EUROPÄISCHE AKADEMIE
zur Erforschung von Folgen wissenschaftlich-technischer Entwicklungen
Bad Neuenahr-Ahrweiler GmbH
Direktor: Professor Dr. Dr. h. c. Carl Friedrich Gethmann

GRAUE REIHE · NO 47 · NOVEMBER 2008

Fuel Cells and Virtual Power Plants

Energy, Environmental, and Technology Policy Aspects of an Efficient Domestic Energy Supply

Executive Summary

B. Droste-Franke, H. Berg, A. Kötter, J. Krüger, K. Mause, J.-C. Pielow, I. Romey, T. Ziesemer

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Foreword

In July 2006 the research project “Fuel cells and virtual power plants as elements for a sustainable development. Innovation barriers and implementation strategies”, funded by the German Federal Ministry of Education and Research (BMBF), was launched by the Europäische Akademie GmbH. Its main task was to scientifically analyse the obstacles which hamper the realisation of the technologies fuel cell and virtual power plant inadequately and derive recommendations to contribute to the societal and political discussion on the implementation and support of innovations in this area. The study focuses on residential energy supply aspects.

The established interdisciplinary project group consisted of experts covering the fields of energy engineering, environmental science, economics, political science, and jurisprudence. During the perennial research work initial individual disciplinary contributions were extensively discussed, further elaborated, and step by step integrated into the final study with the aim of a common authorship of all project members. In this way, a consequent and consistent setup of the study could be realised which starts from general normative goals and proceeds via technology assessment and the identification of barriers to the deduction of adequate strategies and respective policy recommendations.

In order to analyse relevant aspects as detailed as possible and to give concrete advice to practitioners, it was decided to focus the analyses onto German conditions and to publish the study in German language. However, many aspects of the results are also crucial in the international context. Therefore, the executive summary of the study is published in form of this booklet so that the major findings of the research group are made available to a broader international readership. The in-depth results can be found in the detailed German report: B. Droste-Franke, H. Berg, A. Kötter, J. Krüger, K. Mause, J.-C. Pielow, I. Romey, T. Ziesemer: Brennstoffzellen und Virtuelle Kraftwerke. Energie-, umwelt- und technologiepolitische Aspekte einer effizienten Hausenergieversorgung. Springer-Verlag, Berlin Heidelberg, 2009 (ISBN 978-3-540-85796-9).

Bad Neuenahr-Ahrweiler, November 2008

Dr.-Ing. Bert Droste-Franke, Dipl.-Phys.
(Project Co-ordinator “Fuel cells and virtual power plants”)

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Executive Summary

1 Background and Status Quo

Current discussions in science, politics, and society about climate change, resource availability, environmental burden, and supply security reveal the new requirements set upon the energy supply of the future. The urgency for creating new concepts in this area can be seen in many situations: from the high goals concerning the mitigation of greenhouse gas emissions, to the long-term capital lockup of investment decisions in the energy industry, not to mention the still unplanned age-induced construction of new power plants for 2020, needed to provide about one third of the current electrical power installed in Germany.

An efficient option for the supply of electricity and heat can be found in the use of local combined heat and power plants (CHP plants). The stationary fuel cell plant is seen as exceptionally promising in this context. The reason for this is its attractive basic technical principle of the reverse electrolysis of water. Driven only by hydrogen and oxygen, harmless water is the only reaction product, besides the power and heat themselves.

Coupling the plants together to create a composite of plants additionally promises improved coverage of the electricity and heat demand compared to the use of individual plants. Thus, peaks in the electricity demand can be satisfied, whereas it would be impossible for an individual plant to do so. In particular, large benefits are expected from centrally controlling the facilities, as this would make it possible to operate many small facilities as if they were one power plant, a so-called "virtual power plant".

In spite of a certain technical progress in the development of the first fuel cell plants, worldwide only about one hundred facilities have been installed for demonstration. Similarly, the combining of facilities to create virtual power plants has only passed the status of pilot project in a few cases and only with a small number of individual facilities.

2 Aim, Methodology and Structure of the Study

Based upon an evaluation of fuel cell and virtual power plant technologies with respect to their potential contribution to a future sustainable energy supply, the aim of this study[1] is to identify non-justifiable barriers to innovations in the area of fuel cell heating systems and virtual power plants, and to derive recommendations by which such barriers can be adequately removed.

The study focuses on the application of small facilities as heaters for the energy supply in buildings. As the application of fuel cells is particularly promising for small CHP plants, so called micro-CHP-plants, and as the heat demand of households and small businesses represents two thirds of the stationary heat demand of Germany, a high application potential is awaited in this area.

Although the opening of European energy markets is progressing well and many decisions are being made on the European level, the basic structures, such as tax systems, governmental funding, and the management of the energy balance, are still anchored at the level of the individual member states. Therefore, this study restricts itself to considering barriers occurring within the analysis of German conditions.

Although these technologies will only be marketable in the future, the investigations in this study must remain based on current circumstances. The study analyses how these circumstances can be adapted in order to remove constraints existing today so that the technologies hypothetically could be optimally employed. Thus, independently of the real market entrance of fuel cell heating systems, guidelines are being developed which can be consulted for the integration of already offered micro-CHP-plants into, respectively, the electricity grid and virtual power plants. These technologies are seen as pathfinders for fuel cell heating plants. The work is based on the status quo of regulations in February 2008.

