand and 22% of the total annual energy demand. As a result of an *energy conservation campaign,* the utility company plans to improve the air-conditioning equipment of its customers from 11.2 to 13.5 SEER. What will be the reduction of

[9] One ton of air-conditioning is 12,000 Btu per hour. Typical air-conditioning units and large refrigerators are rated in tons.

the total electricity demand for the utility and the reduction of the peak power that is needed?[10]

10. A large supermarket, which operates 24 hours every day for 361 days per year, is to substitute 950 kW of fluorescent lamps with LED's that will provide the same amount of illumination, but will only consume 150 kW. The supermarket is heated for 65 days every year and air-conditioned for 210 days. Using typical efficiency and c.o.p. values determine the annual electric energy savings resulting from this energy efficiency measure.
11. Five large hotels in Miami, USA, use their own air-conditioning units, which have a c.o.p. 3.1. It is proposed that the cooling systems of the five hotels be substituted with a larger, modern unit that would have a c.o.p. 3.7. The total installed capacity of the five hotels is 2,600 tons of air-conditioning and the current systems are in use for 3,200 hours every year. Determine: a) the annual energy savings from this substitution and b) the annual avoidance of CO_2 emissions if, currently, 72% of the electric energy in the Miami area is obtained from coal power plants and 28% from nuclear power plants.
12. The humidity in Tucson, Arizona frequently hovers near 40%, while the temperature is 38°C. Determine the temperature reduction that would occur in a building if the humidity were to increase adiabatically to 60% and to 70%.
13. In 2009 the USA consumed 17,910,000 barrels of oil per day, of which 62% was used by small cars and light trucks with an average mileage 18.5 gallons per mile. If the national standard were to increase to 22 miles per gallon, what would be the annual savings in barrels per year? What are the monetary savings, if the average price of oil is $90/bbl?
14. It is proposed that a percentage of cars be substituted by electric cars. Japan used 4,680,000 barrels of oil per day in 2009, with 69% going to small cars and trucks. If 20% of these were to be converted to electric cars and trucks, what would be the annual savings in barrels of oil? Assume typical efficiencies. If all these oil savings come from octane (C_8H_{18}) what is the annual avoidance in the total CO_2 emissions?
15. It is proposed that a percentage of cars be substituted by cars powered by hydrogen fuel cells. Germany used 2,460,000 barrels of oil per day in 2009, with approximately 70% going to small cars and trucks. If 20% of these were to be converted to fuel cell cars and trucks, what would be the annual savings in barrels of oil in the country? Assume typical efficiencies. If all these oil savings come from octane (C_8H_{18}) what is the annual avoidance in the total CO_2 emissions? All the hydrogen will be produced by electrolysis with electricity provided by wind power plants.

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[10] It appears to be counterintuitive for a utility company to seek demand reduction. However, given the high capital cost and environmental restrictions on the construction of new power plants, many local utilities in areas of growing demand prefer the demand reduction strategy to constructing new and more costly power plants. Thus, they satisfy the new customers with the surplus power that comes from conservation and higher efficiency measures.

16. "The OECD countries have an enormous potential to conserve energy in comparison to the developing countries. Therefore, developing countries should be excluded from all international protocols and agreements on CO_2 reduction." Comment in a short essay of 250–300 words.
17. "If we were to only apply energy conservation measures in the USA, we would not have to build another electric power plant until 2045." Comment in a short essay of 250–300 words.
18. A compressor in a Brayton cycle raises the air pressure from 1 atm and 27°C to 25 atm and has an isentropic efficiency 78%. It is proposed to substitute this compressor with two other compressors and an intercooler. Both compressors will have a pressure ratio of 5 (that is the first produces air at 5 atm and the second at 5*5 = 25 atm) and efficiency 80%. The intercooler cools the air after the first compressor to 37°C. Determine:

    a. The specific work, in kJ/kg required for the operation of the old and the new system of compressors.
    b. If the Brayton cycle admits 2 kg/s of air and is in operation for 25% of the time, the annual power savings from this substitution.

Reference

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