Decentralised energy systems: state of the art and potentials

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Abstract: The increasing liberalisation of the energy market as well as the ecological and business environment of public heat and power supply are leading to a re-evaluation of established and innovative energy conversion systems. A more efficient usage of fossil and regenerative primary energy resources is to be achieved by decentralised systems providing combined heat and electrical power. This paper discusses the potentials and challenges of today’s and future energy conversion systems.

Keywords: decentralised energy systems.

Reference to this paper should be made as follows: Bohn, D. (2005) ‘Decentralised energy systems: state of the art and potentials’, Int. J. Energy Technology and Policy, Vol. 3, Nos. 1/2, pp.1–11.

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1 Introduction

The liberalisation of the European power market in 1999 has lead to a re-evaluation of energy conversion technologies regarding power and heat supply at the national and European Union levels.

Centralised power generation in large-scale power plants characterises the present power market. These large-scale power plants are operated by public and commercial power suppliers who also distribute electrical energy to the power grids. At high voltages, low electrical transfer losses over long distances adversely affect the overall efficiency.

Supply to domestic consumers for water heating and heating of buildings and for industrial processes is predominantly decentralised. The main reason for this is that transferring centrally generated heat over long distances is only possible with advanced technology and related costs. Block-type thermal power stations are used for district heating by public utility companies. The usage of large-scale plants for this purpose is an exception.

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Present prognoses point towards increasing decentralised electrical power supply resulting from the liberalisation of the power market. The supply infrastructure for electricity and heat align to each other. This results in heat and electricity becoming equal goals for energy conversion. Therefore, heat and electricity have to be equally taken into account when evaluating energy conversion processes. Besides low costs, the main requirements for decentralised power and heat/cold generation systems are high reliability, continuous disposability of electrical power and heat, high operating safety, low maintenance and long revision cycles (> 8,000 h). Furthermore, the possibility of automation of the plant is important for trouble-free operation. Long economic lifetime (> 40,000 h), low emission of noise and pollutants, stability of frequency and high efficiency are additional requirements. Nevertheless, reliability and operating safety are of highest priority (Moore, 1998).

Efficiency definitions of processes and plants used for electrical power generation predominantly take emitted heat as a ‘waste product’, which means it is not taken into account.

In a decentralised infrastructure for power supply, however, electrical efficiency will not be the only evaluation criterion for energy conversion processes. Energy efficiency, which is defined as the ratio between the total amount of useful energy (heat and power) and the utilised primary energy, will come to the fore. If an energy conversion process provides electrical power and heat at the same time, the possibility of changing the ratio between these two forms of energy must be taken into account as well, in order to comply with the daily and seasonal fluctuations of demand.

2 Energy conversion technologies

A large number of machines and systems are available for the conversion of different primary energy carriers into useful forms of energy, electricity and heat. Usually the conversion follows a chain of steps until the desired form of energy is available. Figure 1 schematically shows the important conversion chains for decentralised energy supply. Two of them should be pointed out first, because they are not capable of providing heat. These are wind turbines, converting kinetic wind energy into mechanical energy, and photocells (photovoltaics), converting radiation energy directly into electrical energy. Furthermore, energy conversion processes using fuel cells and photocells stand out from other processes by not having energy present in the form of mechanical energy, which means that no rotating parts are found in these processes.

Providing electrical power by the use of turbomachines and reciprocating engines additionally requires a generator to convert the mechanical energy. Reciprocating engines as well as thermal turbomachines convert the internal energy of a fluid into mechanical energy. The internal energy of the fluid can be increased in combustion chambers, reactors or by heat exchangers, depending on the primary energy carrier. Heat is a fundamental part of the conversion chain of every energy conversion process, increasing the internal energy of a fluid. The different processes differ in the temperature levels of incidental heat, resulting in different possibilities of their usage. In turbomachines and reciprocating engines the technically useful heat is contained in the exhaust gas. The conversion of chemical energy into electrical energy by using fuel cells requires heat for the chemical reaction in the cell stack. This heat can also be used as useful heat energy.
Most of the worldwide demand for energy is covered by fossil primary energy carriers. It is aspired, though, to enlarge the fraction of regenerative energies for ecological reasons, especially for the reduction of CO₂ emissions. These primary energy carriers and their corresponding technical conversion processes must be economical to use in order to compete with the existing systems. Only if a cost-effective operation is guaranteed will these new energy conversion systems stand a chance to be established in the long term. Aspects, such as operation safety and availability are also to be regarded as important (Ali and Zeh, 1998).