In order to create relevant policy recommendations, respective aspects of energy engineering, energy economics, environmental economics, politics, and jurisprudence must be tied together. Therefore, the interdisciplinary project group has been chosen as the methodology for the investigations: Individual discipli-

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1 B. Droste-Franke, H. Berg, A. Kötter, J. Krüger, K. Mause, J.-C. Pielow, I. Romey, T. Ziesemer: Brennstoffzellen und Virtuelle Kraftwerke. Energie-, umwelt- und technologiepolitische Aspekte einer effizienten Hausenergieversorgung. Springer-Verlag, Berlin Heidelberg, 2009 (ISBN 978-3-540-85796-9).

nary contributions were discussed interdisciplinarily between the project group members and were then combined to create a consistent study. Additionally, in two workshops – one carried out at the beginning of the study and one midway through the project – the working programme and the interim results were discussed and peer-reviewed by practitioners and scientists from the relevant fields. Furthermore, interviews with fuel cell producers were carried out.

In the first part of the study, normative foundations for the evaluation of technologies and measurements are developed. In the second part, technologies are described and appraised. In the third part, the economic and legal conditions of potential obstacles are analysed. Based on this, the fourth part presents strategies and, finally, derived recommendations.

3 Normative Foundations

3.1 Futurability

For an energy supply to be empowered for the future (futurability[2]), it is claimed that it must support basic macro-economic societal aims in the best possible way. Therefore, an operative action rule can be derived, starting with the two elementary goals of the economy:

- the optimal assignment of scarce means to given purposes (efficiency);
- the just apportionment of available means to individuals (distribution).

Therefore, and firstly, the concepts for guaranteeing a fair inter- and intra-generational distribution and intertemporal efficiency are presented. This is followed by, secondly, a combination of the two. To summarise, the following *action rule* results and can be subdivided into four priorities:

Priority 1:
Protection from unacceptable damage through compliance with critical limits
Critical stocks of each relevant societal asset component[3] must not be under-run.

Priority 2:
Maintenance of the total value of produced and natural capital
Provided that priority 1 is met, adequately evaluated changes of all relevant societal asset components must add up, at minimum, to zero. In the case that priority 1 can only be reached with a negative balance, this must be minimised.[4]

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[2] The term ‘futurability‘ is intentionally chosen to emphasise the importance of empowering energy supply for the future without having already in mind the sub-aspects of sustaining specific issues and ensuring economic efficiency. Thus, using “sustainability” instead would be an inadequate here.

[3] These include, among other things, natural assets, e.g. ecosystems. The stocks can principally be measured in arbitrary units.

[4] This addition is introduced in order to cover the case in which the efforts for guaranteeing the protection from inacceptable damage are so great that a reduction of the total assets is necessary. An equivalent fomulation is: In the case that priority 1 cannot be reached without a negative balance, the maximum level of societal assets must be aimed for with which a balance of zero can be reached.

Priority 3:
Maximising intertemporal welfare
The present value[5] of the intertemporal benefit must be maximised, thus achieving priorities 1 and 2.

Priority 4:
Just distribution of basics at present.
The basics for meeting needs, after achieving priorities 1 to 3, must be justly distributed within and between societies according to societally-defined rules.

3.2 Market Imperfections

A welfare maximum is found if a so-called "Pareto-optimum" is reached, i.e. no-one can be made better off without making someone else worse off. The reasons why the market does not reach a Pareto optimum and thus, why un-used possibilities for welfare improvement exist, represent market imperfections. In order to maximise welfare (priority three) these imperfections must be avoided as much as possible. Therefore, market imperfections relevant to the technologies being examined – fuel cells and virtual power plants – are investigated. They evolve in areas affected by:

- monopolistic power and market power, respectively;
- non- or badly regulated ownership rights;
- uncertainty due to incomplete market structures.

A monopoly shows three essential disadvantages compared to strong competition: The price of offered products is higher; the amount of products produced and sold is smaller; and the income is redistributed to firms and their owners. Technical-economic reasons for the development of monopolies include overly high fixed costs in the production of a good and advantages through compatibility and networking, respectively. Additionally, monopolies can be initiated by the state. Furthermore, interlinked markets can lead to a situation in which a monopolist in one area also becomes a monopolist in another area. Thus, monopolies can be tackled

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[5] By using the present value of the benefit as a uniform value, present prices are used and future benefits are expressed by discounting the present values.

in the following ways: by enabling competition, taxing excessive profits, removing badly or unreasonable bureaucratic regulations and state monopolies, accelerating approval procedures, publicly auctioning natural monopolies like railway and energy transport networks, only cautiously defining technological standards by the government, as well as banning the abuse of network advantages and, if necessary, unbundling parts of firms.

Ownership rights which are non- or only badly regulated are particularly observed as far as environmental goods (public goods) and innovations are concerned. In the environmental area, missing regulations lead to the disregarding of social costs and thus, to the distortion of competition. Furthermore, innovation incentives are wrongly set. In order to regulate them, many challenges must be reckoned with: free-rider behaviour, effects from monopolies, and inadequate execution due to government failure. In the area of innovations, if it is feared that information brought about by a new invention or product could reach the public or rival firms, ownership rights can be protected by patents, copyrights, registered brands, etc.

In the industry, uncertainties arise particularly in the fields of production loss and sales, mid- and long-term transactions, and research activity. Companies can insure themselves only incompletely with respect to their own losses[6]. Transactions far in the future can only partly be insured by contracts which can be very expensive. Public research funding can cover the financial risks related to failure at research activities.

In order to implement regulations for the removal or mitigation of market imperfections, respectively, extensive economic analyses must be available, political will has to be given, and implementation into law and regulations has to be efficient. Therefore, good teamwork among politicians, economists, lawyers, and technical experts must be ensured.

