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Energy Scientific and Technological Indicators and References

Study coordinated by
Fraunhofer Institute for Systems and Innovation Research FhG-ISI

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2005

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Preface

Energy research is facing tremendous challenges to enhance knowledge and develop new technologies for cleaner and more efficient energy production, transport, conversion and final use.

Therefore, measuring the best state of the art of given technologies against a set of relevant parameters, identifying ambitious but realistic objectives to be attained over various time lines, and assessing the progress made over time are major issues for programme managers, researchers or decision-makers.

The present study, which builds upon preliminary work undertaken within the Commission services[1], intends:

- to better define the present state of the art of key energy technologies in seven areas;
- to characterise the major bottlenecks to be overcome or the main challenges to be addressed by each technology in its future development over various time periods (short, medium and long term).

This work is part of a wider effort to pave the way towards the establishment of a commonly agreed, validated and updated system of energy scientific and technological indicators and references (ESTIR).

Consequently, an important feature of the study has been the active involvement of representatives from research and industry who have been invited to discuss, comment and validate the draft results of the study, before it is finalised.

This ‘quantitative’ method, based on quantifiable and verifiable indicators, can in certain cases be complemented by a more ‘qualitative’ one, in order to preserve the possibility of disruptive breakthroughs emerging from any sharp discontinuity in scientific and technological progress, or from the unexpected combination of cross-cutting and transdisciplinary approaches.

It is expected that the work undertaken throughout this ESTIR study will be continued on a broader basis so as to complement, refine and adapt those indicators to take into account changes and progress made by energy research and industry. It will also provide the best support for user needs in programme and project design, monitoring and assessment.

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[1] http://www.cordis.lu/eesd/src/indicators.htm

Methodology

A common methodology[2] was applied to all seven sections in order to establish a consistent, well-justified analysis and to produce a report which is coherent in terms of structure and content. More specifically, the following tasks have been performed in each section:

- a review of the previous test analysis carried out by the Commission on energy technology indicators;
- a screening of the technologies with respect to their R&D relevance;
- the description of technological and socio-economic bottlenecks through relevant parameters, and the identification of critical indicators for the characterisation of measures to further R&D progress so as to overcome the main bottlenecks.

Identification of the critical and relevant sub-technologies was the first step to be performed in an effort to pinpoint the most relevant bottlenecks and indicators for the further improvement of a specific technological sector.

In a second step, the state of the art of the different technologies and the critical indicators for further progress were identified. Technologies that are already mature and show limited R&D-driven potential for further progress have been deemed of little relevance, unless specific socio-economic R&D issues could have a critical impact on their future deployment.

In a third step, the main bottlenecks were selected. The costs per kWh of energy production turned out to be the most critical aggregated bottleneck for the majority of technologies considered within the ESTIR project. (Some very immature technologies investigated in the section 'cross-cutting technologies' constitute an exception to this rule.) Simultaneously, critical parameters were identified which best characterise the corresponding bottleneck.

In a last step, indicators to future progress and specific improvement measures were assessed. Therefore, relevant indicators influencing future progress in overcoming the barriers have been identified. However, very frequently the indicators are only of a qualitative nature, e.g. in a case where the introduction of a different material will change the characteristic properties of a technology or process, resulting in significant progress. In such cases, the qualitative measures for further improvements are listed.

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[2] A more complete description can be found at http://www.eu.fraunhofer.de/estir/

Abbreviations of fuel cell types:

PEMFC	Proton Exchange Membrane Fuel Cell
MCFC	Molten Carbonate Fuel Cell
SOFC	Solid Oxide Fuel Cell
DMFC	Direct Methanol Fuel Cell
AFC	Alkaline Fuel Cell
PAFC	Phosphoric Acid Fuel Cell

Fuel cells and hydrogen technologies

Fuel cells

Technologies

The demand for R&D is on the one hand determined by the technical particularities of single fuel cell types and on the other guided by application-oriented requirements. Each fuel cell type has special characteristics, making it suitable for different applications and fuels. In the following only the most promising fuel cell types are analysed in the context of the most obvious application field. Thus target values given in the course of this document will refer to this application field. Target values for the PEMFC e.g. are defined for passenger transport using pure hydrogen, although it is also suitable for stationary or portable applications. MCFC and SOFC are analysed in the context of stationary applications using natural gas, DMFC in the portable application field with methanol as fuel and AFC using pure hydrogen in the smaller-scale application field (e.g. back-up power, auxiliary power or fork-lift vehicles). The fuel cell type PAFC was not examined as interest in PAFC technology is currently declining, on both the producer and user sides. The main reason for this development is that the necessary cost reduction and technological improvement for commercialisation – even with further research and development activity – is not feasible (according to the former PAFC producer UTC [USA] and the project coordinator of a PAFC demonstration project in Nürnberg, Germany [1997-2003]). Table 1 shows the state of the art of different fuel cell technologies. All types are currently being tested in various demonstration projects. Parallel to the demonstrations further R&D is being carried out. Simultaneously, portable devices with DMFC and PEMFC as well as stationary devices with MCFC and SOFC recently entered the niche/ prestige market as prototypes[3]. AFC devices have been used for aerospace and submarine applications for several years. Current research activity aims to bring the price of this technology down to earth as an inexpensive durable fuel cell for everyday applications.

Table 1 - State of the art of different fuel cell types

Technology	MCFC SOFC PEMFC DMFC AFC	**MCFC** **SOFC** **PEMFC** **DMFC** **AFC**	MCFC SOFC PEMFC DMFC AFC
	Commercial	**Demonstration**	**R&D**

Technical and socio-economic bottlenecks

- The main bottleneck for fuel cell technologies is the high cost. All fuel cell types are currently a long way off from the required target cost for market introduction. At present, fuel cells are only attractive for niche applications or prestige projects. Early markets like 4C (computer, camcorders, cellular phones, cordless tools) and other portable applications accept higher costs, due to the specific benefits of fuel cells. The transport sector is a high barrier market for fuel cells, and they will enter this market at a later time. However, the fuel cell cost, that the market will accept are inter alia highly dependent on changes in oil prices. See Figure 1 for market-accepted fuel cell costs and estimated market introduction time for different application fields. Fuel cell costs will be reduced in two principal ways. First, by production in large quantities, as such an economy of scale has the potential to reduce fuel cell costs by around 40 to 70%. The second way is by technological improvements to the cells. This additional cost reduction potential is estimated to be around 20 to 50%. The overall cost reduction potential is therefore 60 to over 90%.

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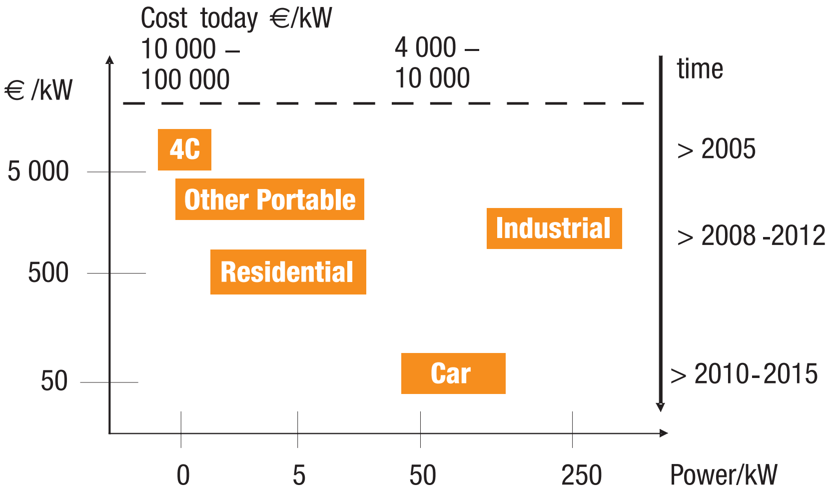
[3] DMFC: e.g. A50 by Smart Fuel Cell GmbH; PEMFC: e.g. Nexa RM by Ballard Power System AG; SOFC: e.g. HXS 1000 Premiere by Sulzer Hexis; MCFC: e.g. Hot Module, by MTU.

- The current lifetime of the fuel cell is also seen as a bottleneck to the introduction of fuel cell types MCFC, SOFC planar design[4], DMFC and AFC. The current lifetime is well below that of comparable conventional systems. The main reasons for this limitation in lifetime are degradation and corrosion processes in the cell. Lifetime directly correlates with the power density of the cells. The highest technically feasible power density of a plant results in a lower lifetime (with currently available materials). Therefore the target is to find new low-cost and efficient materials and the optimum design for each specific application field. The lifetime of PEMFC for passenger cars and SOFC tubular design is already sufficient.
- The efficiency of DMFC is quite low compared to other fuel cell types and is seen as a bottleneck. In contrast, the efficiency of MCFC, SOFC, PEMFC and AFC systems is considered to be sufficient. Current plants are usually not designed towards maximum efficiency (it is technically feasible to achieve 55 to 60% el. efficiency). The aim is rather to find the optimal trade-off between efficiency, cost, lifetime and size for each specific application field. However, all fuel cell types have a potential for further cost reduction and efficiency increase by a better integration and adaptation of ancillary components like compressors, fans, etc., which are usually not specifically designed for the fuel cell's requirements.
- The absence of common codes and standards as well as a limited public acceptance have been identified as the main socio-economic bottlenecks for both fuel cell and hydrogen technologies. Indicators for the absence of codes and standards can be fields of low or missing coverage. The total number of demonstration projects in the European Union indirectly reflects the level of public acceptance. The socio-economic bottlenecks are addressed in the hydrogen section (see Table 14).

Figure 1 – Market-accepted fuel cell cost and estimated market introduction time for different application fields.



Source: FhG-ISI, according to manufacturer estimations

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[4] For SOFC two different concepts exist, the planar and the tubular design, each with different properties and research emphasis. They are therefore considered separately in this report.

Parameters for characterisation of the critical bottlenecks

Table 2 gives an overview of the quantitative parameters describing the main bottlenecks for the introduction of fuel cells. State of the art and target values are given. For comparison reasons efficiency is also listed, although it does not represent a critical bottleneck for MCFC, SOFC, PEMFC and AFC. The same is true for lifetime, which is not a bottleneck for SOFC with a tubular design.

Table 2 – Quantitative parameters for characterisation of critical bottlenecks

Parameters	Unit	2004	Target	Target year
MCFC (stationary) source [1,2,3]				
Investment cost (250 kW system)	€/kW	8,500	1,500	2007
Lifetime (operation)	h	21,560	40,000	2009
Efficiency (system)	%	47	50	2007
SOFC (planar design, stationary) source [4]				
Investment cost (system)[5]	€/kW	16,000-20,000	1,500	2015
Lifetime (operation)	h	2,000-5,000	40,000	2015
Efficiency (system)	%	40-45	50	2010
SOFC (tubular design, stationary) source [5]				
Investment cost (100 kW system)	€/kW	> 10,000	1,500	2015
Lifetime (operation)	h	20,000-70,000	40,000-80,000	2015
Efficiency (system)	%	45	45-55	2015
PEMFC (mobile, passenger car) source [6]				
Investment cost (system)	€/kW	2,000	200	2010
Lifetime (operation)	h	> 8000	> 8000	-
Efficiency (system)	%	45	45	-
DMFC (portable) source [4, 7,8]				
Investment cost	€/kW	10,000-100,000	3,000-5,000	2007
Lifetime (operation)	h	< 1,000	1,000-5,000	2007
Efficiency (system)	%	20 -30	30-35	2007
AFC (smaller scale applications) source [9]				
Investment cost (system)	€/kW	11,000-15,000	< 1,000	-
Lifetime (operation)	h	2000	-	-
Efficiency (system)	%	60	60	-

[1] MTU 2004a
[2] MTU 2004b
[3] Michelin 2004
[4] FZ-Jülich 2004
[5] Siemens Westinghaus
[6] Ned-Stack 2005
[7] Motorola Laboratories 2002
[8] SRA 2005
[9] Asrtis Energi Inc 2005

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[5] Rough estimate as no prototypes exist.

Analysis of the critical indicators to further progress

In order to coordinate R&D activities it is necessary to know which specific measures will contribute to improve the bottleneck. In Tables 3 to 8 these measures are listed and critical indicators to further progress are given, wherever possible. Measures and indicators are allocated to the corresponding bottleneck parameters. The tables also indicate where research has to take place by technology components. The list does not contain every possible improvement measure and indicator, but only the most important and most promising ones. The information is mainly based on interviews with technology providers or research institutes. Information from current studies and websites is also included.

Table 3 – Critical indicators to further progress – MCFC, industrial applications

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>System</td><td>Investment cost</td><td>Serial production (MTU 2004b)</td><td>Cost reduction will mainly be achieved by automated high volume production.</td></tr>
<tr><td>System</td><td>Investment cost</td><td>Simplification of stack design and fuel preparation (reduction of material and size) (Michelin 2004)</td><td>The current plant is five times bigger than a comparable CHP; this reduces the number of possible users due to space problems (Michelin 2004).</td></tr>
<tr><td>System</td><td>Investment cost</td><td>Adaptation to other fuels/ increase of fuel flexibility e.g. to synthesis gases from the thermal gasification of residues (MTU 2004b)</td><td></td></tr>
<tr><td>System</td><td>Lifetime</td><td>Reduction of temperature and increase of area-related power density
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>Operating Temperature [°C]</td><td>650</td><td>620-630</td><td>2007</td></tr>
<tr><td>Area related power density [W/cell]</td><td>700</td><td>800</td><td>2007</td></tr>
</table></td><td>A reduced operating temperature can considerably increase the current lifetime. On the other hand, lower temperatures result in lower efficiency, due to reduced reactions. An important development target is therefore to activate the electro-chemical reactions in the cell in order to get the desired power at lower temperatures.</td></tr>
<tr><td>Stack</td><td>Lifetime</td><td>Reduction of bipolar plate corrosion, and carbonate depletion/ degradation, increase of mechanical stability and catalyst activity, prevention of catalyst toxification (MTU 2004a/b)</td><td></td></tr>
</table>

Table 4 – Critical indicators to further progress – SOFC, planar design, stationary applications

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>Stack</td><td>Investment cost</td><td>Development of new electrolyte materials with good conductibility at lower temperatures and reduction of electrode thickness
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>T [°C]</td><td>800</td><td>600-700</td><td>2010</td></tr>
<tr><td>Anode thickness [µm]</td><td>10</td><td>5-10</td><td>2015</td></tr>
<tr><td>Cathode thickness [µm]</td><td>50</td><td>25</td><td>2015</td></tr>
</table>
(FZ Jülich 2004/2005)</td><td>The reduction of temperature for SOFC is desirable as high temperatures imply restrictions with respect to plant design and materials. Lower temperatures however reduce the conductibility of the currently used electrolyte (Siemens Westinghaus 2004).
Recently the reduction of operating temperatures from 950 to 800 °C for SOFC with a planar design has been achieved by scientists from the Forschungszentrum Jülich, Germany. However further reduction is still feasible and desirable (FZ Jülich 2004a/b).
One possible way to further improve system properties and lower the operating temperature is by using thinner electrolyte films.</td></tr>
<tr><td>System</td><td>Investment cost</td><td>Optimisation of component and system design (FZ Jülich 2004b)</td><td>Basic research is necessary for system development. So far research is limited to system components (FZ Jülich 2004b).</td></tr>
<tr><td>System</td><td>Lifetime</td><td>Increase of number of thermal cycles and reduction of start-up and cooling down time (Large stationary applications, 250 kW)
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>Number of thermal cycles* [times]</td><td>50</td><td>50</td><td></td></tr>
<tr><td>Start-up and cooling down time [h]</td><td>6-8</td><td>3-4</td><td>< 2010</td></tr>
</table>
*without noticeable degradation (FZ-Jülich 2005)</td><td>The **start-up and cooling down time** for high temperature fuel cells ranges from 1 to 10 hours for small and large systems respectively (slow heating up and cooling down is needed to avoid cracking of brittle components); this requirement is problematic for many applications.
For the same reason the number of **thermal cycles between room and operating temperatures is limited** to typically 20-100 cycles for the life of a fuel cell, depending on the fuel cell type and application. This again is a bottleneck for certain applications due to the fact that the fuel cell has to be kept at the operation temperature even when power is not needed.</td></tr>
</table>

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Stack	Lifetime/ reliability	Improve redox-stability of the anodes and adopt gasket materials to fluctuating temperatures (FZ Jülich 2004b)	If the oxygen or fuel gas supply is cut due to maintenance work or disturbances, the fuel cell will be considerably damaged and its lifetime is reduced. The nickel at the anodes oxidises and gaskets fail due to the fluctuating temperatures (thermal cycling). This is the major bottleneck of SOFC with planar design (FZ Jülich 2004b).
	Lifetime	Develop material which do not react at their interfaces (FZ Jülich 2004b)	

Table 5 – Critical indicators to further progress – SOFC, tubular design, stationary applications

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>System</td><td>Investment cost</td><td>Develop an optimal design of the plant (balance of plant) (Siemens Westinghaus 2004)</td><td>Peripheral components like fans and compressors contribute considerably to the overall cost and also consume energy. The cost for those components will not go down as they are already commercial. Therefore the target is to develop an optimised design which needs smaller and less peripheral components (Siemens Westinghaus 2004).</td></tr>
<tr><td>System</td><td>Investment cost</td><td>Development of new electrolyte materials with good conductibility at lower temperatures
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>T [°C]</td><td>900-1,000</td><td>800</td><td>2015</td></tr>
</table>
(Siemens Westinghaus 2004)</td><td>The reduction of temperature for SOFC is desirable as high temperatures imply restrictions with respect to plant design and materials. Lower temperatures however reduce the conductibility of the currently used electrolyte (Siemens Westinghaus 2004).</td></tr>
<tr><td></td><td>Investment cost</td><td>Improvement of cell geometry (flat, compact tubes) promises a higher power density (High power density cells: HDP-cells).
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>Power density [mW/cm²]</td><td>200</td><td>400</td><td>2015</td></tr>
</table>
(Siemens Westinghaus 2004)</td><td></td></tr>
<tr><td colspan="4">Dependent on the application the number of thermal cycles can be a bottleneck for SOFC (tubular design). For stationary industrial applications 100 thermal cycles are currently possible without significant degradation. This is considered to be sufficient. For other applications, however (e.g. on-board power supply), this issue needs to be improved.
The start-up and cooling down time is strongly dependent on the plant size. For large plant as for stationary industrial applications the start-up and cooling down time is 12 to 24 hours, which is sufficient for this application field. For smaller applications (e.g. on-board power supply) the time is shorter but can still be a bottleneck (Siemens Westinghaus 2005).</td></tr>
</table>

Table 6 - Critical indicators to further progress – PEMFC, transport applications

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>GDL</td><td>Investment cost</td><td>Reduction of GDL cost and thickness
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>GDL cost [€/m^2]</td><td>200</td><td>< 5</td><td>2010</td></tr>
<tr><td>GDL thickness [µm]</td><td>500</td><td>250</td><td>2008</td></tr>
</table>
(NedStack 2005)</td><td>The gas diffusion layer (GDL) is currently the most expensive part of the stack, followed by the MEA and the bipolar plates.</td></tr>
<tr><td>Membrane</td><td>Investment cost</td><td>Reduction of membrane cost and thickness
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>Membrane cost [€/m^2]</td><td>200 - 250</td><td>?</td><td></td></tr>
<tr><td>Membrane thickness [µm]</td><td>25</td><td>12</td><td>2006</td></tr>
</table>
(NedStack 2005)</td><td></td></tr>
<tr><td>Bipolar plates</td><td>Investment cost</td><td>Reduction of bipolar plates cost
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>Bipolar plates cost [€/m^2]</td><td>200</td><td>< 5</td><td>2010</td></tr>
</table>
(NedStack 2005)</td><td></td></tr>
<tr><td>MEA</td><td>Investment cost</td><td>Increase of the activity of the catalyst and reduction of platinum content of MEA
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>Share of active platinum at total platinum content [%]</td><td>25-40</td><td>95</td><td>2010</td></tr>
<tr><td>Platinum content [mg/cm^2]</td><td>0.45</td><td>0.225</td><td>2008</td></tr>
</table>
(NedStack 2005)</td><td>In current fuel cells more than half of the platinum is inactive. The major goal is therefore to increase catalyst activity. This will result in higher power density and a reduced overall platinum content. However the reduction of platinum is not seen as a dominant research topic as platinum will be recycled and reused.</td></tr>
<tr><td>Stack</td><td>Investment cost</td><td>Improvement of system power density
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>System power density [kW/m^2]</td><td>8</td><td>10-12</td><td>2007</td></tr>
</table>
(NedStack 2005)</td><td>A higher system power density will be achieved by an optimised system design and a reduced amount of materials used.
System power density can be increased with higher temperatures or higher pressure. An increase in temperature and pressure, however, would demote currently applied materials quicker, resulting in a reduced lifetime. Therefore the optimal trade-off between temperature, pressure, power density, size and lifetime has to be found and new materials have to be developed.</td></tr>
</table>

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>Fabricating process</td><td>Investment cost</td><td>Development of low-cost, high-volume manufacturing processes especially for bipolar plates and membranes
(Proton Motor 2004, US DOE 2003)/</td><td></td></tr>
<tr><td colspan="4">PEMFC are also suitable for residential stationary applications. In this context the integrated reforming of natural gas and system-stability is a major research topic.</td></tr>
</table>

Table 7 – Critical indicators to further progress – DMFC, portable applications

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>MEA</td><td>Investment cost</td><td>Reduction of platinum content of the MEA
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>Platinum content [mg/cm^2/cell]</td><td>8</td><td>2</td><td>2010</td></tr>
</table>
(FZ Jülich 2004b)</td><td></td></tr>
<tr><td>MEA</td><td>Lifetime</td><td>Development of stable membranes and stable, corrosion-free catalysts
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>Degradation of power density [%/ 1000h]</td><td>> 10</td><td>2-10</td><td>2007</td></tr>
</table>
(FZ-Jülich, 2004b)</td><td></td></tr>
<tr><td>MEA</td><td>Efficiency</td><td>Development of new membrane materials with reduced methanol and water diffusion and remaining high proton conductibility, e.g. composite membranes
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>Methanol cross-over [%]</td><td>10-30</td><td>< 5</td><td>2010</td></tr>
</table>
(FZ-Jülich 2004b)</td><td>In order to improve DMFC, research on new membranes which allow only a low permeation of methanol is the most important task. Currently-used membranes need to absorb water in order to keep its optimal proton conductibility. As methanol and water are chemically quite similar, the membranes in the DMFC also absorb methanol, which permeates through the membrane and leads to a reduced FC voltage and blocks the cathodic catalyst, which reduces the maximal possible amperage. Furthermore it causes fuel losses and requires a costly treatment of exhaust gas, where methanol is regained and or burnt catalytically (FZ-Jülich 2004a).</td></tr>
</table>

<table>
<tr><td>System</td><td>Efficiency</td><td>Reduction of specific volume and weight e.g. by better integrating peripheral components into the system and by developing an optimal design.
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>Volumetric system power density [W/l]</td><td>10-100</td><td>100-200</td><td>2007</td></tr>
<tr><td>Gravimetric system power density [W/kg]</td><td>10-100</td><td>100-200</td><td>2007</td></tr>
</table>
(FZ Jülich 2004b)</td><td></td></tr>
<tr><td>System</td><td>Efficiency</td><td>Improvement of water management, development of a closed water circuit (FZ Jülich 2004b).</td><td>A self-sustaining system operation requires a closed water circuit. Water on the cathode side needs to be led back to the anode side. So far this has not been achieved. Furthermore, water on the cathode side blocks oxygen transport and leads to reduced efficiency.</td></tr>
</table>

Table 8 – Critical indicators to further progress – AFC, smaller scale applications

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
System	Investment cost	Serial production (MTU 2004b)	Cost reduction will mainly be achieved by automated high volume production. Material costs are already very low (300 €/kW).

Hydrogen

Technologies

Annual production and use of hydrogen is 600 billion Nm³, mainly for industrial purposes (ammonia/methanol synthesis, oil refinement). In the first part of the 20th century all gas supplies were based on town gas, a coal gas containing more than 50% hydrogen, and so several technologies for hydrogen production and handling are known and well developed. However, an energy economy using hydrogen as a main energy carrier in all parts of daily life is quite challenging. The requirements for energy efficiency, cost, safety and environmental concerns are high and new solutions have to be found. Hydrogen applications in the mobile and portable sector, for example, require efficient, lightweight and compact storage systems allowing reasonable coverage. In the long term the target is to produce hydrogen from renewable energy sources. The renewable potential for hydrogen production from biomass or renewable electricity, however, is limited in the short and mid term. Therefore the properties of innovative renewable hydrogen production technologies such as solar thermo-chemical hydrogen production[6], biophotolysis or fermentation need to be investigated. With respect to carbon emissions, CO_2 capture and storage in the context of fossil hydrogen production will probably play an important role. From the technological point of view pre-combustion carbon sequestration in the context of fossil hydrogen production is well known

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[6] This technology is also feasible in the context of nuclear power plants.

and well developed as it is a standard step in the production process[7]. Table 9 shows a selection of hydrogen technologies in commercial, demonstration and R&D states. The focus in this study is limited to the technologies typed in bold.

Table 9 – State of the art of different hydrogen technologies

Production	Fossil hydrogen production Water electrolysis (alkaline)	Biomass gasification*	**Thermo-chemical hydrogen production** **High temperature electrolysis** Biophotolysis** Fermentation** Photo-electrolysis[8] NGSA electrolysis[9]
Conditioning	Liquefaction Compression		
Distribution	Pipeline Liquid road transport		
Storage		**High pressure storage (700 bar)** **Liquid hydrogen storage** **Metal hydrides (for mobile applications)**	Carbon nanostructures** Complex hydrides[10]
	Commercial	**Demonstration**	**R&D**

* considered in the 'biomass' section

** considered in the section 'cross-cutting technologies'

Technical and socio-economic bottlenecks

- **Thermo-chemical hydrogen production** is a two-stage process based on metal oxides that separate oxygen from water molecules and bond them reversibly in a metal grid. In the first step, steam with a temperature of 600 to 800°C is passed over the metal oxides. Oxygen is

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[7] If hydrogen is produced from fossil fuels, whether through reforming, partial oxidation or gasification, the result is a syngas which contains H_2 and CO as main components. Shifting the CO present in the gas to CO_2 results in a flow consisting mainly of hydrogen and carbon dioxide. For hydrogen production this flow is split between a hydrogen flow and a flow consisting mainly of CO_2. Before the CO_2 can be compressed, transported and stored it needs to be dried and other components need to be separated out. The methods depend on the types of processes for CH4, N_2 (in particular in air-blown partial oxidation and gasification processes) and other components, for example CO and H_2. However these steps are independent from hydrogen production and are addressed in the section 'Carbon dioxide capture and sequestration'.

