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**LINKING DISTRIBUTED EUROPEAN
HYDROGEN PRODUCTION SOURCES**

**PART II: Analysis of Electricity Grid Development Strategies and
Constraints**

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Document Number: R2H2014PU

Date: 2 October 2008

The European Commission is supporting the Coordination Action "HyLights" and the Integrated Project "Roads2HyCom" in the field of Hydrogen and Fuel Cells. The two projects support the Commission in the monitoring and coordination of ongoing activities of the HFP, and provide input to the HFP for the planning and preparation of future research and demonstration activities within an integrated EU strategy.

The two projects are complementary and are working in close coordination. HyLights focuses on the preparation of the large scale demonstration for transport applications, while Roads2HyCom focuses on identifying opportunities for research activities relative to the needs of industrial stakeholders and Hydrogen Communities that could contribute to the early adoption of hydrogen as a universal energy vector.

Further information on the projects and their partners is available on the project web-sites www.roads2hy.com and www.hylights.org



ABSTRACT

This report is a deliverable of the Roads2HyCom project, which is studying technical and socio-economic issues associated with the use of Fuel Cells and Hydrogen in a sustainable energy economy. Within the project, several studies have been made related to the question of primary energy sources to produce Hydrogen. This report is one of three that looks at the linking of those primary energy sources, in this case focusing on the development of the Electricity grid itself.

Traditionally, electricity infrastructure is built vertically with a unidirectional energy flow from its central point of generation to the point of use. However, co-generation units and renewable energy installations are now becoming more serious players in the generation sector. The emergence of these energy sources, differently located to the traditional centres of power generation, and having their own different supply fluctuation characteristics, poses a not yet solved challenge to the grid in its traditional set-up.

What is needed is a more flexible, bi- or even multidirectional connection between energy producers and the energy consumers. Especially in the light of today's policies that strive for more efficiency in the production sector and attempts to internalise external costs by trading emission certificates, an increase of distributed generation can be expected which calls for a quick transformation of the traditional grid to a highly connected, multidirectional, fast-responding network for energy exchange. Micro-grids and virtual utilities are models for such a grid that can respond to changes of the flow of electricity, depending on the current situation of production and demand. If reliability and control issues can be solved, which is not an easy task in such highly complex systems; there is a great scope for cost savings due to a reduced transmission loss and a better integration of a growing renewable energy sector.

The emergence of Electricity as an intermediate vector for the production of Hydrogen further complicates the situation, in that new energy demands are added to the grid, and yet the production of Hydrogen introduces the possibility of buffering. The latter issue is explored in the Part III report, but it is important to understand future grid development in the context of Hydrogen production.



LINKING DISTRIBUTED EUROPEAN HYDROGEN PRODUCTION SOURCES

PART II: ANALYSIS OF ELECTRICITY GRID DEVELOPMENT STRATEGIES AND CONSTRAINTS

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1. Introduction

This report is a deliverable of the Roads2HyCom project, a partnership of 29 stakeholder organisations supported by the European Commission Framework Six programme. The project is studying technical and socio-economic issues associated with the use of Fuel Cells and Hydrogen in a sustainable energy economy. Within the project, several studies have been made related to the question of primary energy sources to produce Hydrogen. This report is one of three that looks at the linking of those primary energy sources. The three reports are:

- Part 1: Distribution Issues (Document R2H2013PU)
- Part 2: Electricity Grid Development Strategies and Constraints (this document)
- Part 3: Hydrogen as a Storage Device (Document R2H2015PU)

The conclusions of these three reports are summarised the Executive Summary (document R2H2012PU).

It is a common phenomenon for so called infrastructural sectors (especially in the area of “critical infrastructure”, i.e. power industry, transport and telecommunication) that they evolve from monopoly structures, which are economically centralized and most often state-controlled, to a set of deregulated, decentralized competitive legal subjects generally privatized. The process of decentralization is not only caused by the existing facilities becoming independent. A new player in the form of distributed resources has appeared in the power sector and will be outlined and defined.

As proposed by the European Commission, the description of distributed generation (“DG”) specifies it as integrated or autonomous use of small modular sources of electric energy by utilities, customers of power companies and private consumers or other third parties in applications which bring profits to the power system, to specific end users or to both these parties.

The distributed generation is based on two generally different technologies:

- A technology using non-renewable fuels, hydrocarbons in general (most often a gas), in gas turbines, piston engines, micro-turbines and fuel cells; most of the solutions currently proposed include heat/electricity generation (co-generation, tri-generation);
- A technology using renewable energy resources (RES) to gain heat (geothermal, solar energy collectors), and/or electric energy (small hydro plants, wind power plants, biomass and biofuels, photovoltaic cells, high-temperature geothermal sources).

At the current stage of RES and DG development, the focus is moving from maturity and competitiveness issues of technologies to co-operation of the new technologies with existing power systems. It becomes necessary to resolve fundamental



problems, such as how to integrate new sources with existing transport grids and how to prepare the field for future infrastructures of energy generation and transmission.

Safety and reliability of the energy market could be improved with RES and DG, but require new forms of co-operation for distributed sources within the grid structures.



2. Evolution and current state of the electricity sector

During the last 100 years the electricity industry evolved from separated (“island-like”) local structures to vertically integrated, monopolistic, most often state-owned structures. It is now experiencing a new change towards decentralized structures that connect competitive areas (generation, energy services) and natural monopoly areas (transmission and distribution grids). This significant decentralization of generation requires balancing of demand in real time and the need for continuous monitoring and effective control of the generating units.

