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Highly Efficient Distributed Generation and High-Capacity Energy Storage.

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This paper is dedicated to the memory of our co-author and friend, Prof. Toshko Zhelev, who passed away on 21st August early in the morning, 2011.

ABSTRACT

With the growing amount of decentralized power production the design and operation of the grid has to be reconsidered. New problems include the two-way flow of electricity and maintaining the power balance given the increased amount of uncertain and fluctuating renewable energy sources like wind and solar that deliver electricity to the grid.

Solution directions are the development of smart grids, demand side management, virtual power plants and storage of electricity. These are directions that, rightly so, are already attracting a lot of attention and R&D funding. In this paper critical issues are identified and specified. However, we will also explore new solution directions based on an integrative approach as proposed by the Dutch Royal Academy of Science foresight committee on renewable energy conversions. These alternative solutions include flexible coproduction and local production of chemicals and fuel that can also fulfill a storage function.

1. Introduction

In the past decades we can observe a trend towards decentralized electricity production known as Decentralized Generation or DG. An important reason for this trend is the development of renewable energy sources such as wind and, to a lesser extent, PV solar that convert locally available renewable energy sources into electricity. With the development of distributed renewable energy conversion technologies a shift from central to decentralized electricity production is occurring. Furthermore, also distributed generation based on fossil fuels has developed in combined heat and power(CHP) applications. In fact CHP in the Netherlands for example constitutes up to 40 % of total electric power production. However, we should take into account that renewable energy is a different source of energy than fossil energy with a fully different character. Solar and wind are characterized by their fluctuating and discontinuous nature. This poses additional problems to the transition from central to distributed generation and from fossil- to renewable energy.

The often proposed and obvious solution for the fluctuating and discontinuous nature of renewable energy is storage. Demand side management, and the development of so-called smart grids are other research directions in which a solution can be found. In this paper we will also propose other possibilities.

Inspiration for alternative solutions can be found in an integrative approach as proposed by the Dutch Royal Academy of Science foresight committee on renewable energy conversions (in Dutch) [1]. The integrative approach is further elaborated upon in a separately published article [2].

This approach yields at least two new solutions namely that of flexible coproduction and storage in a fuel. Both are falling in the category of distributed Multi Source Multi Product energy systems [3].

These new directions will be further explored and explained in this paper.

We will first sketch the characteristics of the energy problem and then introduce the integration concepts with some examples to illustrate possible new research directions in the field of distributed generation. Finally the consequences of distributed generation for the electric grid will be analyzed in more depth, illustrating the type of problems and directions of solutions that are needed to accommodate more distributed generation into the electricity grid.

When we want to study future developments we should try not just to extrapolate present tendencies and certainly not take our system boundaries too narrow. Therefore in this paper different forms of integration as proposed elsewhere will be analyzed for their possible role in the further development of distributed generation.[2]

In this paper we focus on electricity generation but we keep in mind that in developed countries electricity consumption is roughly only one third of the total energy consumption. So in order to make a transition from a fossil-based energy system to a renewable- energy based system also other forms of energy than

just electricity have to be taken into account. These other forms obviously include heat, but also chemicals and fuel. That means that not only the storage of electricity has to be studied but also the possible storage of heat or the storage of energy in all other forms should be considered, next to alternatives for storage to solve the problem of the fluctuating nature of renewable energy and its integration into the electricity grid.

2 The world energy problem and the energy paradox

In general the energy problem can be seen as a fourfold problem:

1. the availability of energy sources relative to demand
2. a mismatch in the form of energy
3. a mismatch between supply and demand in space
4. a mismatch between supply and demand in time.

2.1 Availability of energy sources relative to demand.

2.1.1 The energy paradox

With regard to the availability of energy sources locally we can say that in principle there is enough supply. Because the energy supplied by the sun is about 10,000 times the yearly energy consumption due to human activity. Or to rephrase it in another way; one hour of sunlight on earth is sufficient to provide the yearly energy consumption by human activity. Secondly, including the amount of energy in the form of geothermal heat, which is (in principle at least) also available everywhere, will contribute to the fact that there is definitely no problem in availability of energy. The problem merely lies in harvesting the energy in an economical way.