[8] It is unclear if photo-electrolysis will exceed the efficiency of an integrated system of PV and electrolysis. The capital and maintenance cost might remain higher as electricity is more easily collected than gases which require additional cover and sealing of the device. Basic research is required in order to explore the viability of the solution (SRA 2005).

[9] NGSA (natural gas assisted steam electrolysis) promises overall efficiencies of up to 80% by using the oxygen at the anode-side directly for partial oxidation of natural gas. This technology is still at laboratory stage and needs basic research (SKH2 2004).

[10] Complex hydrides (e.g. $LiBH_4$ or $Al(BH4)_3$) represent a very interesting and challenging new hydrogen storage material. Volumetric and gravimetric storage density promise to exceed that of gaseous, liquid or metal hydride storage systems. However, very little is known about the stability, the sorption kinetics and the reversibility, and basic research is needed to understand the interaction of hydrogen in solid-state materials and identify suitable materials for hydrogen storage (SRA 2005, Züttel 2004).

bonded and hydrogen released. In a second step oxygen is released from the metal oxides at temperatures of 1200 to 1300°C. The high temperatures can be provided by concentrated solar radiation (EU project Hydrosol) or by nuclear reactors. The main bottleneck of the technology at this stage is the high **cost** for hydrogen production and the **long-term durability** of the metal oxide coating.

- **High temperature electrolysis** is in the stage of basic research. By making use of an external source of heat such as concentrated solar or nuclear reactors, it is possible to increase the electrical efficiency far beyond that of conventional electrolysis. Besides high **cost**, the major bottleneck of the technology is the short **lifetime** due to degradation processes.
- For **gaseous hydrogen storage**, accredited 700 bar tank concepts are available (e.g. from Quantum Technology, California). The tanks consist of resin-drained carbon fibres on a steel, aluminium or plastic vessel (liner). The bottleneck of this technology is its very high **cost**. More than 80% of the tank system costs are currently related to the material cost of the tank, while manufacturing has only a minor effect on the total cost. Carbon fibres, the main and most expensive material of the tank, are currently fabricated in Japan, predominantly for high-profit niche markets (e.g. golf). The interest for mass production with lower profit margins seems to be low in Japan and in Europe very little is known about their material properties, fabricating processes or composite structure design. This leads to restricted availability of the material and high cost. Therefore R&D is especially needed for material research on carbon fibres (Opel 2004).
- The main bottleneck for **liquid hydrogen storage** is also **cost**. Hydrogen is stored in stainless steel tanks with super insulation (double walls, vacuum, aluminium foil). The applied materials are quite cheap compared to pressure storage tanks. The cost driver for liquid hydrogen storages is the fabrication process, which is normally manual. Currently the fabrication process is approximately 60% of the total cost. An automated process for the application of the insulation, for example, could reduce costs considerably. Another bottleneck of the technology is **boil-off**. A tank concept can either be optimised towards a long autonomy (the time where no boil-off occurs) or towards a low (but constant) boil-off (Opel 2004, Linde Gas AG 2004).
- Hydrogen storage in **metal hydrides** (e.g. $LaNiH_6$, Mg_2NiH_4, $TiFeH_2$…) is a well-developed technology with many advantages compared to gaseous and liquid hydrogen storage (high volumetric density, no losses, no safety risks). The bottlenecks of the technology are high **cost** and **weight**, especially in the context of transport applications. Parameters describing these bottlenecks are material cost and gravimetric density. The main research activity is therefore aimed at the exploration of new lightweight and cheap materials with similar properties (HERA 2004).
- The absence of common **codes and standards** as well as a limited **public acceptance** are identified as the main socio-economic bottlenecks for both fuel cell and hydrogen technologies. Indicators for the bottleneck absence of codes and standards can be fields of low or missing coverage. The total number of demonstration projects in the European Union indirectly reflects the level of public acceptance (see Table 14).

Parameters for characterisation of the critical bottlenecks

Table 10 lists the parameters that can describe the identified bottlenecks in quantitative terms.

Table 10 – Parameters for characterisation of critical bottleneck at various time-horizons

Parameters of bottleneck	unit	2004	target	target year
Thermo-chemical hydrogen production source [1]				
Hydrogen production cost	c/kWh	12-18	< 10	2030
Long-term durability (operational hours during sunshine only)	h	< 330	33,000	2010
High temperature electrolysis, source [2]				
Hydrogen production cost[11]	c/kWh	-	-	-
Investment cost[11]	€/kW	-	400	> 2015
Lifetime	h	100 – 1,000	40,000	> 2013
Gaseous hydrogen storage (700 bar), source [3, 4]				
Investment cost (tank system, 5kg H_2 storage)	€	-	1,000*	-
Material cost	€/kg	20-200[12]	< 8*	2015
Liquid hydrogen storage, source [3, 4]				
Investment cost (tank system, 5 kg H_2 storage)	€	10,000-50,000	1,000*	> 2015
Boil-off	%/d	0.7[13]	0.07*	2015
Autonomy	d	2-3	> 14*	2015
Metal hydrides, source [5, 6, 7]				
Investment cost (tank system, 5 kg H_2 storage)	€	-	1,000*	-
Material cost (alloy)	€/kgH_2	> 1,000	200*	-
Gravimetric density	mass %	1.5-2	6-13*	-

* political target

[1] DLR 2005
[2] EDF 2005
[3] Opel 2004
[4] Linde Gas AG 2004
[5] Züttel 2004
[6] HERA 2004
[7] SKH_2 2005

Analysis of the critical indicators to further progress

In this paragraph the specific research measures to overcome the identified bottlenecks are listed and critical indicators to further progress are given, wherever possible. Measures and indicators are allocated to the corresponding bottleneck parameters. The tables also indicate at which technology component research activity has to take place. The list does not contain all improvement measures and indicators, but only the most important and most promising ones. The information is mainly based on interviews with technology providers or research institutes. Information from current studies and websites are also included.

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[11] Due to the early stage of development neither complete system costs nor hydrogen production costs can be estimated.

[12] Costs are strongly dependent on material quality. 20 €/kg refers to standard carbon fibres, whereas current maximum consolidated carbon fibres cost around 200 €/kg.

[13] After 2 or 3 days autonomy.

Table 11 – Critical indicators to further progress – ***Thermo-chemical hydrogen production***

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>System</td><td>Hydrogen cost</td><td>Reduction of investment cost
<table>
<tr><th></th><th>2005</th><th>target</th><th>target year</th></tr>
<tr><td>Investment cost [€/kW$_{th}$][14] estimated[15]</td><td>700</td><td>450</td><td>2030</td></tr>
</table>
(DLR 2005)</td><td>Investment is dominated by the solar field (50%) and receiver reactor and process engineering (25%).
Approximately 55% of the indicated cost reduction can be achieved by upscaling and mass production.</td></tr>
<tr><td>System</td><td>Hydrogen cost</td><td>Reduction of operating temperature
<table>
<tr><th></th><th>2005</th><th>target</th><th>target year</th></tr>
<tr><td>Temperature [°C]</td><td>1,200-1,300</td><td>1,000-1,100</td><td>2006</td></tr>
</table>
(DLR 2005)</td><td>Temperature can be reduced by
• Development of new metal oxide compositions that release oxygen at lower temperatures / enhancement of existing compositions
• Enhancement of coating procedures
Lower temperatures allow the use of cheaper materials and reduce thermal losses.</td></tr>
<tr><td>Receiver-reactor</td><td>Hydrogen cost</td><td>Optimisation of receiver-reactor design. Indicator is the system efficiency:
<table>
<tr><th></th><th>2005</th><th>target</th><th>target year</th></tr>
<tr><td>Efficiency (solar radiation to hydrogen) [%]</td><td>≤ 40</td><td>45</td><td>2010</td></tr>
</table>
(DLR 2005)</td><td>Optimisation of receiver-reactor design can be achieved by
• Usage of suitable optical components, e.g. secondary concentrators
• Optimisation of process strategy (gas supply, recovery of excess heat, temperature management)
• Improvement of radiation absorber/converter unit</td></tr>
<tr><td>Metal oxide-and coating system</td><td>Long term durability</td><td>Improve long-term durability of metal oxide coating
<table>
<tr><th></th><th>2005</th><th>target</th><th>target year</th></tr>
<tr><td>Number of thermo-chemical cycles [times]</td><td>< 500</td><td>50,000</td><td>2010</td></tr>
</table>
(DLR 2005)</td><td>The long-term durability of metal oxide coatings can be increased by
• Development of improved metal-oxide and coating systems
• Optimisation of operating schemes (e.g. optimised operating temperature)
• Optimisation of mass flows, receiver geometry and radiation profiles</td></tr>
</table>

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[14] Net power for reactions (in the receiver).

[15] Estimation: plant capacity: 70 MW solar hydrogen production, 2 Mio kg/a.

*Table 12 – Critical indicators to further progress – **High temperature electrolysis***

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>System</td><td>Investment cost</td><td>Reduction of operating temperature
<table>
<tr><th></th><th>2005</th><th>target</th><th>target year</th></tr>
<tr><td>Temperature [°C]</td><td>850</td><td>700</td><td>> 2008 (laboratory)
> 2013 (prototype)</td></tr>
</table>
(EDF 2005)</td><td>In principle the same research topics as for SOFC (planar design) can be applied. However due to the early stage of development information about, e.g. current investment cost, number of thermal cycles, start-up and cooling down time are not available.</td></tr>
<tr><td>System</td><td>Investment cost</td><td>Increase of electrical efficiency (Electricity to hydrogen)
<table>
<tr><th></th><th>2005</th><th>target</th><th>target year</th></tr>
<tr><td>Efficiency [%]</td><td>90</td><td>100</td><td>2008 (laboratory)
2013 (prototype)</td></tr>
</table>
(EDF 2005)</td><td></td></tr>
<tr><td>System</td><td>Investment cost</td><td>Increase of power density
<table>
<tr><th></th><th>2005</th><th>target</th><th>target year</th></tr>
<tr><td>Power density [mA/ cm^2]</td><td>300</td><td>1,000-2,000</td><td>2008 (lab.)
2013 (protot.)</td></tr>
</table>
(EDF 2005)</td><td></td></tr>
<tr><td>Electrodes</td><td>Investment cost</td><td>Reduction of electrolyte thickness without degradation of lifetime
<table>
<tr><th></th><th>2005</th><th>target</th><th>target year</th></tr>
<tr><td>Electrolyte thickness [µm]</td><td>50-200</td><td>10</td><td>> 2008 (laboratory)
> 2013 (prototype)</td></tr>
</table>
(EDF 2005)</td><td>The idea is to have a metal-supported cell (anode/ electrolyte/ cathode) instead of an electrolyte-supported cell (1st generation cells) or anode-supported cells (2nd generation cells). This makes possible thin electrolytes for high performance and low quantities of expensive ceramic materials and nickel because all three layers of the cell (anode/ electrolyte/ cathode) are applied as layers on a cheaper metal support. However, for this to work, lower working temperatures are needed to prevent degradation caused by corrosion of the metal (EDF 2005).</td></tr>
<tr><td>System</td><td>Investment cost</td><td>Apply cheaper materials and steels</td><td></td></tr>
</table>

<table>
<tr><td></td><td>Investment cost</td><td>Scale-up: Increase the size of the electrolysis cells and stack
<table>
<tr><th></th><th>2005</th><th>target</th><th>target year</th></tr>
<tr><td>Cell size [cm^2]</td><td>25</td><td>2500</td><td>> 2008 (laboratory)
> 2013 (prototype)</td></tr>
<tr><td>Stack power [Nm^3H_2/h]</td><td>0.1</td><td>7000</td><td>> 2010 (laboratory)
> 2015 (prototype)</td></tr>
</table>
(EDF 2005)</td><td></td></tr>
<tr><td>Electrodes</td><td>Lifetime</td><td>Prevent degradation processes at the electrodes
<table>
<tr><th></th><th>2005</th><th>target</th><th>target year</th></tr>
<tr><td>Electrode degradation [%/1000h]</td><td>> 10</td><td>< 0.1</td><td>> 2010 (laboratory)
> 2015 (prototype)</td></tr>
</table>
(EDF 2005)</td><td></td></tr>
</table>

*Table 13 – Critical indicators to further progress – **Hydrogen storage** systems*

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
High pressure storage			
Carbon Fibres	Investment cost	Development of low-cost, strong and light carbon fibre materials and fibre reinforced composites in Europe (Opel 2004)	The development and research of carbon fibres can bring about lower material cost and improved properties.
Liquid hydrogen storage			
Manufacturing	Investment cost	Development of automated fabrication processes.	
Insulation	Boil-off	Development of novel insulation and tank concepts (e.g. insulation with liquid air or nitrogen).	
Metal hydrides			
Materials	Cost/ gravimetric density	Explore the properties of cheap lightweight metals (Züttel 2004, HERA 2004).	

Table 14 – Critical indicators to further progress – ***Codes and standards/Public acceptance***

<table>
<tr><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th></tr>
<tr><td>Absence of codes and standards</td><td>Fields of low or missing coverage of common codes and standards
<table>
<tr><th>HySociety</th><th>US DOE</th><th>SKH_2</th></tr>
<tr><td>• Safety of hydrogen on-board storage systems
• Hydrogen fuelled IC-engines
• Siting of and permission for hydrogen refuelling stations
• Small portable applications</td><td>• Hydrogen specific piping design, installation, training and certification
• Hydrogen storage tank for portable and stationary service. Standard independent of adsorbent. New standard for vehicular transport of high pressure hydrogen to pressures of 700 bars
• Ensure public safety, health and general welfare through proper selection of materials for hydrogen service.
• Ensure safety by defining testing methods to determine the quality of the fuel independent of production technique.
• Define methods to quantify hydrogen mass flow rate to determine appliance efficiency
• Review and modify existing piping standards and underground storage</td><td>• Hydrogen generation, handling and usage
• Hydrogen refuelling stations
• H_2 refuelling – coupling
• Fuel cells</td></tr>
</table>
(HySociety 2004, US DOE 2003, SKH2 2005)</td></tr>
<tr><td>Public acceptance</td><td>Number of demonstration projects in EU-15
<table>
<tr><td>Total number of hydrogen and fuel cell demonstration projects</td><td>255</td></tr>
<tr><td>Resulting projects with fuel cells</td><td>179</td></tr>
</table>
(source: HyWays 2005)</td></tr>
</table>

Other renewable energy sources

Photovoltaics

Technologies

Photovoltaic systems are composed by PV modules (with PV cells as the main component) and system components such as inverters, batteries and mounting structures, which depend on the particular application. The demand for R&D is on the one hand determined by the technical particularities of the single PV cell types and on the other hand guided by application-oriented requirements, in particular grid-connected or stand-alone applications. In the following the most promising cell technologies are analysed in the context of grid-connected applications, which is considered to be the most relevant application in EU countries.

An overview of different PV cell and system technologies is given in Table 1. PV cells based on new materials such as dye-sensitised solar cells (DSC) and organic solar cells, which are most probably not relevant for short- or medium-term applications, are covered in more detail in the section ‘cross-cutting technologies’.

Table 1 – State of the art of different PV cell/system technologies

Cell technology	monocrystalline Si polycrystalline Si[16] gallium-arsenide	monocrystalline Si polycrystalline Si thin film crystalline Si thin film amorphous Si	thin film amorphous Si thin film CIS[17] thin film CdTe (organic cells) (polymer cells)
System technology	off-grid professional consumer products	off-grid residential grid-connected decentral grid-connected central	
	Commercial	**Demonstration**	**R&D**

Note: There are also commercial applications for thin film amorphous, CIS and CdTe solar cells, but they represent a small share in the market.

Technical and socio-economic bottlenecks

The major technical and socio-economic bottlenecks of the different **cell technologies** can be grouped into the following main classes:

- **High electricity generation costs:** costs of PV-generated electricity are five to ten times higher than the costs for conventional bulk power generation (see Figure 1 of the target development of the (levelled) electricity costs for PV (assuming average module costs). Important factors which contribute to high electricity costs from PV are, across all technologies, the PV module costs with the main component being the cell material costs (and, mainly for thin film cells, also other cost components such as cell production and the cost of module production), the availability of cell material (mainly for bulk crystalline silicon), and the efficiency of PV cell technology. For thin-film amorphous silicon solar cells the loss in initial cell efficiency is also a bottleneck for future applications for target development.
- **Toxicity:** for technologies like CdTe, III-V and CIS solar cells the toxicity of the substances composing the solar cells could impede their large-scale deployment. Also manufacturing

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[16] Generally there is also the term ‘multicrystalline silicon’ used for this cell type in order to distinguish this cell type from the poly-crystalline silicon feedstock to the solar (and the electronics) industry.

[17] CIS: copper-indium-diselenide solar cell. There are variants of this cell type, for example the copper-indium/gallium-selenide/sulphide solar cell (CIGS).

processes using toxic substances pose a problem, such as cyanides and other toxic substances used in the CIGS manufacturing process. Also tin (Sn) and lead (Pb) present a problem due to their toxicity.

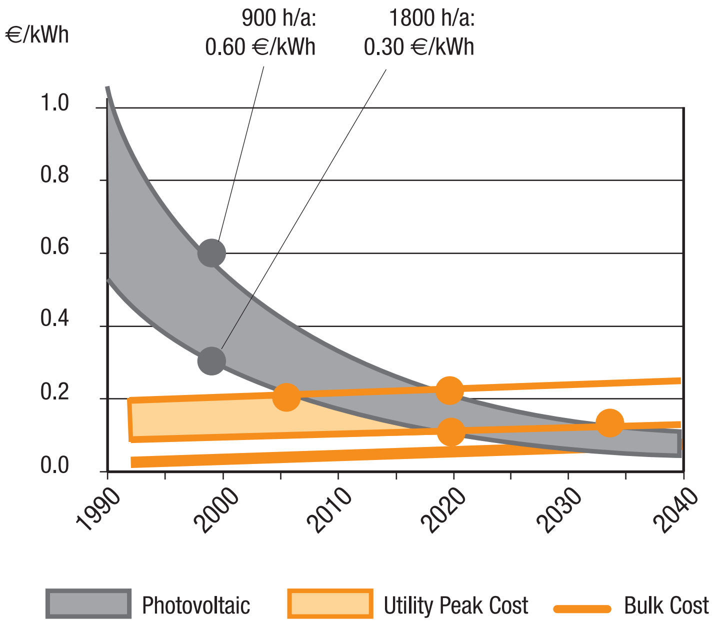
- **Feedstock availability:** limited availability of silicon feedstock could be a strong bottleneck for further implementation of crystalline silicon solar cells in the future.
- **Availability of other resources:** scarcity of resources like silver (for contacts) and indium (for CIS/CIGS) could complicate large-scale implementation.
- **Difficult system integration:** in the built environment it is often difficult to integrate PV systems due to poor interchangeability between PV elements and conventional building elements (power roofs, power facades, combination of solar heating and photovoltaic). This bottleneck is difficult to quantify, however balance-of-system (BOS) costs for mounting can be considered a proxy for this bottleneck.

The major technical and economic bottleneck for **system technologies** are related to the:

- **Balance of system components.** The main parameters describing this bottleneck are cost (BOS cost), lifetime and reliability. All three are mainly an issue for inverters, as well as integration in the built environment. The efficiency of solar cells is crucial not only for module manufacturing costs per watt-peak but also for lower system costs (because area-related BOS-costs are reduced) and allows for efficient use of scarce or expensive space, which may become an issue in densely populated regions. BOS costs are also strongly influenced by whether electricity storage is required (stand-alone application) or not (grid-connected application).

Figure 1 – Price development of grid-connected PV-generated electricity versus utility price of electricity. Calculations based on a turnkey price of a PV system (subsidies excluded) of 13 €/Wp in 1990 and 8 €/Wp in 2000 and on 1-sun insolation of 900 h/year in Germany and 1800 h/year in southern Europe. Assumed is an annual price decrease of a PV system of 5% during 2000-2040, identical as the price decrease observed during 1990-2000

Sources: PV TRAC (2004), Hoffmann (2004)



In the following, the main bottlenecks ‘high electricity generation costs’ of PV technology and ‘balance of system components’ for system technologies will be analysed more in detail with respect to the parameters characterising the bottleneck as well as indicators for the further progress.

Parameters for characterisation of the critical bottlenecks

The following table gives an overview of the quantitative parameters describing the main bottlenecks for the introduction of PV technology. As stated in the previous chapter, the main bottleneck for cell technology is the high electricity generation cost. The bottleneck can be described in quantitative terms by the main parameter (levelled) of electricity generation cost and the related parameters of investment cost for the modules, and cell efficiency. For bulk crystalline silicon the availability of the cell material is added, and for amorphous silicon the decrease in cell efficiency over time is also considered. Values for these parameters are given for each technology for the state of the art as well as for different time horizons. In the context of system technology the main bottleneck balance of system components is described in quantitative terms by the parameters of reliability, cost, lifetime and integration in the built environment.

Table 2 – Quantitative parameters for characterisation of critical bottlenecks

Parameters characterising the bottleneck electricity generation cost	unit	2004	5 years	10 years	> 15 years
Monocrystalline solar cells (wafer)					
Electricity generation cost 1)	€ cent/kWh	20-50	-	-	10-20 2)
Module efficiency	%	17	-	-	20 3)
Module lifetime	year	25	35 4)	-	-
Availability of cell material:					
Weight of feed material (incl. sawing loss)	g/W_p	14	12	11	10
Share all c-Si PV cells in world production	%	95 5)			> 80 3)
Multi-crystalline solar cells (wafer)					
Electricity generation cost 1)	€ cent/kWh	20-50	-	-	10-20 2), 3)
Module efficiency	%	15	-	-	< 20
Module lifetime	year	25	35 4)	-	-
Availability of cell material:					
Weight of feed material (incl sawing losses)	g/W_p	14	12	11	10
Share all c-Si PV cells in world production	%	95 5)			> 80 3)
EFG silicon					
Cell efficiency (production)	%	12.5-14.5	17 4)	-	19 4)
Availability of cell material:					
Weight of feed material	g/W_p	6-7	2.7-3	-	<1
Share all c-Si PV cells in world production		95 5)			> 80 3)
III-V technology (gallium arsenide cells)					
Electricity generation cost	€ cent/kWh	40-200	-	-	-
Module efficiency	%	25	25	27	30
Thin film: crystalline Si					
Electricity generation cost 1)	€ cent/kWh	20-50	-	-	> 10-20 3)
Module efficiency	%	10	12	14	15
Availability of cell material:					
Weight of feed material	g/W_p	<< 1	<< 1	<< 1	<< 1

Parameters characterising the bottleneck electricity generation cost	unit	2004	5 years	10 years	> 15 years
Thin film: amorphous Si					
Electricity generation cost	€ cent/kWh	20-50	-	-	> 10-20 3)
Module efficiency	%	8	-	-	10 3) -13 6)
Loss in initial cell efficiency 7)	%	10-25	-	-	10
Thin film: CdTe					
Electricity generation cost	€ cent/kWh	20-50	-	-	> 10-20 3)
Module efficiency	%	7	10-12 4)	-	15 4)
Thin film: CIS					
Electricity generation cost	€ cent/kWh	20-50	-	-	> 10-20 3)
Module efficiency	%	10	10-12 4)	-	15 4)
Balance of system components					
Cost of inverters	€/kW_p	800	500	-	200
Reliability of inverters: mean time to failure	years	5	-	10	20
Lifetime inverters	years	2-10	-	-	20
Integration in built environment	€/kW_p	0.6	0.5	-	0.3

Sources: PVNET (2004), PV TRAC (2004), DTI (2001), Ecofys (2002)

Notes for Table 2

1) Electricity production cost: grid-connected costs (i.e. excluding costs for batteries). Costs are provided for a sunny (1800 h/year full sunshine hours) and a large volume purchase (> 500 kWp system) at the lower end of the range, and for a cloudy location (900 h/year full sunshine hours) and a small volume purchase (2 kWp system) at the high end of the cost range. The cost degression assumed is 4%/year which was the historically observed degression for 1995-2004.

2) Source: Hoffmann (2004)

3) Source: Werner (2005)

4) Target from EPIA Roadmap (EPIA (2004))

5) Overall market share of single crystalline, multi crystalline and ribbon silicon technologies in 2003 (Werner [2004 c])

6) Source: Goetzberger (2004)

7) Triple junction amorphous solar cells stabilise after three months at around 10% losses. Single junction devices may lose 25% and more.

Analysis of the critical indicators to further progress

In order to coordinate R&D activities it is necessary to know which measures will contribute to improve the identified bottleneck. In this paragraph these measures are listed and critical indicators to further progress are given, wherever possible. Measures and indicators are allocated to the corresponding bottleneck parameters. The table also indicates at which technology component research activity has to take place. The list does not contain all possible improvement measures and indicators, but only the most important and most promising ones. The information is mainly based on interviews with technology providers or research institutes. Information from current studies and websites are also included.

Currently costs of electricity generation from PV are dominated by the costs of PV modules. Costs of PV modules, as well as opportunities for cost reduction or improvement of characteristics by future R&D, are strongly correlated with the type of cell technology used. Module costs are critically influenced by the availability of the feedstock material as well as the cell efficiencies.