Development of distributed sources originates from a series of advantages in technological solutions, financial competitiveness, operating versatility and environmental control. In principle, evolution of technology proceeds in two directions. The first direction includes small units using conventional fossil fuels (most often natural gas) to produce, in a combined cycle, heating or cooling and electricity. The other group covers sources based on technologies using renewable power resources: water, solar, wind, geothermal, and biomass energy. Combined small power generation units feature differentiated fuels and engines (gas turbine, combined cycle gas/steam unit, piston engine, fuel cell) addressed for the required heat and electric power levels. Modern cogeneration units are of high efficiency (80-90%), use primary fuel energy, are highly reliable, of small dimensions, low capital expenditure, modular construction and short construction time (or more precisely – in situ assembly time), and – most often – they are unmanned.

Since the “the petroleum shock” of 1973/74 and successive shocks and anti-shocks in the 70s and 80s, it was called in question the correlation between economic/social development and energy consumption. There have appeared suppositions (confirmed in practice) about potentials of “zero-energy-development” or even with reduced energy demand where resources are relocated in the best possible manner to reach minimized costs and to satisfy energy demands.

Nowadays, the supply side is greatly affected by distributed technologies (distributed resources – DR, distributed generation – DG) including those based on renewable energy sources (RES). This report is to evaluate the effects of development of RES and DG infrastructure, especially the consequences for electrical grid development and management. This evaluation will include the following factors:

- Legislation and regulations referring to the power sector,
- Trends of electricity demand growth,
- RES and DG penetration depth expressed as the share in total electric energy generation,
- Structures of technological options in RES and DG,
- Development tendencies for individual RES and DG technologies,



- Development of grid infrastructure (at all voltage levels) related with RES and DG integration.

The large number of generating units of small and very small installed power levels and highly differentiated operating characteristics of these units create fundamental problems in controlling the grid. The diverse structures in DG - from small residential units to large stationary power plants - are monitored and co-ordinated by a control centre and business operator. Due to the complexity of these systems, an extended control of all components and their power output distribution in the grid is required. Today's possibilities to control and monitor via internet connections creates new opportunities for the control and integration of DG systems.

2.1 Strategic goals

Modern society is strongly dependent on energy and it is inevitable to have discussions and controversies in a time where "peak oil" is feared and prices have risen significantly over recent years. Although there is much debate on the application of fuels, the technologies used to process them, power industry structures, legal regulations and also financing rules for this sector, there seems to be a common consensus about the strategic targets of the power industry:

- To minimize energy prices paid by end-users and
- To ensure security of supply for the country.

Unfortunately, these targets are to some extent conflicting each other; for example, (i) the technologies with the lowest emission of pollutants ("environmentally friendly") cause higher costs, (ii) to ensure safety, energy shall be supplied from various sources, so deviations from the lowest-cost (or cost-ideal) solutions need to be made.

2.2 European energy policy

The European Commission had presented a comprehensive set of documents related to the energy sector, "The Energy Package" [1], on 10 January 2007 in which it addresses energy policies to improve competition, security of supply as well as climate and environmental protection [2]. The European Council has largely confirmed this package on this year's first meeting at the beginning of March [3]. On the EU Summit the heads of state and government of the 25 member countries laid down guidelines for an integrated climate protection and energy policy and passed an action plan called "Energy Policy for Europe" that supports objectives of strategic EC documents of January 2007 in which it tries to tackle the demand for energy world-wide, rising dependency on energy imports and global climate warnings.

In short, the package is called "20-20-20 by 2020", meaning 20% reduction of greenhouse gas emissions, 20% share of RES, and the increase of efficiency by 20%. All this by the year 2020.

Despite all the need to act politically, one fact from the perspective of a company operating Europe-wide must not be left unmentioned: To secure energy supplies in Europe it is also important that the distribution of roles between business and politics



be preserved. In the future it will continue to remain primarily a task of companies to ensure the security of external energy supply for Europe and to take on the challenges on international markets with strategies which comprise both cautious long-term action to secure energy supplies as well as the ability to respond flexibly to short-term changes in the security situation. In the future the companies must continue to commercially represent the diversification of energy sources, suppliers, transportation routes and types of transportation, to maintain and extend the required infrastructures with high levels of investment, and to maintain Europe as an attractive market for energy suppliers in competition with other importing regions [5-15].

2.3 Generation technologies – model of centralized power plants

Various sources indicate that no substantial change in the current energy supply structure can be expected in the next 20-30 years [16, 25]. It can therefore not be expected that emissions from the power sector will be significantly reduced by the increased use of renewable energy sources (RES). Within the next few decades, the market will be still dominated by traditional, fossil fuel based technologies. Two classes of technologies need to be mentioned here: those based on coal and those based on hydrocarbons – subject to further advances in coal technologies (with PC and FBC boilers), integrated gasification combined cycle systems for solid fuels (IGCC) and combine cycle gas turbine systems (CCGT).

2.3.1 Nuclear technologies

Redefinition of views about nuclear power engineering stemmed from searching for alternative solutions in low or even zero-emission technologies, operating reliability, and the cost competitiveness of already paid-off reactors. Also, there occurred a psychological turning point in social acceptance due to the increase of energy prices and the fear of black-outs.

Now new generation reactor types are in discussion (Gen-IV) but have not been build and proven yet.