But on the other hand there is what we can call *the energy paradox*. Although renewable energy is plentiful available, its present contribution to the energy mix is small and very hard to increase up to a significant percentage, because of the huge amounts of fossil energy that we are currently using.

Moreover the world-wide energy consumption is even increasing due to a growing population and a growing economic development, not in the least in third world countries with a huge population.

In Figure 1 we have depicted calculated production capacity of an imaginary technology that is now available at a capacity of 1 MW and growing at a certain rate per year (doubling every year and growing 50, 20 and 5%/year). Also indicated is a -maybe more realistic- growth curve with a rapid growth rate in early years leveling off when larger production capacities have been reached. When realizing that a country as the Netherlands for example needs about 15 GW of production capacity for electric power, the scale in the figure reaches only to 17% (2.5GW) of what is needed for the Netherlands. When looking at

realized growth of renewable energy in the Netherlands we see that actual growth rates are quite low. So it is obvious that developing any new technology or new source of energy will take decades unless by huge investments we can somehow speed up the up scaling and implementation of new technology.

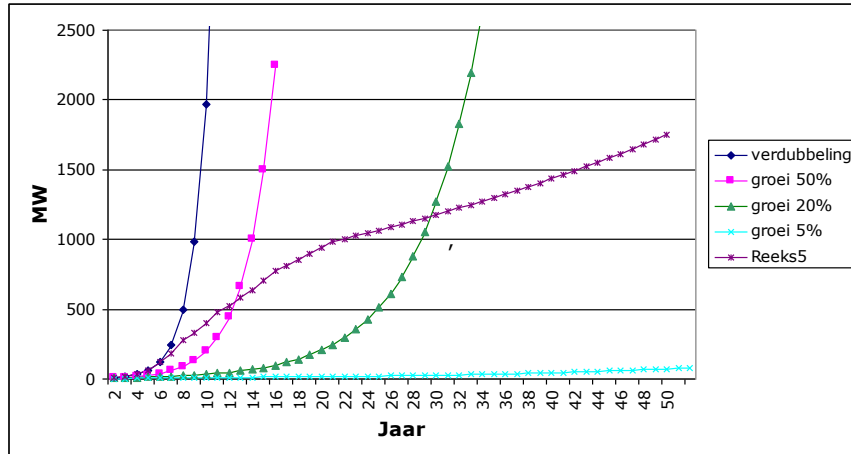


Figure 1. Theoretical grow curves for a technology with 1 MW production capacity in year zero.

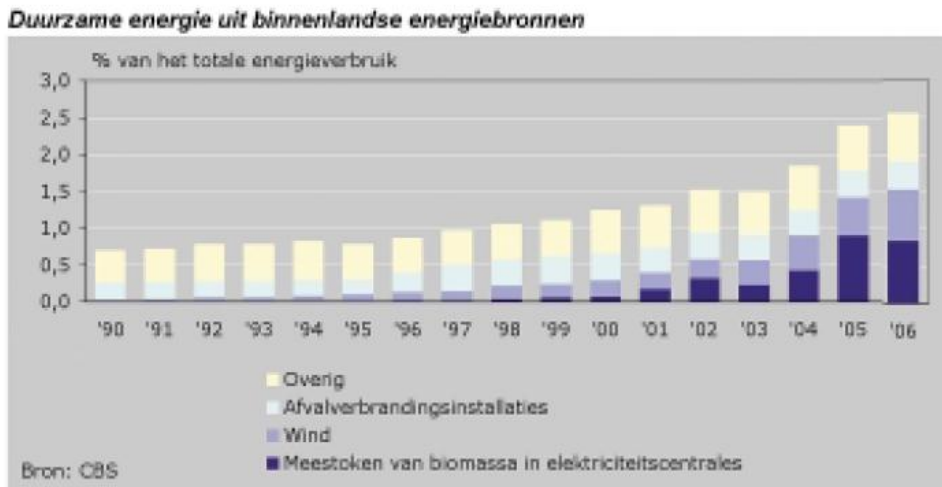


Figure 2. Realized growth of renewable energy in the Netherlands (source www.CBS.nl)