Table 3 – Most critical bottlenecks and indicators to further progress – ***Crystalline silicon wafer technology***

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Measures and critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>Wafer production</td><td>module cost</td><td>Further development of alternative silicon production process like EFG (ribbon technology)[18]
<table>
<tr><th></th><th>2003</th><th>2005</th><th>2010</th></tr>
<tr><td>Silicon consumption [t/MWp]</td><td>14</td><td>12</td><td>10</td></tr>
</table>
(Source: EPIA 2004)</td><td>Loss of material during production process, especially due to cutting of ingots with wire saws.</td></tr>
<tr><td>Wafer</td><td>module cost</td><td>Critical indicators for smaller wafer thickness:
- need for improved wire saw technique using thinner wires [EPIA (2004)]
- development of metallisation and interconnection techniques in order to be able to handle more fragile (thinner) cells [Novem (2000)]
Development of wafer thickness
<table>
<tr><th></th><th>2004</th><th>2010</th><th>2020</th></tr>
<tr><td>Wafer thickness [μm]</td><td>300</td><td>180</td><td>100</td></tr>
</table>
(source: EPIA 2004)</td><td>Thick layers result in poor use of material.</td></tr>
<tr><td>Cells</td><td>efficiency</td><td>Higher cell efficiencies by improvements in [DTI (2001)]:
- process control
- front contact shadowing (mono-c)
- hydrogen passivation (multi-c-Si)
- back surface modification
- need for light trapping and surface passivation [Novem (2000)]</td><td>Higher efficiency results in lower electricity generation costs (€/kWh) and occupation of less space.</td></tr>
<tr><td>Module</td><td>electricity production cost</td><td>Decrease of production costs by [Novem (2000)]:
- increase of plant size (e.g. from typical 10 MWp/year to typical 50 MWp/year)
- process integration, e.g. sealing and framing
- develop alternatives for batch-type production processes like soldering and wet chemical cleaning</td><td></td></tr>
</table>

Table 4 – Most critical bottlenecks and indicators to further progress – ***III-V technology***

Technology component	Parameters of bottlenecks	Measures and critical indicators to further progress	Comments
Concentrator	Costs concentrator systems	Development of low-cost solar cells for use in mid-range concentrations (200-500 suns)	Costs of optical and tracking systems are relatively high. Unavailability of low-cost solar cells for use in mid-range concentrations (200-500 suns).
Cell	Layer growth	High growth in throughput needed to apply III-V materials in non-concentrating systems	Higher throughput results into lower electricity generation costs (€/kWh).

[18] Although the idea of edge-defined film-fed growth (EFG) technology dates from the 1980s, EFG solar cells did not enter production. This has changed in recent years however: RWE Schott Solar GmbH produces several MW of solar cells based on EFG technology once developed at Mobil Solar. Another producer of the ribbon technology for large-scale cell manufacturing is Evergreen Solar. The French company Solarforce plans to start production of thin 150 μm wafers using an innovative crystalline silicon ribbon technology in 2005 (see http://www.photon-magazine.com/news/news_2004-06_eu_feat_Solarforce.htm). Solar cell efficiency from this process is currently 14-15%.

Table 5 – Most critical bottlenecks and indicators to further progress – Thin film technology

Technology component	Parameters of bottlenecks	Measures and critical indicators to further progress	Comments
Cell	Efficiency / production process	For thin film crystalline Si technologies in general [Werner (2005)]: • grain boundary passivation • nano-crystalline films: growth of films with 110 texture • light trapping • increase of deposition/crystallisation speed • single crystalline films: module fabrication For high stabilised efficiencies of a-Si research is needed regarding [Novem (2000)]: • material structure on atomic and nano scales • nature and control of defects in pure and alloyed materials, especially behaviour and role of H, and doping and carrier mobility In case of tandem structures research is needed for [Novem (2000)]: • optimal thickness and doping profiles of the different layers to maximise the current and minimise the light-induced degradation (Stäbler-Wronski effect) For increasing CIS efficiency research is needed on • contact enhancement [DTI (2001)] • development of wide band gap materials such as $CuInS_2$ [Klenk (2000)] • increase of electrical homogeneity [Werner (2005)] • decrease of shunting [Werner (2005)] • homogeneous Na supply from glass substrate • module stability • theoretical understanding of grain boundaries in CIGS For increasing CdTe efficiency research is needed on • contact enhancement [DTI (2001)], • point defects (deep-level impurities) • grain boundary passivation [Novem (2000)]	Efficiency is still low compared to crystalline silicon.
CdTe, CIS	Toxicity		
CIS	Scarcity of indium		
Cell (a-Si / µc-Si)	Module cost	High-throughput deposition process (µc-Si). Research required on new deposition techniques like hot-wire chemical vapour deposition and cascade arc deposition [Novem (2000)]	Long deposition time for µc-Si layer.
Cell (a-Si / µc-Si)	Module cost	Optimisation of light trapping to allow for thinner layer	
Cell (a-Si / µc-Si)	Costs of production equipment	Standardisation of production equipment; more use of demonstrated manufacturing technologies from other industries	
Cell (CIS)	Cost of production process	Optimisation of production process	Currently expensive components like In, Ga and Se are used.

Balance of system (BOS) components

- Inverter reliability and lifetime is a key issue for the annual electricity output from a PV system, in particular for thin-film PV systems with proportionally higher shares of BOS.
- Costs of accumulators form a substantial part of the overall costs of a stand-alone PV system (up to 30%).

Table 6 – Most critical bottlenecks and indicators to further progress –
Balance of system components

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Measures and critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>Inverter</td><td>Reliability</td><td>Increase of reliability due to standardisation and optimised inverter design</td><td></td></tr>
<tr><td>Inverter</td><td>Lifetime</td><td>Increase of lifetime by optimised inverter design (based on thermal analysis)</td><td>Inverter lifetime is 5 - 10 years. Increase of lifetime might result into substantial increase of costs.</td></tr>
<tr><td>Accumulator</td><td>Costs</td><td>Reduction of investment costs of accumulator (per kWh capacity):
<table>
<tr><th></th><th>2000</th><th>2005</th></tr>
<tr><td>Investment cost
[€/ kWh capacity]</td><td>80-120</td><td>65-100</td></tr>
</table>
(source: EUREC [2002], PVNET [2004])</td><td>Costs of accumulator can account for 30% of total system costs of a stand-alone PV system.</td></tr>
<tr><td>Accumulator</td><td>Lifetime</td><td>Development of new battery types and new energy storage systems with longer lifetime</td><td>Battery lifetime is 3 - 10 years. Difficult to improve lead-acid battery. Increase of lifetime might result into substantial increase of costs.</td></tr>
<tr><td>Mounting structure</td><td>Integration in built environment</td><td>Interchangeability between standard building materials and PV elements</td><td></td></tr>
</table>

Wind energy

Technologies

Wind energy is a secondary form of solar energy. Wind turbines transform the kinetic energy of air currents into mechanical energy, which can be used in many ways to generate electricity, for example, in irrigation, drainage or other applications. The current standard application is the conversion of wind energy into electricity, mainly in parallel operation to central grids. Other applications e.g. in isolated grids, remote power supplies, for water pumping or desalination are within the scope of technical appliances as well. Wind energy technologies are in the stage of commercial applications for about 20 years.

The following technologies will be considered in this section:

- Horizontal axis wind energy converters (HAWT)
- Medium- to large-sized turbines (0.2MW … 5 MW)
- Onshore and offshore applications

Table 1 – State of the art of different wind turbine sizes

Technology	Onshore HAWT 0.2 … 2.5 MW ~ 40 GW installed capacity online worldwide. Growth rate (1999 – 2003): ~ 26% [EWEA] There is also a market for small wind turbines in the range of ~50 … 5000 W. These are mainly used as battery chargers or for remote applications.	Onshore HAWT 3 … 5 MW Offshore HAWT 0.5 … 2.0 MW Multi MW wind turbines are tested onshore for offshore projects to come.	Small turbines < 10 kW Flexible systems Urban turbines Wind potential Predictability Forecast methods Advanced O&M methods Advanced transmission system integration Grid competitiveness New materials New turbine concepts
	Commercial	**Demonstration**	**R&D**

Technical and socio-economic bottlenecks

The major technical and socio-economic bottlenecks of this technology can be grouped into the following main classes:

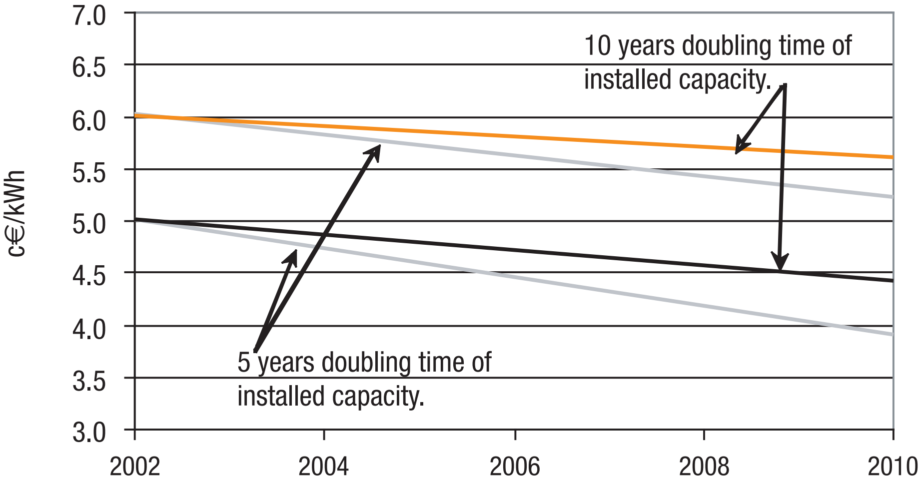
- **Size:** Wind capture is proportional to wind speed and rotor area (P ~ A). The present technology is limited in size. On the one hand limitations of infrastructure (transport) and hoisting capacities limit the size of large wind turbine types. On the other the strength properties of materials, e.g. glass-fibre reinforced plastic (GRP) are reaching their limits. The weight of gearless multi-pole generators is comparably high and the price/availability of materials for permanent magnet generators limits the use of this technology.
- **Energy cost:** Depending on the wind regime at different turbine sites, investment and O&M cost of wind-generated electricity is competitive with nuclear and coal power plants. These figures improve substantially if externalities are considered as well so that wind energy can even compete with power plants fired with natural gas. The main parameters influencing the cost of wind power are investment cost, long-term O&M cost and interest rates. The maintenance

and service of a huge number of large wind turbines will be a challenge, especially for offshore applications. New service and maintenance concepts have to be developed.

- **Technology risk:** Due to the continuous up-scaling of turbine models there is a lack of long-term operational experiences. The reliability of main components (blades, gearboxes, generators) has to be improved. With current technology it cannot be guaranteed that the turbines will reach their projected lifetime. Gear box and drive train transmissions in particular need better understanding and improved simulation and design tools.
- **Dispatchability:** wind energy 'as is' is not despatchable. The power duration characteristics vary with regional wind regimes. Integration into the structure of present supply systems requires improvement of tools for short- and medium-term prognoses of wind power, which are in demonstration phase at present. In future a partial remote control (P, cos phi) of wind turbines / wind farms by grid operators will be implemented in order to improve grid compatibility and to support and stabilise the grid in case of faults.
- **Grid:** The transmission capacities of electrical grids are limited or insufficient in order to transport energy from remote areas to the load centres. Grid access is partially restricted.
- **Public acceptance:** impacts of wind energy on society are related to noise, visual disturbance of landscape, land use, bird life, electromagnetic interference and the life cycle of energy consumption.

The cost of electricity produced by wind turbines depends on many frame conditions and assumptions. Figure 1 shows the future development of wind turbine economics until 2010 for different scenarios. Initial costs for medium-sized turbines at a medium quality wind site is 5 to 6 € cent/kWh. Depending on the assumptions of future growth rates, learning rates and the corresponding times for each doubling of installed capacity, the electricity costs are expected to decrease to values of 4 to 5.5 € cent/kWh by 2010 (Morthorst 2004).

Figure 1 – Using experience curve to illustrate the future of wind energy economics until 2010 (P.E. Morthorst 2004)



Parameters for characterisation of the critical bottlenecks

The main parameters characterising the bottlenecks given in previous section are summarised in Table 4.

Table 2 – Main parameters of physical indicators and their limits (onshore installations)

Physical dimensions	Unit	Achieved	Barriers, assuming extrapolation of present technologies
Rated power	MW	5	~ 10 –12
Hub height	m	125	n.a.
Rotor diameter	m	126	155 – 175
Blade length	m	61.5	76 – 86
Max. chord	m	4.6	-
Blade mass	t	17.7	25 – 35
Blade mass/diameter	kg/m	141	170 – 190

Table 3 – Overview of achieved installation and production rate by countries

country	Capacity [MW]	Production [TWh]	Capacity factor [%]
DE	16.394	25.90	18%
ES	8.263	19.00	26%
DK	3.118	7.30	27%
NL	1.096	2.50	26%
AT	606	1.20	23%
GR	465	0.85	21%
IT	1.265	-	-
UK	889	-	-
PT	522	-	-
SE	455	-	-
FR	399	-	-
IR	339	-	-
NO	169	-	-
BE	97	-	-
FI	80	-	-
Total	34157	Min.70	Avg. 20%

Source: Langenbach, 2005

Table 4 – Quantitative parameters for characterisation of the critical bottlenecks

Parameters	Present	5 years	5 – 10 years	> 15 years
Cost (onshore systems)				
Investment costs €/kW	900 –1,200	810 – 1,080	730 – 970	650 – 880
Electricity costs € cent/kWh if doubling time = 10 yrs if doubling time = 5 yrs (Morthorst, 2004)	5 – 6		4.4 – 5.6 3.9 – 5.2	
O&M cost € cent/kWh	1-2	-	-	-
Lifetime	10 – 20	15 - 20	-	-
Cost (offshore systems)			target	
Investment costs € /kW	2,000	-	-	-

Parameters	Present	5 years	5 – 10 years	> 15 years
Electricity costs € cent/kWh	5 – 8	-	3 – 4	-
O&M cost € cent/kWh	n.a.	-	-	-
Lifetime [years]	10 – 20	-	20	-
Dispatchability				
Annual capacity factor [%]	15 – 35	-	-	-
Power duration of interconnected systems (hours per year) at 75% load at 50% load at 25% load	500 h 1,000 h 2,500 h	-	-	-

Analysis of the critical indicators to further progress

The critical indicators for further progress is shown below. Most important for the progress of wind turbines are the reduction of the rotor mass by deployment of new innovative materials and the decline in cost of the individual components.

Table 5 – Critical indicators to further progress – ***Wind energy technology***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Rotor blades	Rotor mass vs. diameter or rotor area Physical properties of materials: • mass • tensile strength • fatigue • stiffness Availability and price of new materials, e.g. biomaterials, compound materials Reliability, MTBF, long-term endurance (These apply also to other components)	• mass/diameter (kg/m) • price/m² swept area (€/m²) A better understanding of how loads affect the turbine and thereby the possibility of designing turbines closer to the physical limits of materials, resulting in a lower weight. This applies also to other components mentioned below. Better and new materials can reduce the weight of the rotor which is always a compromise between strength/stiffness and dampening properties. (BTM, 2000).	Present material (GRP) and rotor design is reaching limits regarding strength of material. The present solution of manufacturing compound rotors is a compromise between physical barriers and cost effectiveness. For the blades, it becomes crucial and even more difficult to keep their weight down at the same time as maintaining stiffness and dampening properties. There is a gap between use of glass/epoxy and carbon fibre/epoxy. Carbon fibre (CRP) is still too expensive, even when its improved strength is taken into account. A greater focus on smart solutions, where the use of carbon fibre or another strong fibre in a mixed composite with glass, is a great challenge (Madsen, 2004).

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Drive train Hub, shaft, bearings, platform	Present design and weight of drive train. Material: steel, cast steel Mass, weight, price	• mass/power (kg/MW) • mass/torque (kg/Nm) The drive train torque load is one of the key design factors of wind turbines. Optimisation of drive train – direct drive by use of multi pole synchronous generators or traditional drive train – gearbox couplings and asynchronous generator. Control of blades and control of rotor speed enables the designer to reduce torque peaks in the transmission. Lower component prices become available. Lower loads on rotor and transmission leaves room for weight reduction of support structure: machine frame, tower, foundation. (BTM, 2000).	The reliability of drive-trains for a traditional WTG concept (with speed increasing gear and a fast-running generator) needs to be improved. There are too many problems with the gear transmission, whether it is 'hidden forces from short transients in the electric grid' or a combination of insufficient lubrication, wrong principles of use of roller bearings. There is a need for a better understanding of that and subsequent improved calculation tools for the gear design (Madsen, 2004). Availability and price of light weight materials with excellent physical properties, e.g. compounds to manufacture components.
Generator	Mass of generator Availability of cost effective materials for permanent magnet generators (PMG) Voltage level	Mass/power (kg/MW)	Efforts to bring the physical dimension/weight of a multi poled generators down, to make them competitive to the traditional drive-train with mechanical gears. Material for magnets to the PMG solution seems to be a barrier, not only price wise, but also the supply of magnets seems to be problem if it becomes widely used (Madsen, 2004).
Grid integration	Capability of grid for access of RES, Cost of grid extension, Power prediction	Capacity/short circuit power (MW/MVA)	A critical indicator is the level of penetration in the electricity system, without harming the system as a whole. Improved focus on grid compatibility is the answer to this challenge. This challenge is increasing along with increased penetration in some EU member states (Madsen, 2004).
O&M	Intelligent systems Accessibility of offshore sites, Condition oriented service	Long-term (life time) average cost for O&M (€/kWh)	At present O&M cost is increasing with lifetime. The average O&M cost in the project lifetime cannot be foreseen. The target is to keep the total O&M cost between 0.56–1.12 cent €/kWh*) as an average value over the entire lifetime of 20 years (BTM, 2002). *) avg. conv. rate (2001): 1 USD = 1.116 EUR (www.oanda.com)

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Total system	Price of electricity for project lifetime. Lifetime Mean time between failures (MTBF)	€/kWh This depends on: • turbine price (€/kW) • additional cost for grid, civil works, approvals, etc. (€/kW) • interest (%) for capital • land rent (€/kW, €/kWh, €/unit) • O&M cost (€/kW, €/kWh) • Insurance (€/kW, €/kWh) • Electricity supply (€/kW, €/kWh) • taxes (€/kW, €/kWh) • etc.	The long-term electricity price of WE projects includes all improvements of subsystems mentioned above. However, this depends on various technical and financial parameters (price, interest, wind resources, etc.) which can vary widely for different regions and points of time. Many materials of components e.g. steel, copper, etc. are linked to trends in the world market and may affect forecasts significantly. For wind power the most critical indicator(s) are cost/unit of electricity and lifetime. A cost per unit of, say 3-3.5 €cent/kWh, along with maintaining a 20 years lifetime for all major component in a wind turbine could be a relevant target for the technical development (Madsen, 2004).

Offshore applications

Wind turbines for offshore applications have to be adapted to a harsh maritime environment. Concerning design, many of the barriers mentioned for onshore turbines (weight, cost) can be applied directly to the design properties and challenges of offshore turbines. However, compared with onshore turbines this is a partial redesign of the turbines, not only due to the corrosive atmosphere but also for the different loads and forces to which they are exposed.

Physical limits [CA-OWEE]:

- distance >> 5 km from shore
- water depth: up to 40m
- North Sea: large tidal range, water depth
- Baltic Sea: ice and ice floes
- Mediterranean: sea bed slope, water depth

*Table 6 – Critical indicators to further progress – **Offshore wind turbines***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Turbine	Mass price	€/kWh €/kW €/m²	Technology bottlenecks are related to onshore technology, e.g. mass of components, price. Special measures (filters, air pressure) have to be met in order to protect sensitive parts of the turbine (e.g. generator, transformer, power electronics, etc.) from corrosion.
Support structure, foundation	Type of support structure and foundation depends on water depth, wave height, ice drift, slope of seabed etc.	Price per unit and technical specifications. E.g. min/max/optimal water depth, max. slope	All problems mentioned before are related to weight reduction, the desire for low-weight gearboxes, results in under-dimensioned gears and problems from this. For future offshore plants in deeper water it will be crucial to reduce the top weight, to avoid severe dynamic problems for the support structure, which may be 100 to 130m tall (100m hub- height + 30m water depth).

Service, O&M	Costly service + maintenance Reliability of components -> Horns Rev, DK	€/kWh MTBF Max. wave height for service boats, Max. wind speed for service helicopters.	Service and O&M of offshore turbines will be difficult to handle. Landing on offshore turbines by service boat or helicopter is dependent on wave height and wind speed. Improved equipment for access to offshore foundation platforms and equipment which is less affected by waves is needed (Madsen, 2004).
Grid	Distance, capacity and installation cost to onshore connection point. Remote control features for transmission system operator (TSO) for integration into grid system.	Km MVA €/MVA	A critical indicator is the level of penetration in an electricity system, without harming the system as a whole. Improved focus on grid compatibility is the answer. The problem/challenge is increasing along with increased penetration in some EU member states.
Environment	Impacts to marine habitats (flora and fauna), risk of collision with sea traffic, reduction of fishing area.	Area (km^2) per installed capacity (Km^2/MW)	
installation	Restricted time for installation process due to wave, tide, general weather conditions and availability of specialised support vessels).		

Solar-thermal concentrating technologies

Technologies

The following technologies will be considered in this section:

- Solar thermal trough systems
- Solar thermal tower systems
- Dish-Stirling systems

Table 7 – State of the art of solar thermal technologies

Technology	Trough system	**Trough system** **Tower system** Dish-Stirling	**Trough system** **Tower system** Dish-Stirling
	Commercial	**Demonstration**	**R&D**

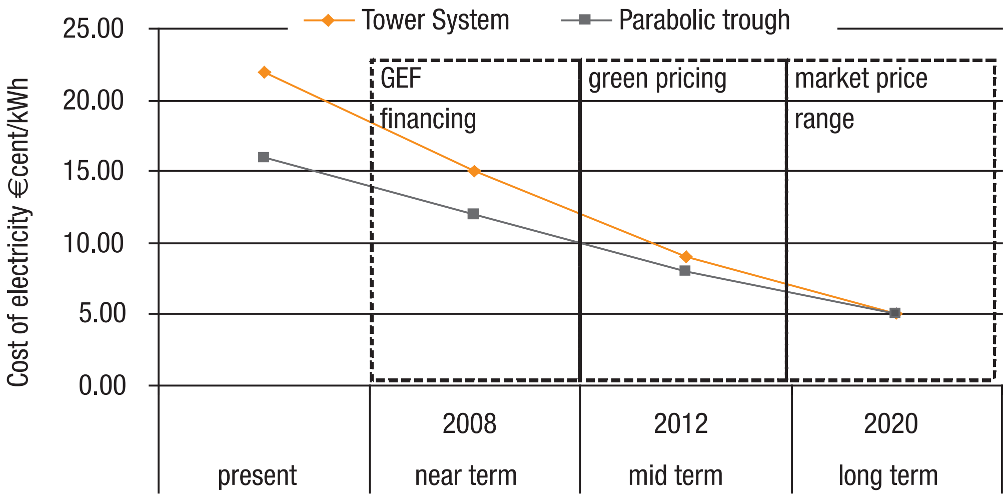
Technical and socio-economic bottlenecks

The major technical and socio-economic bottlenecks of this technology cluster can be grouped into the following three main classes:

- **Energy costs:** Levelled electricity costs (LEC) are still a factor of three to four higher than those of conventional technologies and represent the main barrier for a faster market penetration. The main parameters influencing the costs of electricity for solar power plants are the investment costs of the plant, and operation and maintenance (O&M) costs as well as the plant's overall efficiency.
- **Risk level** (technology, scheduling, finances, politics, exchange rate): The level of risk will determine whether or not a project can be financed and at which internal rate of return. A number of the risks relevant to the market development cannot primarily be overcome by means of R&D measures, e.g. political risks in developing countries. Therefore risks as a group of bottlenecks to technological development will only play a minor role in this analysis.
- **Dispatchability:** one of the main benefits of CSP technologies is that they can be dispatched by using solar storage or by hybridisation with conventional fuels. Targeted dispatchability should be based on storage concepts (avoiding hybridisation with conventional plants). The development of improved storage concepts still represents a relevant bottleneck.

The cost of electricity produced by solar thermal technologies represents the major bottleneck to further progress. Significant cost reduction potentials for all technologies exist (in particular due to economies of scale and further R&D) and can be exploited as shown for parabolic troughs and for solar tower systems in Figure 2.

Figure 2 – Cost of solar thermal electricity generation – possible cost reduction due to market development and R&D (Sargent & Lundy 2003, ECOSTAR 2004)



Cost reduction potentials have their origin in a number of different technological and financial opportunities. The most promising options are:

- increase of power plant size (up-scaling)
- economies of scale – automated mass production of components

- increase of operating hours by hybridisation with conventional power plants with special focus on the integrated solar combined-cycle system (only if solar share can be sufficiently increased) or the application of storage
- technological improvements of the individual components of each power plant's technology
- development of multiple plants at the same location in a solar power plant environment
- development of innovative financial models and funds adequate for financing capital intensive projects with high risk levels
- creation of competition in the manufacturing of key components, such as receivers and reflectors etc.

(Not all of these options for cost reduction are multiplicative.)

Parameters for characterisation of the critical bottlenecks

The main parameters characterising the bottlenecks given in previous section are summarised in Table 8. State of the art and estimated values at different time horizons are given. For future values the potentials for volume production, plant scale-up and intensive R&D are included. For tower systems, figures represent US molten salt technology.

Table 8 – Main parameters for the characterisation of critical bottlenecks

Parameters	unit	present	5 years	10 years	>15 years
Cost (Trough systems)					
Electricity costs	€ cent/kWh	16	12	8-9	5-6
Investment costs	€ /kW	3,500	2,900	2,400	1,500-1,800
O&M cost	€ cent/kWh	2	1.5	1.3	1.1
Efficiency (solar to electricity)	%	14	15.5	17	17
Cost (Tower systems)					
Electricity costs	€ cent/kWh	18-24	14-16	8-9	4-5
Investment costs	€ /kW	3,500-5,000	3,000-3,500	2,600	2,200
O&M cost	€ cent/kWh	3	2	0.5	0.25
Efficiency (solar to electricity)	%	8	14	17	19
Risk					
Equity IRR	%	18	15	15	15
Dept Interest Rate	%	9.5	8	8	8
Dispatchability					
Peak-Capacity Factor	%	95	95	90	90
Peak-Period Duration	h	3	3	6	6
Preferred Technology		fossil	fossil	thermal	thermal
Annual Capacity Factor	%	30	30	40	50

Source: Sargent & Lundy 2003, ECOSTAR 2004

See page 58 for more detailed information on the various critical parameters of solar thermal electricity.