2.3.2 Gas technologies

Higher efficiencies of the power plants and a lower CO₂ emission per kWh make gas a popular option in today's power production portfolio. However, as with oil an increase of use means also an increase of dependency in its supply. Recent political developments in Russia (a major gas supplier to the EU) and subsequent quarrels in that geographical area give a taste of possible future issues.

Technically interesting are also gas application for cogeneration sources of low and medium power – the mentioned proposal to create a renewable/gas segment [26] of distributed generation shows high-efficiencies and reliable and versatile technologies. These features are inherent for systems using both gas turbines and gas piston engines.



2.3.3 Coal technologies

There are many indications that coal as a fuel for power plants will maintain its strong position on the market, especially in Poland, within the next twenty years.

Although on a global scale, the use of coal is anticipated to be reduced, its domination of the fuel market is still reality in many countries. Even the impressive development of the renewable/gas sector (its share in electricity generation increased fivefold [27]) does not change the quasi-monopolistic position of coal (with the share of about 70%) in Poland. This is also the situation in many other European countries.

This is based on numerous reasons: coal is cheap; energy from coal costs much less than those from hydrocarbon fuels; coal is abundant; resources are big and relatively uniformly spread over all continents – this is an important aspect in the context of security of supply.

The coal industry is currently developing concepts for new technologies, some of them being:

- Hybridisation with new technologies (especially fuel cells)
- More effective coal combustion
- Multi-product processes of coal fuel conversion (heat, electric energy, cold, chemical synthesis products, hydrogen)

There is little doubt that coal will remain the number one fossil fuel used in production of electric energy (about 30% share in electricity generation in EU). This is also acknowledged by politics, stating: that a “predominating part of future increase of energy consumption will be covered by coal fuel (...). Coal is and will stay the main factor ensuring safety of electric energy supplies in EU(...). Even when we assume that the strategy for increase of energy efficiency and use of renewable sources would be progressed, coal should stay, during the next decades, an essential alternative enabling to cover the main demand for electricity which would not be fulfilled by renewable sources. Coal may still provide a valuable contribution to safety of energy supplies only when such technologies are used which enable drastic reduction of carbon dioxide emission and ensure high efficiency as well”. [1]

Unfortunately, there are some major drawbacks attached to coal: high emissions of CO₂ and other pollutants are a continuous problem of this energy source and due to more and more restrictive regulations coming in place, also an increasing problem.

Capturing and sequestration of carbon dioxide (CCS) is the available critical technology that is able to reduce considerably coal emissions and to allow for covering global demand for energy at the same time [28, 31]. The Technological Platform for Natural Fuel Zero Emission Power Plant (ZEP), a program initiated by the power industry, announced plans for constructing 10-15 coal power plants as an experimental ground for various CCS technologies in industrial scale, aiming at a commercial profitability of CCS technology in the next 10-15 years. However, CCS technologies have not yet been proven on a large-scale, neither exist realistic case-



studies or LCAs for the entire production chain (capturing, transport, sequestration, storage) which seriously questions the proposed timelines for commercial availability.

2.4 Traditional grid – centralized model

The development of Trans-European Grids (TENs) (including electric grids) constitutes an element of integration. It contributes to establishing an international market by expanding the exchange potential, providing access to a larger market of competitive power. The reason is that by opening the internal energy markets (IEM) there will be an increase of trans-border electricity exchange, at the same time raising the exchange volumes and making power flows more dynamic.

Available transmission capacities are currently determined on the national level, using national rules and definitions, which frequently may be considered as too conservative. These rules and definitions need to be reviewed to determine whether current transmission potentials for interconnection could be increased. In order to ensure proper operation of the extended European market, it is equally important to have adequate infrastructure interconnecting the member states as well as sufficient rules and standards.

EU-policies identify a number of grids, which are, based on history, not yet sufficiently linked with electrical interconnections, e.g. the Baltic Energy Ring: Germany-Poland-Russia-Estonia-Latvia-Lithuania-Sweden-Finland-Denmark-Belorussia [48]. There are, therefore, priority actions to further develop a European internal market of electricity and gas.

These are:

- *European Transmission Grid* – “consumers need a unified European grid in order a real European energy market could come into being”.
- *Plan of priority interconnections* – “the chiefs of countries and governments agreed to increase the minimum levels of interconnections between member states up to 10%. A real, competitive, uniform European market could not exist without additional physical power; this is of special importance for Baltic Countries. Infrastructure investments need some stimulation; the higher number of interconnections in European electricity transmission grid, the lower will be the need to keep power reserves, and the lower – with time – will be the costs”.

It needs to be noted that the transmission infrastructure often serves for the functions which are not directly related to the system management needs, and current trans-border connections are not sufficient to create effective competition to the scale of an internal market of the EU. Improved access capabilities for energy transmission over borders of national power systems would allow for more competition in the common market, but especially in the co-operation between UCTE countries and the 13 countries of post-Soviet era there are open questions about how a synchronous operation of electrical power systems of these countries is possible and what the related costs would be.



2.5 Effectiveness of electricity use, energy management

Further to the Directive of European Commission on effectiveness of electricity use, there was issued the document named “Action Plan” [4] presented on 9 October 2006 by European Commission and evaluating the potential of total energy savings in final use to the horizon of 2020 and with division to four selected sectors (table 1).