**Figure 1** Forms of energy and energy conversion technologies

![Diagram of energy conversion technologies](image)

### 3 Regenerative energies

#### 3.1 Wind power

Wind has been used for centuries as a primary energy carrier for windmills. Its usage for electrical power generation has increased in the past two decades. The plants’ electrical power output as well as the total power installed has increased significantly in the past years (Figure 2). This increase in power output corresponds to an increase in rotor diameters and hub heights.

Additional installation of wind power units is supported by public financial promotions, for example, the stipulations in the German law about regenerative energies (Erneuerbare-Energien-Gesetz, EEG). Because of law’s mandatory commission of 9.1 ct/kWh, economical operation of wind power units is possible in Germany.

Power generation costs of wind turbine units depend strongly on the average and maximal wind speeds present at the installation sites (Figure 3). Hence, prior to choosing a site, an analysis of the environment is essential. So-called strong-wind sites are mostly found in regions near the sea. Due to the law about regenerative energies (EEG), these areas have already been exploited in Germany. Hence, further installations along the sea are unlikely. However, a large potential of well-suited locations is present worldwide.
Replacement of old units with new ones on sites close to the sea is possible in Germany. New sites with less favourable wind characteristics can be used by developing low-load wind power units with good conversion efficiency at low wind speeds. Further potential is seen in offshore sites; these, however, still require considerable R&D efforts. Aspects, such as reduction of maintenance, safety of the installation and also power transfer to the mainland are important issues for these sites.

Figure 2  Power output improvement of wind turbines

![Figure 2](image1)

Figure 3  Power generation costs of wind turbine units

![Figure 3](image2)

Source: Siempelkamp, Nordex (Fechner, 2002/2003)
Regarding the decentralised power market, it has to be stated that current and future wind power units are not capable of supplying heat. But their advantage in power generation is that the primary energy resource is infinitely available. The amount of generated power, though, fluctuates at a large scale over time, cannot be influenced significantly by the operating company. Therefore, secure operation of a power grid with excessive use of wind power units is only possible with significant technological efforts and requires the installation of conventional power plants that are capable of quick automatic regulation. Here, gas turbine and hydroelectric storage water power plants, which can provide grid stability due to their flexibility and quick-start capabilities, are required.

Due to the establishment of wind power in Germany and parts of the European power market, the technological development of wind power units has been boosted; German manufacturers have also participated in this. A promising future export potential for wind power units is apparent.

3.2 Solar power

3.2.1 Photovoltaics

Using photovoltaics, radiation energy can be converted to electrical energy by the photo-electric effect. Photocells show efficiencies of between 7% and 17% under realistic operating conditions and can be manufactured from different metal semiconductors. Inside laboratories without interfering environmental effects, the efficiency of precisely manufactured photocells can be brought up to 30%.

Due to the disadvantageous conditions of solar radiation in Germany, an economical usage of photovoltaics is barely possible. Due to the high specific costs per installed power and the resulting high power generation costs, photovoltaics have so far been used in small applications, for example to generate power for domestic water heating.

3.2.2 Solar-thermic power

Solar-thermic power uses the energy of solar radiation to increase the internal energy of a fluid. This procedure of using solar energy provides energy in the form of heat, contrary to photovoltaics. This heat can be drawn from the process and used for heating or process heat purposes.

The power plant concepts available for central solar-thermic usage of solar energy are the parabolic trench concept, the parabolic reflector concept and the tower concept. All these are based upon the principle of focusing sunlight with reflectors (Figure 4). However, economical operation of these plants is not possible due to the high investment costs. The challenge lies in the manufacturing of reflectors as well as in the realisation of a control system aligning the reflectors to the position of the sun.

The above three power plant concepts can be coupled with conventional power plant concepts. This allows for saving fossil primary energy carriers in case of sufficient solar radiation while in case of insufficient solar radiation the plant can still provide the demanded amount of energy.

In Germany, economical usage of solar-thermic concepts is unlikely because of the disadvantageous conditions of solar radiation, as already mentioned. Additionally, considerably large areas are required for such installations, which are not easily available.
There are, however, regions in the rest of the world with better solar conditions as well as large areas sparsely populated, where electrical power and heat could be provided by solar-thermic power plants. Essential points in order to achieve economical usage will be the lowering of installation costs, energy storage for supply of electrical power and heat on demand and the coupling of solar-thermic plants with conventional power plants to increase flexibility.