Analysis of the critical indicators to further progress

Solar troughs

The critical indicators for further progress will be shown in the following. Most importantly for the progress of solar trough systems is the decline in cost of the individual components. The total medium-term cost reduction potential is estimated to be more than 50% and improvements on the receiver tube contribute the largest share to the total cost reduction potential. Table 9 summarises all major technical and economic bottlenecks as well as the critical indicators to further progress on the different time horizons (short term, medium term, long term) for solar trough systems.

*Table 9 – Critical indicators to further progress – **Solar trough technology***

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>Mirrors</td><td>High electricity costs due to high investment costs and low reflectivity</td><td>• Fresnel collector types with standardised components
• low iron glass back-silvered mirrors
• dust repellent mirrors
Targeted reflectivity: 93%
<table>
<tr><th></th><th>Present</th><th>5 y</th><th>10 y</th><th>> 15 y</th></tr>
<tr><td>invest cost [€/m2]</td><td>43</td><td>43</td><td>28</td><td>18</td></tr>
</table>
(IEA 2004) (Sargent & Lundy 2003), (ECOSTAR 2004)</td><td>Fresnel collectors will be significantly less efficient than curved mirrors because of lower optical precision.</td></tr>
<tr><td>Heat transfer medium</td><td>High overall costs of organic heat transfer medium and thermodynamic disadvantages of an intermediate heat transfer system</td><td>Heat transfer by the direct vaporisation of water (FVS 2004)
5-10 y</td><td></td></tr>
<tr><td>Receiver tube</td><td>Low overall efficiency</td><td>Increase of absorber temperatures from 400-450°C to 550-600°C through
• improved engineering of the vacuum tube
• the development of innovative highly efficient absorber materials, enhancing selective coatings
<table>
<tr><th></th><th>Present</th><th>5 y</th><th>10 y</th><th>> 15 y</th></tr>
<tr><td>abs. temp. [°C]</td><td>425</td><td>450</td><td>500</td><td>550</td></tr>
</table></td><td>Very high temperatures increase the risk of thermal losses and lower absorber pipe durability.</td></tr>
<tr><td>Process control</td><td>High O&M costs (Table 5-8)</td><td>Automation of process control 5 y</td><td></td></tr>
</table>

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>Storage</td><td>Limited dispatchability (Table 5-8)</td><td>Development of improved storage concepts based on:
• phase-change materials in cascade design
• concrete-oil-iron storage system 5-10 y
<table>
<tr><th></th><th>Present</th><th>5 y</th><th>10 y</th><th>> 15 y</th></tr>
<tr><td>Invest cost [€/kWh]</td><td>40</td><td>25</td><td>15</td><td>10</td></tr>
</table>
(Tamme 2004)</td><td></td></tr>
<tr><td>Solar power cycle optimisation</td><td>Limited dispatchability, high costs of electricity</td><td>Detailed ISCCS design integration assessment to analyse performance parameters 10-15 y</td><td></td></tr>
<tr><td>Structure</td><td>High investment costs of structure</td><td>Advanced concepts for innovative structures (multilayer plastics) 5-10 y</td><td></td></tr>
<tr><td>Resource assessment</td><td>Limited quality of direct normal insulation (DNI) data</td><td>Generation of high resolution DNI maps by the use of higher resolution satellite data 5 y</td><td></td></tr>
<tr><td>Economic parameter</td><td>High financial and technological risk</td><td>Development of a fund to act as guarantee for future projects 5 y</td><td></td></tr>
</table>

Central receiver systems (CRS):

The critical indicators for further progress will be shown in the following. Most importantly for the progress of central receiver systems (CRS) is the cost decline of the individual components. Generally the following main variants of CRS exist:

- CRS using molten salt as heat transfer medium
- CRS using saturated steam as heat transfer medium
- CRS using atmospheric air as heat transfer medium
- CRS using pressurised air as heat transfer medium in combination with a solar hybrid gas turbine

Table 10 summarises all major technical and economic bottlenecks as well as the critical indicators to further progress on the different time horizons (short term, medium term, long term) for central receiver systems.

*Table 10 – Critical indicators to further progress – **Solar tower systems***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Heliostats	High investment costs	Development of low cost and highly automated production techniques to reduce costs by a factor of four (FVS 2004) Development of large area heliostats with about 200 m^2 surface 'megahelio' Development of autonomous and ganged heliostats *Time horizon: 5-10 y*	
Receiver	Limited efficiency and high maintenance	Development of smaller and better optimised receivers (FVS 2004) Improved 'hot spots management' Different types of receivers exist (air, steam, molten salt) (see comments) *Time horizon: 5-15 y*	*Molten salt receivers:* increase of homogeneity of solar insulation and fluid flow; maximisation of working fluid temperature *Steam receivers:* better working fluid flow management and absorption instabilities management
Storage	Limited dispatchability (Table 5-8)	Development of improved storage concepts based on: • 1-tank thermocline molten salt storage and room temperature ionic liquids (RTIL) • phase-change materials in cascade design	
Gas turbine	Limited process efficiency	Technological developments to directly feed the solar process heat into gas turbines to use the high temperature heat (FVS 2004) Efficiency improvements in the steam cycle provide the largest contribution to overall cost reduction (FVS 2004) *Time horizon: 10 y*	

*Table 11 – Critical indicators to further progress – **Dish-Stirling systems***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
System integration	Limited dispatchability	Development of solar-fossil or solar-biomass hybrid plants *Time horizon: 10-15 y*	
Mass production	Start mass production	Create manufacturing chain	
Hybridisation	Limited dispatchability	Develop gas-fired systems	

Ocean energy

Technologies

General

Covering two-thirds of the surface of our planet, oceans represent a theoretical energy resource that exceeds the global primary energy consumption by three orders of magnitude. However, most of this energy resource is not accessible by today's technology. Apart from offshore wind energy, which is addressed separately, energy technologies are under development which use tidal and marine currents, the energy of waves, the temperature gradient between surface and deep sea, potential energy from tides (tidal barrages) and the salinity gradient between fresh water from rivers and seawater. Finally, marine biomass fuels are being considered as ocean energy farms, similar to ocean food farms (aquaculture), producing methane as a fuel. None of these ocean energy technologies have achieved a commercial phase yet. The most important ocean energy power plant – the only one at industrial scale in Europe – is the 240 MW tidal power plant at the river La Rance near St Malo at the French Atlantic coast, built in 1966. From the available ocean energy resources, only a few have been studied with respect to their technical and economic potential.

The following technologies will be considered in this section:

- Tidal barrages
- Wave energy conversion technologies
- Tidal/marine current energy converters
- Salinity energy
- Temperature gradient

Tidal energy is included because it is still the most important technology in the sector but has very limited potential for future exploitation.

Salinity energy is the only technology considered which still requires fundamental material science research. The membranes currently available are too expensive and not reliable. Therefore salinity power is not yet in the demonstration phase. However, there are some R&D activities going on in Europe, partially with EC funds.

Technologies that use thermal gradients are unlikely to become feasible in Europe. The only applicable approach is to use shoreline ocean thermal electric (OTEC systems), where water is heated onshore and the sea is used as a cool heatsink. There are currently no investigations made for such projects in Europe.

Marine biomass is also not a relevant issue for Europe. Currently aquatic plants such as seaweed only contribute to about 3% of the total aquaculture sector in Europe which in itself is small since it represents less than 5% of the global production volumes. Although the systems and projects listed in Table 12 have demonstrated their feasibility, none of them has yet achieved the full scale for commercialisation in the current demonstration projects.

Table 12 – State of the art of different ocean energy technologies

Technology	Tidal barrage*	Current turbines (SEAFLOW, Blue Concept, Kobold) Wave energy technologies (Limpet, Pelamis, Tapchan, AWS, Wavedragon)	Salinity energy (Saltkratf, PRO) Various wave energy and current turbine concepts
	Commercial	**Demonstration**	**R&D**

* Comment: Tidal barrages are currently the only relevant technology in operation at a commercial scale. However, energy costs are not yet competitive on a free market.

Technical and socio-economic bottlenecks

The major technical and socio-economic bottlenecks of this technology can be grouped into the following main classes:

- **Marine environment constraints:** The installation and operation of any structure in a marine environment, whether at the coast, near shore or offshore, is always strongly influenced by wind and waves, currents and tides. In particular sites, where various energy technologies have a high potential, sea conditions are typically difficult. This affects the use of boats and barges, shipping of the structures, operation of heavy devices, accessibility for maintenance personnel etc. For many of these problems, special safety procedures are required to overcome the difficulties, but in any case, strong winds will make access to any structure temporarily impossible. Another important aspect is the reliability of the structure itself, which has to cope with extreme load conditions.
- **Availability of resource data:** None of the resources for ocean energy technologies are very well known. A number of studies estimate or calculate the overall technical resources, but for the application of a particular technology at a particular site, these rather rough data are often not good enough. Typically, the spatial and temporal resolution of available data is not high enough to calculate site-specific economic feasibility. For marine currents and waves, the methodologies to generate resource data are not yet well developed. In particular for waves, a number of different definitions exist to calculate energy content. Most available resource data have not been generated for the purpose of energy use. This leads to an economic and to some extent technical risk for any project.
- **Mobilisation and grid connection cost:** The costs for any grid connection to an offshore energy system are significantly higher than for onshore technologies. This is a particular problem for the relatively small pilot or demonstration test systems. This leads to the situation that most pilot systems are not equipped with a grid connection, causing problems with reliable operation and demonstration. Once the technology has achieved a status where multi-megawatt installations are justifiable, these costs will reduce to being a minor share only. Connecting very large schemes to the grid on land is likely to require strengthening of the grid, including extra power lines to congested areas with high demand. The mobilisation costs for any heavy equipment, such as barges, cranes etc, are almost the same for one pilot plant as they would be for a whole farm. A special problem for floating devices is managing a reliable cable connection in moving water, and to the structure relative to the seabed.
- **Licensing and environmental constraints:** Even the limited operation of a larger pilot system will normally require planning and building permission. This in itself is a complicated administrative procedure when the responsible authorities are not clear. In addition, the scope of an environmental impact assessment (EIA) is not clear at all. Even if effects on aquatic life are expected, their relevance is often not clear and measures to overcome or avoid these effects can be hard to prove or even understand. In the worst case, the local effect on the environment is unacceptable. For tidal barrage projects this is the main obstacle.
- **Energy cost:** As in many other renewable energy systems, high investment costs leading to high capital costs plus the O&M costs lead to an electricity cost higher than market prices. This is not different in ocean energy technologies. A particular uncertainty results from the lack of experience in operating such technology over many years. A factor causing higher investment compared to onshore technologies as e.g. in the case of wind energy is the requirement for reduced maintenance. This leads to other designs and higher lifetime requirements for the components. Reduced availability of cranes etc, requires compensation measures such as cranes on board, and smaller and so more easily replaceable units, etc.

- **Dispatchability:** Ocean energies fall into three different categories of dispatchability. Wave energy has a random nature like wind, the main generator for waves, and is therefore not dispatchable. Short-term prediction should be possible in the future. The second category is technologies which use tides, such as tidal barrages and marine currents at most sites. These systems operate intermittently in correlation with local tidal regimes and typically show a few hours of continuous operation with varying power output followed by one or more hours without operation. The last category are systems with an almost constant output and consequently very high dispatchability such as salinity power, OTEC systems, etc.
- **Reliability of operation:** Due to the technological status of most systems, the load factors for commercial operation have not yet been achieved. Again, the only exception is the La Rance tidal power plant which has operated reliably over 40 years. Demonstrators and pilot systems typically do not operate continuously due to special test operations, variations of operating conditions, high maintenance and monitoring requirements and finally a high amount of unintended breaks of operation due to malfunctions, damage from storms etc. This aspect is critical since only a proven technology with satisfying operational periods will attract the necessary investment for a commercial exploitation.

Parameters for characterisation of the critical bottlenecks

Table 13 – Quantitative parameters for characterisation of critical bottlenecks

	Unit	Present	5 years	10 years	>15 years
Cost OWC/IPS					
Electricity generation costs	€ cent /kWh	10-40	-	6-14	-
Investment cost	€/kW	1,680-3,000	-	1,600	-
Annual output	kWh/kW	4,000	-	5,000	-
Cost current turbines					
Electricity generation costs	€ cent /kWh	30	15	6	-
Dispatchability: Load factors					
Tidal barrage	%	20-30	-	-	-
OWCs	%	20-35	-	-	-
Current turbine	%	25-35	-	-	-

See page 59 for more detailed information on the various critical parameters of ocean energy technologies.

Analysis of the critical indicators to further progress

*Table 14 – Critical indicators to further progress – **Ocean energy***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Generic	Marine environment specific design	Reliable overall and detailed design Improvement of technologies for corrosion protection Development of design and operational standards for unmanned marine structures	
	Resource data	Availability, accuracy, spatial resolution, duration of monitoring period	Improvement of resource assessment methods for more detailed knowledge of the resource data relevant for energy use
	Mobilisation and grid connection cost	Development of low-cost grid connection especially for cable laying and fixing or other measures against disruption	
	Licensing and environmental constraints	Implementation of harmonised planning permission and EIA procedures Improvement of EIA methodologies e.g. reaction of marine mammals to structures and noise and required compensatory measures	
	Energy cost	Improvements in engineering know-how through experimental and theoretical work Technical optimisation and cost reduction of the energy conversion systems Development of low-cost installation methods, such as drilling or ramming for stationary devices, mooring of floating devices etc	
	Reliability of operation	Generation of field experiment data through longer-term operation of several years	
Wave energy	Marine environment	Careful material selection and coating	
	Resource data	Improved understanding of hydrodynamics for mathematical and physical modelling	
	Mobilisation and grid connection cost	Low-cost mooring and grid connection using flexible cables and connectors	
	Energy cost	Development of improved components with lower cost and higher efficiency and reliability such as air turbines, electrical equipment, hydraulic equipment, ancillary mechanical equipment, large size bearings and seals Improved design and construction methods	
	Reliability of operation	Move on from successful demonstrated shoreline or small near-shore scale floating devices to full-scale offshore demonstrators with longer periods of operation	

Current turbines	Marine environment	Improvement of sealing and monitoring of submerged components	
	Resource data	Improved understanding of hydrodynamics for mathematical and physical modelling in particular for turbulence and profiles in the flow	
	Energy cost	Development of more cost-effective installation methods Improved design and construction methods	
Salinity	Membrane	Development of improved membranes with lower cost and higher permeability	
	Energy cost	System design with minimum civil engineering requirements Development of adapted turbine technology for power take-off	

Geothermal energy

Technologies

General remark: Geothermal technologies are characterised by a broad spectrum of technologies and applications and most technologies actually applied in geothermal projects are selected on a case-by-case basis. Moreover quantitative specifications as, for example, drilling costs, resource exploration risks, and power plant efficiencies are highly dependent on the actual geothermal generation site and can therefore hardly be generalised.

Geothermal technologies for energy generation include as main technological streamlines geothermal heat pumps for the use of surface heat (only heat generation), hydrothermal geothermal applications (electricity and heat generation) and enhanced geothermal systems (EGS) such as hot dry rock and hot fracture rock (HDR/HFR) technologies, which deal with low permeability, fluid-deficient resources and are able to generate electricity and heat. Low-temperature applications for heat production based on geothermal heat pumps can be considered as technologically matured and in the short and medium term these technologies will be supported mainly by market incentive programmes. Furthermore, high enthalpy resources do not require major research and development efforts in the short and long term.

The most important geothermal pilot plant at the European Union level is the HFR research project at Soultz-Sous-Forets, located on the western edge of the Rhine Graben. This project started in 1987 and is coordinated by a European Economic Interest Group called GEIE Exploitation Minière de la Chaleur (‘heat mining’).

The pilot plant will use three boreholes (one injection, two production wells) of 5000 metres depth each, drilled from the same platform. It is expected that by the end of 2005 this plant will be able to produce around 50 MW of thermal power at temperatures above 180°C. From these temperatures, up to 6 MW electricity will be produced. The net output of the plant is estimated to be in the order of 4.5 MWe. [1]

Two main stages are considered for the development of the pilot plant. The first stage between 2001 and 2004 consisted of accessing the resource by drilling into hot granite horizons at around 5000m and creating a heat exchanger by injection of fluid under high pressure (stimulation). The second stage, between 2004 and 2007, will focus on the installation of a power plant on the surface and the characterisation and monitoring of the underground heat exchanger in the middle and long term.

According to GEIE, it is expected that the industrial development of the HDR/HFR technology will continue with an industrial prototype which could produce around 25 MW of electricity using a multi-well approach with various injection (3) and production (6) wells. Moreover, in the long term, multiple production plants could be constructed in order to improve the economics of HDR/HFR.

Besides the Soultz-Sous project, several other projects are being developed at member state level.

Table 15 shows the state of the art of different geothermal technologies.

Table 15 – State of the art of different geothermal technologies

Technology	Geothermal heat pumps high-enthalpy and hydro-geothermal applications for electricity generation	Enhanced geothermal systems HDR/HFR	**Enhanced geothermal systems HDR/HFR**
	Commercial	**Demonstration**	**R&D**

Technical and socio-economic bottlenecks

The most critical R&D relevant bottlenecks are seen for four cross-cutting technological and socio-economic streamlines with special relevance for HDR/HFR and hydrothermal technologies for the production of electricity and heat:

- Exploration: obtain basic geological data for imaging and modelling of geothermal reservoirs
- Exploitation: drilling costs and improved stimulation technologies
- Energy conversion: thermodynamic conversion at low temperatures
- Appropriate financing and support schemes

The following matrix shows the relevance of the different cross-cutting technologies for each of the main areas of application:

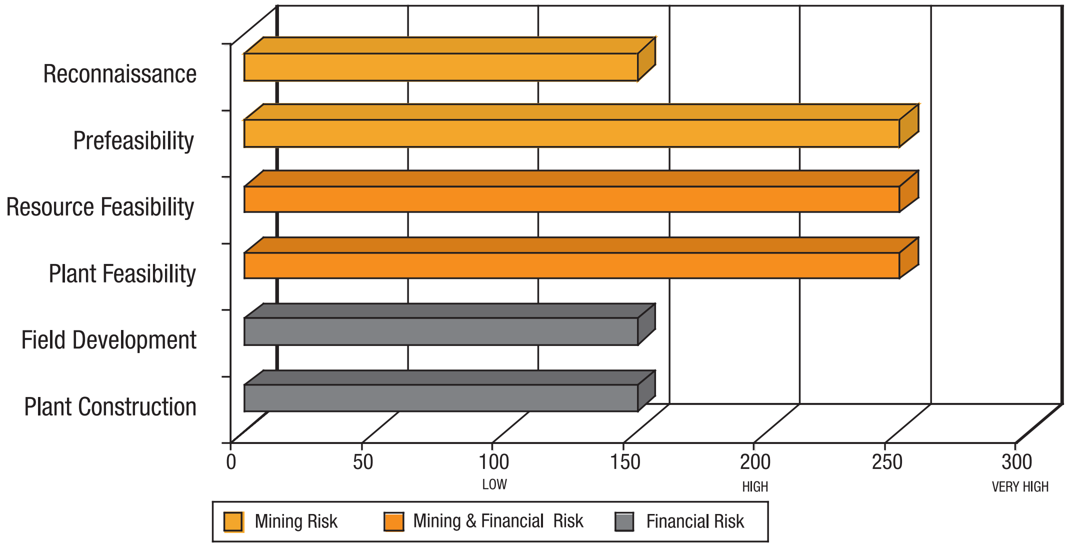
Table 16 – Cross-cutting technologies for geothermal energy production

Application Technology	Geothermal heat pumps (low temperature heat)	Hydrothermal applications	Enhanced geothermal systems HDR/HFR
Exploration		■	■
Drilling & stimulation		■	■
Energy conversion		■	■
Support schemes	■	■	■

Exploration and geothermal reservoir identification

Important bottlenecks for geothermal power production concern the development of more accurate and cost-effective methods for identifying, mapping and exploring geothermal reservoirs. Finding geothermal resources (as well as the basic geologic data) with specific characteristics such as minimum geothermal gradient, specific rock properties, number and spacing of fractures, flow impedance, water loss and minimum thermal drawdown rate, depends on several engineering parameters and therefore is far from an easy task. Exploration and reservoir identification represents an important risk for future geothermal energy development. Figure 3 shows the risks estimated for different phases of the construction of a geothermal power plant.

Figure 3 – Risks estimated for different phases of the construction of a geothermal power plant



Drilling and stimulation costs

The cost of drilling for exploration and production purposes can be a considerably large part of the overall geothermal plant costs and therefore an important technical and economic bottleneck for geothermal energy production.

Drilling research has focused on means to reduce the costs of drilling through hard rock in high-temperature, corrosive environments, by developing longer-lasting bits and better systems for faster and thereby less expensive drilling. In addition, advanced systems to transmit and gather information faster and in real time between the bit and the surface are also being investigated.

In some member states (e.g. Germany's Groß Schönebeck), new stimulation techniques are currently being investigated and tested in order to increase the productivity of each wellhead of this project. However, it is important to remark that stimulation technologies depend exclusively on the geological horizon in question, and generalisations cannot be made.

Energy extraction and conversion

With regard to energy extraction and conversion from geothermal sources, improving casing and tubing materials to resist corrosion and high temperatures and to prevent scaling as well as increasing power plant efficiency and performance, are considered to be important technical bottlenecks in order to obtain lower delivered electricity costs in the middle and longer term. Furthermore, with regard to HDR/HFR systems, geothermal pumps are still a problem due to the fact that they currently operate satisfactorily at a maximum of 300m depth, whereas these systems require pumps operation between 500-600m depth as well as at 200°C and able to deliver 80 l/s geothermal flow.

Geothermal power plants operate at relatively low temperatures compared to other power plants and therefore at low electric efficiencies of about 8-12%. CHP applications typically increase significantly the performance of geothermal power plants. Research efforts should concentrate on new designs of water- and air-cooled condensers as well as improved thermodynamic cycles that extract more energy.

Some accomplishments include the improvement of heat exchanger linings that protect low-cost heat exchanger materials from corrosion and scaling as well as the use of ORC and Kalina cycles (binary cycles). ORC processes have been demonstrated to have 30% higher efficiency than the conventional cycles (at same temperatures). With regard to the Kalina cycle, these processes are currently at a demonstration stage in various member states and their future success will depend on the results obtained in the short and middle term.

In addition, equipment cost and O&M costs for geothermal plants are considered to be important economic bottlenecks for geothermal energy development and should also be reduced in the middle and long term with increased automation.

Appropriate financing and support schemes

For most geothermal applications the existing support schemes and financial incentive mechanisms are not adequate. Geothermal heat pumps might be more efficiently supported by means of building regulations rather than by investment incentives and for hydrothermal applications and enhanced geothermal systems the exploration risk coverage (exploration wells) should be incorporated into financial support mechanisms.

Parameters for characterisation of the critical bottlenecks

Quantitative figures characterising the individual bottlenecks for geothermal technologies cannot be given due to the wide spectrum of these values depending on the very site-specific conditions of each individual project. Therefore quantitative values are shown for the most general parameters (electricity and heat generation costs, plant efficiencies, water mass flow rate).

See below for more detailed information on the various critical parameters of geothermal technologies.

Table 17 – Quantitative parameters for characterisation of critical bottlenecks

Parameters	Unit	Present	5 years	10 years	>15 years
Cost					
Electricity generation costs HDR/HFR [19]	€ cent/kWh	20-30	-	10-15	-
Heat generation costs HDR/HFR	€ cent/kWh	3-8	-	2-5	-
Investment cost	€/kWe	6,000-18,000	-	3,000	-
Electric efficiency	%	8-12	-	10-14	-
Water mass flow rate circulated through the doublet/triplet	kg/s	30	-	50-100	-

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[19] We would like to mention here that high enthalpy resources allow for electricity production costs of 5-8 € cent/kWh at present and are targeted to reach 3-5 cent/kWh for the next ten years. These lower cost figures correspond to already commercially available technologies, which should not be confused with EGS technologies mainly dealt with in this document.

Analysis of the critical indicators to further progress

*Table 18 – Critical indicators to further progress – **Geothermal technologies***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Exploration	Exploration and geothermal reservoir identification	Exploration and resource definition • Develop and demonstrate techniques for combining geophysical (e.g. microgravity, self-potential, MT, CSAMT, seismic), geochemical (e.g. noble gases, chloride distribution, etc.) data and remote sensing techniques with traditional reservoir engineering data to develop more robust reservoir models and expand exploration capabilities. • Rapid resource evaluation via airborne EM and gravity component analysis. • Satellite observations for imaging geothermal reservoirs. • 3D magneto telluric data and imaging systems for geothermal resource exploration. • Improve numerical reservoir modelling techniques (e.g. incorporation of fluid chemistry, non-conservative tracers). • Publish case studies to demonstrate the efficacy of reservoir modelling.	
Drilling and stimulation	Drilling costs and stimulation techniques for increased productivity and reduction of costs	• Optimised drilling controls and improve reservoir definition with the help of high-temperature instrumentation reducing number of drillings and costs. • Silicon-on-insulator technology for geothermal instruments has been demonstrated and tested in some countries and projects. • Test SOI equipment and benchmark improvements with industry. • Develop improved materials and techniques for controlling lost circulation, which is the biggest problem in geothermal drilling. • Interpretation data from hydraulics, seismic, tracers and forward modelling needs to be encouraged to get better description of the reservoir and its sustainability. • If penetration rates and bit life could be doubled from their current levels, well costs could be reduced by about 15%.	
Use	Energy extraction and conversion Low efficiency of thermodynamic energy converters for low temperature-input at surface	• Improvements of ORC and Kalina processes • Encourage R&D of binary or even trilateral-vapour cycles	
Use	High O&M costs	• Increased automation of power production • Standardising technology for scale inhibition and corrosion prevention	

Support schemes	Industrial base development Start-up stage	• Various tasks and areas of this industry remain uncompetitive; therefore the establishment of project quotas per year (number of projects [including pilot projects]/year) should be encouraged. • Support schemes in the form of investment support for new projects could be allocated for up-front investments such as exploration wells in order to stimulate the development of HFR.	

Biomass-based technologies

Technologies

In general terms, ‘biomass’ is the name for the organic resources that can be used to produce energy using different processes. At EU level, biomass is defined as the biodegradable fraction of products, waste from agriculture (including vegetable and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste.[20] In this document, only the bottlenecks and indicators for production of biofuels are considered. The bottlenecks and indicators for feedstock production and pre-treatment, end-use integration are not discussed in this report.

