A better way to meet heat demand

Saving energy through system integration and heat pumping

IEA
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heat pump centre

The integrated systems approach

The heat demand for buildings and industries typically accounts for half of a nation's energy resources. In the development of energy policies, it is therefore crucial to examine the way such heating needs are met.

In any society, there are many different heating needs, ranging, for example, from the high-temperature needs of the steel industry to the low-temperature requirements of buildings. Traditionally, each heating need is treated separately. And with today's modern boilers and furnaces, each heating need can be met with energy efficiencies close to 100%. Surprisingly, such a performance can easily be bettered.

This brochure argues that heat can be supplied much more efficiently by adopting the *integrated systems* approach. Following this approach, the energy needs of a whole community are considered to be one large *integrated* energy system. Every heating need is looked at as part of the larger system, alongside other energy needs such as electric power and cooling.

With careful design, the sub-systems used to meet different energy needs can be coupled together so that the heat rejected by one sub-system can be used again by another. This reduces the need for primary energy resources such as fuel or renewable energy.

The heat demand for buildings and industries typically accounts for half of a nation's energy resources.

A useful tool to help reach the best design is the *quality of energy* concept. Following this concept, it is not only possible to measure the *quantity* of energy, but also to define its *quality*. For heat energy, quality depends on temperature.

In this Brochure

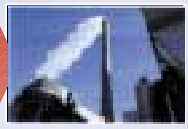
How to use 10 m^3

1. The traditional approach

10 m^3 (370 MJ)

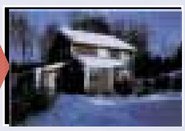
Heat steel

10 m^3 (370 MJ)



Generate 50 kWh electricity

10 m^3 (370 MJ)



Heat a house for 2 days

Front cover illustration based on a drawing by M.C. Escher

To minimize the consumption of energy resources, unnecessary drops in energy quality must be avoided. For in the design of integrated energy systems, it's quality that counts.

Figure 1 illustrates how the *quality of energy* concept can improve upon the traditional approach of separate supply of heat and power. There are two important methods. The first is to apply *energy cascading* (central figure), whereby waste heat is used to meet a heating need at a lower temperature. Here, waste heat from heating steel is used to generate power, and the heat from power generation is transported for use in houses. The second method is to use *energy upgrading* (right-hand figure). Here, a gas-driven heat pump is used to upgrade environmental heat to a higher temperature.

As shown, both energy cascading and energy upgrading deliver much more energy than with the traditional approach. Combining these two approaches in an integrated system can bring still greater energy savings.

To illustrate the integrated systems approach, this brochure considers the situation where energy managers must plan for the energy needs of buildings and industry in the development of a new imaginary community. To simplify the discussion, we first assume that the only readily available energy resource is natural gas. The implications for energy systems with other energy resources are also explained (see purple boxes).

The first step for our energy managers is to limit heat demand through measures such as using advanced thermal insulation and by making optimal use of passive solar heating in buildings. Step two is to consider the options for heat and power supply.

The following pages describe how the traditional policy option of separate supply of power and heat (policy option 1) is found to be wasteful of gas resources. Following the *quality of energy* concept (explained further on page 5) the energy managers then examine how waste heat recovery (policy option 2) can reduce gas consumption. Finally, they look at the affect of using heat pumps as well – policy option 3. Compared with the traditional option, a heat pumping policy, combining heat recovery and heat pumps, is shown to offer gas savings of 30% for this imaginary community.

# of gas

Figure 1: By developing energy systems with energy cascading and energy upgrading, much better use is made of energy resources than with the traditional approach.

Option 1
Separate supply of power and heat

In line with the infrastructure of many industrialized countries, the energy managers of our imaginary community draw up a plan to to equip all buildings and industrial plants with high efficiency gas boilers connected to a gas network. Advanced combined-cycle gas-fired power generators supply electricity at an overall efficiency of 50%.

The energy flow of this system is depicted in **Figure 2**. Here, the energy needs of buildings and industry are represented by separate blocks. The third block represents power generation. The total consumption of gas is set at 100 units to allow comparison with the other energy systems described further on in this brochure.

On discussing this proposed system with thermodynamic experts, the energy managers are surprised to learn that, despite the use of the most advanced technology, their proposed energy system is relatively inefficient. Referring to a concept known as the *quality of energy*, the experts say that the system fails to make good use of the primary energy content of the gas. The facing page helps to explain this further.

Direct combustion to make low-temperature heat is never the most efficient use of fuel.

In the proposed system, heat and power needs are met by burning gas and supplying heat at the temperature required for industrial processes, space heating, power generation and other needs. After use, this heat is rejected along with heat from other sources such as cooling equipment, machinery and computers.

According to the *quality of energy* concept, burning gas in a boiler to make heat at 70°C for space heating, for example, is a waste of a valuable energy resource. In fact direct combustion to make low-temperature heat is never the most efficient use of fuel. A much better way is to build an integrated energy system so that waste heat can be re-used in applications at lower temperatures.