Figure 4  Chances of solar-thermic power plants in the energy market

4  Progressive energy systems

4.1  Micro gas turbines

Heavy-duty gas turbines use the chemical energy mainly of fossil primary energy carriers in a combustion chamber to increase the internal energy of a working fluid. The heat is converted into mechanical power and used to drive the compressor and the generator of the turbine. The exhaust gas provides significant heat flow usable for heating or process heat. Gas turbines, therefore, are suitable for application in coupled heat and power systems.

The power output of heavy-duty gas turbines ranges from 30 kW to 260 MW. Micro gas turbines often emerge from enhancements of turbochargers and operate at low pressure ratios of 3:1 to 7:1 at high revolution speeds. Typically, they are combined with high-speed generators and rectifier/inverter units. So, a reduction gear unit is not required (Campanari and Macchi, 1999).

Generally, gas turbines can be classified by their power output into heavy-duty gas turbines having electrical power output exceeding 50 MW, small- and medium-sized turbines having between 1 and 50 MW of electrical power output, and micro gas turbines
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with an electrical power output of less than 1 MW. The worldwide market for heavy-duty gas turbines is shared by a few manufacturers. There are new markets for medium-sized gas turbines if their efficiency can be increased and the turbines can be made flexible to couple with heat and power supply matched to the customer’s needs.

Observation of the current market indicates that future R&D work must concentrate on micro gas turbines with an electrical power output of less than 300 kW. Sophisticated heavy-duty gas turbines in the market stand out due to their high operational availability and reliability, simple and robust construction, low maintenance, and an expected lifetime of more than 100,000 hours of operation. Micro gas turbines have to meet these expectations as well, if they are to be marketed successfully.

Current developments in the field of micro gas turbines range in a power output between 20 and 100 kW. State-of-the-art gas turbines of this size supplied with a recuperator exhibit an efficiency of about 26%. Current R&D programmes target an increase in efficiency of these to 35% or 40%. To increase the inlet temperature to 850°C–950°C, an increase in the efficiency of the components is necessary. Further development of the recuperators and the development of solutions using new materials allowing for higher inlet temperatures without increased cooling efforts is required for an increase in electrical efficiency. A prognosis about the several steps of development and their corresponding expected efficiencies is shown in Figure 5.

Figure 5 Prognosis of the development for micro gas turbine (MGT) technology

Source: McDonald (2000)
In comparison to reciprocating engines, which are capable of fulfilling similar requirement specifications like small- and medium-sized gas turbines, the gas turbines stand out by lower pollutant emissions, especially of toxic gases, such as nitrogen oxide and carbon monoxide. The handicap of lower efficiency can be overcome by the mentioned enhancements.

4.2 Fuel cells

Fuel cells generate electricity by the chemical reaction of an oxygen source (O₂, air or CO₂) with a fuel (H₂, CH₄, CO). The reaction emits electrons within an electrolyte (membrane), resulting in a current. The gases and operating temperatures possible in fuel cells depend on the employed materials. The operating temperatures of the different types of fuel cells are shown in Figure 6. An increase of the power output of a fuel cell is possible by shunt circuits of several cells to a stack.

**Figure 6** Fuel gas production for different fuel cell types

Using pure oxygen and pure hydrogen, a fuel cell would solely emit water to the environment and thus would not produce any toxic substances or gases contributing to the greenhouse effect. Conditioning of pure hydrogen is, however, not feasible at the moment due to economic reasons. Usually, natural gas consisting of methane is used instead and air serves as the oxygen source. Using these gases the emissions of CO and NOₓ of fuel cells are negligible as well.

After a purification process is applied to the fuel gas, the hydrogen is provided by means of a reforming process. Depending on the operating temperature of the fuel cell the heat required for the endothermal reforming process can be provided by the stack itself (MCFC, SOFC) or has to be provided externally (PAFC, PEMFC).