The goal specified in the Directive on energy effectiveness – “energy saving of 9% in the ninth year of implementing the Directive” – takes a more ambitious level, i.e. 20% basing on the total saving potential in this time horizon. This goal is to be reached for the scenario which assumes 2.3% increase of annual gross national product in EU countries (treated as the whole) and for 0.5% of the annual rise of energy consumption. Intensity of energy use is to be reduced by 3.3% per year, and according to Table 1, the total energy saving potential shall reach 354 Mtoe in 2020.

Table 1: Evaluation of energy saving potential

Sector	Energy consumption [Mtoe] 2005	Energy consumption [Mtoe] 2020 (business-as-usual scenario with no energy saving actions)	Energy saving potential 2020 [Mtoe]	Total energy saving potential 2020 [%]
Households	280	338	91	27
Commercial buildings	157	211	63	30
Transport	332	405	105	26
Manufacturing industry	297	382	95	25



3. Cost of electricity

3.1 Costs and prices

Electric energy is a product/service of special nature, and the electric energy market is an exceptional real-time market where supply and demand are balanced on an ad-hoc basis. Four basic methods of electric energy pricing may be classified:

- Cost-related
- Supply-demand related (market based)
- International comparison based
- Utility value based

The two first methods are of practical importance, the supply-demand method being generally used as a complement of the basic cost-related method. Evaluated costs are the grounds to prepare prices and tariffs for energy and its management. Utilities have various costs, which are traditionally classified as the “fixed” and “variable”. Production of electric energy represents especially high capital expenditures, so the structure of costs is here of paramount importance [34,35].

A three-part cost structure is generally assumed for pricing purposes:

- Costs referred to energy consumed by energy users
- Costs referred to the delivered power
- Costs resulting from connecting the user to the grid and from their supplies

When tariffs are created, it is necessary to consider not only the running and averaged costs, but also so called alternative costs like marginal costs. Long-term marginal costs allow estimation of future costs, depending on the choice of energy consumer for a product.

As opposed to long-term marginal costs (LTMC, reflecting developments of the entire system), short-term marginal costs (STMC), are based on the constantly installed power in the system and can reflect short-term system load variations.

The opening of electric energy markets requires for the utility to separate their grid-related activities from their trading business. As a result the public gets to see information and costs of grid-related activities (“operator’s tariff”) and energy prices separately.

Depending on the market model, prices are established; thus, on the *wholesale market*, there are contract prices (as a result of agreement of the parties entering into contract for energy supplies), exchange prices (which determine the balance level price, i.e. the clearing price at the electric energy commodity exchange), and



balancing market prices (managed by the utility) resulting from increment and decrement offers submitted.

On the *retail market* there are two market segments: the competitive market and the regulated market. In the case of the competitive market, the demand side is represented by consumers authorized to use the third party access rule (TPA), i.e. to buy energy from a supplier of their choice (these rules are the same on the wholesale market). In the case of the regulated market, trading is made between distributing companies and non-authorized consumers (or those who do not want to use the TPA rule). Pricing in this market segment is controlled by regulators. In table 2 current fuel and electricity prices are compared for European countries and the USA.

The basic factor influencing the costs of electricity as follows:

- Prices of energy at the international wholesale market
- Cost of production, processing, transportation and distribution
- Energy policy of the particular country

In many countries fuels and energy are also partly subsidised.



Table 2: Fuel and energy prices in the EU and the US.

Country	Gasoline [EUR/litre] ¹⁾	Natural Gas [EUR/kWh] ²⁾	Electricity [EUR/kWh] ³⁾
Austria	1.17	0.08	0.27
Belgium	1.36	0.08	0.24
Bulgaria	1.00	0.03	0.07
Croatia	1.09	0.03	0.18
Czech Republic	0.94	0.05	0.23
Denmark	1.36	0.19	0.27
Estonia	1.33	0.04	0.08
France	1.06	0.09	0.23
Germany	1.17	0.09	0.33
Greece	1.18	-	0.12
Hungary	1.36	0.04	0.15
Ireland	0.96	0.11	0.46
Italy	0.96	0.07	0.13
Latvia	1.18	0.03	0.07
Lithuania	1.08	0.04	0.10
Luxembourg	1.50	0.06	0.22
Netherlands	1.17	0.10	-
Norway	1.37	-	0.36
Poland	1.16	0.05	0.15
Portugal	1.09	0.08	0.19
Romania	1.09	0.03	0.11
Slovakia	1.30	0.08	0.22
Slovenia	1.43	0.06	0.23
Spain	-	0.07	0.30
Sweden	-	0.11	0.29
United Kingdom	-	0.04	0.17
USA	0.54 ⁴⁾	0.03 ⁵⁾	0.07 ⁶⁾

¹⁾ Premium unleaded gasoline, 95 RON, price at pump, all taxes included, based on half-yearly prices, second half of 2007; source: Eurostat

²⁾ Natural gas, higher heating value, domestic consumers, consumption band <20 GJ/year (=555.6 kWh/year), all taxes included, based on half-yearly prices, second half of 2007; source: Eurostat

³⁾ Domestic consumers, consumption band <1000 kWh/year, all taxes included, based on half-yearly prices, second half of 2007; source: Eurostat

⁴⁾ Premium unleaded gasoline, U.S. City Average Retail Price, all taxes included, 2007 average price, based on currency conversion rate of 2007-12-12 (0.6802, nominal rate); source: US Energy Information Administration; conversion rates: Bank of Canada