2.1.2 Energy demand

On the demand side we can expect a large increase on a global scale. Focusing on developed countries a part of the increase will be due to an increase in electricity demand. However when it comes to the demand for heat for domestic purposes we can expect a decrease because of two reasons:

1. Increased insulation of the houses
2. Global warming

Although locally on earth also lower average temperatures may be observed, climate change caused by the enhanced greenhouse effect due to the large -scale emission of carbon dioxide in general involves an increase in average temperature on earth; called global warming. If average temperature in the wintertime is increasing, on average there is lower demand for heat in the domestic sector. This does have consequences for example for the use of micro combined heat and power installations in that sector. Secondly better insulation of houses also decreases the demand for heat in winter time. More often the heat produced by the combined heat and power installations will not be needed and therefore energy is 'wasted' and economic feasibility is decreased. On the other hand because of global warming and an increased demand for comfort we can observe an increase in the demand for cooling in summertime in developed countries. Developing countries which often already have a hot climate are most likely to follow soon. Since cooling requires a lot of energy too and the market is large and still growing, energy systems providing cooling must not be forgotten in an exploration of future energy needs and technology assessments.

2.2 Mismatch between forms of energy.

A mismatch between the forms of energy is solved by applying a conversion device. Conventionally we are thinking of a linear system in which the device converts one form of energy into another. However as is clear from the example 'combined heat and power' often more forms of energy are produced by a conversion device. In the case of combined heat and power it is electricity as well as heat. Both can be usefully applied. Combined heat and power illustrates the case that sometimes we need more forms of energy at the same time and by integrating solutions and devices we obtain more efficient systems. Often cooling needs to be supplied as well, as has been explained in the section above. Therefore future distributed generation systems should be able to produce power, heat as well as cooling in an efficient and flexible way. Such tri-generation systems are for example proposed by Goswami et al. [4]. The generalization of this concept is the concept of a multisource multiproduct energy system. This will be explained further in section 4.2.

2.3 Mismatch between supply and demand in space.

With regard to the mismatch between supply and demand in space this problem definitely holds for fossil energy sources because there are only certain places where fossil energy can be found. If these places are limited as is the case for oil in particular, this can also lead to geopolitical problems. The solution to a mismatch in place obviously is transportation of the energy. The form of this energy however, need not be the original energy form of the source, although it often is [Gas, oil, coal].

Preprocessing or conversion is an option to obtain a more suitable form of energy to transport. LNG is an example in which gas from remote areas can be transported without the use of a pipeline infrastructure. Another example would be the preprocessing of biomass to reduce water content and thereby weight and or chemically convert the biomass into a chemical with a higher energy density before transporting it to a 'central' conversion plant. The advantage of distributed generation is of course that transportation of energy is limited to small distances. Thereby transportation losses and costs are minimized and almost diminished.

2.4 Mismatch between supply and demand in time.

With regard to a mismatch between supply and demand in time the often proposed and obvious solution for the fluctuating and discontinuous nature of renewable energy is storage. However this solution implicitly assumes that the only source of energy is the fluctuating renewable energy source, whereas in general at present and still for decades to come our energy supply will come from a mix of sources. Therefore a mismatch in time between supply and demand need not be solved by storage. In this paper we will also propose another possibility namely that of flexible coproduction. Other sources of energy can jump in, when renewable energy production is low and vice versa when the renewable energy production is high the other sources can be controlled down, also without loss in efficiency. If only one renewable energy source is available, if it is fluctuating and if it is sometimes not available, then and only then storage is inevitable. That is to say, if we assume that we always need energy. Please note the many "if's ", which indicate conditions that are often not fulfilled. Therefore storage seems to be a solution that comes forward only if all other options fail, or simply cannot be applied, in contrast with general belief. We will say more about this when we deal with the so-called Superwind concept. [See separate frame]