The first step of this analysis is presented in this report and focuses on the **conversion processes** of biomass. In follow-up projects feedstock production/pre-treatment and end-use integration should be included. Furthermore, more basic R&D in the field of modern biotechnology is not taken into account, as these technologies are discussed in greater detail on page 65 (‘Generic cross-cutting and horizontal technologies with relevance to energy’). The focus will be on the production of biofuels and electricity/heat. Biorefineries have a large potential, but are excluded in this study. The production of ethanol from sugar or starch, biodiesel production from rapeseed, anaerobic digestion, carbonisation, large-scale CHP and combustion will not be considered. These technologies have little improvement potential, as they already are matured technologies.

The technologies included in this report are fermentation of lignocelluloses, synthesis of syngas [biomass-to-liquids (BTL) fuel: FT-diesel, methanol, hydrogen, synthetic natural gas (SNG)], hydro thermal upgrading (HTU), flash pyrolysis, (biomass integrated gasification/combined cycle) BIGCC, supercritical gasification and small-scale CHP (wood combustion). Co-combustion with low biomass share is considered to be a commercial technology, for which the current barriers for implementation are not in the technological field, but on the policy/permissions level. Co-combustion of large amounts of biomass is technically limited and R&D could solve this. In follow-up projects this should be included. Table 1 shows the state of the art and prospects of the biomass-based technologies considered.

Table 1 – State of the art and prospects of the biomass-based technologies.
Technologies that are already considered to be commercial are not reviewed further

Fuel production technologies (biomass to biofuel)	Pressing/extraction (pure plant oil [PPO]) PPO esterification (biodiesel [RME]) Fermentation of sugars/ starch (ethanol) Anaerobic digestion (biogas)	Fermentation of lignocelluloses (ethanol) Gasification (syngas) Synthesis of syngas (biomass-to-liquids (BTL) fuel, e.g. FT-diesel, methanol) Flash pyrolysis	HTU
Conversion technologies (biomass/ or biofuel to electricity and heat)	Combustion Large-scale CHP Anaerobic digestion (biogas)	BIGCC Small-scale CHP (<100 kWe wood combustion)[21] Flash pyrolysis Co-combustion	Supercritical gasification
	Commercial	**Demonstration**	**R&D**

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[20] EU Directive 2003/30/EC on the promotion of the use of biofuels or other renewable fuels for transport.

[21] The Stirling engine is considered as it has very flexible fuel usage and promising overall efficiency [see Biedermann 2004].

Technical and socio-economic bottlenecks

The major technical and socio-economic bottlenecks of the various technologies can be grouped into the following main classes:

- **Cost:** Electricity, heat and fuel costs from biomass origin are still higher than those of conventional technologies and represent the main barrier for a fast market penetration. The main parameters characterising the product costs of biomass-based technologies are investment costs, the operation and maintenance costs of the plant, and costs of biomass feedstock. The most promising cost reduction options are technological improvements (e.g. efficiency improvements), an increase of power plant size (up-scaling) and a switch to technologies in which cheaper biomass feedstocks can be used
- **Efficiency:** Parameters characterising this bottleneck are overall efficiency and pre-treatment (including logistics) efficiency. Apart from cost reduction, improvement of efficiency will lead to a larger overall greenhouse gas emission reduction in the whole life cycle of biomass-to-energy systems. Furthermore, the potential of the available biomass will increase since more end-product (electricity, heat or bio-fuel) will be produced from the same amount of biomass

Besides the above-mentioned techno-economic bottlenecks, several socio-economic bottlenecks are related to biomass technologies. These cannot be expressed in quantitative terms and are not discussed further in this document. However they are important for an overall picture of the topic and should be listed.

- **Use of biofuels:** ethanol: direct ethanol blending in gasoline increases gasoline vapour pressure and therefore requires adaptations of the gasoline. EU legislation does not allow blending over 5%v/v ethanol in gasoline, however there are no technical problems to make blends with more than 5% ethanol content in gasoline.

The bottlenecks for the use of methanol and hydrogen in a fuel cell were discussed abovein (see section ‘fuel cells’).

- **Availability and contractibility of feedstock:** Long-term contracts at acceptable prices are difficult to obtain due to a non transparent international biomass market.
- **Sustainability of biomass:** the biomass used has to comply with sustainability standards.
- **Public acceptance of biomass technologies:** Biomass plants are easily associated with the (chemical) industry, resulting in the NIMBY effect, which could be identified as a bottleneck for further implementation. Besides this the principle behind its sustainability (i.e. CO_2 cycle) is relatively difficult for the general public to understand.
- **Competition with food production and feed stock for e.g. pulp and paper:** Biomass has various potential uses, e.g. for food or as raw material. If biomass for energy prices become too attractive e.g. in comparison to food, competition is likely to occur.
- **Biorefineries:** Biorefineries have a big potential and R&D is needed in this field. However, biorefeneries are excluded in this study.

Parameters for characterisation of the critical bottlenecks

The following table gives an overview over the quantitative parameters describing the main bottlenecks for the introduction of the technology. State of the art and values for different time horizons are given.

Table 2 – Quantitative parameters for characterisation of critical bottlenecks

Parameters characterising the bottleneck cost[22]	Unit	2004	5 years	10 years	> 15 years
Fermentation of lignocelluloses (ethanol)					
Ethanol cost[23]	€/GJ_{HH}	22	-	-	12
Investment cost (production plant)	M€	290	-	-	220
Operation and maintenance cost[24]	€/GJ_{HH}	5.0	-	-	1.0
Overall efficiency	%	34.9	-	-	47.3
Gasification and methanol synthesis (methanol)					
Methanol cost[23]	€/GJ_{HH}	12	-	-	9
Investment cost (production plant)	M€	235	-	-	190
Operation and maintenance cost	€/GJ_{HH}	1.3	-	-	0.9
Overall efficiency	%	58.9	-	-	57[25]
Gasification and hydrogen production (hydrogen)					
Hydrogen cost[23]	€/GJ_{HH}	16	-	-	9
Investment cost (production plant)	M€	250	-	-	210
Operation and maintenance cost	€/GJ_{HH}	2.1	-	-	1.3
Overall efficiency	%	34.8	-	-	41.3
Gasification and FT-synthesis (FT-diesel)					
FT-diesel cost[23]	€/GJ_{HH}	18	-	-	13
Investment cost (production plant)	M€	290	-	-	235
Operation and maintenance cost	€/GJ_{HH}	2.5	-	-	1.3
Overall efficiency	%	42.1	-	-	42.1
HTU (HTU-biocrude)					
Production cost HTU-biocrude	€/GJ	-	-	-	4.8[26a]
Investment cost (production plant)	M€	-	-	-	32[26b]
Operation and maintenance cost	€/GJ_{HH}	-	-	-	2.2[26c]
Overall efficiency	%	-	-	-	75-90 [26d]
Supercritical gasification					
Cost	€/GJ	-	-	-	-
Investment cost (production plant)	M€	-	-	-	-
Operation and maintenance cost	€/GJ_{HH}	-	-	-	-
Overall efficiency	%	-	-	-	-

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[22] Sources: [Palmers, 2004; Hamelinck, 2004; Broek, et al., 2003; Biofuels, 2003]. Note that instead of gasification as well, the syngas produced via supercritical gasification could be used. However, this experimental process has not yet been economically evaluated.

[23] See also appendix A, Reduction investment costs biofuel production.

[24] O&M for ethanol is very dependent on cellulose required.

[25] Lower fuel efficiency, but in the future option electricity production is included

[26] [Biofuels BV, 2003],a) based on feedstock cost of 0 €/tonne and a conversion rate $:€ of 0.8 b) for a plant producing nearly 12 ktonne/yr LCR and 8.5 ktonne/yr HCR c) based on 47% O&M costs d), depending on configuration and feedstock.

Parameters characterising the bottleneck cost[22]	Unit	2004	5 years	10 years	> 15 years
Flash pyrolysis					
Production cost pyrolysis oil	€/GJ	4-6[27]	-	-	-
Investment cost (production plant)	M€/ton $_{input}$	1.2[28]	-	-	-
Operation and maintenance cost	€/GJ$_{HH}$	-	-	-	-
Overall efficiency	%	-	-	-	-
Small scale CHP (<100 kWe wood combustion)					
Investment cost	€/kWe	2500	-	-	-
Overall efficiency (35 kWe)	%$_{LHV}$ electric	25%[29]	30%	-	-
BIGCC (30 Mwe; wood gasification, electricity and heat)					
Investment cost	€/kWe	-	1700	1660	1620
Efficiency	%$_{LHV}$ electric	-	40$_e$	43 $_e$	45 $_e$

Analysis of the critical indicators to further progress

In order to coordinate R&D activities it is necessary to know which measures will contribute to improve the identified bottlenecks. In the following tables these measures are listed and critical indicators to further progress are given, wherever possible. Measures and indicators are allocated to the corresponding bottleneck parameters (second column). The table does not contain all possible improvement measures and indicators, but only the most important and most promising ones. The information is mainly based on recent studies and Internet sources.

*Table 3 – Critical indicators to further progress – **Fermentation** (lignocelluloses)*

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
System	Overall efficiency	Process optimisation mainly through larger scales and high-efficiency enzymes production, availability	
Enzymes production	Cost reduction O&M	Development of new micro-organisms for the fermentation of woody biomass	Costs of O&M for ethanol production depend largely on celluloses costs. Via the development of cost-efficient enzymes production, e.g. in consolidated bio processing, this can be achieved.

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[27] [Hamelinck et al., 2005]: Pyrolysis oil can be produced for 4 – 6 €/GJ, at feedstock costs of 3 €/GJ.

[28] See also appendix A section Pyrolysis.

[29] Technology option is the Stirling engine (Based on Biedermann 2004).

Table 4 – Critical indicators to further progress – ***Gasification***

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>System</td><td>Gasification efficiency</td><td><table><tr><th></th><th>2004</th><th>target</th><th>target year</th></tr><tr><td>Cold gas efficiency</td><td>80-82%</td><td>>82%</td><td>2020</td></tr></table></td><td>Gasification efficiency can be increased by an optimisation of pressure, temperature and exposure time.</td></tr>
<tr><td>System</td><td>Availability</td><td>The amount of hours that a gasification system can fully operate per year<table><tr><th></th><th>2004</th><th>target</th><th>target year</th></tr><tr><td>Operational hours</td><td>-</td><td>8000 hrs/yr</td><td>2020</td></tr></table></td><td>Establish process simplifications. Tthe reliability of the syngas cleaning (especially tar reduction) needs improvement.</td></tr>
<tr><td>Gas cleaning</td><td>Overall efficiency</td><td>High temperature gas cleaning will improve overall efficiency<table><tr><th></th><th>2004</th><th>target</th><th>target year</th></tr><tr><td>Temperature [ºC]</td><td>120–250</td><td>350-800</td><td>2020</td></tr></table></td><td>Higher temperatures result in lower gas dilution, an increase in C-conversion and a lower tar content.</td></tr>
</table>

Table 5 – Critical indicators to further progress – ***Supercritical gasification***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
System	Demo plant	Commercialisation of the process is not expected before 2020.	Still basic experiments have to be done. Scale-up will reduce costs significantly.

Table 6 – Critical indicators to further progress – ***HTU***

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>End-product</td><td>Proof of utilisation</td><td>Acceptance and utilisation standards for end-product</td><td>Upgrading process for biocrude has to produce a product that will be acceptable, e.g. for blending with diesel.</td></tr>
<tr><td>System</td><td>Size (demo) plant</td><td><table><tr><th></th><th>2010</th><th>target</th><th>target year</th></tr><tr><td>PJ/jr biocrude</td><td>0.3</td><td>>1.3</td><td>2015</td></tr></table></td><td>The first demo-plant still has to be built (but is being planned). Scale-up will reduce costs significantly.</td></tr>
<tr><td>System</td><td>Costs biocrude</td><td><table><tr><th></th><th>2015</th><th>Target</th><th>target year</th></tr><tr><td>€/GJ biocrude</td><td>4.8</td><td><2.8</td><td>2020</td></tr></table>(assuming feedstock costs of 0 €/GJ)</td><td>Apart from scale-up, learning will also reduce costs.</td></tr>
</table>

*Table 7 – Critical indicators to further progress – **Flash pyrolysis***

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>comments</th></tr>
<tr><td>System</td><td>Size (demo) plant</td><td><table><tr><th></th><th>2004</th><th>target</th><th>target year</th></tr><tr><td>Ton$_{input}$/hr</td><td>0.2</td><td>>10</td><td>2010</td></tr></table></td><td>Scale-up will reduce costs significantly.</td></tr>
<tr><td>System</td><td>Integration existing systems</td><td></td><td></td></tr>
</table>

*Table 8 – Critical indicators to further progress – **BIGCC***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	comments
Improvement gasification process	See Table 6-4	See Table 6-4	
Gas turbine	Overall efficiency/ electricity cost	Improvement of gas turbine technology	

*Table 9 – Critical indicators to further progress – **Small-scale CHP***

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>comments</th></tr>
<tr><td>System</td><td>Cost reduction
Investment</td><td>Increase of lifetime of piston rod seal, increase of maintenance intervals and improvement of reliability and availability<table><tr><th></th><th>2005</th><th>target</th><th>target year</th></tr><tr><td>Operating hours</td><td>< 10.000</td><td>40.000</td><td>2010</td></tr></table></td><td></td></tr>
<tr><td>System</td><td>Efficiency (electric)</td><td>Heat transfer from combustion to working gas, heat integration in the overall process</td><td></td></tr>
</table>

*Table 10 – Critical indicators to further progress – **Pre-treatment and logistical processes***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	comments
Pre-treatment	Pre-treatment efficiency	Reduction of biomass losses during pre-treatment process (including storage). Integration of mechanical or thermal pre-treatment processes into the production chain.	Targets are difficult to quantify due to the diversity per chain.
Transport	Transport efficiency	Long-distance ocean transport might cost 5-10% of the total energy content of the biomass.	Shortening transport distances or increase of bulk size will reduce this. Targets are difficult to quantify due to the diversity per chain.

Recommendations

- For a good analysis of the bottlenecks and indicators the whole chain (feedstock production and pre-treatment, conversion processes, end-use integration) should be included in this study. The first step of this analysis is presented in this report and focuses on the conversion processes of biomass. In follow-up projects feedstock production/pre-treatment (torrefaction, pyrolysis, etc) and end-use integration (fuel cells, gas engines, microturbines, etc) should be included.
- Co-combustion of small amounts of biomass is considered to be a commercial technology, for which the current barriers for implementation are not technical, but on the policy/permitting level. Co-combustion of large amounts of biomass is technically limited and R&D could solve this. In follow-up projects this should be included.

Power storage technologies and integration of distributed generation of energy

Power storage techniques

Technologies

Any storage technology is always a compromise between many characteristics: costs (including all the devices or power electronics necessary to make the storage system operational), specific power and energy, overall efficiency, self-discharge rate, rechargeability, optimal operating temperature range, ability to withstand a wide range of charge/discharge conditions, maintenance conditions, etc.

Each storage type therefore has special characteristics, making it suitable for different application fields.

The demand for R&D is on the one hand determined by the technical particularities of single power storage types and on the other hand guided by application-oriented requirements.

In the following only the most promising storage technologies are analysed in the context of the most obvious specific application fields.

Generally, storage can be classified into 11 types:

- lead-acid batteries
- lithium batteries
- nickel batteries
- metal air batteries
- pumped hydro storage
- flywheels
- fuel cells and hydrogen
- supercapacitors
- superconducting magnetic energy storage
- compressed air
- redox.

Pumped hydro storage and flywheels are regarded as technically mature and are not examined here. Fuel cells and hydrogen technologies have already been considered in the section 'fuel cells and hydrogen technology'.

Table 1 – State of the art of different storage technologies

Technology	**lead acid** **lithium-ion** **nickel** supercapacitors SMEs compressed air	lead acid **lithium-ion** nickel metal-air **supercapacitors** **SMEs** **compressed air** **redox**	lead acid **lithium-ion** **metal-air** **supercapacitors** SMEs compressed air redox
	Commercial	**Demonstration**	**R&D**

Table 1 shows the state of the art of different storage technologies, which is quite hard to define. All types are currently being tested in various demonstration projects. Further R&D is also being carried out parallel to the demonstrations for most of the types, even for the most conventional lead-acid type.

Technical and socio-economic bottlenecks

The situation is not similar with all the storage technologies.

On the one hand, lead-acid batteries can be considered as a reference, because it is the most widespread among many applications and the cheapest technology. Over the last decades, it has slowly continued to improve its reliability while continuing a slow price decrease.

On the other hand, most of the alternative technologies are generally more, or even much more, expensive, but are able to present one or two specific advantages which are key for the expected application such as a different range of operational temperatures, a higher energy or power density, etc.

Therefore, the main bottlenecks are different.

For the **lead-acid battery**, the main bottleneck is its lifetime. Improvements are still expected, the main objective being providing the lower-cost batteries with the performance that usually comes with the strongest design (thick plates, tubular design). New technological advances such as new alloys and coatings, plate compression, or the more innovative use of metallic foam, are associated with better storage system monitoring and management, and may help in extending considerably the batteries' lifetime, therefore decreasing the cost of ownership.

For most of the **other storage technologies**, the main bottleneck is their high cost. That is why they usually enter the market in niche markets such as portable applications. This reduces the cost disadvantage, while proposing a key feature such as, for instance, a better 'power to weight' combination. That is the case with **nickel and lithium batteries**, among others. Lithium batteries especially have decreased their very high costs while gradually improving the power and energy density. But they remain very expensive.

Improvements are still possible mainly by decreasing the amount of active materials and by using cheaper materials. The main strategy is usually to introduce new and enhanced chemical combinations, while creating more surface area for a given amount of material. Material sciences and material processing are therefore key for most storage technologies. The development and use of specific coatings, surface structure, particle shapes or sizes, nano-particles, etc, are ways of improving the 'surface/volume' ratio.

Such advances usually come along with improved performances (power or energy density in W or Wh/kg) and an extended lifetime or cycling life, by reducing the ageing processes (corrosion of electrodes, degradation of membranes, interfaces, electrolytes). The lifetime extension is finally another way of decreasing the cost of ownership of a storage system.

The main bottleneck for **supercapacitors** is the cost and lifespan of the material. Nanotechnology is being used to develop smaller and faster supercapacitors, with higher power energy densities.

The main bottleneck in **superconducting magnetic energy storage** (SMES) is the cost of the superconductor, where high temperature superconductors are a very attractive option, because they would enable the application of a more common refrigerant (liquid nitrogen).

The main bottleneck in **compressed air energy storage** (CAES) is the storage container for the compressed air. The normally containers used are geological cavities, such as man-made caves, salt caves, or porous rock, either created by water-bearing aquifers or as a result of oil and gas extraction. The main drawback of CAES is its reliance on geological structures.

Redox in this context refers to vanadium-based storage systems. Such systems are commercially available in the USA and Japan, but very few European companies use this technology. There are only very few installations in Europe. Redox batteries have the potential to achieve very high capacities in the range of hundreds of MWh, but such systems still have to be developed by scaling of the cells and stacks and using adequate power electronics. A critical component is the membrane with respect to cost and stability. Electrolyte circulation causes still high self-consumption losses and some technical problems with pumping, electrolyte distribution, etc.

Parameters for characterisation of the critical bottlenecks

The following table gives an overview of the quantitative parameters describing the main bottlenecks for the introduction of the technology. State of the art and target values are given. These selected criteria will also help in calculating the expected cost of the energy coming out of the storage system, taking into account the figures (investment cost, lifetime, efficiency, etc) relevant to the application under consideration.

Table 2 – Quantitative parameters for characterisation of critical bottlenecks

Parameters	Unit	2004	Target	Target year
Lead-acid batteries – energy storage for automotive and standby applications (kWh to MWh range)				
Energy density	Wh/kg	35-45	60	2010
Energy density	Wh/l	70-120	-	-
Power density	W/kg	200-400	200-600	2010
Energy cost	€/kWh	50-150	50-120	2010
Cycling service	Deep cycle	100-1 500	200-2 000	2010
Lifetime	Years	3-15	5-20	2010
Energy efficiency	%	75-85	75-85	-
Lithium batteries (lithium-ion) – power storage for transport applications, energy storage (Wh to some kWh range) for small portable electronics (cell phones, computers, etc.)				
Energy density	Wh/kg	80-200	180-300	2010
Energy density	Wh/l	300-400	-	-
Power density	W/kg	200-1 500	400-2 000	2010
Energy cost	€/kWh	500-800	150-200	2010
Cycling service	Deep cycle	600-1 000	1 000-2 500	-
Lifetime	Years	3-10	5-20	-
Energy efficiency	%	90-95	90-97	-
Lithium batteries (lithium metal) – energy storage (Wh to some kWh range) for small portable electronics (cell phones, computers, etc.)				
Energy density	Wh/kg	120-180	-	-
Energy density	Wh/l	300-400	-	-
Energy cost	€/kWh	500	200	2010
Cycling service	Deep cycle	100-300	1 000	2010
Lifetime	Years	3-20	-	-
Energy efficiency	%	92-97	-	-
Nickel batteries (nickel-zinc) – energy storage for stand-by and transportation applications (<kWh to some kWh)				
Energy density	Wh/kg	50-80	65-100	2010
Energy density	Wh/l	75-110	-	-
Power density	W/kg	40-65	-	-
Energy cost	€/kWh	200-400	150-200	2010
Cycling service	Deep cycle	500	600-1 000	2010

Parameters	Unit	2004	Target	Target year
Energy efficiency	%	80	-	-
Nickel batteries (nickel-cadmium) – energy storage for standby and transportation applications, (Wh to MWh range)				
Energy density	Wh/kg	35-45	50-100	-
Energy density	Wh/l	80-200	-	-
Power density	W/kg	100-1 000	-	-
Cycling service	Deep cycle	800-2 500	-	-
Lifetime	Years		-	-
Energy efficiency	%	65-75	-	-
Nickel batteries (nickel-metal hydride) – Power storage for small transportation applications, energy storage for portable electronics (Wh to some kWh range)				
Energy density	Wh/kg	50-80	80-100	2010
Energy density	Wh/l	80-200	80-300	2010
Power density	W/kg	500-1 000	-	-
Energy cost	€/kWh	350-500	-	-
Cycling service	Deep cycle	600-1 200	-	-
Energy efficiency	%	65-70	-	-
Metal air batteries (zinc/air) – energy storage for portable and standby applications (kWh range)				
Energy density	Wh/kg	200-300	200-400	-
Energy density	Wh/l	250-300	135-300	-
Power density	W/kg	70-150	200-500	-
Energy cost	€/kWh	200-250	150-800	-
Cycling service	Deep cycle	400-500	700	-
Energy efficiency	%	n.a.	-	-
Supercapacitors – power storage for power quality applications mainly				
Investment cost	€/Wh	50-150	20-50	-
Power density	W/kg	100-5 000	10 000-12 000	-
Energy density	Wh/kg	5-10	20	-
Energy efficiency	%	85-97	98	-
Cycling service	Deep cycle	100 000-500 000	500 000	-
Superconducting magnetic energy storage – power and energy storage for power quality and standby applications				
Investment cost	€/kW	-	-	-
Power range	MW	10-1 000	2 000	
Capacity	MWh	0.8		
Power density	W/kg	-	-	-
Energy density	Wh/kg	-	-	-
Energy efficiency	%	97-98	-	-
Lifetime	Years	40	-	-
Redox (vanadium system) – energy storage for standby applications				
Investment cost	€/kWh	300	<200	2010
Power range	kW	2,5-3 000	10 000	-
Capacity range	kWh	50-5 000	-	-
Power density	W/kg	60-166	-	-
Energy density	Wh/kg	25-35	50	-
Energy efficiency	%	70-80	-	-

Parameters	Unit	2004	Target	Target year
Lifetime	Years	10-15	-	-
Compressed air – energy storage for standby applications (10 kWh to MWh range)				
Investment cost	€/kW	450	-	-
Power	MW	300	-	-
Energy efficiency	%	42-54	-	-

Analysis of the critical indicators to further progress

In order to coordinate R&D activities it is necessary to know which measures will contribute to improve the identified bottlenecks. In this paragraph these measures are listed and critical indicators to further progress are given, where possible. Measures and indicators are allocated to the corresponding bottleneck parameters. The tables below indicate at which technology component research activity has to take place. The list does not contain all possible improvement measures and indicators, but only the most important and most promising ones.

*Table 3 – Critical indicators to further progress – **Lead-acid batteries***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Current technology	Lifetime reliability	Increased grid corrosion resistance of current technologies, which provides positive plates with longer life potential.	Several opportunities: • use of new alloys, with higher purity control • new material processing, resulting in an enhanced control of metallurgical structure • improved plate design (thickness, optimised grid structure).
Current technology	Lifetime reliability/ deep cycle performance Partial state of charge operation	Increased resistance to sulphation and electrolyte stratification.	New additives, negative plate expander.
New plate design	Lifetime reliability/ deep cycle performance and Partial state of charge operation	Increased grid corrosion performance and sulphation resistance: technological breakthroughs are achievable through research at the material level and on material processing.	Issues of interest: • plate compression • new electrode design, providing more surface area for battery chemistry to occur (metallic foam, composite plates, insertion of nanocomposites)
System integration	Lifetime reliability/ cost of ownership	A cost-effective and efficient storage system relies upon a good battery technology and a well-designed system integration, which optimises the overall service provided to the end-user.	For a given installed capacity, optimisation of the daily useable capacity and of the lifetime, through optimised management strategy. State of charge and state of health indicators.