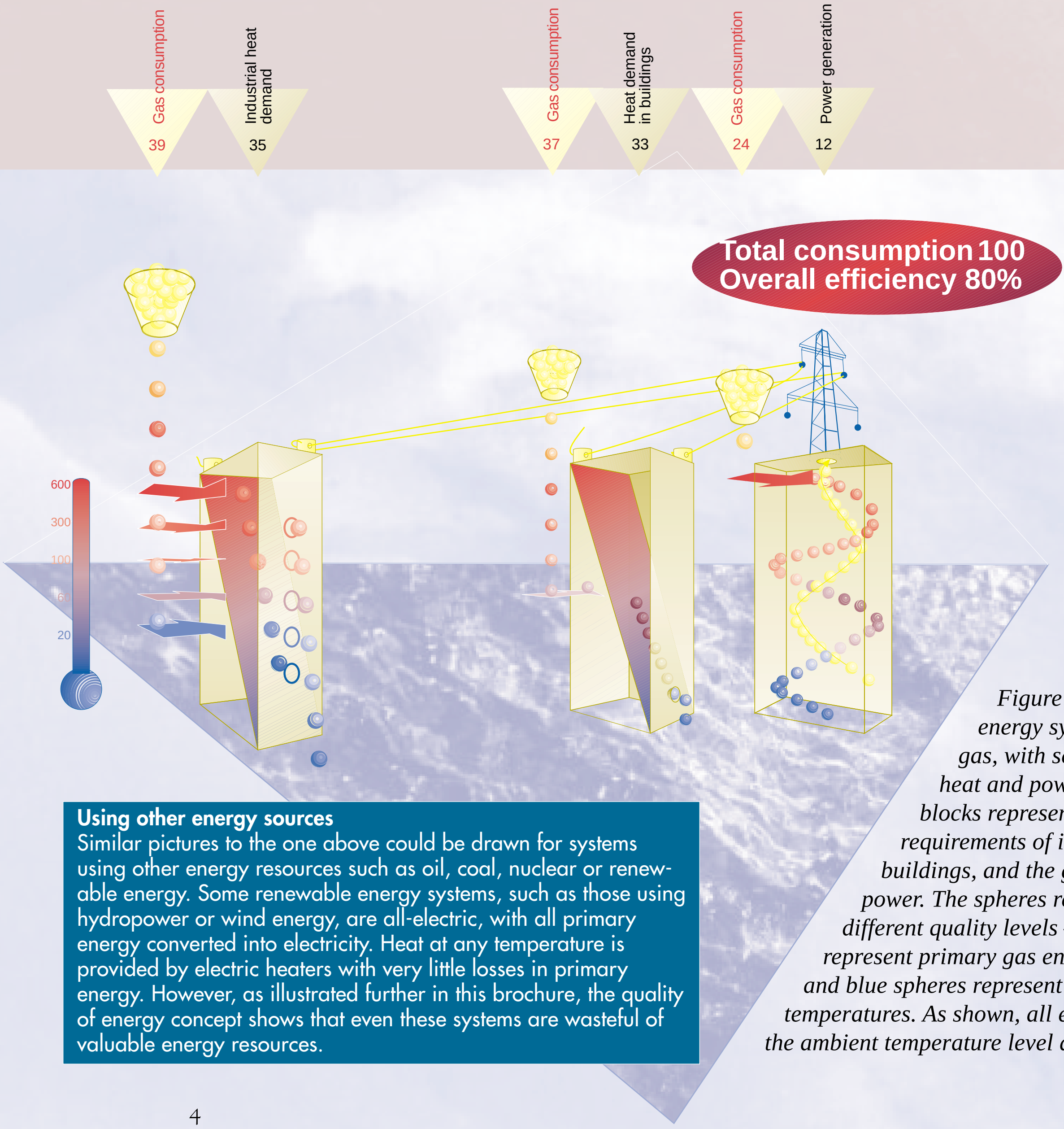


Figure 2: Traditional energy system, based on gas, with separate supply of heat and power. The three blocks represent the heating requirements of industry and buildings, and the generation of power. The spheres represent energy at different quality levels – yellow spheres represent primary gas energy, while red and blue spheres represent heat at different temperatures. As shown, all energy drops to the ambient temperature level at the bottom.

Using other energy sources

Similar pictures to the one above could be drawn for systems using other energy resources such as oil, coal, nuclear or renewable energy. Some renewable energy systems, such as those using hydropower or wind energy, are all-electric, with all primary energy converted into electricity. Heat at any temperature is provided by electric heaters with very little losses in primary energy. However, as illustrated further in this brochure, the quality of energy concept shows that even these systems are wasteful of valuable energy resources.

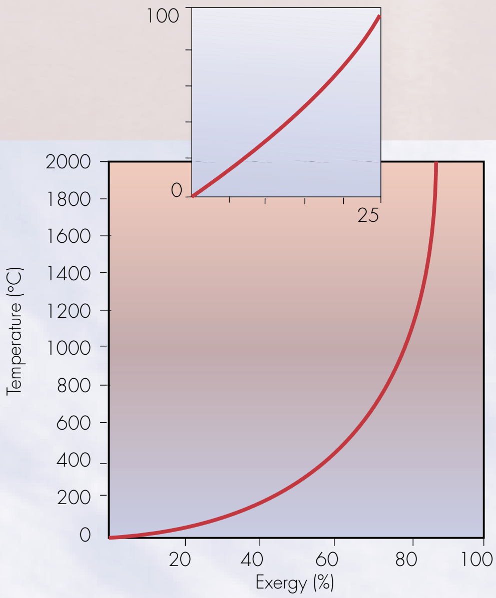
The quality of energy concept

Energy cannot be lost – it is always and completely saved. So states the first law of thermodynamics. But common experience appears to contradict this:

If your washing machine uses one kWh of electricity, the first law may state that this kWh is not "lost", although clearly it cannot be given back or used again to drive the vacuum cleaner. You will have to pay for it. A closer look, however, shows that the first law has not been broken. The kWh is still there, but has been converted into heat energy. It marginally contributes to the heating of the home, and is later released outdoors. There is an intuitive notion that something has been irreversibly lost. Although the kWh is still somewhere, it appears to have lost its value – its ability to "do something".