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[6] In contrast, private investors can insure themselves by diversification of their parcels of shares. Employees of such companies profit from labour laws as well as unemployment insurance, which is regulated by the state.

3.3 Indicators

Based upon the elaborations of the operative action rule and the discussion of market imperfections, indicators can be derived for the evaluation of energy technologies. For this purpose, and based upon existing studies in that area, the characteristics of energy technologies can be presented according to the following three central aims. This categorisation can then be applied to compile detailed indicators for their evaluation:

- warranty of resource availability;
- protection of the environment;
- (just) configuration of the energy supply system.

In order to guarantee resource availability, in keeping with the concept of conserving the total value of capital, at least the benefits connected with the resources, i.e. their functions for society, must be preserved. Therefore, substitutes must be applicable early enough before the resources begin to run short. Thus, the length of time during which the resource is securely available should be longer than the time required to switch to an alternative resource. Respectively, a resource usage can be referred to as sustainable or 'futurable' if the ratio of reserves to production[7] is not falling unnecessarily strongly and higher than the inertness of the energy system which is estimated at about 60 years. Additionally, further reasons which can influence the availability of resources are considered. These include strong price changes, the ratio of material used to available resources, and a strong regional concentration of the delivery and revenue chain as well as in the occurrences.

In the area of environmental protection, according to the priorities, concerned parties must distinguish in principle between effects leading to short- and long-term impacts and those effects which could lead to unacceptable damage. Keeping in mind long-term investments and the aim to follow a successful path for the energy supply in the future as well, and with the use of these technologies, unavoidable and recurring environmental effects will be passed on to subsequent generations. Concerning critical effects, limits should be adhered to in order to guarantee the prevention of unacceptable damages. As for the evaluation of technologies, their contributions to critical burden (e.g. emissions of greenhouse gases)

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7 For the calculation of the reserves-to-production ratio the production ratio is hypothetically assumed to remain constant in the future.

and the costs of the damage they cause to the environment, which are not yet considered in the market and thus are called “external costs”, are taken into account. Among others, important environmental impacts included are: consequences of climate change, impacts on human health, and impacts on ecosystems.

As individual technologies, and not complete energy systems, are analysed, the comparison of important system characteristics is carried out qualitatively. Aspects of supply security, risk avoidance, and flexibility to different options of the system are considered.

4 Fuel Cells, Virtual Power Plants and their Evaluation with Respect to a Futurable Energy Supply

4.1 Status Quo and Development Potentials

The investigation of the technical development of fuel cell facilities and virtual power plants being focused upon revealed that both, as defined in the study, are not yet technically mature. Therefore, further technical development is necessary in order to make them marketable.

Fuel cell plants turn out to be particularly promising in the area of small electrical power units of below 5 kW_{el}. These facilities are used as heaters for the energy supply of buildings and thus are called “fuel cell heating devices”. Compared to other small plants, which can be used to generate combined electricity and heat (micro-combined heat and power (CHP) plants), they primarily offer a significantly higher yield of electric current per amount of fuel used. This is far more valuable than the respective amount of heat, as it can be applied in a much more flexible manner. The so-called “annual degree of utilisation”, measured in order to derive a value for the efficiency of energy usage, not only at the optimal operation point but also including start-up procedures, etc., is nearly 30 percent. The stated technical development target is to be able to convert about 40 percent of one year’s energy input into electrical current. In the area of competing micro-CHP-technologies like traditional motor-block heat and power plants, Stirling engines, and steam engines, a maximum of 10 to 25 percent can be reached. The total annual degree of energy utilisation for fuel cells (electricity plus heat) is estimated at about 85 percent, which is slightly below the total usage degrees of the directly competing micro-CHP-technologies.

Further development is particularly required in the area of lifetime, energy efficiency, degree of utilisation, reliability, and complexity of the devices. Additionally, the processes required to generate high hydrogen content gases from natural gas, which take place inside the device, can be improved. Further development in these areas will prospectively also lead to reductions in investment and variable costs.

Many different concepts are connected to the phrase "virtual power plant". In the current study, the definition of a virtual power plant chosen is as follows:

> A *virtual power plant* is a network consisting of a number of small, peripherally-installed electricity-producing devices which are connected to each other und which are enabled so as to replace the centrally available electrical power of generating plants.

In contrast to other ways of understanding virtual power plants, some of which have been partly implemented with success, the central controllability of the devices represents a fundamental element of the definition. Furthermore, composites of small devices, which can take over the local energy supply of complete settlements and parts of cities, are being considered. At the same time, in addition to micro CHP plants, other decentralised plants can be integrated. However, the great advantage of micro-CHP-plants is the good controllability that they offer.

Up until now, virtual power plants of this kind had been realised with only a small number of individual devices. The intention is to couple several thousand devices so that an amount of power could be provided to allow the sale of electricity at the balancing energy market. In order to reach such a size, particular improvements are required in the technical and conceptual development of the central control so as to be able to cope with the resulting immense amounts of data.