Table 4 – Critical indicators to further progress – ***Lithium batteries***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Positive electrode	Cost of the active material	Research on new components and new chemistry design is required, because the existing $LiCoO_2$ is too expensive due to the cobalt. Cheaper and less toxic material, with similar or higher performance are needed, especially for the development of larger sizes of batteries and for high power applications.	Several alternative options exist: • replacement of Co by a compound Mn/Co/Ni, with an optimised ratio between the elements • $LiMn^2O^4$ and $LiFePO^4$ may present a comparable energy density performance and could be interesting for power applications, (up to 2000 W/kg, and 80 to 150 Wh/kg) Whatever the active materials, the ways of synthesis, the particle sizes, and the conductive cathode coatings also have strong impacts on the overall performance.
Negative electrode	Cost of the active material	This cost is less important than the one of the positive, but research is necessary to decrease the cost.	New low-cost graphite materials (with optimised particle size and shape and surface properties through nano-structuration) or $Li_4Ti_5O_{12}$ are some alternative options
Electrolyte	Performance/ safety/ recycleability	The electrolyte is currently based on organic solvents which results in safety and environmental concerns. There is a need for stable and non-reactive electrolytes, especially in large capacity batteries, where the amount of material is larger and the heat exchange more critical.	Environmentally friendly electrolytes that do not contain any halogens would be ideal. The addition of nano-particles as dopant has to be investigated. Electrolyte based on non-flammable ionic liquids, such as molten salts operating over a large temperature range seems achievable, would solve safety concerns due to abuse conditions (overcharge, over-heating, external short-circuit, internal short-circuit by penetration, crushing).
System integration	Investment cost	Cell to cell voltage divergence has to be avoided. Charge equalizer needs power electronics which increases the total cost of the energy storage systems.	Power electronics has to fulfil several requirements: cell monitoring, maintaining the state of charge balance of the cells, and to provide state of charge and state of health indicators.

Table 5 – Critical indicators to further progress – ***Nickel batteries***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Electrode	Investment cost	The main concern is the cost reduction of battery components and raw materials. The main goal is therefore to improve the active material efficiency.	Cobalt, a key additive of the nickel electrode, can be replaced by less expensive graphite (as powder or fibres), with some adjustments for power applications. Additional additives like Y, Ca, Ti, or Nb, as elements or compounds may also improve the charge acceptance.
NiMH Battery	Environmental issues	Development of recycling processes.	There are no processes today that can recycle the metal hydride alloy in NiMH batteries.
NiZn battery	Reliability	As the zinc electrode is known to have a limited cycle life within alkaline electrolytes, the specific R&D needs are mainly to improve cycle life and reliability.	More than 1000 cycles have been reached with NiZn batteries at 80% DOD, with the use of metallic foam and nano particles of ceramics.

Table 6 – Critical indicators to further progress – ***Metal/air batteries***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Anode	Energy and power density	Improvement of the reaction capacity through an optimised texture and structure of the surface. A higher specific surface area increases energy and power density.	Anode is made up of pure metal (zinc, magnesium or aluminium), magnesium alloys, or specific alloys (Magnesium-aluminium-zinc). The size and the structure of the active material as well as catalysts and inhibitors have a great impact on the electrode kinetics.
Anode	Easy or continuous fuel supply	The mechanical replacement of the exhausted anode has to be made easier or suppressed.	Several options : • quick mechanically rechargeable cell • development of special metal/air-chargers
Air Cathode	Energy and power density	The use of new materials, particularly high-surface-area high porosity media for the gas diffusion electrode	The development of bifunctional air electrodes is crucial and depends on advances in material science and catalyst technologies
Stack	Energy and power density cycling life reliability	Increased reliability and reduced costs. Zn/air: • solid or fixed electrolyte • cell for high cycles uses • cheap and reliable bifunctional electrodes	This research will lead to more compact metal-air systems for energy storage and generation

Table 7 – Critical indicators to further progress – ***Supercapacitors***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
System	Cost	Cost reduction must be made especially in the carbon, electrolyte and separator fields, where target as low as 10 €/kg or 1 €/m² has to be reached.	Nanotechnology will allow production costs to be lowered with an expectation of 50% cost reduction year-on-year. One of the enabling materials of supercapacitors is carbon, and it is in the engineering of this material where nanotechnology is used. Based on activated carbon an increase of the surface area is looked for by working down the particle size from 50nm to 2nm. Also the pore size is tailored for the particular power and amount of energy store required.
System	Recycleability	Development of non-toxic cell components especially for the applications in transport.	
System	Lifetime	Research on degradation phenomena and improvement of ageing performances during cycling or floating.	
System	Energy density	Better use of the volume of the carbon material, Higher cell voltage and thus higher electrolyte stability, Novel definition of the electrode structure.	
Cell	Voltage	For high energy density the nominal voltage has to be increased using an organic electrolyte. [6]	
Cell	Balance	Improvement of cell structure by the development of an intermediate modular structure, reliable cell-balancing systems and battery management systems.	

Table 8 – Critical indicators to further progress – ***Superconducting magnetic energy storage***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Superconductor	Cost	Application of oxide superconductors.	Oxide superconductors have hidden potential to achieve the further improvement in economic efficiency. For high fields at the higher operating temperatures some form of thin film YBCO-coated conductor will be used. The most promising route to a coated conductor is RABiTS whereby thin, flexible textured metallic substrates form the basis for textured YBCO thin films with extremely high current density.

System	Design	Development of cost-minimum design of superconducting metal coils.	In AC applications, there are still electrical losses, but these can be minimised through appropriate wire architecture and device design.
Electronics	Temperature	Development of low-temperature electronics.	Currently applied electronics require expensive heating system – radioisotope heating units.

Table 9 – Critical indicators to further progress – ***Redox***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Circulation system	Self consumption	Reduction of circulation, improvement of pump management; Development of no-flow systems for small systems Improvement in electrolyte distribution (flow geometries).	
Membranes	Stability, cost	Improved membranes, new materials.	
Electrodes	Cost, stability	New materials (polymers), new production process; Introduction of bipolar plates (bonding of electrodes).	
Electrolyte	Stability	Formula	

Table 10 – Critical indicators to further progress – ***Compressed air***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Vessel	Availability	Development of man-made storage vessels and buried high pressure piping for small (5-15 MW) CAES plants.	Availability of natural caverns for air storage is very limited.
Compressor	Efficiency	Application of concepts like HAT and CHAT[30] thermal cycles that use humidified air as a working fluid, thus reducing the specific air consumption and parasitic power consumption by compressors.	The combustion turbine compressor is directly driven by a combustion turbine expander that takes over 50% of its power. Unfortunately, the HAT and CHAT concepts have not yet found attractive market applications, because they require some combustion turbine modifications. The manufacturers have not yet concluded that the potential market is large enough to justify the required investments.
Combustion turbine	Efficiency	Development of humidification process of the stored compressed air before injection into combustion turbine.	Avoids complications associated with HAT and CHAT concepts.

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[30] HAT – Humidified Air Turbine; CHAT - Cascade Humidified Advanced Turbine.

Integration of distributed generation of energy

Technologies

Distributed energy resources (DER) include distributed generation, storage technologies and demand-side measures. Distributed generation is by small-scale electricity generation sources connected to the distribution network or the customer side of the meter, which are based on the use of renewable energy sources[31] or technologies for combined heat and power generation[32].

The area of DER integration is large. For instance, it may include integration of microsources into island systems, or certain local impacts of particular technologies. However, taking into account the European dimension of the task, the highest priority and particular emphasis should be put on the large-scale integration of DER into European interconnected power systems with respect to power system impacts and security of supply.

Table 11 – State of the art of different concepts of DER integration

Concept	Virtual power plant microgrids	Virtual power plant microgrids	Large-scale virtual power plant microgrids
	Commercial	**Demonstration**	**R&D**

Technical and socio-economic bottlenecks

There are a number of technical and socio-economic bottlenecks in the field of DER integration. Controllability and intermittency represent the most important bottlenecks for further development of DER.

- **Controllability:** DER can supply a substantial part of energy demand, but unless it becomes controllable, it will not displace the centralised generation needed for system operation, thus using increased network and generation capacities (with associated costs). There are now several innovative concepts of improved DER integration, which will allow DER to participate in system support, displacing parts of centralised power plants without affecting power system reliability. There are already some available solutions, for instance DEMS [5], but they are able to solve only local optimisation tasks. However, in order to ensure reliable and secure operation of the European power system with high penetration of DER, system-wide approaches must be developed to provide DER control on both distribution and transmission levels. In general, two approaches are anticipated:
    - **Large-scale virtual power plants** that are an aggregation of a large number of DER units, responsive loads and storage devices, which, when integrated, have flexibility and controllability similar to large conventional power plants. This approach presents an evolution of power systems, facilitates DER integration into the whole operation hierarchy and enables DER to take over system services.
    - **MicroGrids** are an innovative approach, which forms a new type of power system on low voltage networks. MicroGrids can be connected to the main power network, or be operated autonomously if they are isolated from the power grid, in a similar manner to the power systems of physical islands.

    For all the advanced integration concepts, there are three main issues to be tackled:

    - design of distributed control system architecture
    - development of communication and information systems to enable distributed control

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[31] Including wind power plants, excluding large hydro power plants.

[32] Emergency units (e.g. UPS) are not considered within the ESTIR project, due to their limited application field and low annual electricity production.

  - ▷ establishment of market and regulatory framework to facilitate secure and cost-effective DER integration. Integrated DER will be able to provide system support and participate in wholesale, balancing and ancillary services markets

- **Intermittency:** Some distributed generation technologies based on renewable energy sources are intermittent by its nature (e.g. wind power, PV, hydro power) or application (e.g. cogeneration). Wind power attracts particular attention with respect to DER integration. Variability, unpredictability and the remoteness of resources from load centres imply additional costs for reliable power system operation with a large wind generation share. Moreover, wind power will amount to a substantial share of future power supplies. This section considers the integration issues of intermittent energy sources (mainly wind power):
  - ▷ **Predictability:** Forecasting of such DER generation can significantly reduce the reserves required and associated costs of integration, which are quite substantial for wind energy, for example. Wind power forecasting systems have almost achieved their limits on accuracy. Further improvement will be based on increasing quality of weather prediction and aggregation of power output from DER installed in a larger area. Accuracy of forecasting systems are characterised by error level, but for system operators the range between the expected minimum and maximum levels has more added value. It is difficult to compare different forecasting systems, if they are not applied at the same location.
  - ▷ **Balancing:** Any power system must be able to balance demand and supply at any time. Apart from demand fluctuations, intermittent energy resources call for additional balancing energy. The magnitude of the balancing energy strongly depends on the wind energy penetration, time horizon, generation mix of power system and geographic distribution of wind power plants. Improved wind power forecasting systems, shortened gate closure, advanced reserves options (storage, demand-side management) can decrease the cost.
  - ▷ **Reserve capacity:** The penetration of intermittent generation increases uncertainty of system operators about generation availability, therefore additional reserve capacity is needed to back up a sudden loss of generation. Higher penetration and longer planning horizons imply a larger reserve capacity. Additional capacity represents a fixed cost per MWh for the power system (independent on energy production) for a certain level of installed wind capacity and market costs of reserve capacity.
  - ▷ **Network infrastructure:** As wind farms are built where the resources are, not the load centres, networks must be reinforced or extended to accommodate and transmit the power generation. The cost of infrastructure measures depends on wind penetration, power system capacity, level of existing interconnections.

Parameters for characterisation of the critical bottlenecks

Table 12 lists the parameters that try to describe the main bottlenecks in quantitative terms, where possible.

All parameters of the bottlenecks of the DER integration depend on (1) characteristics of power systems (generation mix, level of internal and external interconnections of electricity networks, requirements for DER interconnection and operational behaviour, etc.); (2) DER generation mix, installation capacity of each DER technology, its geographical distribution. Since both prerequisites for the determination of integration parameters (and thus setting up indicators) are very county-specific and technology-specific, it is hardly possible to generalise them to derive quantitative indicators.

Integration of DER is more than a technology. It is a set of measures (or concepts) required to adapt legacy power systems (being designed for the operation and management of large, centralised, controllable power plants) to accommodate a large number of small, distributed, intermittent generation sources without jeopardising the security of supply.

Table 12 – Parameters for characterisation of critical bottlenecks

Parameters of bottlenecks		Unit	2004	Target	Target year
Controllability					
Control system architecture			-	-	-
Information and communication system architecture			-	-	-
Regulatory and market framework			-	-	-
DER coordinated control system	Investment in innovative DER control solutions		-	-	-
Ancillary services markets	DER share in network ancillary services markets	%	-	-	-
Intermittency					
Accuracy of prediction systems	Root mean square error (wind power forecasting)[33]	%	7.18	6.06	2010
Penetration of intermittent generation	Ability of a power system to integrate intermittent energy resources	%	-	-	-
Energy reserve costs	Cost of extra generation reserve required to offset DER unpredictability	€/ MWh	-	-	-

Analysis of the critical indicators to further progress

In the following tables research measures to overcome the identified bottlenecks and critical indicators to further progress are identified. The table is structured in the same way as in the power storage techniques chapter. Please see page 60 for an introduction to the structure.

*Table 13 – Critical indicators to further progress – **Controllability***

Parameters of bottlenecks	Measures and critical indicators to further progress	Comments
Control system architecture	Improvement of intelligent local and central controllers	Local controllers are responsible for individual generation unit control, providing basic functions, such as self-protection, simple control of active and reactive power and advanced functions, such as island operation, anticipating disturbances. Central controllers should allow DER aggregators to take over some responsibilities of system operators, such as management of power flows and congestions, frequency controls, reactive power and voltage control, black start.
Information and communication system architecture	Development of information architecture	New architecture will facilitate data and communications exchange between controllers and power system actors. Controllers' software will also be developed monitoring, control and data management.
Regulatory and market framework	Improvement of market access and operation rules	This activity is aimed at offering market-related incentives to DER portfolio operators against the new advantages which these DER bring to network operators : - reduced emissions - distributed VAR control - network stability.

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[33] On the base of ISET Advanced Wind Power Prediction Tool results for German power system for day ahead (in % of installed wind turbines capacity).

Table 14 – Critical indicators to further progress – ***Intermittency***

Parameters of bottlenecks	Measures and critical indicators to further progress	Comments
Accuracy of prediction systems	Improvement of weather prediction models and forecasting of DER output from larger areas.	Wind power forecasting calculations are based on the input of weather forecasting, which still has a potential of improvement. For DER installed in large areas a self-balancing effect is valid, which reduces forecasting error.
Penetration of intermittent generation	Improvement of generation forecasting and controllability. Development of technical capabilities of DER.	Extended technical capabilities are required from DER units by network operators with increase of DER penetration. Such capabilities include the ability to operate at wide ranges of frequencies and voltages, provide frequency and voltage control, withstand short circuits, and contribute to system restoration.
Energy reserves	Improvement of generation forecasting, shortening gate closure time, advanced reserves options (storage, demand side management).	

Use of fossil fuels in power and heat generation, including carbon dioxide capture and storage

Use of fossil fuels in power and heat generation

Technologies

The market for large-scale fossil fuel-based power generation technologies is mature. There is a continuous striving to improve environmental performance and reduce costs for existing technologies and to develop competing technologies. An overview of fossil fuel-based power generation technologies is given in Table 1.

A major power generation technology is pulverised fuel combustion (PFC). Identified landmarks in improved technology are the supercritical, the ultra-supercritical and the pressurised versions of PFC, requiring further R&D. The natural gas combined cycle has a fast-growing market share, due to its superior environmental characteristics and competitive costs compared to other power generation technologies. Nevertheless, there is still a substantial improvement in terms of efficiency and costs expected, which require R&D efforts. No major R&D issues were identified for fluidised bed combustion technologies. It should be noted that these technologies will also benefit from any development of ultra-supercritical steam conditions for PFC plants. Pressurised fluidised bed combustion (PFBC) is believed to be more costly and complex and there is hardly any uptake in the European market. Co-combustion is considered to be a commercial technology, for which the current barriers for implementation are not in the technological field, but on the policy/permitting level. Chemical looping combustion is still at a laboratory-scale level.

Table 1 – State of the art of fossil fuel-based power generation technologies

Fossil fuel based power generation technologies	Integrated gasification combined cycle (IGCC) Pulverised fuel combustion (PFC) Atmospheric fluidised bed combustion (GT) Natural gas combined cycle (NGGC) Co-combustion (coal-biomass)	Air blown gasification cycle (ABGC) Supercritical PFC (FPC-SC) Pressurised fluidised bed combustion (PFBC) Fuel cells	Ultra supercritical PFC (PFC-USC) Pressurised PFC (PPFC) Chemical looping combustion (CLC)
	Commercial	**Demonstration**	**R&D**

Technical and socio-economic bottlenecks

The major technical and socio-economic bottlenecks of this technology cluster can be grouped into the following classes:

- **Security of supply:** power generation based on fossil fuels makes the electricity supply dependent on a source of energy which is decreasingly unavailable. From the point of view of security of supply this is not desirable, especially as in this way the European Union will become more and more dependent on the import of fossil fuels. Apart from a shift to renewable energy sources, an increase in **energy conversion efficiency** of fossil fuel-based power plants is also an important contribution to securing Europe's energy supply.
- **CO_2 emissions:** electricity generation based on fossil fuels results in large CO_2 emissions. An effective way of reducing the CO_2 emissions per kWh generated electricity is increasing

the **energy conversion efficiency** of the power generation. **A fuel shift** to fuels with lower carbon levels or a shift to renewable energy sources are also effective measures in reducing CO_2 emissions. An alternative way of reducing CO_2 emissions resulting from fossil fuel-based power generation is the **capture and storage of CO_2**. This technology is discussed in a separate section of this report beginning at page 85

- **Environmental performance:** emission standards need to be met in order to get a permit for a power plant. Emissions of NO_x, SO_2 and particulate matter from conventional coal-fired PFC power plants are relatively high and therefore a point of attention.
- **Cost:** for the relatively new technology for integrated gasifier combined cycles, which is being introduced to the market and which offer low emissions to air and potentially high efficiency compared to conventional coal-fired power generation, costs (capital costs and O&M costs) need to be reduced to allow further penetration into the market.

Parameters for characterisation of the critical bottlenecks

In the previous chapter, efficiency has been stated to be the most important quantitative parameter characterising and influencing the bottlenecks security of supply and emissions. The following table gives an overview throughout the single technologies. Electricity cost and emissions are also given.

Table 2 – Quantitative parameters for characterisation of critical bottlenecks [Lako, 2004; Ecofys, 2004]

Parameters	Unit	2000	> 15 years
PFC / PFC-USC [1,2]			
Efficiency	%	47	52
CO_2-emissions [a]	g/kWh el.	201	181
NO_x-emissions [b]	g/kWh el.	1.2	1.2
SO_2-emissions [c]	g/kWh el.	0.60	0.53
IGCC			
Capital cost	(€$_{2000}$/kW)	1400	994
O&M cost	(€$_{2000}$/kW)	71	51
Efficiency	%	45	52
Efficiency with higher inlet temperature	%	48	52
CO_2-emissions [a]	g/kWh el.	205	181
CO_2-emissions with higher inlet temperature[a]	g/kWh el.	196	-
NO_x-emissions [b]	g/kWh el.	0.4	0.4
SO_2-emissions [c]	g/kWh el.	0.06	0.05
NGCC			
Efficiency	%	56	60
CO_2-emissions [a]	g/kWh el.	98	92

[a] based on 96 g CO_2/GJ-coal and 56 g CO_2/GJ-NG

[b] based on low-NO_x burners

[c] based on 1% sulphur content and LHV of 26.5 GJ/tonne

Analysis of the critical indicators to further progress

In order to coordinate R&D activities it is necessary to know which specific measures will contribute to improve the identified bottlenecks. In the following table these measures are listed and explained. Critical indicators to further progress are given, wherever possible (see yellow tables). Measures and indicators are allocated to the corresponding bottleneck parameters. The tables also indicate at which technology component research activity has to take place. Only the most important and most promising measures and indicators are presented in the tables.

Table 3 – Critical indicators to further progress – ***Pulverised Fuel Combustion (PFC)***

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td></td><td>Efficiency</td><td colspan="2">The efficiency of a PFC power plant is mainly determined by the efficiencies of the steam cycle and boiler.
Efficiencies of side aggregates and plant integration also play an important role in the overall power plant efficiency.</td></tr>
<tr><td>Steam cycle</td><td>Efficiency
(ultra supercritical steam conditions)</td><td>Increase of temperature and pressure
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>temperature [°C]</td><td>600-620</td><td>700-760</td><td>< 2010</td></tr>
<tr><td>pressure [bar]</td><td>300</td><td>350-375</td><td>< 2010</td></tr>
</table>
(source: AGO 2000, US-DOE 2004)
<table>
<tr><th></th><th>1970</th><th>2000</th><th>2010</th></tr>
<tr><td>efficiency [%]</td><td>36</td><td>45</td><td>50</td></tr>
<tr><td>steam temp. [°C]</td><td>540</td><td>600</td><td>700</td></tr>
</table>
Development of efficiency and steam temperature (PFC-power plant)
(source: PowerClean 2004)</td><td>The development of conventional sub critical PFC plant to supercritical and ultra-supercritical PFC plant implies the application of higher steam temperatures and pressures. Material development is key, particularly the development of new nickel-based alloys and the improvement of the manufacturability of the alloys.</td></tr>
<tr><td>Steam cycle</td><td>Efficiency</td><td>Use one or two steam reheat processes</td><td>Single reheat of steam cycle with conditions of 25 MPa, 560/560°C gives an efficiency of over 45% LHV basis (already in operation). Double reheat of steam cycle with conditions of 28.5 MPa, 580/580/580°C gives an efficiency of over 47% LHV basis [AGO (2000)]. The double reheat cycle has been stated to add 6% to the capital cost of the power plant.</td></tr>
<tr><td>Steam turbine</td><td>Efficiency</td><td>Improvement of turbine blading shape</td><td>Improvements in turbine blading shape can result in a turbine efficiency improvement of 0.4-2% [AGO (2000), DUT (2000)]</td></tr>
</table>

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>Boiler</td><td>Efficiency</td><td>Improvement of design</td><td>Horizontal furnace design with internally rifled vertical furnace pipes allows for lower construction costs (vertical low-mass-flux once-through boiler with horizontal furnace developed by Siemens) [PowerClean (2004)]</td></tr>
<tr><td>Boiler</td><td>Efficiency</td><td>Decrease of flue gas temperature</td><td>By lowering the temperature of the flue gas, less heat is lost resulting in a higher efficiency. Limit of the lowest level of the final flue gas temperature is the corrosion of downstream components. The final flue gas temperature can be lowered by the inclusion of extra heating surface area in the boiler, usually in the air heater. For every 10°C decrease in final flue gas temperature an efficiency increase of the boiler of 0.5 - 1% can be achieved [AGO (2000)].</td></tr>
<tr><td>System</td><td>NO_x-emissions</td><td>Reduction of NO_x-emissions
<table>
<tr><th>Combustion modification % NO_x reduction</th><th></th></tr>
<tr><td>• low NO_x burner</td><td>30-70%</td></tr>
<tr><td>• furnace air-staging</td><td>20-40%</td></tr>
<tr><td>• item 1 and 2 combined</td><td>50-60%</td></tr>
<tr><td>• reburn</td><td>50-60%</td></tr>
<tr><td>• item 1 and 4 combined</td><td>70%</td></tr>
<tr><th>Flue gas treatment % NO_x reduction</th><th></th></tr>
<tr><td>SNCR</td><td>30-50%</td></tr>
<tr><td>SCR</td><td>80-90%</td></tr>
</table>
(source: DTI 1999)</td><td>NO_x emissions can be reduced by integrated (combustion modification) and add-on (flue gas treatment) technologies.
Low-NO_x burners and furnace air staging have been employed in hundreds of plants world-wide. Furnace fuel staging (reburn) is still in demonstration phase. Existent research aims at improving low-NO_x burners and developing furnace fuel staging.
Flue gas treatment technologies selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) are commercially available. SCR has been applied in Japan and Germany to meet stringent NO_x emission limits.</td></tr>
</table>

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>System</td><td>So$_2$ emissions</td><td>Reduction of SO$_2$-emissions
<table>
<tr><td>flue gas desulphurisation technology</td><td>2004</td></tr>
<tr><td>add-on</td><td></td></tr>
<tr><td>SO$_2$-reduction regenerable FGD [%]</td><td>> 95</td></tr>
<tr><td>SO$_2$-reduction non-regenerable FGD [%]</td><td>> 95</td></tr>
</table>
(source: IEA 1999)</td><td>SO$_2$ emissions can be reduced by integrated technologies (reducing the sulphur content by coal preparation, coal gas desulphurisation) and add-on (flue gas desulphurisation, FGD) technologies.
Two main FGD technologies exist: regenerable FGD and non-regenerable FGD. Most coal-fired plants have been equipped with non-regenerable FGD, of which wet scrubbing is the most common.</td></tr>
<tr><td>System</td><td>Particular matter emissions</td><td>Reduction of particular matter (PM) emissions
<table>
<tr><td>flue gas desulphurisation technology</td><td>2004</td></tr>
<tr><td>add-on</td><td></td></tr>
<tr><td>PM reduction, electrostatic precipitators (ESP) [%]</td><td>> 99.5</td></tr>
<tr><td>PM reduction fabric filters (baghouses) [%]</td><td>> 99.9</td></tr>
</table>
(source: IEA 1999)</td><td></td></tr>
</table>

Table 4 – Critical indicators to further progress – **Integrated Gasification Combined Cycle (IGCC)**

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
System	Capital cost	Integration of components	Integration has the advantage of improving efficiency, but may increase the complexity of the process
System	Costs	Improve reliability and availability of the plant (availability of IGCC plant in Buggenum, NL increased from 4 000 in 1997, to 7 000 in 2004)	Reduction of complexity of the plant and 'learning-by-doing' reduces plant failures
Gasifier	Capital cost	Gasifier component development, including improved materials for refractories and heat recovery steam generators (HRSGs), and improved feeding and handling systems	
Air separation units	Capital cost	Reduction of air separation units cost	

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>Gas Turbine</td><td>Efficiency</td><td>Increase of turbine inlet temperature and improvement of heat recovery steam generator and steam cycle
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>inlet temperature [°C]</td><td>1200</td><td>1400</td><td>< 2015</td></tr>
<tr><td>efficiency [%]</td><td>48</td><td>52</td><td>2020</td></tr>
<tr><td>CO_2 emissions [g/kWh]</td><td>196</td><td>181</td><td>2020</td></tr>
</table>
(source: PowerClean 2004; Ecofys 2004)</td><td>Studies under FP4 showed that the design efficiency of 45% of the Puertollano IGCC could be increased up to 48% by increasing the turbine inlet temperature (from 1120°C to 1250°C) and by improving the heat recovery steam generator and steam cycle. Modelling the benefits of a major system redesign showed that 51.5% is achievable (IGCC98).</td></tr>
<tr><td>Gasifier</td><td>Efficiency</td><td>Increase of fuel gas temperature and development of dry high temperature gas cleaning</td><td></td></tr>
<tr><td>Steam cycle</td><td>Efficiency</td><td>Establishment of supercritical steam conditions</td><td></td></tr>
<tr><td>Air separation units</td><td>Efficiency</td><td>Development of ion-electron conducting membranes using non-porous ceramic membranes, and advanced cryogenic processes
<table>
<tr><th></th><th>2004</th><th>target</th><th>target year</th></tr>
<tr><td>energy requirement [kWh/tO_2]</td><td>235</td><td>150</td><td>2010</td></tr>
</table></td><td>Reduction of energy requirement of oxygen separation includes ion-electron conducting membranes using non-porous ceramic membranes, and advanced cryogenic processes. New inorganic membrane-based systems may reduce the energy requirement for cryogenic separation from 235 kWh/ton O_2 to less than 150 kWh/ton O_2. For an IGCC this implies an increase of efficiency of more than 3%-points [Ecofys (2004), Stein (2001)]</td></tr>
<tr><td>System</td><td>Emissions</td><td>Development of gas turbine combustion systems, which can use hydrogen as a fuel.</td><td>The development of zero emission IGCC power plants based on pre-combustion carbon capture requires the development of gas turbine combustion systems, which can use hydrogen as a fuel.</td></tr>
</table>

Table 5 – Critical indicators to further progress –
Gas-fired Power Generation Technologies (NGCC)

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Gas turbine	Efficiency	Increase of turbine inlet temperature and development of new materials allowing higher temperatures	
Gas turbine	Efficiency	Optimisation of compressor design, increase of polytrophic efficiency	
Gas turbine	Efficiency	Improvement in turbine blading shape (among others by using 3D modelling instead of today's 2D modelling)	
Steam cycle	Efficiency	Improvements in turbine blading shape	

Table 6 – Critical indicators to further progress – **Chemical Looping Combustion (CLC)**

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
System		CLC principle is to stage traditional combustion into two separate reaction phases, thus CLC can result in a direct concentration of CO_2 during its formation. CLC is still in an early stage of development. To take this technology forward, reactor concepts and stable reactive materials at acceptable costs must be developed.	
System	Efficiency/ costs	Reactivity	Development of oxygen-carrier particles of sufficient reactivity and lifetime
System	Costs	Loss of fines, i.e. small particles	
System	Efficiency	Reactor concept	
System	Security of supply	Applicability to multiple fuels	The most suitable fuels are natural gas and coal, but in principle biomass is also applicable.