Thermodynamics confirms that the ability to "do something", or, more precisely, the potential to be converted into work, is the correct way to express the quality of energy. The second law of thermodynamics states that work can be converted completely into heat (or other forms of energy), but that heat can only partially be converted back into work. The fraction of a given amount of energy that can be converted into work is called "exergy". The remainder is "anergy". The second law means that, in any energy conversion, the amount of exergy is at best maintained, and is always reduced in practice.

Electricity is a form of pure, 100%, exergy since it can be converted completely into work. Less obviously, perhaps, is that the heating value of a fuel is also pure exergy. But according to the second law, "heat" is of more limited thermodynamic value. Heat can be loosely defined as an energy flow driven by a temperature difference. One senses that its value or quality will rise with the temperature at which it flows. Indeed the exergy content of heat varies in temperature as shown by the curve and the formula on the left.



$$\text{Exergy} = \frac{T_{heat} - T_{environment}}{T_{heat}}$$

T_{heat} = temperature of heat in Kelvin

$T_{environment}$ = temperature of environment in Kelvin

In the figure, $T_{environment}$ = 0°C (273 Kelvin)

The formula shows that the exergy of heat depends not only on its own temperature, but also on that of the environment – the ambient temperature. Heat can only "do something" when it flows at a temperature above ambient. The kWh released by your house has lost its value completely when it reaches the ambient temperature outside.

The second law of thermodynamics has important consequences for the design of energy systems. It must be recognized that only the "value" of energy has a price – both economically and ecologically. Fuels provide pure exergy, and this exergy must be used to the utmost. Saving energy really means saving its quality.

On the basis of this so-called "quality of energy concept", two important design principles for energy systems emerge – namely *energy cascading* and *energy upgrading*. **Figure 1**, on pages 2 and 3, illustrates these principles and how they can be applied to reduce the consumption of primary energy.

Energy cascading avoids unnecessary degradation of heat. High-quality heat is firstly used for high-quality purposes such as mechanical drive energy, electricity, or high-temperature heating. The waste heat from these processes is then used for a lower-temperature process, and so on. The original exergy meets a number of demands before it is finally reduced to ambient heat.

Energy upgrading allows low-quality energy to be used to meet heat demand at a higher temperature. It is accomplished by means of heat pumps. Unlike a conventional heating system, a heat pump does not allow exergy to "degrade" into the required heat. Instead, it uses exergy to upgrade low-quality energy to the temperature needed. For example, a 50°C heat flow of 10 kJ, contains only 1.5 kJ of exergy. Theoretically, to supply this heat, a heat pump need only provide 1.5 kJ of exergy from fuel or electricity. The remaining 8.5 kJ of "anergy" can be extracted from a low-temperature (say 0°C) heat source such as ground or air. While more exergy is needed in practice, heat pumps can reach remarkably high energy efficiencies.

An optimized energy system – whether for single processes or buildings, or for districts or even society as a whole – minimizes degradation through energy cascading, and complements this with energy upgrading where necessary.

Option 2
A waste heat recovery policy

Following advice from the thermodynamic experts, our energy managers draw up an inventory of waste heat sources such as heat from industrial effluents, power generators, cooling equipment, office equipment, ventilation air and sewage water. They also list society's heating needs, such as for space heating, hot water and industrial heating. A plan is then made to meet these heating needs by recovering as much heat as possible from the waste heat sources.

Energy cascading

Such a process can be called *energy cascading* and is already common practice in many industries, where heat is used again and again for different processes at different temperatures. In this way, one quantity of heat can be used several times, yet paid for only once!

Unfortunately, the impact of these measures is limited. Most of society's waste heat streams are at too low a temperature to be used in buildings. In response, the thermodynamic experts introduce two concepts that can help to overcome this difficulty.

The way to unlock low-temperature resources is to introduce heat pump technology.

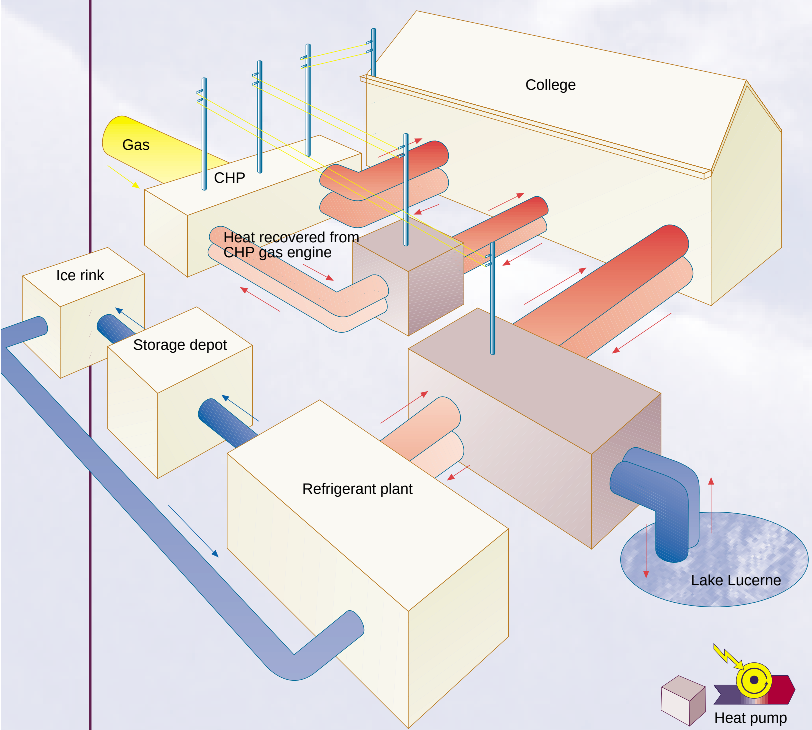
Low-temperature heating

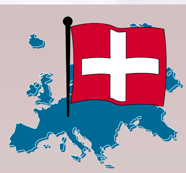
The first is to lower the temperature of one of society's most significant heating needs, by using low-temperature space heating systems in buildings. Such systems use air circulation or large surface-area piping in floors or walls to supply heat at temperatures as low as 35°C, instead of the conventional 65 to 85°C.