⁵⁾ Natural gas, residential consumers, 2007 average price, based on currency conversion rate of 2007-12-12 (0.6802, nominal rate); source: US Energy Information Administration; conversion rates: Bank of Canada

⁶⁾ Average retail price of electricity to ultimate customers, residential consumers, 2006 average price, based on currency conversion rate of 2007-12-12 (0.6802, nominal rate); source: US Energy Information Administration; conversion rates: Bank of Canada



3.2 External costs and its internalization

Producing energy also involves external costs that go beyond the sole cost of electricity production, including costs of system services, environmental control and transmission. The methodology proposed in [26] reduces the cost of system services¹, maintaining reserves, and costs of emission losses to the costs of CO₂ emission certificates (according to the value recommended by European Commission). table 3 summarizes the external costs (CO₂ emission, power capacity reserves, transmission) in minimum and maximum CO₂ emission versions (10 and 40 €/ton in product perspective, respectively). Such perspective allows reference prices of electricity supplies (sales/purchase) for final consumers to be determined, as resulting from various power generation technologies applied.

Cost analyses were made for four system technologies (centralized, interconnected with transmission grid), three cogeneration technologies with diversified power rating and three integrated renewable/gas technologies as a case-study based on the situation in Poland [26]:

- Nuclear power unit with power rating of 1000 (1500) MW interconnected with nodes of 400 kV grid spread over the territory of the whole country (technology which requires large grid-related capital investments).
- New lignite-fired power plant, located beside deposits of this coal near Legnica, provisionally called Legnica Power Plant (technology which requires large mining- and grid-related capital investments).
- Lignite-fired power unit with power rating of 880 MW, for instance in Bełchatów II Power Plant (technology which requires moderate mining- and grid-related capital investments).
- Hard coal-fired power unit with power rating of 440 MW, for instance in Łagisza Power Plant (technology which is oriented to market supplies of hard coal and which requires small grid-related capital investments).
- Gas-fired co-generation source with power rating of 15...50 MW_{el}, interconnected with 110 kV grid (in such case, the reference source could be PEC Siedlce).
- Gas-fired co-generation source with power rating of 1...7,5 MW_{el}, interconnected with medium voltage grid (in such case, the reference source could be EC Harcerska constructed by Energetyka Ciepłna Opolszczyzny).
- Gas-fired co-generation source with power rating of 60...400 kW_{el}, interconnected with low voltage grid (in such case, the reference source could be EC Tuchów constructed by Polskie Elektrownie Gazowe).

¹ Which include control of frequency and exchangeable power, control of voltage levels and reactive power distribution, control of power reserve with differentiated access time and taking part in system restoring after catastrophic failure – black start capability



- Wind/gas power plant using natural gas. (The reference could constitute the project for northern/eastern region of Poland, where for system related reasons, peak load sources are necessary and where good conditions for wind power engineering exist at the same time)
- Combined bio-methane technology including biogas generation station and local co-generation source, or biogas treatment plant and a station connecting bio-methane system with natural gas grid. (In this case there is no reference yet on the market)
- Small hydro-electric power plant. (A reference project for this case may be one of power plants in ESP Capital Group for Upper Odra River, e.g. the latest Krapkowice Power Plant)
- Fuel cell (In this case, the fundamental importance lies in the determination of characteristic, model conditions within which the fuel cell would be used in the future)

The reference prices are calculated for the electricity supply via four different grid types.

- Low voltage grids with sufficient transmission capacities for end-users
- Medium voltage grids with sufficient transmission capacities for end-users
- Low and medium voltage grids for rural areas with insufficient transmission capacities for end-users, requiring modernisation (which on the other hand creates opportunities for the introduction of distributed generation and storage)
- The 110 kV grids (with possible division to closed grids operating in closed sections and radial grids)

Prices will consider:

- External environmental costs (by taking into account the external environmental costs, related for instance with CO₂ emission, to distribution of CO₂ permits)
- Pricing of system services
- Transmission

Results of initial calculations are presented in Table 3 [26].



Table 3: Total external costs (environment, services and transmission) vs. type of power plant in €/MWh

Power plant (fuel)	Costs of CO ₂ emissions		Costs of power reserves	Transmission costs	Total	
	min	max			min	max
Nuclear	0.00	0.00	1.54	6.36	7.92	7.92
Lignite	11.49	45.97	1.19	5.28	17.97	52.44
Hard coal	10.87	43.48	1.08	6.18	18.12	50.73
Nat. gas 20-50 MW	6.57	26.27	0.58	-5.73	1.41	21.12
Nat. gas 1-7,5 MW	5.75	22.98	0.45	-6.81	-0.60	16.62
Nat. gas up to 0,4 MW	5.75	22.98	0.26	-16.47	-10.47	6.78
Wind/gas	4.60	18.39	0.05	-11.43	-6.78	6.99
Biomethane	0.00	0.00	0.16	-37.38	-37.23	-37.23
Small hydro	0.00	0.00	0.85	-25.89	-25.05	-25.05
Fuel cell	5.75	22.98	2.09	-37.38	-29.55	-12.30

From table 3 it can be conclude that using external costs is a possible means to identify reference costs for a variety of power generation technologies. For example, the best technology from an economic point of view (given that costs of CO₂ emission certificates are 40 €/t) is co-generation with biomethane. The most non-efficient technology, on the other hand, are lignite fired power plants.