Carbon dioxide capture and storage

Technologies

The demand for R&D is determined by improvement of the performance of existing separation technologies (reduced energy need and capital) and development of novel competitive separation techniques. In post-combustion techniques (separation of carbon dioxide from flue gases), the main challenge is to adapt existing processes to specific requirements (i.e. to scale, temperature and flue gas conditions). Pre-combustion techniques are associated with hydrogen production and CO_2 separation from high-concentrate, high-pressure gases. R&D in pre-combustion is needed to integrate existing technology in power production and to improve the overall performance. Denitrogenated conversion (also called oxy-fuel techniques) is a novel approach in which oxygen is separated from air and used in combustion to generate gases with a high concentration of CO_2 avoiding the need for further separation. The demand for R&D for this kind of technology is on a more fundamental level.

An overview of carbon capture technologies is given in Table 7 whereas Table 8 provides an overview of carbon storage technologies.

Table 7 – State of the art of carbon capture technologies

Post-combustion	Absorption (MEA)		Absorption (improved solvents, improved technologies)
Pre-combustion	Absorption (MDEA, Selexol, Rectisol)		Absorption (improved solvents, membranes) H_2 combustion technology
Denitrogenated conversion	O_2 production (cryogenic distillation, PSA)		O_2/CO_2 combustion technology; CLC
	Commercial	**Demonstration**	**R&D**

Table 8 – State of the art of carbon storage technologies

Carbon storage technologies	Enhanced oil recovery (mainly in USA)	Deep saline reservoir	EOR (combined with storage) Depleted oil field Depleted gas field Unmineable coal beds / ECBM Enhanced gas recovery Deep ocean Mineralisation
	Commercial	**Demonstration**	**R&D**

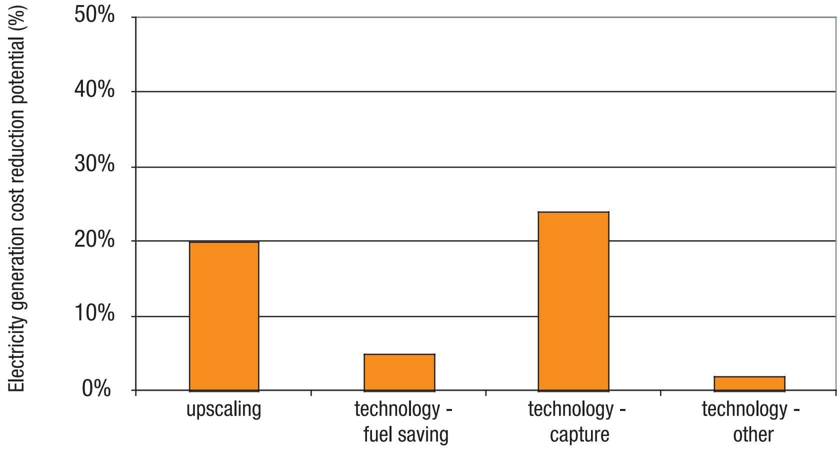
Technical and socio-economic bottlenecks

The major technical and socio-economic bottlenecks of this technology cluster can be grouped into the following four main classes:

- **Costs of carbon capture and storage:** Carbon capture and storage from power plants adds significantly to the total electricity cost and is therefore seen as the most important bottleneck. The costs of carbon capture and storage are made up by the costs for capture, compression, transport and storage. The costs are related to capital and O&M costs as well as to the production of extra electricity needed for capture and storage. Estimated cost increases for carbon capture and storage to electricity production costs vary from 1.5 €ct/kWh (NGCC) to 3.0 €ct/kWh (coal-fired PFC). Electricity production costs for natural gas-based technologies are dominated by the fuel price, whereas costs for coal-based technologies are dominated by plant investment costs. The cost increase for carbon capture and storage to electricity production costs amounts to 60-70% in case of NGCC and IGCC plants and 80% in case of coal-fired PFC plants. There exists a high potential of cost reduction for carbon capture and storage as it is still a very new technology and considerable room for improvement exists. Especially the costs of carbon capture and the fuel costs related to the energy consumption of carbon capture leave room for further improvements. The potentials for cost reduction of carbon capture and storage are shown in Figure 1.
- **Energy requirement of carbon capture:** existing CO_2 capture technologies require a lot of energy, therefore significantly reducing the overall **energy conversion efficiency** of a power plant equipped with carbon capture and storage. The most widely-used CO_2 capture technology is absorption of carbon dioxide from flue gases by monoethanolamine (MEA). The disadvantages of capture using MEA are high costs and the high need for energy for the regeneration of the solvent. Compression of captured CO_2 also involves a relatively significant amount of energy. Pre-combustion techniques are generally believed to be more energy-efficient than post-combustion techniques, but further R&D is required on this issue.

- **Public acceptance:** the technology of carbon capture and storage is still largely unknown to the public. **Demonstration projects**, which show the feasibility of long-term CO_2 storage, are needed to support **dissemination** of the technology to the public. Thorough **monitoring** of these projects has to prove that the technology is safe and reliable and that no leakage of CO_2 occurs (or only at acceptable low levels).
- **Legal framework:** currently a legal framework for carbon capture and storage is lacking, and needs to be put in place. Among other aspects, the **liability** of carbon storage needs to be addressed.

Figure 1 – Long-term (2050) cost reduction potentials of carbon capture and storage



Source: calculation Ecofys

Parameters for characterisation of the critical bottlenecks

Table 9 gives an overview of the quantitative parameters describing the main bottlenecks for the introduction of the technology. State of the art and values at different time horizons are given.

Table 9 – Quantitative parameters for characterisation of critical bottlenecks

Parameters	Unit	2000 [a]	5 years	10 years	> 15 years
Pre-combustion, Selexol (IGCC)					
Cost increase of electricity generation due to carbon capture and storage	c/kWh	2,3	-	-	-
El. efficiency loss by CO_2 capture	%	8,2	-	-	6.6
Post-combustion, MEA (Coal-PF)					
Cost increase of electricity generation due to carbon capture and storage	c/kWh	3	-	-	
El. efficiency loss by CO_2 capture	%	11.6	-	-	9.3
Post-combustion, MEA (NGCC)					
Cost increase of electricity generation due to carbon capture and storage	c/kWh	1.5	-	-	
El. efficiency loss by CO_2 capture	%	7.1	-	-	6.1
Denitrogenated conversion, PSA					
Cost increase of electricity generation due to carbon capture and storage	c/kWh	n.a.	n.a.	n.a.	n.a.
El efficiency loss by CO_2 capture	%	n.a.	n.a	n.a.	n.a

Source: Ecofys 2003; Ecofys 2004

[a] Costs estimates based on studies (not valid for first-in-its-kind plant)

Analysis of the critical indicators to further progress

In order to coordinate R&D activities it is necessary to know which specific R&D measures will contribute to improve the identified bottlenecks and which indicators are important to monitor progress. The following tables list these specific measures and indicators. They are allocated to the corresponding bottleneck parameters. The table also indicates at which technology component research activity has to take place. The list does not contain all possible improvement measures and indicators, but only the most important and most promising ones. The information is mainly based on interviews with technology providers or research institutes.

Table 10 – Critical indicators to further progress – ***Post-combustion capture***

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>System</td><td>Cost increase</td><td>Development of cheaper CO_2 capture technologies
<table>
<tr><th></th><th>2000</th><th>2020</th><th>2050</th></tr>
<tr><td>Investment cost PFC-USC [€/kW]</td><td>680</td><td>544</td><td>340</td></tr>
<tr><td>Investment cost NGCC [€/kW]</td><td>360</td><td>288</td><td>180</td></tr>
</table>
(source: Ecofys 2004)</td><td>E.g. absorption solvent containing more CO_2 per g solvent, improved reactor design, reduction of loss and degradation of absorbing solvent, and learning by doing.</td></tr>
<tr><td>System</td><td>Efficiency loss</td><td>Development of less energy-intensive CO_2 capture technologies (e.g. absorption solvent which is easier to regenerate at lower temperatures)
Reduction of electric efficiency loss and improvement of capture efficiency of carbon capture
<table>
<tr><th>PFC-USC</th><th>2000</th><th>2020</th><th>2050</th></tr>
<tr><td>el. efficiency loss [%]</td><td>11.6</td><td>9.33</td><td>5.8</td></tr>
<tr><td>capture efficiency [%]</td><td>85</td><td>90</td><td>95</td></tr>
</table>
(source: Ecofys 2004)
<table>
<tr><th>NGCC</th><th>2000</th><th>2020</th><th>2050</th></tr>
<tr><td>el. efficiency loss [%]</td><td>7.1</td><td>6.1</td><td>4.6</td></tr>
<tr><td>capture efficiency [%]</td><td>85</td><td>90</td><td>95</td></tr>
</table>
(source: Ecofys 2004)</td><td>Higher capture efficiencies lead to higher energy requirements. However it is expected that in the future it will be possible to decrease electric efficiency loss, while capture efficiency increases as well.</td></tr>
</table>

*Table 11 – Critical indicators to further progress – **Pre-combustion capture***

<table>
<tr><th>Technology component</th><th>Parameters of bottlenecks</th><th>Critical indicators to further progress</th><th>Comments</th></tr>
<tr><td>System</td><td>Cost increase</td><td>Development of cheaper CO_2 capture technologies
<table>
<tr><th>[€/kW]</th><th>2000</th><th>2020</th><th>2050</th></tr>
<tr><td>Investment cost IGCC</td><td>620</td><td>496</td><td>310</td></tr>
<tr><td>Investment cost NGCC</td><td>350</td><td>280</td><td>200</td></tr>
</table>
(source: Ecofys 2004)</td><td>E.g. absorption solvent containing more CO_2 per g solvent, improved reactor design</td></tr>
<tr><td>System</td><td>Efficiency loss</td><td>Development of improved and less energy-intensive CO_2 capture technologies.
Reduction of electric efficiency loss and improvement of capture efficiency of carbon capture [Ecofys (2004)]:
<table>
<tr><th>IGCC</th><th>2000</th><th>2020</th><th>2050</th></tr>
<tr><td>capture efficiency [%]</td><td>85%</td><td>90%</td><td>95%</td></tr>
<tr><td>el. efficiency loss IGCC [%]</td><td>8.2%</td><td>6.6%</td><td>4.1%</td></tr>
<tr><td>el. efficiency loss NGCC [%]</td><td>9%</td><td>7.5%</td><td>4.5%</td></tr>
</table>
(source: Ecofys 2004)</td><td>For instance by better heat integration, improved catalyst for fuel conversion, and development of membrane separation.</td></tr>
</table>

*Table 12 – Critical indicators to further progress – **Denitrogenated conversion***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Oxyfuel	Efficiency loss/ cost increase	Reduction of electric efficiency loss (%) of carbon capture and reduce costs of total system (avoiding air separation unit)	The use of oxygen transfer membranes provides the opportunity to perform combustion of fuels in absence of nitrogen. The technology is the core of AZEP (advanced zero emission power plant).

*Table 13 – Critical indicators to further progress – **Storage of carbon dioxide***

Technology component	Parameters of bottlenecks	Critical indicators to further progress	Comments
Storage	Retention time	Leakage rate in percentage per year of stored carbon dioxide	Acceptable leakage rate is under discussion and is related to the need for how long the stored carbon dioxide must stay out of the atmosphere

Generic cross-cutting and horizontal technologies

General

Innovative technologies for the generation, storage and distribution of energy originate from a heterogeneous technological field. Among them are nanotechnology and biotechnology. Different scientific disciplines such as engineering sciences, computer science, life sciences and material sciences have to be combined for further development, and industrial applications have a long-term perspective. Due to this early stage of development little data is available for commercial evaluation. With a time horizon of 15 to 30 years for commercial application the focus has to be to identify bottlenecks within the process in order to shape research process towards efficient industrial use.

Innovative biotechnologies

Introduction

Biotechnological processes can be applied for the production of energy sources from various raw materials and sources. Established processes use biomass in order to generate hydrogen, ethanol, methanol, and acetone with butanol and ethanol (ABE). The processes listed below for the examples of ethanol and ABE characterise key issues for future industrial commercialisation of innovative advancement. Procedural details are outlined in the section ‘hydrogen and fuel cell technologies’ and the section ‘biomass’. Innovative process optimisation focuses on the use of cheaper carbon sources and aim on the improvement of strains and strain metabolism by genetic engineering. A third area for innovation is the improved efficiency of product recovery.

Biogas and biomass for energy generation employ biotechnological techniques as well, however at present there are few efforts for high-tech improvement. Thus these techniques are solely discussed in the section ‘biomass’.

A future trend of innovative biotechnology offers the application of photosynthesis for energy generation. At present this process is pure basic research. According to experts industrial applications are expected to have a long-term perspective for commercialisation. The chapter will outline underlying principles and trends towards industrial application.

Indicators for the evaluation of innovative biotechnologies

Innovative biotechnological processes for energy generation such as hydrogen production and light utilisation via artificial photosynthesis share a number of bottlenecks with already established biotechnological processes such as ethanol production. For future industrial application the following aspects must be improved:

- stability of process (e.g. biological contamination, strain degeneration)
- end product and by-product inhibition of metabolic pathway
- share of desired end product of all metabolic products and/or high quality usability of by-products
- production costs of biotechnological products compared to petrochemical products, mostly influenced by required carbon source (e.g. glucose, molasses, starch, lignocelluloses, liquid waste material, solid waste material)
- operating costs of production plant (e.g. for water, steam, electrical power, additives (vitamins, trace elements)

- costs and practicability of downstream processing/product recovery compared to petrochemical processes
- willingness and availability of human resources to conduct biotechnological processes.
- frame conditions for biological processes (e.g. threshold of air and water pollution, CO_2 emission).

Table 1 summarises the bottlenecks for selected processes. The subsequent chapters in this report describe these processes in more detail by an analysis of the present state of the art, future perspectives, and key issues for improvement.

Table 1 – Most critical bottlenecks for the industrial commercialisation of innovative biotechnological processes

<table>
<tr><th>Process</th><th>Bottleneck</th><th colspan="3">Critical indicators to further progress</th><th>Time horizon</th></tr>
<tr><td rowspan="3">Hydrogen production</td><td rowspan="3">Low activity of the key enzymes hydrogenase and nitrogenase</td><td colspan="3">1. genetic engineering of producer strain
• increase of specific activity of key enzymes
• inactivation of competing metabolic pathways
2. development of cell-free systems</td><td>Long term</td></tr>
<tr><td></td><td>Today</td><td>Aim</td><td rowspan="2">Middle term</td></tr>
<tr><td>process efficiency</td><td>5%</td><td>10%</td></tr>
<tr><td></td><td>Supply with adequate amount of organic compounds</td><td colspan="3">process development for various substrates (e.g. adjustment of process to utilise waste water)</td><td>Middle term</td></tr>
<tr><td></td><td>Disposal of fermentative by-products</td><td colspan="3">1. process development with mixed cultures for the complete conversion into CO_2 and H_2
2. extension of substrate specificity of one organism by genetic engineering</td><td>Middle term
Long term</td></tr>
<tr><td rowspan="6">Ethanol production</td><td rowspan="6">Expensive carbon source</td><td colspan="3">1. genetic engineering of producer strain to grow on lignocelluloses
• integration of cellulase genes into ethanol producing bacteria (e.g. E. coli)
• integration of ethanol metabolism into plant pathogenic micro-organisms (e.g. *Erwinia*)</td><td rowspan="6">Long term
Short term</td></tr>
<tr><td></td><td>Today</td><td>Aim</td></tr>
<tr><td>Ethanol recovery rate on lignocelluloses</td><td>> 90% (dependent on substrate)</td><td>90–95%</td></tr>
<tr><td colspan="3">2. development of two-stepped process with an extra cellular hydrolysis of cellulose followed by fermentation</td></tr>
<tr><td></td><td>Today</td><td>Aim</td></tr>
<tr><td>Enzyme costs</td><td>0.18 US$ /l Ethanol</td><td>0.018 US$ /l Ethanol</td></tr>
</table>

<table>
<tr><th>Process</th><th>Bottleneck</th><th colspan="4">Critical indicators to further progress</th><th>Time horizon</th></tr>
<tr><td></td><td>Inhibition by side products</td><td colspan="4">1. development of biological, physical or chemical processes for detoxification
2. development of side product tolerant production strains by genetic engineering</td><td>Short term
Long term</td></tr>
<tr><td></td><td></td><td></td><td>Today</td><td>2007</td><td>Aim</td><td></td></tr>
<tr><td></td><td></td><td>ethanol production costs</td><td>0.32 US$/l EtOH</td><td>0.26 US$/l EtOH</td><td>> 0.21 US$ /lEtOH</td><td></td></tr>
<tr><td>ABE production</td><td>Strain degeneration</td><td colspan="4">Determination of gene localisation and stable integration of desired gene into the genome</td><td>Middle term</td></tr>
<tr><td></td><td>Expensive carbon source</td><td colspan="4">1. genetic engineering of producer strain to grow on lignocelluloses
2. recycling of fermentation broth</td><td>Long term</td></tr>
<tr><td></td><td></td><td colspan="2"></td><td>Today</td><td>Aim</td><td></td></tr>
<tr><td></td><td></td><td colspan="2">Butanol production costs</td><td>0.55 US $/kg butanol</td><td>> 0.44 US $ /kg butanol</td><td></td></tr>
<tr><td></td><td>Expensive product recovery</td><td colspan="4">Development of more efficient methods for product recovery such as nanofiltration</td><td>Middle term</td></tr>
<tr><td>Photo-synthesis</td><td>Short durability</td><td colspan="4">Development of processes that allow flushing cells with fresh protein solution</td><td>Long term</td></tr>
<tr><td></td><td>Low efficiency</td><td colspan="4">Development of thicker protein layers</td><td>Long term</td></tr>
<tr><td></td><td></td><td colspan="2"></td><td>Today</td><td>Aim</td><td></td></tr>
<tr><td></td><td></td><td colspan="2">Efficiency</td><td>1%</td><td>20%</td><td></td></tr>
<tr><td>All iotechno-logical processes</td><td>Human resources in traditional chemical industry lack qualifications for the introduction of biotechnological processes</td><td colspan="4">1. special advanced courses for technicians
2. integration of biotechnology into existing curricula</td><td>Short term
Middle term</td></tr>
<tr><td></td><td>Regulations and frame conditions often favour petrochemical alternatives</td><td colspan="4">1. compulsory cost calculation that includes environmental effects
2. subsidies for environmental-friendly energy sources to be retained and/or extended</td><td>Short term
Short to middle term</td></tr>
</table>

Hydrogen

Present state of the art

Three different metabolic principles can be applied for biological hydrogen production. All are in the status of basic research. Industrial application is expected for 2030–2040 (Cammack 2001).

Table 2 – Characteristics of three types of biological hydrogen production

Type	Metabolism	Organisms	Light required	Electron donor	Products
Biophotolytic hydrogen generation	Oxygenic photosynthesis	Green algae, cyanobacteria	Yes	Water	Hydrogen, oxygen
Photoproduction of hydrogen	Anoxygenic photosynthesis	Phototrophic bacteria	Yes	Organic compounds or reduced sulphur compounds	Hydrogen, CO_2, oxidised sulphur compounds
Fermentative hydrogen production from biomass	Fermentation	Fermenting bacteria	No	Organic compounds	Hydrogen, CO_2, organic compounds

Source: Reiß and Hüsing 1993

Future perspectives

- Biophotolytic hydrogen generation is an ideal type of biological hydrogen generation. However low efficiency is due to the complex regulation of the key enzymes hydrogenase and nitrogenase. The production strain may be optimised by genetic engineering (e.g. increase of specific activity of hydrogen producing enzymes, inactivation of competing metabolic pathways) or the development of cell-free systems.
- Coupling of photoproduction and fermentation with waste-water treatment, as organic compounds are required as electron donors.
- Development of strategies for the integrated use of substrate and fermentation product.
- Development of bioelectronic fuel cells.

Key issues for hydrogen

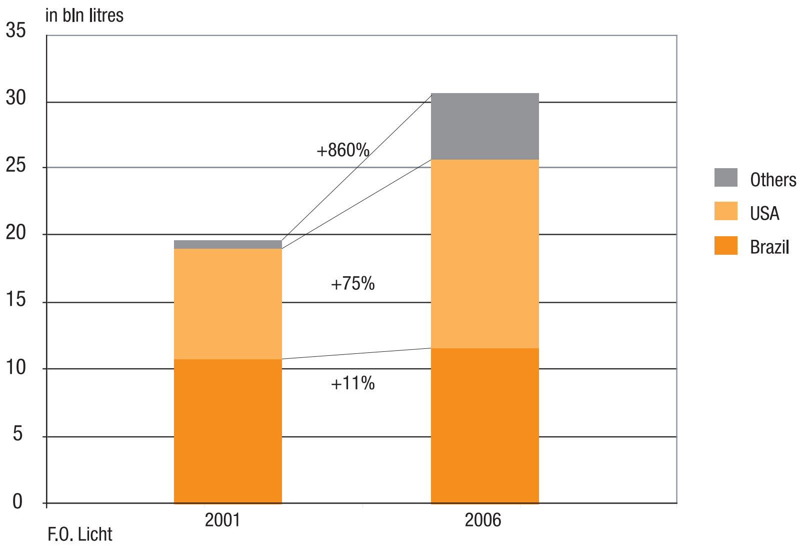
- Increase of efficiency of the process towards the theoretical maximum (the present degree of efficiency is 5%, the desirable degree for economic competitiveness is 10%) (Jaeckel et al.1993)
- Increase of the long-term stability of the process
- Development of a concept for commercial production plant including ecological supply with substrates, water, nutrients and use of resulting biomass. Previous experience has been gained solely from laboratory-scale work.

Ethanol

Present state of the art

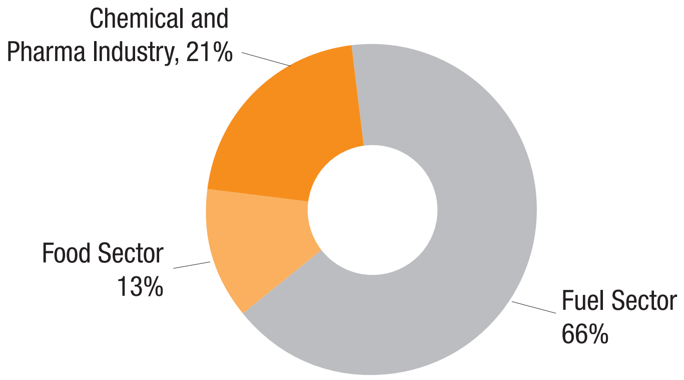
- 31 million m^3 ethanol produced worldwide per annum, more than 90% of world ethanol production is produced by fermentation. The USA produces 65% of worldwide production.
- Increase by over 40% is expected until 2006 due to extension of bioethanol programmes and specific regulations (e.g. EU directive for gasoline blends).
- Two-thirds of global ethanol production is used for the fuel sector.

Figure 1 – World fuel ethanol production 2001 v. 2006



F.O. Licht

Figure 2 – Sector-specific use of ethanol



- Established processes use sugars from sugar cane, sugar beet, corn and potatoes. Fermentation is generally carried out in large-volume fermenters by yeast fermentation followed by distillation for removal of the desired product. Production costs are in the range of 0.85–1.20 €/l, with 0.24–0.32 €/l for raw material (Schmitz 2004).
- At present basic research is carried out for fermentation of lignocelluloses as a cheaper raw material, which will reduce ethanol production costs by 15 cent/l. This process requires combination of mechanical disintegration, sulphuric acid hydrolysis, enzymatic hydrolysis by cellulases for the conversion of carbohydrates into monomeric sugars.