Combined heat and power

The second concept is to use combined heat & power (CHP) technology (also known as cogeneration). With CHP, the operation of the power generator is changed so that heat is rejected at a higher temperature than with conventional technology. While this results in a slight drop in the amount of power generated, the overall efficiency is higher. CHP can be applied on different scales. Small-scale CHP equipment may serve a single building or industrial plant. With large-scale CHP, heat is transported via district heating networks.

Showcase 1





Exploiting all available energy sources

In Switzerland, the heating system of a college near Lake Lucerne is utilizing a range of heat sources so that gas consumption is minimized. As illustrated, the gas is used to drive a CHP plant which provides heat to the college plus more than enough power to drive two electric heat pumps. One heat pump is able to use two heat sources:

- the heat rejected from refrigeration equipment in a nearby butter storage depot
- environmental heat from Lake Lucerne.

The second heat pump upgrades waste heat from the CHP engine room.

On average, the energy supplied by this system is about 1.3 times the energy value of the gas consumed. Compared with the conventional option of using gas boilers, gas consumption has been cut by some 30%.

As illustrated in **Figure 3**, the application of a waste heat recovery policy, incorporating the principles of energy cascading, low-temperature heating and CHP, sharply reduces the consumption of gas in our imaginary community. With this policy, many buildings are heated with waste heat that has been recovered from industry and power generation. In the figure, the piping network represents all heat transfer in the community, including district heating along with all other forms of heat transfer.

Even with these measures, there is insufficient waste heat to meet all low-temperature heat demand, especially that required by buildings. Also, the distance between buildings and industry puts practical constraints on the transfer of waste heat. As illustrated, gas energy must continue to be supplied to buildings to meet heat demand using conventional gas boilers. Referring once again to the *quality of energy* concept, the energy experts inform our energy managers that many potential heat sources continue to be wasted. All communities have a wealth of low-temperature energy resources including industrial and community waste heat, plus natural heat in ground, air and water. And the way to unlock these low-temperature energy resources is to introduce heat pump technology.