3 Renewable energy and distributed generation

As stated in the introduction with the development of renewable energy sources and technologies, the problems related to distributed generation have become more urgent. However distributed generation and renewable energy are not synonyms. Renewable energy can be large-scale and centralized just as fossil power plants. While, fossil fuel-based electricity generation can be small-scale and distributed as well as large-scale and centralized. With the development of large-scale harvesting of power from renewable energy, by in particular offshore wind parks and by concentrated solar power for example, it is clear that renewable energy is by no means synonym to distributed generation. In this respect the development of the Desertec program that comprises the development of large-scale concentrated solar power in the north of Africa and transporting the electricity to the south of Europe should also be mentioned [5, 6]. The fully developed technology of hydropower further illustrates the case that renewable energy can be large-scale and centralized as well as a distributed source of energy on a local scale.

In Table 1 examples are summarized to illustrate the fact that both fossil energy and renewable energy can be local and distributed as well as centralized.

Table 1.

	Fossil energy	Renewable energy
Local/distributed	Combined heat and power(With gas engine or fuel cell)	Solar panels wind turbines
Centralized	Coal-fired power plant	Hydropower offshore wind park concentrated solar power

4 Integrative approach

In our analysis concerning the future of distributed generation we will use the concepts of integration as described elsewhere [2]. We can distinguish seven different forms:

1. integration of components into a system
2. integration of energy sources into multisource multiproduct energy systems
3. integration of industries into an industrial ecology complex
4. Integration of new technology into existing technology
5. Integration of sectors
6. Integration of functions
7. integration of the broad concept of sustainability in energy systems

4.1 *Integration of components into a system*

Much of present energy research is focused on the component level. It is obvious that this is necessary, because without components with a long endurance and good performance specifications it is impossible to construct well-functioning energy systems. Yet the perception and relative importance of the design criteria on the component level is often different from those from a system perspective. In addition, one should distinguish between theory and simulation and real operation of an energy system in a complex socioeconomic context of daily practice. In daily practice completely different issues may be determining system performance that can cause a shift in the priority of the component specifications. Therefore it is important to couple R&D, and also long-term R&D to direct implementation as fast as possible without losing a long-term vision depending on the specific development phase of the technology or a combination of technologies under study.

4.1.1 Flexibility.

On the component level a very important aspect should be mentioned that has been receiving less attention than it deserves. To achieve local balancing of supply and demand a trivial solution is storage. However, because of inefficiencies in the storage and additional costs this should be avoided as much as possible. The alternative is to have flexible production units that maintain high conversion efficiency in part load as well as in full load. Therefore there will be a tendency to increase the flexibility of power producing units in general. In particular fuel cells have this property at least potentially. This is a paradigm shift in the development of power generators and fuel cells. In first instance, fuel cells were developed to replace central power plants. Mainly the molten carbonate fuel cells were originally thought to replace central power plants [7]. But it became obvious that they could not be produced on short-term in such huge quantities for installations on a (sub-) Gigawatt scale. It was also noticed that fuel cells are modular units that remain high efficient when producing on a smaller scale; the efficiency of the fuel cell is independent of size and capacity. However it was not fully recognize that it could be very important that fuel cells should also be able to dynamically produce electric power and heat in a very flexible way. In the case of the Superwind concept the fuel cell should even be able to flexibly produce power, hydrogen and heat thereby being able to compensate for fluctuations in wind or solar electricity production. [See separate frame]

Also the liberalization of the markets introduced in the past decade in the electric power sector and the fluctuating prices that are a result of that are a driving force for electricity producing units to become more flexible.