4. Looking into the future

4.1 Distributed generation and future grid infrastructures

The current grid infrastructure in Europe has grown over more than a century and is best characterised by centralised generation and high voltage transmission systems. End users are supplied via local high-, medium- and low-voltage distribution grids. It is a unidirectional system where energy is distributed vertically top-down rather than horizontally or even bottom-up. The European electricity grid relies on the interconnected generating capacity of the whole of Europe (UCTE grid) to supply balancing and peak power to stabilise the grid in view of the fluctuations in electricity demand. This increases the security of supply whilst lowering the costs of grid failure. It also requires a structured and centralised grid management.

Since the liberalisation of the energy markets, it has become necessary to privatise parts of this infrastructure (operation of transmission and distribution grids) in order to fulfil the required transparency and non-discriminatory access of new market players. In the near future, the electric utilities might continue to control the distribution system, but in the long term, manufacturing, turnover and sales, as well as energy services, could become competitive elements offered to energy markets by new players.

Changing the unidirectional energy flow into an interactive, bi-directional system will require fundamental changes to the conventional transmission and distribution grids. This applies to the 'conventional' distributed generation as offered by independent power producers (IPP) from combined heat and power generation (CHP) at scales from few hundred kW_{el} to several MW_{el}, as well as to 'micro' units grouped into 'virtual power plants' (residential CHP and photovoltaic arrays) and large renewable energy developments (wind farms on- and offshore, large PV arrays, biomass fired plant etc.). All these will be summarised by the term 'distributed generation' in the following.

“Distributed generation will play key part in this new conception of the sector by using a wide range of technologies and bringing small scale generating sources closer to the customers. Pretty large dynamics are observed for highly-effective combined heat and power sources as well as reserve and peak load systems. Together with renewable energy sources, new technologies make use of potentials created by the market and enlarge competitive power of the total economy. A complete integration of renewable and other sources needs to occur to show the way to the power engineering of the future based on balanced development rules and substantial use of distributed generation” – as concluded by the European Commission in 2003 [49].

In general, distributed generation reduces transmission and distribution losses that constitute a substantial component (approximately 10%) of the total electric energy production. Despite this obvious advantage, it will still require a tremendous effort to transform the current grid structures. It will be necessary to undertake an initiative of a European Electricity Distribution Roadmap – an iteration process that integrates technologies of generation, transmission, distribution and use of electric energy contextual with their social, economic and regulating aspects [7].



4.1.1 Integrating Large Scale Renewable Electricity Production

Wind power plants are a component of a wider set of renewable sources (RES) of especially high fluctuation dynamics [37, 40]. Therefore, we will discuss wind power in the following as a proxy for other large scale RES development in Europe.

Within the period 1995-2005, the global installed wind power grew from 5 to 59 GW. In particular, large progress has been made in Europe where the wind power share in total electricity generation volume was, for example, 6.4% in Germany in 2007 [51]. Regionally, wind delivered 33% (Northern Germany) and over 28% (Western Denmark) of electricity consumed in 2006 [50].

Since on-shore opportunities for large wind plant are increasingly difficult to develop, efforts have focused on offshore wind farms. A large number of these units are currently being planned, expecting stronger and more persistent winds than on-shore.

Wind farms constitute a challenge to the existing grids as power output fluctuates with strong positive and negative gradients in production. In addition, most of the large inland wind farms and all of the planned offshore projects are (naturally) located in areas with low electricity demand and subsequently underdeveloped grids. These problems grow with higher penetration of wind energy and a larger amount of installed power and generation capacity [50]. Especially the planned offshore farms with GW-rating will require strengthening of onshore feed-in nodes and the transport capacity from the coasts to the inland power consumption agglomerations.

The challenge for grid operators is therefore twofold. On one hand they need to integrate an unpredictable yet powerful contribution to electricity production. On the other hand, this contribution often accesses the grid at its weakest point: the remote areas where only the thinnest branches of the hierarchical electricity networks reach.

The first point can be assisted by implementing prediction and forecasting of wind energy production as a means of reducing the uncertainty of wind power production. Weather forecasts have been applied in electricity grid and power production management for decades in order to improve matching of electricity production and consumption. Nevertheless, there is no alternative to extensive grid reinforcement programmes due to recurring theme of location of renewable feed-in at 'the wrong end' of the grid structures.

Electricity producing renewable generators are a concept which traditional networks have not planned for and are little prepared to cope with. Whereas the traditional distribution systems relied on uni-directional flow of energy, renewable energy production reverses the direction of power flow. This causes a number of technical issues, although it needs to be said that "soft issues" like the lack of operational experience or reluctance of network operators to change working protocols or re-train staff add to the slow and difficult integration of renewables.

Network reinforcement progresses at very slow pace in many areas which has to do with high investments the grid operators are reluctant to tackle, but also the fact that in some areas wind projects are being built faster than transmission systems can be modified or strengthened, given the necessary lead times for planning and obtaining building permits.



The following calculation shall serve as an example for the challenges to come: when large anticyclones drift over Europe in winter, an area of several hundred square kilometres is usually affected by this weather situation, resulting in low or no wind for several days in this zone. In order to fully substitute the area covered by the anticyclone with wind electricity from a different region in Europe, wind energy would have to be 'transported' over a distance of several hundred kilometres [52], i.e. power production in another European region would need to serve as backup.