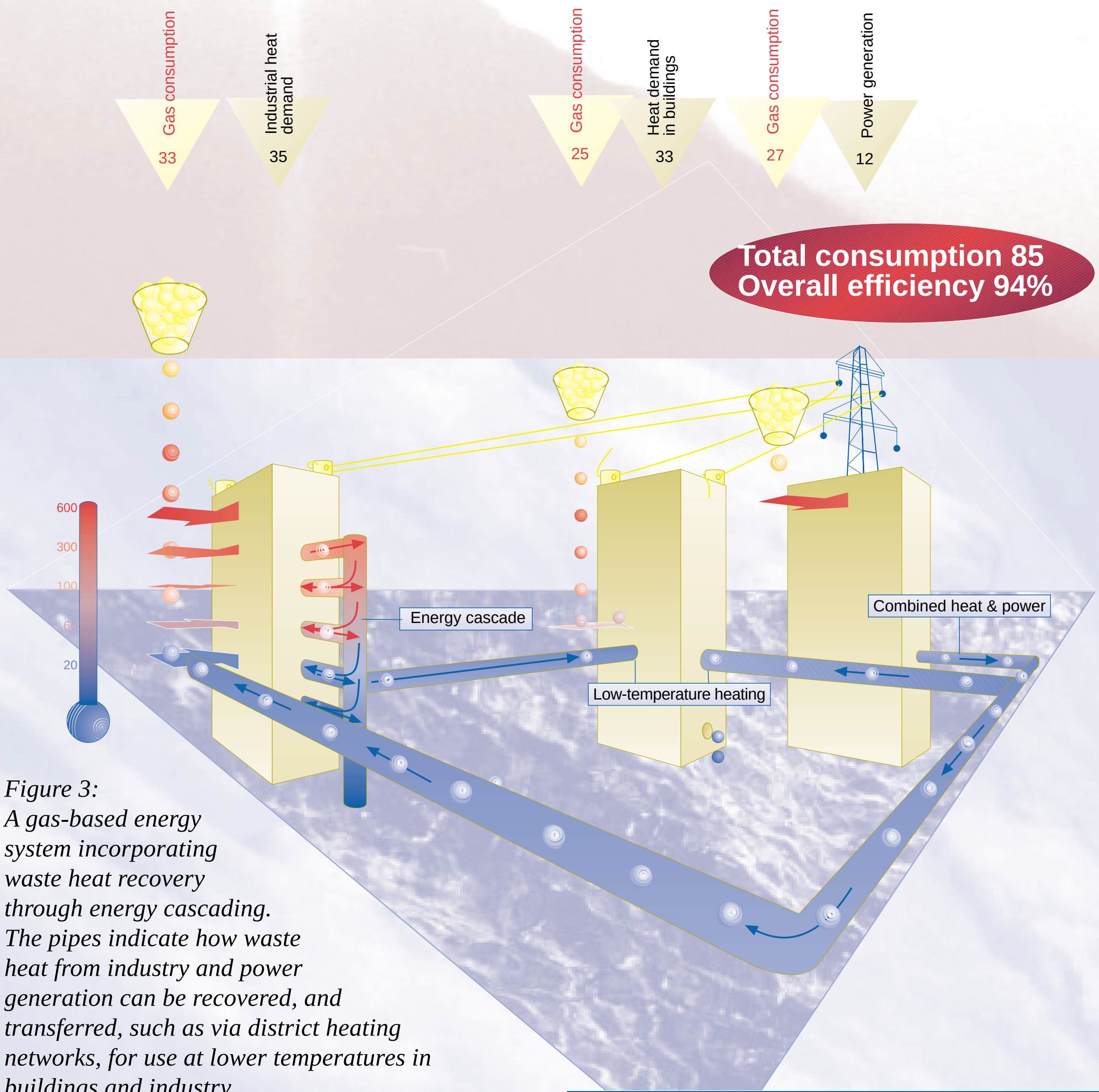


Figure 3:
A gas-based energy system incorporating waste heat recovery through energy cascading. The pipes indicate how waste heat from industry and power generation can be recovered, and transferred, such as via district heating networks, for use at lower temperatures in buildings and industry.

Using other energy sources

The principles of energy cascading and low-temperature heating should be applied whatever combination of primary energy resources is used, be they gas, coal, oil, renewables or nuclear energy. However, the concept of combined heat and power is not relevant to power sources such as wind, wave or hydropower. In such systems, the impact of waste heat recovery is significantly less.

Operating in the same way as a domestic refrigerator, a heat pump can remove heat energy at one temperature, and release it at a higher temperature. To do this, heat pumps must be driven by electricity, gas or heat. In all cases, the amount of primary energy (such as gas) required is much less than the heat delivered, and is typically between 50 and 70% of the energy requirements of a very efficient gas boiler. **Figure 4** illustrates how heat pumps save energy.

Energy upgrading

Because of their unique ability to *upgrade* low-temperature heat, heat pumps can be considered as the key to a low consumption energy policy. With heat pumps, waste heat that is not hot enough to be used again by energy cascading, can be upgraded to the temperature needed. Heat pumps can thus make use of large quantities of free heat energy such as industrial effluent, sewage water, ventilation air or heat from refrigeration equipment. And they can use natural heat sources such as the ground, water or air – renewable sources that offer a free supply of heat that is continuously replenished by the sun or the earth.

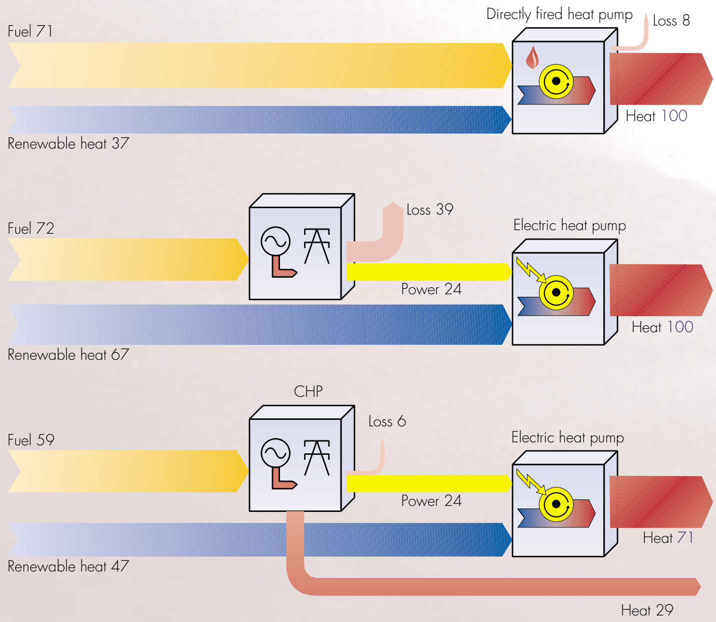
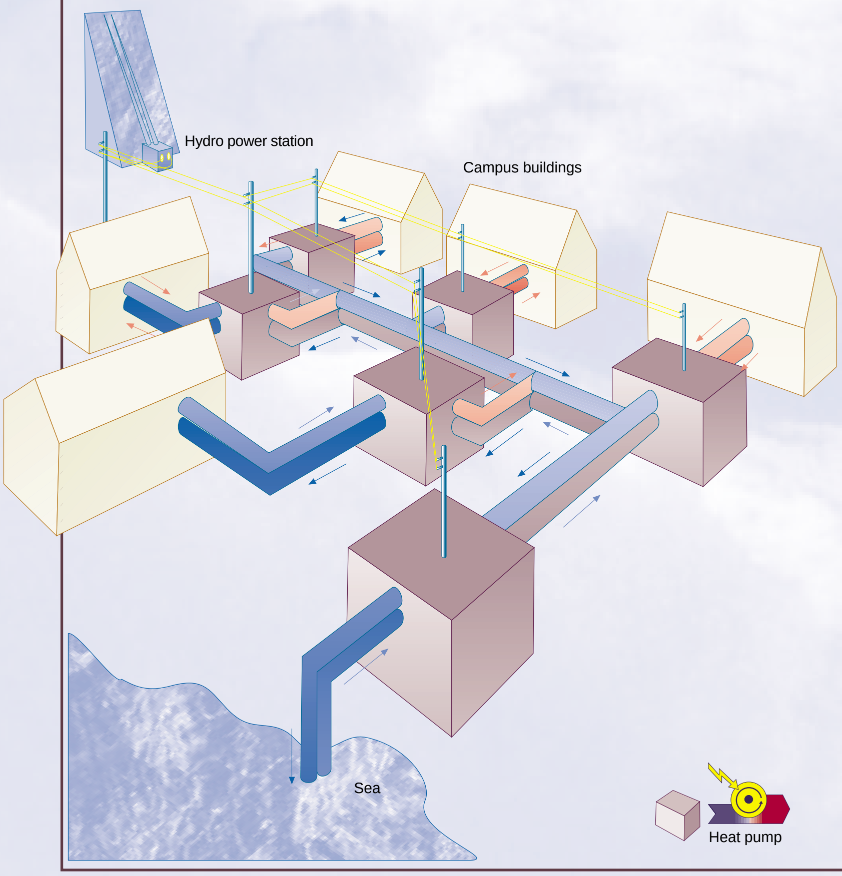


Figure 4: How heat pumps save energy.