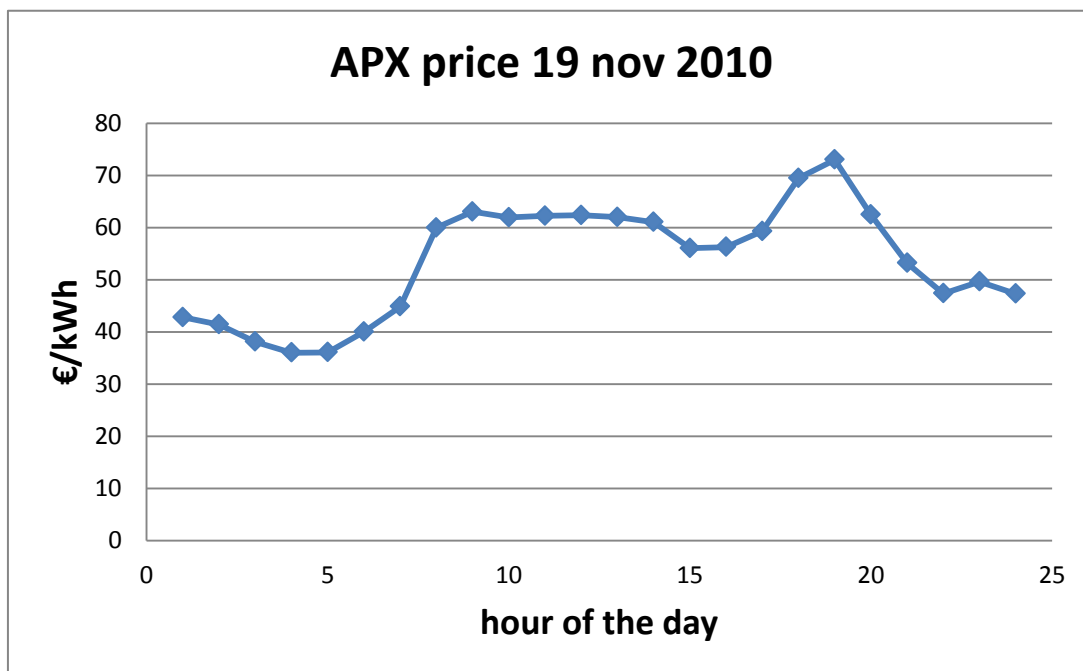


Figure 3. APX electricity prices on 19th November 2010.

In Figure 3 actual price fluctuations on the APX (Amsterdam Power Exchange) are shown to illustrate that prices of electricity can vary significantly. This has consequences for the design of distributed power systems including fuel cells.

All fuel cells have a very delicate heat management system. All parts of the fuel cell maintain a temperature within a limited temperature range, to be able to function well. When the power density is fluctuating this will increase the fluctuations in heat production and thereby increase temperature differences and changes within the fuel cell (temperature variations in space and time). So that should be studied and engineered even further in order to prohibit large temperature excursions and consequent degradation of the fuel cell by those large temperature excursions.

4.1.2 Breakthroughs

What new technologies and components can we envision? What kind of breakthroughs can we expect?. What would be possible in the future and what would totally revolutionize our way of thinking about distributed generation?

As we've seen from the analysis of the world energy problem, solar energy is available in huge amounts. So a breakthrough that would revolutionize our electricity production system would be the developments of highly efficient and affordable solar to electricity conversion devices, or more in general, solar conversion devices that can produce high quality forms of energy including fuel. Is that possible? We have seen the development of photovoltaic cells and the achievement of high efficiencies in the laboratory up to 40 % by photovoltaic cells and the use of advanced semiconductors such as gallium-arsenic [8]. The cells are high efficient in our way of thinking and definition but it's still not approaching 80 or 90% efficiency. Since there are no theoretical limits for the conversion of solar energy into electricity 80 or 90% efficiency should be possible by other ways of converting solar energy into electricity or hydrogen for that matter. So it is theoretically not impossible that these devices will be developed in the near future. What kind of technologies will possibly be available to do so and can we define research areas that will increase the chance of discovering those new breakthrough technologies? It seems that using semiconductors has fundamental limitations in achieving high-efficiency because of the conversion mechanism. In the past decades a lot of research has been spent in reaching higher efficiencies but a limit seems to have been achieved with this semiconductor technology. So probably other conversion mechanisms should be found to achieve efficiencies of 80 or 90%. A research direction that might lead to such high efficiencies is solar antennas.