4.2 Technical Possibilities and Energy Economic Potentials of Grid Integration

Since for fuel cells, like for all other micro-CHP-plants, the ratio of produced electricity and produced heat is fixed at any given time, various possibilities result by which to design the implementation and operate the facilities. In the case of operation, a difference is made between 'power-driven', 'heat-driven', and 'externally-driven'[8] operation modes. In the case of power- and heat-driven operation, an attempt is made to meet the demands of power and heat of the supplied object, respectively. In a direct rationing of resources without storages, the facilities are driven in such a way that the production temporarily corresponds directly to the consumption. The usage of energy storages, in general heat storages, makes it pos-

[8] The "externally-driven" operation mode sometimes is also called "grid-driven" operation mode.

sible to temporarily decouple the production from the consumption and the power production from the heat production. In the case of an externally-driven operation, operation schedules are externally set. Thereby, fixed and variable schedules can be implemented in the device, a peripheral management system can be applied, or a direct control from outside can be installed. In order to profit from their advantages, the amounts of power and heat produced in the facilities have to be used up completely, as much as possible. Therefore, in case of a pure heat-driven operation, irregular feed-in into the electricity grid may occur and in all operation modes the heat has to be utilised within the supplied object. This heat restriction can represent an obstacle for the operation of the facility. It can be reduced by heat storages.

Concerning grid integration, it is important to consider that negative feedback can occur in the case of a large number of devices feeding in irregularly. Keeping the voltage level within the allowed range can be hard to guarantee in specific regions with low current capacity, even with a small number of peripheral suppliers. For the integration of the devices, safety measures installed to protect facilities, electricity grids, and persons against malfunctioning, for the maintenance of the voltage level, and for the insurance of voltage quality have to be revised. Currently they are specifically designed for central electricity production. By applying intelligent power inverters at the peripheral plants, the integration can be facilitated and the grid management can be significantly supported. Several economic potentials result from coupling the individual facilities to a virtual power plant, besides the high efficiency of the individual plants, smaller grid losses by close-to-consumer electricity production, various tax advantages, and funding via the specific monetary benefits for electricity fed into the grid (as per the law on the modernisation and the extension of combined heat and power production (KWKG) and the law on renewable energies for power production (EEG)). An example, among many others, of these economic potentials is the offer of services for grid management. Benefits, and therefore potential economic revenues, are particularly awaited in the areas of idle power and balancing power supply, avoiding the usage of compensation energy, the reduction of maximum grid load, the provision of peak load, selling on the spot market, and, if systematic controllability of the plants can be provided, even demand-oriented supply.

Economic analyses of the various operation methods of fuel cell heating devices show that for single- and multi-family homes, a temporary mixture of externally-driven and heat-driven operation is preferable; this way, electricity can be supplied to external consumers if sufficient revenue is gained. An electricity-driven operation of micro-CHP-plants can be of interest for specific objects if the revenue from electricity sales is smaller than the price paid for the electricity taken from the grid. In this case, however, one must note that these plants may be much more stressed by the higher number of cold starts and fast load changes required.

Assuming the expected investment costs of the 1,000 to 2,000 Euro-per-kilowatt electrical power installed, the optimal plant sizes for single-family houses end up being some hundred watts of installed electrical power, in the case of self-operation and usage of the plant. In multi-family homes, larger power classes are also cost-effective. In the case of contracting, larger power classes can be economically operated in all objects.

4.3 Evaluation of Technologies with Regard to their Contribution to the Futurability of the Energy Supply

The evaluation of fuel cells and virtual power plants, with respect to their futurability based on technology development data, is oriented towards the derived indicators and their respective categorisation into three areas: resource use, environmental effects and system aspects. The foundation of the analysis is made up of the results of life cycle analyses, which take into account production, operation and disposal or recycling processes as well as the provision of materials and fuels. An overview of the results is shown in table 1.

Table 1: Evaluation of Futurability of Fuel Cells and Virtual Power Plants		
	Indicator	**Evaluation**[a]
Resource Usage	Ratio of available reserves to production – Height and stability of "period of secure practice"	Reserves-to-production ratio smaller than period required for system switch: chromium, copper, manganese, nickel, zirconium oxide Decreasing reserves-to-production ratio: yttrium, manganese, iron, bauxite, platinum group metals
	Amount of material required for production of the plants	Critical in widespread application of technologies: yttrium oxide, zircon oxide
	Amount of overall available resources	Resources-to-production ratio below 100 years: nickel, zircon oxide
	Price changes	Price increase from 2001 to 2006 > 300%: nickel, copper
	Regional concentration of reserve occurrences	Two countries > 70%: platinum group metals, chromium, lithium
	Regional concentration of delivery and revenues	Two countries > 70%: yttrium (China: 99%), platinum, palladium (Russia: 44%), zircon oxide
Environmental Effects	Green house gas emissions and external social costs due to climate change	Emissions and external costs: for micro-CHP-plants fired with natural gas lower than for central power plants, but higher than for the application of renewable energies. Within the micro-CHP-plants, fuel cell heating devices with high electrical degree of utilisation show the lowest costs.
	External costs in the area of human health and ecosystems	External costs: for fuel cell heating devices fired by natural gas, significantly lower than for other micro-CHP-plants, hard coal power plants, lignite power plants, and photovoltaics; similar (but higher): gas and steam cogeneration plants; lower: water and wind turbines

Table 1: Evaluation of Futurability of Fuel Cells and Virtual Power Plants		
	Indicator	**Evaluation**[a]
Energy Supply System	Supply security – fair and affordable access	Can be configured after market entrance by respective contracts. Framework conditions should ensure a free grid connection and access and allow for an economical operation of peripheral plants.
	Supply security – breakdown and quality	Revision of protection systems with respect to peripheral feed-in required; compared to photovoltaic and wind by micro-CHP-plants essential contributions for ensuring voltage height and quality possible (idle power, short-circuit power, balancing and compensation energy)
	Supply security – diversity	Depends on the configuration and framework conditions; the diversity of the currently predominantly centrally-adjusted energy system increases.
	Supply security – participation	Everyone has the possibility to contribute to the system configuration and thus the potential for co-determination exists.
	Risk avoidance – technical risks	Even by using hydrogen, prospectively no increased risks emerge.
	Risk avoidance – environmental risks	Emissions of pollutants affecting the local environment are comparably small and smaller than those of the currently widely-applied condensing boilers.
	Risk avoidance – meeting critical limits	Implemented in the right way, these technologies can contribute to the compliance with critical limits for climate change as well as critical levels and loads concerning acidifying and eutrophying substances for the protection of ecosystems.
	Open for alternative options	The system of centrally-controlled, individual, decentralised power plants shows the greatest possible modularity and flexibility. Micro-CHP-plants and especially fuel cells represent one possible option.