Future perspectives

- New (transgenic) production organisms will allow the fermentation of ethanol from lignocelluloses (e.g. *E. coli, Klebsiella oxytoca, Zymomonas mobilis*). An economically sustainable process requires conversion rates of 90-95% of the sugar used into ethanol.
- Integration of the cellulose-hydrolysis into the ethanol production stage either by integration of ethanol biosynthesis into plant pathogenic bacteria (*Erwinia*) with a volumetric productivity of 1.5 g ethanol l^{-1} h^{-1} or integration of cellulase genes into ethanol producing *E. coli.*

- Development of measures for detoxification of (phenolic) by-products by biological treatment with laccase or fungi, chemical treatment (precipitation), or physical treatment (extraction, ion exchange) or development by-product tolerant production strains.

Key issues for ethanol

- Cost-efficient hydrolysis of lignocelluloses into fermentable sugars without formation of inhibiting substances (at present production costs of bioethanol are calculated at approx. 0.3 €/l of ethanol, competitiveness to fuel on crude oil basis is reached if production costs of ethanol are below 0.18 €/l.
- Complete fermentation of all sugars (hexoses and pentoses) into ethanol, avoidance of by-products (e.g. glycerine, succinate)
- Avoidance of contamination
- Minimisation of number of process steps
- Use of by-products
- Substrate diversification for year-round production-processes.

Acetone with butanol and ethanol (ABE)

Present state of the art

- Fermentative production of acetone with butanol and ethanol (ABE) was of industrial importance in the first half of the 20th century. Now it has lost economic competitiveness in comparison to petrochemical processes.
- National importance under certain economic niche strategies may be possible (e.g. China).
- Basic research with *Chlostridium acetobutylicum* in order to elucidate regulative processes.
- Traditional ABE-fermentation is a strict anaerobic batch process with molasses, corn and potato mash as a carbon source. The process has to be sterile as it is prone to contamination. After the initial growth phase solventogenesis is induced at transition to a stationary phase. Final product concentrations reach 20 g/l (ratio 3:6:1 for acetone:butanol:ethanol) with a maximum of 12 g/l of butanol due to its toxicity.
- Increase in end product concentration is possible by specific mutants of *Clostridium beijerininckii* with productivity of 33 g/l ABE (ratio 3:16:1) (Qureshi 2001).
- Downstream processing and end product recovery is carried out by distillation.

Future perspectives

- Development of production strains that maintain their capability of solventogenesis for an unlimited number of cultivation passages. Knowledge of organisation and localisation of genes involved in solventogenesis will allow the generation of stable strains by genetic engineering.
- Development of efficient measures to avoid phage contamination either by improved fermentation technologies or by development of phage-resistant strains (phage immunisation)
- Optimisation of product recovery by distillation, nanofiltration
- Recycling of remaining fermentation broth (contains butyrate, acetate, non recovered butanol, biomass, formiate, lactate) as substrate for further fermentation such as biotechnological production of polyhydroxyalcanoate (PHA). As concentrations are low measures to concentrate the broth have to be developed (Parrer et al. 2000).

Key issues for ABE

- Decrease of production costs by industrial development of cheaper and easily available raw material
- Development of energy-efficient downstream processing for cost-saving product recovery
- Improvement of long-term process stability and reproductivity (e.g. avoidance of phage contamination and degeneration of production strain)
- Approximation of practical process towards theoretical limits of yield and end product concentration
- Complete and high-grade usage of all fermentation products.

Photosynthesis

Present state of the art

- Principle: photosynthetic proteins (approximately 2 billion) from spinach and the bacterium Rhodobacter sphaeroides are harvested and deposited onto a glass support The glass substrate is coated with indium tin oxide as transparent electrode. The proteins are embedded in a synthetic membrane and covered with a soft layer of organic semiconductor. This is topped with a silver electrode (Rupa et al. 2004).
- Durability: 3 weeks
- Efficiency: 1% (conventional silicon cells 20%), expected efficiency: 20 to 30%
- Major problem: light goes straight through the device, as protein layer is too thin.

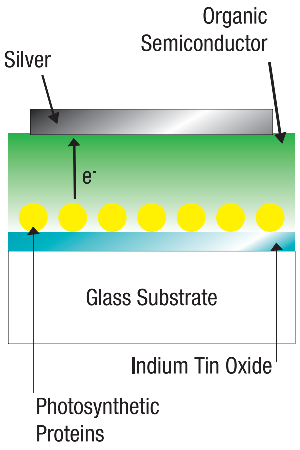
Future perspectives

- Longer-lasting photovoltaic cells, from self-repairing proteins and by flushing the cell with fresh protein solution
- Cheaper and environment-friendly production of biological cells (Baldo, personal communication 2004).

Key issues for photosynthesis

- Number of proteins to be packed into the device in order to increase the power output, as efficiency of biological solar cells is too small compared to conventional silicon solar cells.
- Durableness of biological solar cells is still too short compared to conventional silicon solar cells.

Figure 3 – Artificial photosynthetic solar cell



Green machine. In this prototype solar cell, photosynthetic proteins (spheres embedded in yellow peptides) absorb light and pump electrons (e–) into a silver electrode.

(Source: M. Baldo)

Material sciences – Nanotechnology

Nanotechnology has the potential to significantly impact energy efficiency, storage and production. Nanotechnology as a multidisciplinary field refers broadly to the creation and use of materials, devices and systems in a size range far below that of human vision or even conventional microscopes, i.e. at nanoscale dimensions (1 to 100 nanometres). At this scale the fundamental characteristics of elements such as colour, strength, weight, conductivity, etc change in unexpected ways. Taking advantage of these, industries are engineering novel materials, some of which have never before been identified in nature.

All conventional materials like metals, semiconductors, glass, ceramic or polymers can, in principle, be obtained with a nanoscale dimension. The main classes of nanoscale structures can be summarised as:

- nanoparticles constitute several hundreds or thousands of atoms or molecules with a variety of possible shapes. Besides carbon black, which has been used industrially for a long time, metal oxide and compound semiconductor nanopowders are of especial importance.
- carbon nanotubes and fullerenes are a special class of nanoparticles that are expected to find a broad range of applications.
- nanocomposites and -ceramics are currently the most important class of nanostructured materials. Through nanoscale engineering of surfaces and layers a vast range of functionalities and new physical effects can be achieved. The most important of these regarding power applications are thermal and chemical properties and electrical and magnetic properties.

Nanotechnology materials are already applied to a large number of industrial sectors for various applications and offers exciting new possibilities for addressing key challenges for the generation, storage and transmission of energy (see Table 3).

Table 3 – Thematic coverage of nanotechnology for the energy sector

	Energy generation	Energy transformation	Energy storage	Efficiency improvement of conventional technology
Nanoparticles	Dye solar cells		Metal oxides/metals	Fuel additives
Carbon nanotubes and fullerenes	Organic solar cells	Catalysts	Hydrogen storage supercondenser	
Nanocomposites / Nanoceramics			Nanostructured membranes and electrodes for fuel cells, batteries and accumulators	Nanoceramics and coatings Magnetic materials OLEDs for displays and lighting
Super conducting materials		Super conducting cables	Super conducting storage coils	

Indicators for the evaluation of nanotechnology

Table 4 summarises the bottlenecks for selected processes. The subsequent parts of this report describe the processes in more detail by an analysis of the present state of the art, possible applications and key issues for improvement.

Table 4 – Most critical bottlenecks for the industrial commercialisation of (nano) materials

Process	Bottleneck	Measure for improvement / Indicator				Time horizon
Dye solar cells	Long-term stability	Use of alternative particle materials				Medium term
	Maximum obtainable solar efficiency	Use of alternative material combinations				Medium term
				Today	Aim	
		Solar efficien		8%	15%	
	Industrial production process			Today	Aim	Long term
		Dye material price per gram		17–50 €	10 €	
Nanotubes and fullerenes (general)	(Mass) production process with controllable material properties	Price today: 150 € per gram (single-walled NTs)				Long term
Organic solar cells	Sensitivity to air and moisture	Use of alternative materials				
	Maximum obtainable solar efficiency	Use of alternative material combinations				
			2004	2010	2015	
		Solar efficacy	3%	5%	10%	
	Industrial production process	Aim: 0.5 €/Wp				Long term
Carbon nanotube hydrogen storage	High adsorption rates under ambient working conditions	Today: 2% (at 77 K) 0.6 mass % (room temperature)				Long term
Supercondenser	Cheap electrode material	See nanotubes and fullerene (general)				Long term
Catalyst materials	Price efficiency of catalysator	See nanotubes and fullerene (general) Use of alternative catalyst material				Long term medium to long term
Nano fuel additives	Price of nanoparticles (use of rare earths)	Detection of other suitable materials Problem depends on fuel price				Short to medium term
Nano coatings	Greater temperature gradient	Improved materials with higher Δt across Thermal Barrier Coating				Short to medium term
				Today	Aim	
		Δt across TBC		175 k	> 250 k	

<table>
<tr><th>Process</th><th>Bottleneck</th><th colspan="5">Measure for improvement / Indicator</th><th>Time horizon</th></tr>
<tr><td>Magnetic Materials</td><td>Production cost</td><td colspan="5">Development of more effective processing methods, especially powder injection moulding (PIM)</td><td>Short to medium term</td></tr>
<tr><td rowspan="5">LEDs</td><td rowspan="3">Quantum efficiency for GaN LEDs</td><td colspan="5">GaN LEDs are relatively new devices. Further research will improve their efficiency</td><td rowspan="3">Medium to long term</td></tr>
<tr><td></td><td>2005</td><td>2007</td><td>2012</td><td>2020</td></tr>
<tr><td>Perfomance of white LEDs (lm/W)</td><td>25</td><td>50</td><td>150</td><td>200</td></tr>
<tr><td>Stability of OLED materials, rapid aging of materials</td><td colspan="5">Development of alternative materials
Encapsulation of polymers</td><td>Medium to long term</td></tr>
<tr><td>Expensive/inefficient production process for OLEDs</td><td colspan="5">Development of alternative processes (loss of organic material << 95%)</td><td>Medium to long term</td></tr>
<tr><td rowspan="6">Superconducting materials</td><td rowspan="4">Critical temperature and anisotropy</td><td colspan="5">Identification of materials with higher critical temperature (77 K and above)</td><td rowspan="6">Long term</td></tr>
<tr><td></td><td colspan="2">Today</td><td colspan="2">Aim</td></tr>
<tr><td>T_c</td><td>20</td><td>108</td><td colspan="2">>> 77 K</td></tr>
<tr><td>Anisotropy</td><td><<1</td><td>50-100</td><td colspan="2"><10</td></tr>
<tr><td>Field</td><td>B</td><td colspan="2"><30 T (4,2 K)
<15 T (10 K)
<10 T (77 K)</td><td colspan="2">3-10 T (at T>>77 K)</td></tr>
<tr><td>Mechanical stability</td><td>Bend radius</td><td colspan="2"></td><td colspan="2">0.1 m (generators) – 2 m (power cables)</td></tr>
</table>

Nanoparticles

Dye solar cells

Conventional photovoltaics with tailor-made III-V semiconductors have achieved a conversion of 30%. Dye solar cells (DSC) or Grätzel cells (Grätzel 2001) represent a recently developed class of solar cells, which is based on completely different principles to semiconductor technology. The basis for production is inexpensive thin-film technology, such as that already applied in industrial processing of glass and polymers. This offers the potential for financially attractive manufacturing.

In the (nanocrystalline) DSC, sunlight is converted to another form of energy with the help of dye molecules, as also happens in photosynthesis. The film of the cell contains TiO_2 nanoparticles or quantum dots with a size distribution showing a wide range of electronic band gaps that determine the wavelength absorbed by the respective particle, so that much of the solar spectrum can be captured by the cell and transformed into electricity. The efficiency value of dye solar cells is currently about 8% and the aim is to increase it to 15% in the future. The current cost to manufacture the dye material is between 17 and 50€ per gramme. The longer-term goal is 10 per gramme (Malsch 2003; Fairley 2004).

If DSCs can be made cheaply with an optimised distribution of nanoparticle diameters, properly aligned, this would form an ideal solar collector. Though several firms (e.g. Konarka) are working on first prototypes to be used in mobile phones and handheld computers, the field is young and changing rapidly. Major problems like long-term stability, maximum obtainable solar efficiencies and industrial production methods still have not been sufficiently clarified (Fairley 2004).

Carbon nanotubes and fullerenes

Besides long-established materials like carbon black, nanostructured carbon consists of relatively new compounds like fullerenes (C_{60} molecules, 'Buckyballs') and carbon nanotubes (CNT). CNTs, which can occur single- or multiwalled, are predicted to have a wide variety of applications due to their outstanding properties like extremely high tensile strength, and excellent thermal and electrical conductance.

The main barrier to a broad use of CNTs is due to the high price of approximately 150€ per gram for single-walled nanotubes. The high price reflects the early development stage of industrial production and purification. Several methods aiming at the mass production of CNTs have been proposed but they are still at the stage of small-scale laboratory tests.

Since the properties of CNT vary depending on the diameter and other factors of nanotubes, it is necessary to control these factors. Though progress has been made it is not yet possible to control these factors to produce CNTs with uniform properties. (Tada 2002; Dai 2002)

Organic solar cells

Another alternative solar cell technology uses a composite material of a conjugated polymer and carbon nanotubes or fullerenes that form films of about 200 nm thickness (Brabec et al. 2003).

Such organic solar cells (OSC) still have low efficiency values of about 3% under normal ambient conditions. The main reason is the low absorption of light in the thin organic layers. OSCs are potentially cheaper to manufacture than silicon or dye cells, but still highly sensitive to air and moisture, making commercial applications difficult. New material concepts, but also improvement of the optical properties, could change this. The aim is to increase the efficiency of such plastic cells to 5% in five years and 10% in the long run (Fairley 2004). A long-term goal is to reduce the cost of solar cells to below 0.5 €/Wp.

This technology is further developed by major enterprises such as Siemens.

Hydrogen storage

Due to their chemical properties, high surface area and low weight, CNTs and fullerenes are discussed as means for hydrogen storage. After a phase of initial euphoria this is being more critically reviewed today. Reproducible experiments show that a hydrogen storage capacity of up to 2 mass % (at very low temperatures) is possible in single-walled CNTs. The much higher absorption rates (5–10 mass %) that were published in the late 1990s seem to be the result of inaccurate experiments. At room temperature the gravimetric storage density drops to 0,6 mass %.

Much research is also needed to obtain a controlled release of hydrogen from these materials under practical conditions.

Despite interesting approaches in hydrogen storage research using CNTs, no breakthrough is in sight (Züttel 2004).

Catalysts

In general, nanoparticles have a high surface area, and hence provide higher catalytic activity. It is possible to synthesise metal nanoparticles in solution in the presence of a surfactant to form highly ordered monodisperse films of the catalyst nanoparticles on a surface. This allows more uniformity in the size and chemical structure of the catalyst, which in turn leads to greater catalytic activity and the production of fewer by-products. It may also be possible to engineer specific or selective activity.

These more active and durable catalysts could find application in fuel cells, where the external surface properties and the pore structure affect performance. The hydrogen used as the immediate fuel in fuel cells may be generated from hydrocarbons by catalytic reforming, usually in a reactor module associated directly with the fuel cell. The potential use of nano-engineered membranes to intensify catalytic processes could enable higher-efficiency, small-scale fuel cells. These could act as distributed sources of electrical power. It may eventually be possible to produce hydrogen locally from sources other than hydrocarbons, which are the feedstocks of current attention.

Nanostructured catalysts using CNTs or other nanoparticles will also be applied in cleaning up waste streams. This will be particularly beneficial if they reduce the demand for platinum-group metals, whose use in standard catalytic units is starting to emerge as a problem, given the limited availability of these metals.

Although progress has been spectacular in the development of nanostructured catalysts, there are still major hurdles to be jumped before rational design of catalysts and other energy-related materials becomes a commercial reality (Steele/Heinzel 2001; Paschen et al. 2004).

Supercondenser

Electrochemical supercondensers (SCs) are another possibility for the short-term storage of energy. They are made up of two porous electrodes insulated by a separator paper impregnated with an ion-conducting medium or electrolyte. The combination of high specific area electrodes with an electrolyte of a high concentration of ions allows the creation of SCs of high potential and great ability to withstand charge-discharge cycles.

SCs are a good complement to batteries and most suitable for the steady delivery of electric current, though they can also be used to compensate for short-term peak loads. Thus the integration of the SCs with other energy storage systems – batteries or fuel cells –allows a more rational design for electricity supply systems.

Besides activated carbons, electrodes can also be formed from carbon aerogels or nanotubes. Both materials have a high surface area and good conductivity, and allow increasing the capacity of a SC significantly. In addition the use of carbon as the electrode material offers the opportunity of low cost and easy accessibility (Frackowiak/Beguin 2001; Paschen et al. 2004).

Fuel additives

As additives to solid and liquid fuels nanoparticles can optimise ignition and burning characteristics. A general advantage of nanoscale particles or structures is that they can be mixed with the components of an energetic material on a molecular scale. This is the best possible mixture, and a precondition for a fast and complete chemical transformation.

For solid rocket propellants aluminium nanoparticles can increase the burning rate in comparison to conventional aluminium powders (Paschen et al. 2004).

Nanoparticles also promise a higher efficiency of liquid fuels like diesel, meaning more kilometres per litre, cleaner engines and less pollution. These diesel additives consist of nanoscale cerium oxide particles, which catalyse the combustion reactions between diesel and air. Cerium oxide functions as a kind of oxygen store that is released to oxidise carbon monoxide and hydrocarbon gases to form carbon dioxide, and also absorbs oxygen to reduce the quantity of nitrogen oxides (Zhang et al. 2002).

Cerium oxide has been studied for some time but has not become a commercial success yet, mainly due to the high price. Cerium oxide nanoparticles can be used at a much lower concentration since their greater surface improves the catalytic reaction. Various tests with this additive have been made in Hong Kong and Scotland. The Oxonica Corporation reports that up to 12% fuel economy benefits were demonstrated in these field trials under commercial operating conditions (Oxonica 2003).

Nanocomposites

Nanoceramic coatings

Coatings with thickness controlled at the nano- or atomic scale have been in routine production for some time, for example in Molecular Beam Epitaxy or metal oxide Chemical Vapor Deposition for optoelectonic devices, or in catalytically active and chemically functionalised surfaces.

Thermal barrier coatings (TBC) are applied in order to reduce the heat flux between the surface and the substrate component. Depending on heat flow conditions and the thickness of the coating, the temperature difference across the thermal barrier coating can reach 175 °C.

TBCs are considered technologically important because of their ability to further increase the operating temperature of any kind of heat engine (combustion engine, gas turbine, etc), reduce cooling requirements, thus achieving higher engine efficiency, lower emissions and increased performance. TBCs using nanoparticles provide better thermic and thermomechanic properties (lower thermal conductivity, better thermal stability and higher toughness) than current coatings. With such advanced TBCs it will be possible to increase the temperature difference across the thermal barrier coating to about 250 °C enabling very high operation temperatures (1650 °C) for gas turbines and propulsion engine systems (Zhu/Miller 2004).

Besides coatings nanoceramics are important materials for other parts of power systems as well. Normally ceramics are hard, brittle and difficult to machine. However, with a reduction in grain size to the nanoscale, ceramic ductility can be increased. Zirconia, normally a hard, brittle ceramic, has even been rendered superplastic. Nanocrystalline ceramics, such as silicon nitride and silicon carbide, have been used in such automotive applications as high-strength springs, ball bearings and valve lifters, because they can be easily formed and machined, as well as exhibiting excellent chemical and high-temperature properties. They are also used as components in high-temperature furnaces. In all this applications the use of nanoceramics can help increase the operation temperature and thus the thermal efficiency (Hahn 2004; Paschen et al. 2004).

Magnetic materials

Soft magnetic materials are those materials that are easily magnetised and demagnetised. They are used primarily to enhance and/or channel the flux produced by an electric current as in electrical generators, motors and power supply transformers. For this purpose the material is continuously cycled from being magnetised in one direction to the other. A high permeability, small conductivity and a narrow hysteresis loop is desirable in order to reduce losses and reach a high efficiency.

Hard magnets, also referred to as permanent magnets, are magnetic materials that retain their magnetism after being magnetised. In recent decades permanent magnets have become increasingly important as they are used in a wide variety of applications (automotive, industrial, astro and aerospace, etc.) Improved permanent magnets with significantly reduced cost, increased maximum operating temperature and improved corrosion resistance may replace energy-consuming electro magnets for many applications. They can be used in 'white goods', such as washing machines, refrigerators etc, in order to improve energy efficiency and reduce CO_2 emissions. Another important use could be in generators for domestic combined heat and power units and in clean energy production such as windmills. The biggest potential however is in electric vehicles.

Recently there has been much interest in nano-crystalline material, which is produced by annealing the amorphous material. These alloys can be single phase but are usually comprised of nano-sized grains, in the range 10-50nm, in an amorphous matrix. They have relatively high resistivity, low anisotropy and good mechanical strength. It has been shown that magnets made of nanocrystalline yttrium–samarium–cobalt grains possess unusual magnetic properties due to their extremely large grain interface area (high coercivity can be obtained because magnetisation flips cannot easily propagate past the grain boundaries). This could lead to applications in motors, analytical instruments like magnetic resonance imaging (MRI), used widely in hospitals, and microsensors. Overall magnetisation, however, is currently limited by the ability to align the grains' direction of magnetisation. Though nanocrystalline materials have shown many good properties they have some drawbacks where the cost of production is still very high. Some more cost-effective production processes have been proposed but have not reached maturity (Inoue 2002, Ramanujan 2003).

Nanostructured membranes for batteries and accumulators

With the growth in portable electronic equipment (mobile phones, navigation devices, laptop computers, remote sensors), there is great demand for lightweight, high-energy density batteries. In the future, rechargeable batteries will become even more important in combination with renewable energy production such as photovoltaics.

Nanocrystalline materials synthesized by sol–gel techniques are candidates for separator plates in batteries because of their foam-like (aerogel) structure, which can hold considerably more energy than conventional ones. Nickel-metal hydride batteries made of nanocrystalline nickel and metal hydrides are envisioned to require less frequent recharging and to last longer because of their large grain boundary (surface) area.

There are mainly two types of rechargeable batteries where nanostructured materials are applied. The first and most advanced is the dry lithium based battery. The other, wet type, uses the same materials as for hydrogen storage, metal hydrides or carbon nanotubes (Tarascon/Armand 2001).

It was recently shown that transition-metal oxide nanoparticles can improve lithium-ion mobility which can not only enhance efficiency but also allow a significant extension to the number of cycles a rechargeable battery can withstand before it deteriorates.

Light emitting diodes for displays and lighting

Significant changes in display and lighting technologies are expected in the next ten years. Semiconductors used in the preparation of light-emitting diodes (LEDs), as lighting can increasingly be sculpted at nanoscale dimensions. Roughly 1% of all electricity is consumed for lighting, including both incandescent and fluorescent lights. Since incandescent light bulbs only convert 5% of the energy into light while even today's gallium nitride (GaN) LEDs have a light efficiency between 60 and 90%. Since researchers believe that they can increase the quantum efficiency of next-generation GaN LEDs close to 100% and though there are other loss mechanisms enormous energy savings will be possible In 10 to 15 years. Projections indicate that such nanotechnology-based lighting advances have the potential to reduce worldwide consumption of energy by more than 0.5% (Zorpette 2002).

Organic LEDs consist of layers of organic thin films sandwiched between two conductors. When an electric current is applied, bright, visible light is emitted. The devices are lightweight, durable, flexible and power efficient, and hence ideal for portable devices but also for conventional application like TV sets and computer displays. They need fewer process steps and use fewer and cheaper materials than the well-established liquid-crystal displays, their marketplace rivals. Since it is believed that OLEDs can be as energy efficient as GaN LEDs, great energy-saving opportunities exist.

Though the general principle of OLEDs is well researched there are still weaknesses. The dyes in organic solar cells and some of the light emitting polymers are very sensitive to air and moisture. The two industrial production processes in use today are relatively expensive, mainly due to the loss of 95% of organic material during the process (Niesing 2002).

Superconducting materials

For superconducting magnetic energy storage (SMES) electric energy is stored by circulating a current in a superconducting coil. Because there are no resistive losses, this current persists indefinitely. The efficiency of charging and discharging is very high because no energy conversion is needed, and for the same reason SMES can respond rapidly, only limited by the time required for AC/DC-conversion. SMES can also be used for load levelling and frequency and voltage control, which will probably be the first application of this technology.

A large-scale application depends on achieving high critical current densities to be cost-competitive with other technologies. At present niobium-titanium, niob-tin and bismuth (2223) alloys are used for storage as well as for transmission purposes at liquid helium or hydrogen temperatures. Widespread use of superconducting materials for higher critical temperatures (at liquid nitrogen temperature and above) still requires more research and development (Labalestier 2001).

Recent theoretical studies of NIST and the University of Pennsylvania show that changing the shape of CNTs can reveal new properties including superconductivity and might be used as a material for power applications in the long run (Dag et al 2003).

Superconducting transmission lines could reduce resistive losses, but requires energy for cryogenic cooling of the cables. It should be possible to use existing tunnels for these cables, thereby reducing cost while increasing the transmission capacity (Dresselhaus 2001).

Since high powers are involved, careful considerations have to be made about the consequences of a failure of cooling. An enormous amount of energy would be released immediately when the superconductor turns into a normal conductor (10 MWh of stored energy would be equivalent of 1.18 tonnes of TNT).

In 2003 American superconductors was selected by the Long Island Power Authority to supply the first high-temperature superconducting power transmission cable (Bi-2223 at 108 K). Cables manufactured by Nexans will provide three to five times more power than conventional cables of the same size (Lane 2003).

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Energy Scientific and Technological Indicators are needed to monitor the status of research and technological development (state of the art), related research and industrial evolution and to define realistic targets or objectives for future activities. Such indicators and data, when properly defined and validated, are a useful tool for policy drivers, decision-makers, programme managers, potential investors, bankers, technology end-users, etc.

They record the complex links between energy use, energy technologies, industrial developments, market needs and socio-economic activities.

This study identifies and justifies a preliminary set of critical indicators and references of a scientific, technological or techno-economic nature. These indicators are based on the present state of the art and characterise the major bottlenecks to be overcome or the main challenges to be addressed by each technology in its future development.

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