Solar antennas; A potential breakthrough technology.

It is well-known that electromagnetic waves can be converted into AC currents by antennas. For example, radio waves are converted into electrical signals. AC currents can be converted into a DC current by diodes. In this way electro-magnetic waves can be converted into a DC current. It has been shown for electromagnetic waves of longer wavelengths that this indeed can be achieved with relatively high efficiencies [9]. In an overview paper Goswami et al. report that experimental efficiencies of 60% for microwave radiation were achieved and that "nanoscale antennas for direct conversion of sunlight to electricity with potential conversion efficiencies approaching 80–90%" are theoretically possible [10]. Because antennas have to be fitted to the wavelengths of the electromagnetic waves that they want to receive the solar antennas have to be very small. The wavelength of visible light is in the range of 400-750 nm so also the antennas should be of this order or even smaller since antennas usually have the size of a half wavelength or a quarter wavelength. With the further development of nanotechnology the construction and design of nano solar cells can be imagined and is already taking place. The whole array of needlelike antennas on a substrate can nowadays be produced with nanotechnology. This will still not lead to solar antennas that can produce DC current; therefore we also need AC to DC conversion. Here lies the main problem. Converting AC currents of such high frequency into DC is certainly not trivial. We cannot use silicon or other semiconductor diodes for this purpose because of the capacity of the PN junctions that is forming the heart of the diodes. This capacitance causes that the AC currents of this high frequency can easily pass through the diodes without being rectified. We therefore have to find rectifying devices on another scale that have a near zero capacitance so that no high-frequency current can bypass the diodes. These rectifiers have to be almost of molecular size. Some molecules have been found in nature that do have rectifying properties, and possibly one of those is suitable for application in solar antennas [11-19].

Another research area that might possibly lead to an important breakthrough is the photochemical conversion route. Photosynthesis in nature has a relative low conversion efficiency. One could argue that there was no need to increase this efficiency because there has always been a surplus of solar energy. Imagine plants would grow 10 or 20 times faster than they do now.....? However, by designing artificial photosynthesis materials possibly higher conversion efficiencies than in nature can be achieved. Yet present state of the art development has not reached that point in spite of the fact that already a lot of research has been done in this still promising area.

4.2 Integration of energy sources into Multi-Source Multi-Product energy systems.

The principle of cogeneration is well-known and widely applied for example in combined heat and power applications. The term tri-generation has been proposed for systems capable of the co-production of electricity, heat and cold, but also for the co-production of electricity and heat in combination with a

chemical product like hydrogen. In general, if more than one product is produced, the secondary products are seen as a byproduct or even just as waste. However, also on the input side more than one source can be supplied, while the degree of integration may differ strongly. Sometimes different sources are not controlled and integrated but largely function independently. For example our electricity is a mix of different independently operating sources (fossil, renewable and nuclear). Integration of energy sources into multisource multiproduct energy systems can be done with more interaction also on a local scale. The Superwind concept is an example of this MSMP concept and is further explained in a separate frame in this paper. Other examples with full integration of the input energy sources are given in a previous article [2].

The superwind concept

In previous projects we have studied the flexible coproduction of hydrogen and power by internal reforming fuel cells [5, 6]. Also the use of this concept to compensate for fluctuations in the production of electricity by wind turbines in the so-called superwind project was studied [7]. The concept of hydrogen production from this type of fuel cell is relatively new, while also the market for conventional CHP use of fuel cells is still under development.

In short, new technology based on fuel cells is being developed capable of producing hydrogen power and heat in varying and flexible amounts at very high efficiency adapted to a specific demand that usually fluctuates in time.