[a] Materials are listed in order of decreasing importance.

In the area of resource use, two influences of the application of fuel cells have to be distinguished. Firstly, energetic resources are used for the operation of the facilities and secondly, materials are applied for their production. In the absence of alternatives which can be realised in the short term, fuel cells will be widely fuelled with natural gas or biogas in natural gas quality. As the essentially competing technologies are also fuelled with natural gas and since, in principle, further gases can be used, this aspect is left out of the evaluation. However, a number of rare materials is employed for the production of fuel cells, and these must be critically monitored concerning their availability (see also table 1).

In the area of environmental effects, life cycle analyses are consulted in order to evaluate the technologies by applying recommended monetary values to the assessment of external costs. In the results, micro-CHP-plants are better evaluated than central condensation power plants, but worse than facilities for the usage of regenerative energies. This becomes particularly obvious with respect to their contribution to climate change. In the category of impacts on human health and ecosystems, they even show lower costs than photovoltaic systems, but higher costs than water and wind turbines.

Concerning the system aspects, many advantages result from the application of fuel cells in virtual power plants. If some adjustments of the grid management procedures currently designed for central power supply are carried out, particularly controllable decentralised facilities can contribute significantly to the grid management. Furthermore, being modular and, thus, very flexible, the system includes no larger risks, not even if hydrogen is used. In contrast, the technologies help to reduce the environmental burden and, therewith, to reduce risks of an environmental overload.

Studies dealing with the overall potential of micro-CHP-facilities result in a maximally installed power of about 1–7 GW as well as a coverage of the heat demand of German houses of maximally 10–25 percent and of the German electricity demand of maximally 10–18 percent. These percentages are dependent upon the assumptions for other developments in the energy supply and the competing technologies, respectively. As the heat demand in summer is much lower than in both winter and the transition months, a much lower coverage is expected in summer. It is estimated to represent, on average, about two percent of the German power demand. These numbers show that the facilities can contribute to energy supply to a certain extent, but must be supplemented by further energy supply systems. However, it has to be taken into account that, among other things, they can provide specifically valuable peak load electricity. For example, the 3.1 to 3.4 GW_{el} control power called for in the minutes reserve market in the year 2006 shows that even small amounts of electricity are relevant in the area of control power.

5 Existing Economic and Legal Framework Conditions

5.1 Determinants and Effects of Innovations

Based upon the previous investigations, innovation processes are now analysed in more detail. In the study, innovation processes are subdivided into three phases: the conception phase (invention), the market introduction phase (innovation in a narrow understanding), and the market penetration phase (diffusion). Barriers may exist in all three phases of the process.

Determinants of the innovation process exist firstly as macro-economic aspects which influence the prices of the employed production factors and thus, the production costs. Besides energy resources and production materials, costs for education and the employment of researchers and developers are considered important for the technologies being analysed. Product-specific aspects include expectations for market behaviour and costs, eventual environmental externalities and thus, where appropriate impacts of environmental policy on sales and production, societal pressure, technological complements and networks, as well as joint production. Furthermore, sectoral aspects are relevant. In the case of the energy supply, monopolistic structures lead to less research activity, which can then be compensated for by public research funding or the generation of more competition.

The impact of innovation on the energy sector is firstly seen in the reduction of labour requirements, energy and the environmental burden. The decreasing primary energy demand can furthermore lead to lower prices, which in turn cause energy prices to decrease due to reduced demand, in spite of resources becoming scarcer.[9] Besides the effect of increased consumption due to higher income caused by increased production and leading to the purchase of new products faster, the new products can lead to higher energy consumption (e.g. more computers, larger TV sets). Additionally, negative side-effects are possible such as in the case of nuclear energy usage and the risk of proliferation. Distributional effects are also possible, e.g. for the advantage of better educated employees. Moreover, products with lower fixed costs can stimulate competition. Fuel cells and virtual power plants are such technologies which explain why the large energy suppliers in Germany prefer large centralised electricity production.

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[9] For gas prices, this mechanism does not work because of the interconnection to the oil price.

5.2 Existing Economical Framework Conditions

To a large extent, the framework conditions for innovations result from economic instruments which have already been created. An effective design of these instruments can contribute to the removal of market imperfections and the creation of economic incentives for the market introduction of innovations.

To insure against research-technological failure, and thus, to guarantee a sufficient macroeconomic research and development activity (R&D) for the fuel cell, R&D subsidies are provided on the supply side. These should be continued as long as fuel cells and virtual power plants are not yet fully developed. In order to consider external effects in a later stage, additional demand-side subsidies, e.g. in the form of a feed-in tariff, can be introduced. Before implementing these subsidies, checks must be made to ensure that they are designed for the right time period and that no alternative innovations would be inadequately hampered by them.