Clearly, the strengthening of transmission lines over such distances will be very costly and the use of conventional generation capacity within the system much cheaper. Moreover, since weather incidents are of a rather statistical nature, increased transmission capacity would have to be supplied along all major electricity transport trajectories Europe-wide. Conventional balancing and reserve power would also be cheaper than any kind of storage of wind energy in the affected area. It does not mean, though, that, following this example, for every kW of wind energy capacity there needs to be a conventional kW capacity in the background.

On the contrary, it is not expected that increased wind generation will equally induce an increased reserve requirement. Added wind generation capacity leads to an overall increase in the total capacity of generation [52], [53]. A larger share of renewables in the grid will free conventional capacities in other areas in Europe, underlining the need to generally strengthen the grid, not for the purpose of replacing wind energy shortages with wind energy, but to allow a more flexible load response, i.e. have a better levelling between different parts of the European grid, and having more renewables integrated into the network. This is important in situations when demand is higher than conventional supply, when the capacity credit of wind energy can be as high as 40% of the installed wind power capacity in areas with low wind energy penetration [50] or only 6% in countries like Germany with a high wind energy penetration [53]. A strong grid is also important in situations when supply is larger than demand. A well interconnected grid can compensate fluctuations in both directions, transferring electricity from high-production areas into other high-demand parts of the grid or enabling reserve power to reach the affected areas. Denmark is a good example for such a great level of interconnection in the grid and the resulting flexibility. With a wind energy penetration of 16% and a highly interconnected grid Denmark has not yet needed to curtail wind output, whereas the Greek island Crete has to keep large amounts of conventional generation capacity with a wind energy penetration level of only 10% due to the fact that Crete is completely isolated from all other mainland electricity systems (see Table 4).



Table 4: Comparison of interconnectivity of grids in Denmark and Greece with high wind energy penetration levels [50]

	Eltra System, Denmark (2001)	Crete System, Greece (2001)
Total conventional generation capacity [MW]	4724	570
Total wind capacity [MW]	1932	70
Installed wind capacity penetration	29%	11%
Wind energy penetration	16%	10%
Transmission capacity to other networks [MW]	2640	0

Studies for Germany indicate that for the integration of the anticipated wind energy generation capacity by 2015, about 400 km of high-voltage power lines would need to be reinforced and 850 km newly built which equals roughly 5% of the existing stock. At that time about 20% of the generation capacity would need to be maintained as reserve capacity in the system which could be covered by existing conventional capacities [53].

In the project of Trans-European Energy Grids (TEENs) marine sub-grids connecting distributed wind farms are an essential component. DC cables resistant to operation in marine environment and high temperature superconductivity cables (HTS) are seen as promising solutions in collecting electrical power offshore and delivering to specially strengthened nodes onshore located closer to consumption concentrations (e.g. Rotterdam, Hamburg, London, etc.). This would reduce the necessity of adding Trans-European transport capacity at a large scale but nevertheless poses very similar requirements on grid integration and interconnection for the sake of the security of electricity supply.

As to the role of hydrogen in transporting electricity in Europe, see Part III (R2H2015PU) of this report. Generally speaking, though, grid reinforcement or building new transport capacity on-shore will always be cheaper than producing hydrogen. This follows directly from the conversion efficiencies involved in the process. Nevertheless, if excess production from fluctuating renewable sources becomes a regular occurrence, hydrogen production for transport fuels or industry gases could become a business opportunity, also adding the aspect of supplying balancing power through additional load management. When wind farms are treated as micro-grids in such circumstances, they could also be “islanded” to protect the rest of the grid [54] and the electrical power output turned to chemical energy.



4.1.2 Superconducting cables

The discovery of high-temperature superconductivity in 1980s was a strong positive pulse in the process of applying superconductivity techniques to practice. Superconductivity is a phenomenon occurring in certain materials at very low temperatures, characterized by exactly zero electrical resistance and the exclusion of the interior magnetic field. Normally only observed with very low temperatures, new materials (“high-temperature superconductors”) display this phenomenon at up to 138K (-135°C) making a possible commercial application more realistic.

The reason is that for electric power grids, the problem lies in the losses resulting from the field of their own current when the intensity of an external magnetic field is low. It is expected that high-temperature superconducting cables, cooled with liquid nitrogen and operating at temperatures around 80K, will be applied in electric power cables. Typical fields of application for these cables are power supply of urban areas with high population density. The properties of HTS (high-temperature superconductors) cables allow transmission capacities of existing cable ducts to be increased. HTS cables could be used as DC (direct current) submarine cables for interlinking or connect offshore wind farms to the grid.

Once the costs are more competitive commercial use of this technology is anticipated by 2025 [14, 41, 44].

4.2 Architectures of future electric power systems: micro-grid and virtual utility

A higher share of distributed sources in the total volume of output power essentially modifies the distribution functions of grid infrastructures [54]. The distribution grids must be designed and operated as an integrated structure, with multi-user operation capability and sufficient information exchange. Three main models are presented:

- *Distribution micro-grid* of local nature, which interconnects numerous customers with numerous generators and energy accumulating units. The micro-grid model is a characteristic solution for autonomous (island-type) systems for energy supply where supply from a transmission grid is economically unjustified. It is also possible that the system co-operates with transmission grids under regular operation and is switched over to island-type operation under system emergency state [36].
- *Active grid* is a model based on the existing passive distribution grids. It has the ability to stimulate development of distributed sources during an initial stage of power sector deregulation. Two innovative concepts are the basis for an active grid: redundant connections between generating nodes and receiving nodes of the distribution grid as well as a bi-directional information exchange with the customers.