Showcase 2



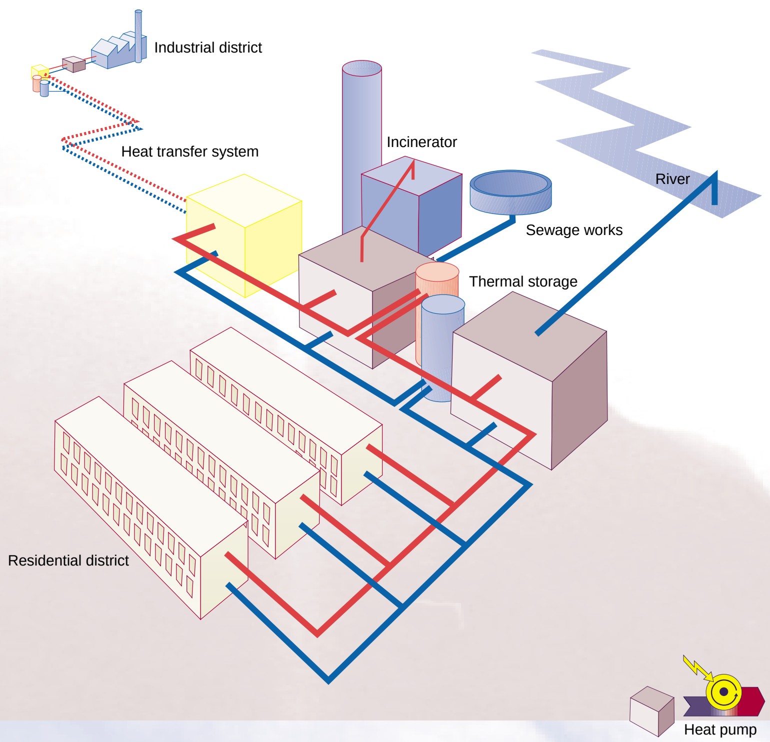
Making the most of renewable energy

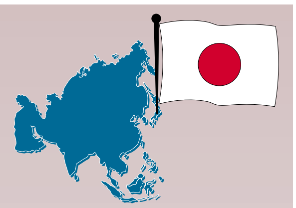
In Norway, where electricity is from hydropower, electric heaters can meet comfort needs with an energy efficiency close to 100%. But such a system is really a waste of a precious high-quality energy resource.

Heat pumps allow the renewable and clean hydropower energy to be put to better use. At the University of Bergen, a heat pump system uses high-quality electric power to extract low-quality heat from the sea.

The system works in two steps. A central heat pump upgrades heat from the sea and transports it at an intermediate temperature to buildings around the campus. In the buildings, smaller heat pumps, upgrade this heat to the temperature needed. In summer, they can be used for cooling, and the extracted heat is recovered for hot water heating. This system uses around one third the amount of hydropower as would be consumed if resistance (baseboard) heaters were used.

Showcase 3





The Eco-Energy city

In Japan, national programmes are underway to develop the technology needed to create large-scale energy systems in which all heat sources are fully utilized. The aim is to develop an "Eco-Energy City" where waste heat, such as from industry, sewage water and environmental sources, is transferred for use in residential and office buildings.

Techniques are being developed to overcome two major difficulties with systems based on the quality of energy concept: that waste heat is often generated a long way from where it is needed and that it is available at the wrong time. By using chemical transfer mechanisms, the Japanese programmes will show how heat can be transferred and stored with minimal losses. Heat pumps can then be used to supply heating and cooling services at the required temperatures, and at the right time.

Heat pumps can be used to meet heating needs at temperatures up to 300°C. And they can range in size from very large-scale equipment supplying hot water and space heating via district heating networks, to small heat pumps meeting the needs of a single room. And every heat pump type can now be made without using ozone depleting substances such as CFCs and HCFCs.

In addition to heating, heat pumps can meet cooling or dehumidification needs as well. This often gives heat pumps an economic advantage over traditional equipment, and is the prime reason for their widespread use for space conditioning in some countries and regions.

There are a number of different heat pump types. Most heat pumps in use today are electrically driven. However, thermally-activated heat pumps – gas-engine or absorption – can make equally good use of primary energy resources such as gas, oil or bio fuel. Absorption heat pumps can even be driven by high-temperature waste heat.

Electric or thermal?

Used in combination with CHP power generation, electric heat pumps generally exhibit a higher energy efficiency than thermally-driven equipment. Also, they can offer the economic advantage of significantly reducing the need for a gas network or for transporting fuel by lorry.

However, one disadvantage of using electric heat pumps is that power capacity must be sized to meet the highest peak in heating demand. In contrast, a system with thermally-driven heat pumps can more easily adapt to peak demand.

With electric heat pumps, measures such as thermal storage and the use of sophisticated control systems, can help reduce peak demand. Another way is to use a back-up heating system using conventional heating technology. Thermally-driven heat pumps also have the advantage of being able to reach higher temperatures than electric heat pumps by utilizing the heat released from the engine or burner. This is useful for water heating and for existing buildings with high-temperature heating systems.