Additionally, another point is important for the market penetration of the innovations: the composition of standards for using fuel cell heating devices in the home energy supply and for their integration into the electricity grid, as well as for the configuration of virtual power plants. Respective standards exist already or are currently being worked out.

Further instruments exist in the form of certificates and taxes. Correctly implementing these tools can foster technologies according to their environmental friendliness and, in this way, avoid going over the critical maximum load and lead to an adequate consideration of external costs on the market. In doing so, it is important that the instruments be efficiently shaped and tuned to each other. Among other things, the specific aim of using the instruments has to be kept in mind: It can consist of either the accomplishment of environmental quality targets or the exact internalisation of occurring and assessable external costs. In order to avoid barriers for micro-CHP-plants in the current realisation of the instruments, several adaptations are reasonable, including: the improvement of possibilities for the integration of small facilities into the emission trading scheme and the implementation of more differentiated incentives for technology improvement and development in the field of ‘eco-taxes’.

As long as they are operated on a natural gas basis, fuel cells and virtual power plants require a connection to the gas distribution system as well as the opportunity to feed electricity into the grid. In order to guarantee open access to the grid, specific energy technologies must not be treated preferably by the network operator. Furthermore, the absorption of monopoly profits should be avoided.

The state, acting as a consumer of innovative technologies, as well as public information campaigns, are deemed less important for the encouragement of technology. However, moral appeals to an environmental awareness and clarifications contributing to political education can have positive effects as accompanying measures.

5.3 Existing Legal Framework Conditions

The examination of legal framework conditions, with respect to their impact upon the introduction of fuel cell heating plants and virtual power plants, must be approached on many levels, due to the large number of legal aspects affected. Besides matters of product approval and on-site application, the grid access, electricity feed-in, the pooling of micro-CHP-plants to virtual power plants as well as contracting and fiscal law have to be considered.

In the case of product approval, the essential foundations for the introduction of small fuel cell systems have been established. Precise product requirements and safety test procedures are known and, if they are complied with, will prospectively ensure a product approval. The impact of the recently-adopted EC directive on the environmentally-sound design of energy-using products (Eco-Design Directive) can not yet be foreseen. In contrast, the German immission control legislation has no direct regulations with specific respect to the marketing of small fuel cell plants.

Many concerns have been investigated with regard to the establishment of fuel cell plants in situ, i.e. aspects of regional planning, town planning, building law, the act on granting priority for renewable energy sources for heat supply *(Erneuerbare-Energien-Wärmegesetz),* compulsory connection to and use of public (network) facilities under local government law *(kommunaler Anschluss- und Benutzerzwang),* immission control, the energy saving act *(Energieeinspargesetz),* and the tenancy law. With respect to the tenancy law, it is important to clarify the extent to which investment and operation costs can be allocated to the tenant.

Additionally, the electricity self-supply of multi-family homes through the use of micro-CHP-plants poses a set of questions which lead to the financially unfavourable option of grid feed-in. The federal building law includes authorisations of local town planning to force the usage of renewable energies in development plans. Micro-CHP-facilities are currently not comprised in this regulation.

In the context of grid access and electricity feed-in, some regulations have come into force which also affect small CHP facilities. Particularly, the law on 'Combined Heat and Power Generation' *(KWKG)* and on the 'Renewable Energy Resources Act' *(EEG)* have to be mentioned. Thus, CHP facilities, for example, are entitled to a preferential connection to the nearest low voltage grid. Alternatively, a connection to the facility via the regulations in the 'Energy Industry Act' (*Energiewirtschaftsgesetz,* paragraphs 17 and 18 EnWG) is possible. For this option, it has to be assumed, among other things that the plants comply with the respective minimum requirements for the avoidance of negative feedback to the grid. These have to be provided by the network operator and are subject to the supervision of the regulation authority. The costs of the connection have to be borne by the facility operator. The payment for the electricity fed in can be carried out according to the KWKG or, if regenerative fuels are used, according to the EEG. Connected to this is an electricity feed-in obligation which often is seen as an inappropriate regulation and, in the course of current reform debates, is extended to include the possibility of self-supply of businesses. The self-supply of dwellings and small businesses, however, which would be interesting for fuel cell heating devices, still remains unconsidered. For the approval of a CHP-facility at serial-production the necessity of a specific expertise can be replaced by respective documents of the producer. In the case of further market penetration of decentralised energy facilities, there must be a clarification of the extent to which the mechanisms for the distribution of feed-in capacities and the obligation for extensions of the distribution grid operators are sufficient.

For the integration of individual facilities to virtual power plants, many different business models are conceivable. In fact, all actors on the electricity market could be involved. A fine differentiation of all the organisational variants and operational models could not be covered in this study. Therefore, the investigations of legal regulations in this area are instead dealing with the basic aspects; the concentration is on the possible limits of the energy industry law and the possible impacts of the KWKG and the EEG on the realisation of virtual power plants with micro-CHP-facilities. Limits of energy industry law consist primarily because of the existing regulations concerning the unbundling of the grid operation from electricity production. These limits allow the control of power plants by the grid operator at most in exceptional cases, and particularly conflict with the active request of peripherally-produced electricity. Furthermore, self-run power plants can only be put to use in limited amounts. Authorisation requirements only exist for closely-located and correlated facilities with a respectively high aggregate power. An obligation to disclosure is already given if end customers are served. In the case that virtual power plants meet the requirements for the wholesale market, they can offer their electricity there. Problems result especially for virtual power plants consisting of facilities in several control areas. Not all benefits of virtual power plants can be realised over the public markets. Partly, direct agreements have to be made, e.g. with the grid operator. The design of the incentive regulation can be used in order to adequately reimburse the performance of virtual power plants for the grid management. There is still a need to develop respective business models which can be used to realise as much revenue potentials as possible. The CHP feed-in bonus can theoretically be received in many different contract constructions. According to the current status, the KWKG and EEG have several components which lead to the primary usage of micro-CHP-facilities as individual plants and thus, hamper the realisation of virtual power plants. Among other things, these components include: the priority for the application of the plants and the amount of the feed-in payment. Further aspects which should be revised with respect to reasonable changes are the current regulations to the grid access and the grid access fee.