While traditional grids are neutral in the case of disruptions on the demand (customer) and supply (generators) side, an active grid tries to react in such situations. As opposed to the linear radial paths having been used so far, the active grid features much more complicated and expanded structures of connections based on relatively small areas of monitoring and control. This allows for effective management of grid limitations including reversing the flow directions according to the current needs. Active management of flows is



also a result of power electronic control systems (like FACTS). Although close coordination between local operator's centres limits the effects of breakdowns at the level of individual components, it would not prevent from a "domino effect" which is a typical threat for sophisticated systems.

- *Internet model* is an expanded version of the active grid model from local to global scale. Information flow via www/Internet makes it possible to implement the idea of dispersed control where each grid node (provided with communication / IT hardware) operates autonomously within the global context. The vision of the internet model is identified by the following description: "Each node of power grid of the future shall be watching, reacting, adapting, sensible to economic and ecological factors, operating in real time, versatile, resistant to disturbances and connected with all other nodes. The data exchange protocol agreed for information about energy demands and available sources to cover them shall enable to control distribution subsystem of large dispersion scale. Each node, while watching the behaviour of the whole grid, adjusts its own level of generation/demand in relation to the general system status" [7]. The level of flow control goes down to individual flat consumers – there are already control systems for home consumers which, for instance, modify thermostat settings to reduce demand in peak hours of the system. The Internet model features easy expansion capabilities while standardisation of its elements and interfaces allows to use the plug-and-play rule.



5. Future challenges

To transform the current generation infrastructure to one that integrates distributed and fluctuating renewable generation in an optimal way, a lot of work and effort will be necessary. Strategic studies are required to understand how CO₂ emissions can be reduced and how much the restructuring process might cost. Special attention needs to be given to the issues of energy supply reliability and quality when decision centres are dispersed, operating procedures are of substantial complexity and when a new statistical variability of power flows is introduced.

Grid enforcement and the increase of Tran-European transportation capacity is an essential issue in improving the capability of the European UCTE grid to cope with large fluctuations in power caused by failure of central, conventional generation capacity (as seen frequently within the past decade, e.g. [55]) or by massive fluctuating renewable power input. The enforcement will be necessary in any case in order to improve the interconnection of the Western and Eastern grids [53], no matter whether renewable generation capacity is added or not. Large scale RES integration will require additional grid capacity in some regions, especially coastal areas, though.

Reliability and quality become an issue when dealing with a much more complex infrastructure than those in traditional grids. Introduction of sources at distribution grid level causes power flows to change their values and directions which affects operational stability and quality of electric energy. Quality of energy is a notion which defines interactions between producers and consumers, and the admissible parameters which define this quality depend on the segment of consumers under consideration. Increasingly often the quality parameters are tailored according to the customer's sensibility; the introduction of local generation or energy storage systems may become a natural way of meeting sensitive customer expectations. Large amounts of different power sources allow the operator to react quickly in order to balance active and reactive power at local level and to compensate the effects of unstable customer demand.

Power system control techniques must take into account the increasing complexity of power systems as well as a certain non-determinism of their operation. New control concepts and strategies must guarantee consistent operation of the unified European transmission grid. A specific feature of new generation structures is the potential to interchange the ability of producer/consumer functions at the distribution level using distributed generation. Such structures need to use interfaces enabling cooperation with local supervisory control and data acquisition (SCADA) systems, distributed control systems (DCS) and Internet links.

Technologies which are the basis for developing interactive infrastructures of energy supplies must also ensure a required quality and the safety of supplies (locally customised). An essential part among these technologies would be assigned to energy storage systems. Storage is an antidote against variability and the inability to predict the precise output of renewable energy systems.

Existing technologies of electricity storage cover a wide range of solutions – from traditional electrochemical cells up to superconducting magnetic systems (SMES) and inertial systems. A promising means of energy storage is hydrogen used to



balance loads even for season-to-season variability. By this the capital expenditure necessary to provide generation capacities is reduced.

An equivalent treatment of energy sources and storing systems is symbolised by an introduction of the term “distributed energy resources” (DER). A substantial progress has been made in information and communication technologies (ICT) and dedicated power electronics systems (like FACTS). Wide-band data transmission over power transmission lines provides communication potentials necessary for implementing new system management concepts and new offers for consumers.

Economics and regulation create new challenges for the system including substantial shares of distributed resources. New technical solutions will reduce the cost of connection and operation, but the existing infrastructure must be used much more intensely while managing both supply and demand sides according to general requirements of system dynamics. These new conditions constitute not only engineering challenges but require new methods applicable to load system components, to offer system-related services and to react to market-generated signals during disturbances. There are no adequate models for the market, regulation and tariff generation that could cope with new challenges of evolving power system at the distribution infrastructure level. Further analyses are necessary for evaluating the competitive power of new source. An important part lies also on the side of standardisation and legislation.

5.1 Necessary actions

The development of a distributed generation (DG) infrastructure is a prerequisite for the growth of other technologies such as:

- Fluctuating renewable energy sources
- Co-generation and poly-generation
- Fuel cells and hydrogen systems

To put this development into practice a total and effective integration of distributed generation via connected grid (“New Unified European Electricity Grid”) is as necessary as the transformation of traditional infrastructure of energy and power supplies into interactive (customer/operator) services-providing grids.

There are still many factors of uncertainty in the short-term and long-term development of DG, such as policies and legislation or the general technological development on all voltage levels in the grid.



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