Option 3
A heat pumping policy

Following advice from energy experts, our energy managers draw up plans for an energy system using heat pumps, in addition to energy cascading, CHP and low-temperature heating. **Figure 5** illustrates how the introduction of heat pumps reduces the gas consumption of the imaginary society by a further 15% in comparison with the heat recovery policy illustrated in Figure 3.

In this figure, heat pump technology is represented by a fourth block. This graphically illustrates how heat pumps are used to upgrade low-quality heat energy to supply heat to buildings and industry. As illustrated, heat pumps are connected to waste heat streams from buildings and industry, and are used to upgrade other low-temperature energy sources such as from the environment.

The connections made to the top of the heat pump block represent the three ways of driving a heat pump – by heat, fuel (in this case gas) and electricity. As shown, a heat pumping policy requires a significant increase in gas consumption for power generation. Indeed, people are often surprised to learn that energy can be saved by building more power plants.

As outlined on the previous page, electric- and thermally-driven heat pumps have both benefits and drawbacks, and a mixture of both heat pump types is often the best option. One strong argument in favour of an all-electric heat pump system is that it allows measures to be taken in the future, to further reduce emissions of environmentally damaging gases.

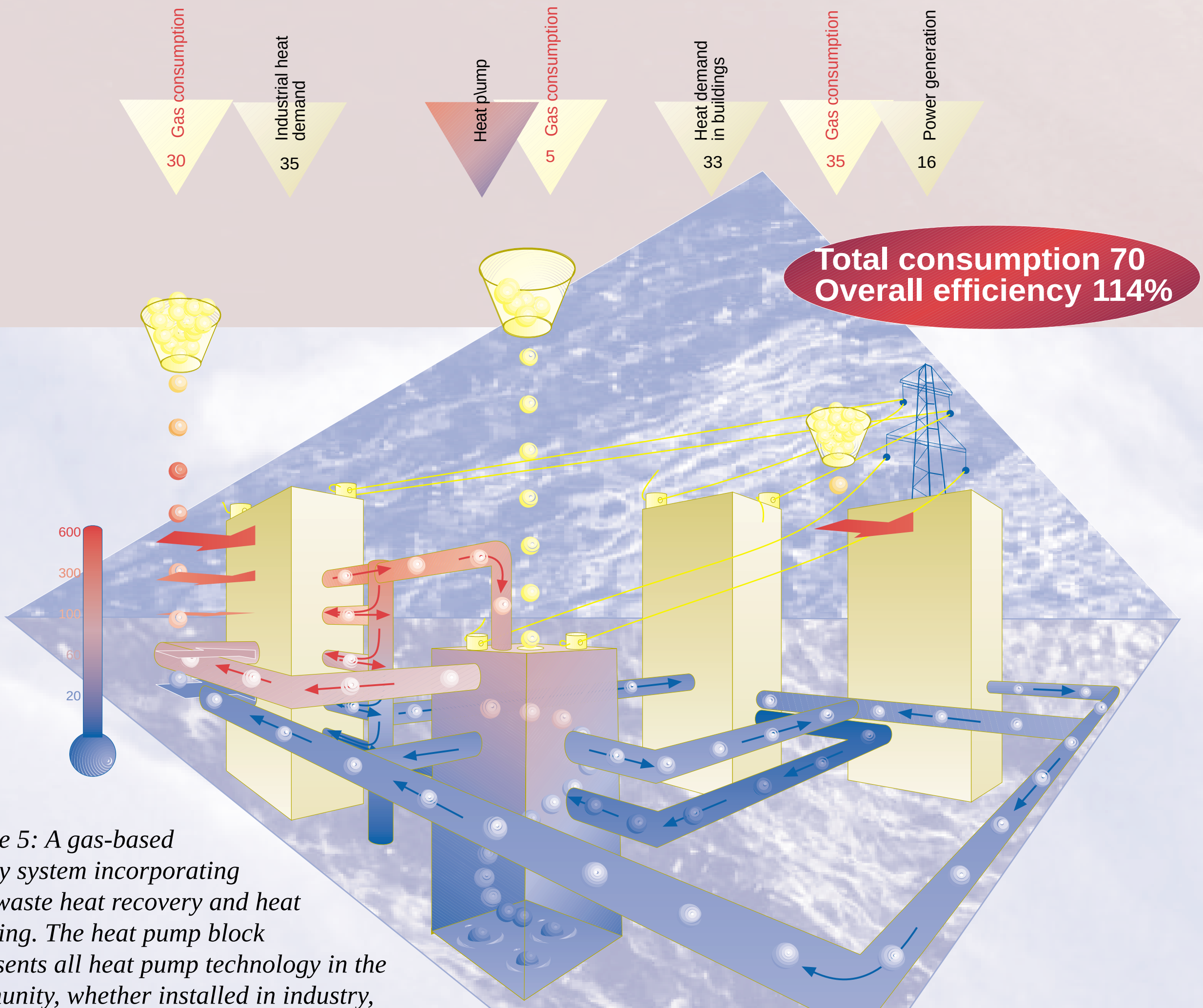


Figure 5: A gas-based energy system incorporating both waste heat recovery and heat pumping. The heat pump block represents all heat pump technology in the community, whether installed in industry, buildings or in district heating systems. Pipes running to and from the heat pump block illustrate how heat pumps extract waste heat from buildings and industry and return it at a higher temperature. As depicted inside the block, even more energy is extracted from the environment. With heat pumps driven by heat, gas and extra power, energy consumption is 70% of that with conventional heating technology.