The effort for fuel gas purification increases with the decrease of operating temperature, which reduces the efficiency of the whole installation. Molten Carbonate Fuel Cells (MCFC) and Solid Oxide Fuel Cells (SOFC) are, therefore, most suitable for obtaining highest efficiencies using fuel cells in a decentralised electricity and
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The development of fuel cells for electric power and heat supply basically follows two road maps. On the one hand, systems for domestic supply providing an electrical power output of approximately 1 kW and a heat supply capacity of approximately 2 kW are being developed. On the other hand, exist concepts and demonstration sites for fuel cells with an electrical power output of 100 kW to 300 kW for use in block heat and power plants (McCahey, McMullan and Williams, 1998; Riensche, 1995).

The fuel cell systems are designed to satisfy the heat demand and partly cover the electricity demand of customers. Crucial for this decision is the condition that fuel cells bear load changes only at small temperature gradients making the system quite inert. Because of heat storage being significantly less expensive than storage of electrical power, fuel cell systems will remain operational with respect to the heat requirements. This makes these systems inappropriate for stand-alone operations in single households or in industrial plants, because in principle heat and electricity are not required at a similar rate and are subject to strong daily fluctuations. Therefore, an external supply with electrical power from central power plants must still be ensured when using fuel cells.

Due to the high investment costs, an economical operation of fuel cells is not possible yet. Optimising the manufacturing processes as well as decreasing manufacturing costs due to mass production, however, should decrease the investment costs in the next few years. The main focus hereby lies in the manufacturing of the fuel cell stacks and in the standardisation of other auxiliary components. The market entry on a competitive basis in the field of domestic installations is expected in a few years. Reliability of the developed fuel cell concepts is being verified in demonstration sites at the moment.

4.3 Coupling of micro gas turbine and fuel cell

High-temperature fuel cells (MCFC and SOFC) are especially well suited for the combination of micro gas turbines and fuel cells in hybrid power plants. The waste heat of the fuel cells can be used as an energy source for the gas turbine process. The exhaust gas heat of the gas turbine can be utilised for preheating the cathode and anode gases at the same time. The close coupling of the fuel process and gas turbine processes, therefore, enables optimal utilisation of the supplied fuel by synergetic effects.

The coupling of micro gas turbines and fuel cells for the simultaneous generation of heat, cold and electrical power in small decentralised power units shows a high potential which has not remotely been made available so far. There are excellent prospects for this type of energy conversion. Electrical efficiencies exceeding those of large-scale power plants are feasible. The direct coupling of the two components allowing for electrical efficiencies up to 70% should especially be mentioned. By direct coupling the fuel cell is used like a combustion chamber in the gas turbine process (Figure 7), contrary to the so-called ‘indirect coupling’, where the waste heat of the fuel cell is provided to the gas turbine process by means of heat exchangers. Another possibility to increase the efficiency lies in an increase of the gas turbine inlet temperature as well as the SOFC operating temperature; these, however, still require technological development, especially in the field of material technology.

The challenges in the design of hybrid power plants lie in the further development of component fuel cells and micro gas turbines, the harmonisation of the two machines
exhibiting very different time scales regarding regulation times at load changes as well as start-up and shut-down behaviour. The gas turbine is capable of reacting to load changes within seconds while the fuel cell requires several minutes to adapt to minor changes. The micro gas turbine takes about 30 minutes to start, while a fuel cell requires approximately 30 hours for a cold start in order to reach the full load operating point. Thus, it is necessary to develop sophisticated control and automation systems to ensure safe cooperation of the two systems.

Hybrid systems consisting of micro gas turbines and fuel cells are expected in the market in about 10 years, depending on the launch of the micro gas turbines. It is anticipated, however, that economical operation without governmental subsidisation similar to the mandatory commission requested by the German law about regenerative energies (EEG) will not be possible by then. The development of this innovative and highly efficient energy conversion system will request the effort of R&D engineers of all fields in the coming years.

**Figure 7** Direct coupling of fuel cell and micro gas turbine

![Diagram](image)

*Source: Bohn et al. (2000)*

## 5 Summary and outlook

Due to the ongoing liberalisation of the energy market, decentralised energy systems will cover an increasing part of the supply of electrical power and heat. High energy efficiencies and local customer-oriented supply can be achieved by the concurrent production of both forms of energy by energy conversion systems, such as fuel cells or micro gas turbines.

Emissions of toxic gases and gases contributing to the greenhouse effect can be reduced by increased usage of conversion systems for regenerative energy resources. Power generation costs becoming competitive to the existing systems for the supply of heat and electricity will be crucial for the success of the several individual technologies. The future challenge to engineers lies in this area.
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References