Additional legal questions arise from a further decentralisation of the energy supply. The following questions are important to mention: the distribution of limited connection capacity in the distribution grid, the regulation of grid extension, the allocation of roles between grid operators and electricity producers currently oriented towards central electricity supply situations as well as the inter-operability of electricity and communication networks.

With respect to the organisational efforts and the allocation difficulties upon implementing micro-CHP-facilities in multi-family homes, a transfer of the heat and electricity supply to a contractor seems to be the best solution. This requires a person-specific and detailed contract configuration as well as a clarification of already indicated uncertainties in (tenancy) law, specifically with regard to the application of micro-CHP-facilities in apartment buildings.

In the area of the taxation framework, the development of taxes on electricity (according to the Act on electricity use – *Stromsteuergesetz*) and on fossil fuels (according to the Act on energy products – *Energiesteuergesetz*) is relevant. An exemption from the electricity tax, to be paid at the delivery of electricity, is possible if in- and output of electricity are in a 'spatial correlation'. The specification of this 'spatial correlation' results in different conclusions and currently requires a case-by-case examination. As efficient CHP-facilities have a degree of utilisation above 70 percent, such fuel cell facilities should be free from electricity taxes. However, for a clear regulation, the wording in the energy industry law must be revised, because only gas turbines and combustion engines are explicitly mentioned. Such ambiguities can also be found in other regulations, among others the building laws of the federal states.

6 Identified Barriers

From the analyses of the individual areas in the study, barriers have been identified which, if they are not removed, could hamper the future application of the technologies. Additionally, the elimination of some of these obstacles could facilitate the adoption of micro-CHP-facilities already existing on the market.

In the areas of both fuel cell heating plants and virtual power plants, there is an extensive need for development in order to ensure that the devices are marketable. In order to guarantee sufficient competitiveness, besides improving the suitability of the devices for daily use and decreasing costs, other things should be considered: that materials which are used will also be available for acceptable prices in the long term; that energy efficiency and thus, the environmental performance is improved; that storage systems are further developed; that devices with small module sizes are designed.

In particular if they are interconnected, peripheral power plants can be very well integrated into the distribution grid. However, because of the orientation of the energy markets is to the central energy supply, among other things in the area of grid services, individual obstacles emerge for peripheral facilities to realise their technological and thus, their financial, potential.

Fuel cell heating devices and other micro-CHP-facilities driven with natural gas are, from an environmental perspective, considered worse than facilities which use renewable energies. Hence, as the requirements for the environmentally-friendly performance of energy supply systems increase, the competition between micro-CHP-facilities and renewable energies continually grows, along with the barriers for the realisation of their potentials.

Further barriers can result from inadequate R&D funding in the area of fuel cells and virtual power plants. Moreover, barriers result from the current implementation of technology policy and the current design of the eco-tax as well as the certificate trade system. In the area of grid access and connection, obstacles can evolve from market power and missing incentives for the reimbursement of grid services where the improvement of supply quality is concerned. Missing information from consumers and handicraft businesses can also create barriers.

Obstacles due to legal regulations arise from, among other things, the existing tenancy law, the high procedural effort and contracting uncertainties, as well as regional planning. Moreover, negative impacts may result from the implementation of the KWKG and EEG, the distributional mechanisms for grid capacities, local affairs, and adaptation requirements in individual laws, e.g. the regulation of the electricity and energy tax.

7 Concrete Conclusions and Recommendations

From the elaborations of the individual aspects and the obstacle-removal strategies, 29 concrete recommendations have been derived which are aimed at the further handling of the technologies. The recommendations are subdivided into the following areas: technical development and implementation of fuel cell heating devices; the integration of peripheral power plants into the grid and their application in virtual power plants; and the design of framework conditions for micro-CHP-facilities and fuel cells, grid integration and virtual power plants, respectively. Below a summary of the recommendations is given:

7.1 Technical Development of Fuel Cell Technology

The technical development should be continued, as it is the only way to solve technical problems of fuel cell heating plants, specifically concerning *life-span, efficiency factor, degree of utilisation, credibility, and complexity of the devices*. At the same time, the technical development should aim at *reducing the cost of components*. The marketability is dependent upon the business model and supply object, prospectively reached at a cost of about 1,000–2,000 euros per installed kilowatt of electrical power. In order to be also applicable at a low heat demand, *facilities with electric power below 1* kW_{el} should also be developed. For a long-term and widespread usage of the technology, additional possibilities to, respectively, recycle and exchange *rare materials* should be worked out. In mass production prospectively the ingredients of the electrodes of Solid Oxide Fuel Cells (SOFC) yttrium oxide and zircon oxide will reveal themselves to be critical. Some of the other materials applied are, in general, not used sustainably, show a high regional concentration in their production chain or in the occurrences, respectively, or have experienced high price increases (see table 1).