Using other energy sources

Heat pumps will have a similar impact on systems based on other fuels such coal, oil or bio-fuel. For systems based on nuclear energy, or renewable energy sources such as hydro, wave or wind energy, the impact of heat pumps will be even greater. In these all-electric systems, the only alternative heating system to the heat pump is the electric heating element which uses three or four times as much primary energy.

For example, coal-fired power generators can be converted to run on cleaner gas; new technologies can be introduced into fossil-fuel power stations to reduce or eliminate harmful emissions, including carbon dioxide; or fossil-fuel power stations can be replaced by renewable technology such as wind, wave or hydropower. With heat pumps, all these options can be taken on the supply side, without having to change the installed heating equipment.

> People are often surprised to learn that energy can be saved by building more power plants.

A better way to meet heat demand

With the system shown in Figure 5, some 60% of our imaginary society's heat demand is met by recovering waste heat sources. Compared with the "traditional" policy of separate supply of power and heat, consumption of gas has been reduced by around 30%. Most of the savings have been made in meeting heat demand from buildings, for which energy consumption has been reduced by around 70%.

The reader should note that the energy savings achieved in any given energy system depend on a great many factors. Industrial energy demands and the availability of waste heat can vary widely, as can the relative amount of power demand. Such variations will affect the significance of the heat pump option.

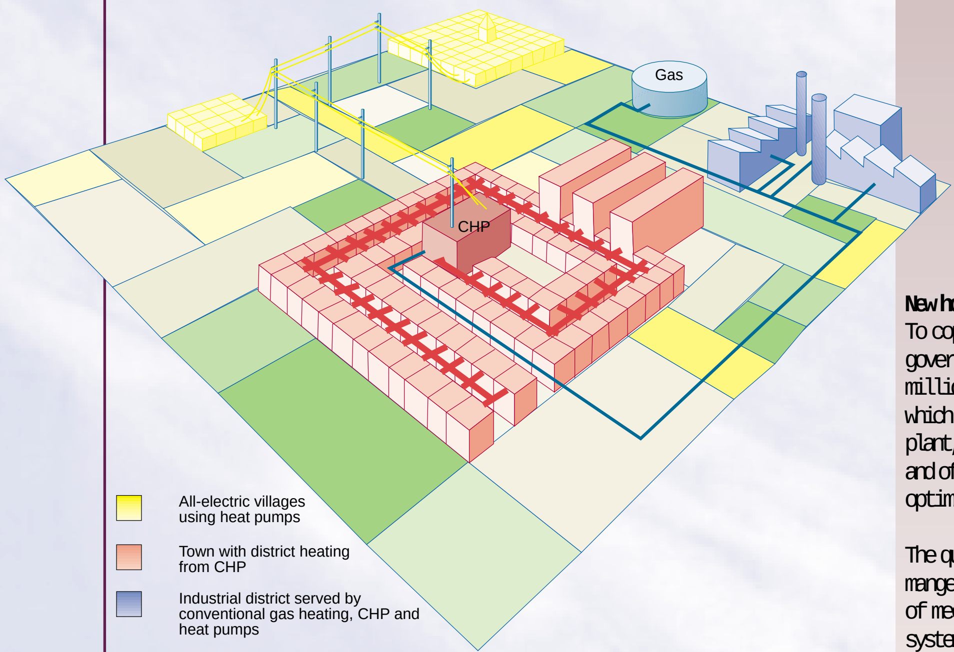
For example, in a community where large amounts of waste heat are produced by industry and power generation, most, if not all low-temperature heat demand could be met by energy cascading. In contrast, a community based only on hydropower, which results in negligible amounts of waste heat, would need to employ heat pumps on a large scale to avoid wasting its primary energy resource.

But in all situations, the principles outlined in this brochure always apply:

Wherever possible, heat should be recovered through energy cascading. And when heat demand still exists, and suitable waste heat streams are available, heat pumps should be used to upgrade waste heat to meet demand.

Through systems integration and heat pumping, heat demand is met by making optimum use of high-quality energy resources. A better way to meet heat demand.

Showcase 4



New housing areas will have quality energy system

To cope with the estimated demand by 2015, the Dutch government has allocated seven areas where around one million new homes will be built. These green field sites, which will also include new industrial and agricultural plant, will require a totally new energy infrastructure and offer an excellent opportunity for the design of optimized energy systems.

The quality of energy concept has persuaded energy mangers to step away from the conventional approach of meeting power and heat demand with separate systems. Instead they are developing integrated energy systems whereby CHP and heat pump systems work together to meet these needs. Many homes will be all-electric and will not be connected to the gas grid - a factor that brings economic as well as energy-saving benefits.

Better by nature

This brochure has been produced by the IEA Heat Pump Centre (HPC) as part of a campaign to highlight the benefits of heat pumps under the slogan "better by nature." The HPC is an international information centre operating for the International Energy Agency under the IEA Heat Pump Programme.

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among its participating countries, to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development.

IEA Heat Pump Programme

Set up by the IEA in 1978, the IEA Heat Pump Programme carries out a strategy to accelerate the development and use of heat pumps, in all applications where they can reduce energy consumption for the benefit of the environment. Within the framework of the programme, participants from different countries collaborate in specific heat pump projects known as Annexes.

IEA Heat Pump Centre

A central role within the programme is played by the IEA Heat Pump Centre (HPC), itself an Annex. The HPC contributes to the general aim of the IEA Heat Pump Programme, through information exchange and promotion. For further information on HPC products and activities, or for general enquiries on heat pumps and the IEA Heat Pump Programme, contact the address below.

The IEA Heat Pump Centre is operated by

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ISBN 90-73741-20-3

Better by nature

HPC-BR4
September 1996

Production: Novem Support Group