Standards should be set early, in order to encourage technical development and market introduction. They should be pushed further in self-regulation according to the present system. As the area of research and development is characterised by great uncertainty with respect to its success, *governmental funding* is to be advised.

7.2 Integration of Fuel Cell Heating Devices into the Energy System

Indeed, fuel cell heating plants and other micro-CHP-facilities which should be seen as precursors of fuel cell heating devices, perform worse in terms of *environmental aspects* than the direct usage of regenerative energies like wind and solar driven facilities. However, particularly where electricity production is concerned, they show the advantage that they can be operated with fast load changes in a large power range and that their production is not directly dependent on the weather conditions. An operation mode of the devices which is oriented to the heat demand of an object and which is oriented at external pre-settings when payments for electricity feed-in are high, turns out to be preferable. This *external control of facilities* is especially sensible if a large number of devices can be co-ordinately operated by a so-called “virtual power plant”, in order to be able to fetch a higher amount of power when demanded. Operated this way, micro-CHP-plants can provide shares of *base and peak load,* which currently are produced in much less efficient large-scale power plants and thus, support the application of regenerative energies with fluctuating availability. In this way, negative feedback to the grid, which could lead to instabilities in the case of an un-co-ordinated operation, can also be easily avoided. The *supply security in the distribution grid* can even be improved through the use of the small facilities.

In order to enable such a combination of individual plants, the development of external control devices and their implementation into the facilities should be advanced, directly at the early stages. In the areas of controlling and concepts for virtual power plants, specific solutions must be found and tested to co-ordinate some hundred or maybe thousand facilities and to integrate different types of plants and peripheral energy systems. By participating in grid management, a *high benefit for grid stability and supply security* in the distribution grid can be provided through the interconnection of plants.

7.3 Support for the Realisation of Benefit Potentials of Virtual Power Plants

The realisation of the benefits of grid management through the integration of micro-CHP-plants implies that, besides grid extensions, these are perceived as an option by the grid operator. One essential item in this context is the respective *design of the quality regulation* in the area of incentive regulation. Additionally, a further transition to more *flexibility in balancing power and the compensation energy market* should be brought about. This would allow markets to emerge through which peripheral facilities could contribute to a larger extent to electricity balancing, even without the way over the transmission network. Additionally, the requirement that electricity must be sold to a third party as a prerequisite for receiving the *CHP governmental funding* should be removed, since, in some business models for virtual power plants, this leads to lack of funding, even though CHP electricity is produced and fed in. Furthermore, the *controllability of small facilities* is supported neither by the current governmental funding options nor by respective associations. In order to use the complete potential of the technologies, this support should be given at least in the intermediate term.

7.4 Configuration of Economic Framework Conditions

In order for the technologies to be accepted, it is important that producers, sellers, associations, and networking organisations provide sufficient *information*. Besides information for potential customers, this must include education of the trade and should be co-ordinated with the market introduction schedule of the devices. Moreover, it would make sense to increase the investment security for customers by offering *long-term contracting options* for the retrieval of fuels, e.g. natural gas. Since a respective communication infrastructure is necessary for the external co-ordination of the devices, it could be a good idea to offer *complete supply packages* including telephone, internet, electricity, and heat. In the case of a strong coalescence in the areas of telephone, internet, and energy, a legislator should check the necessary interweaving of the appropriate fields of law (e.g. regarding security standards).

According to the current regulation of taxes, charges, and subsidies, as well as the different governmental funding systems, a number of *market distortions* exist which should be removed wherever possible. In the area of the emission trading system, besides the more restrictive distribution of certificates, a *consideration of small plants* is reasonable for the intermediate-term. As for the short-term, instruments such as Joint Implementation, Clean Development Mechanism, and "white certificates" should be made more usable; this would require decreasing the bureaucratic effort and could be supported by the option to carry out projects in one's own country. *Tax regulations* such as "eco-taxes" should, as far as possible, be directly tied to the emitted amounts so that technology innovations could also be considered without adjusting the assessment base. The *funding systems in the context of the KWKG and EEG* are justifiable in terms of greenhouse-gas reduction targets, but include the danger of creating barriers for other technologies. Therefore, such systems should be continuously monitored and, if necessary, adapted. Fuel cell heating devices, with respect to their development status, should also be considered explicitely, once this becomes reasonable. In new funding programmes, other *complementary new technologies* with regard to the usage of renewable energies, like electricity storage systems, should additionally be adequately considered. Competition distortions in other areas of the energy industry should also be removed.

7.5 Configuration of Further Framework Conditions

Due to the lingering market dominance in the energy industry, it is important to guarantee that *grid access and feed-in of small power plants* be free of any discrimination. Furthermore, incentives should be provided to depart from the *priority principle* when operating a plant and modifications to the distribution mechanisms should be considered for cases of insufficient grid capacity. In the area of regional planning, the *extent of communal competences* must be clarified. In addition to the usage of regenerative energies, at least combining with CHP facilities should be prescribable. Furthermore, an adequate consideration of the fuel cell in the formulation of laws should be provided. Particularly, the technology is not explicitly mentioned in the KWKG, in the energy tax law, and in the regional planning laws of the federal states.

For the *implementation of the technologies in practice* a clarification must be made about the way in which the cost burden can be allocated if changing to *heat-contracting* in running tenancies. The changeover from pure heat production to a combined production of heat and power leads to conflicts with the tenancy law. Again, the allocation of investment and operation costs is questionable, as is the obligatory tolerance in existing tenancies. Because of the large administrative effort to directly supply the residence with electricity, it has to be assumed that it will be used for, respectively, the general home electricity or be fed into the grid.

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