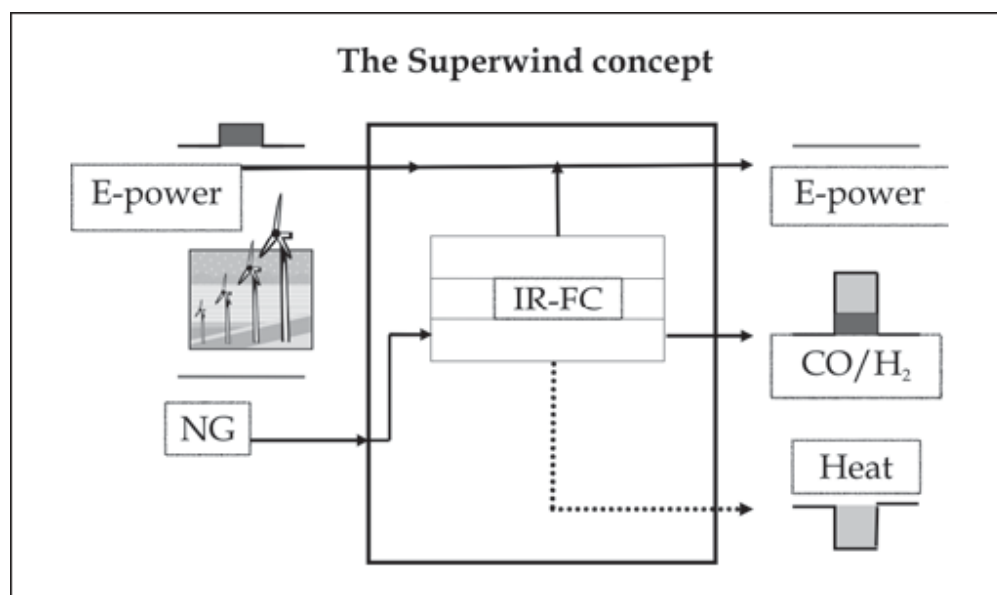


Figure 4. Schematic of the superwind concept based on a high temperature internal reforming fuel cell (IR-FC).

The concept: A high temperature internal reforming fuel cell as a tri-generation unit.

Tri-generation systems are an extension of combined heat and power units in the sense that besides electric power and heat, a third product can be produced. New developments in the area of HT-IR fuel cells allow production of hydrogen as a third product, whereas in the conventional situation hydrogen is only used as an input for the system and not produced as an output.

Therefore, the concept of tri-generation goes one step further than cogeneration. Using a high temperature internal reforming fuel cell it produces combined generation of three different products electricity, hydrogen and heat. When producing hydrogen together with electricity, less heat is generated. As such two products with high exergetic content, namely electricity and hydrogen, are generated and the exergetic efficiency of the system increases.

The main characteristic of these fuel cells is that they run directly on natural gas and/or biogas, which they can convert internally into hydrogen. This takes place by so-called steam methane reforming, an endothermic reaction. The hydrogen produced is then used by the fuel cell for its internal consumption in electrochemical reactions under the production of electric power and heat. Part of that heat is effectively used for the endothermic reforming reaction thereby minimizing waste heat and increasing overall efficiency. Moreover, by decreasing electric power output or increasing natural gas input, the exhaust gas of the fuel cell still contains significant amounts of hydrogen which essentially is reformed natural gas. The hydrogen can be separated from this off-gas as done in conventional hydrogen production by steam methane reforming of natural gas for instance in oil refineries. An interesting beneficial side effect for the fuel cell is that apart from the already mentioned efficient use of waste heat inside the fuel cell, the fuel cell also becomes more efficient because significant amounts of hydrogen exit the fuel cell. In conventional application of fuel cells, the hydrogen content is decreased to a minimum by internal consumption in the fuel cell. This means that at the output side of a fuel cell only a low fuel concentration is available. This leads to the so-called Nernst loss constituting about 50% of all the losses in the standard operation of the fuel cell. By producing hydrogen this Nernst loss is minimized [5].

Therefore, overall system efficiency for the production of hydrogen and electric power can reach 90%, as was found by flow sheet simulations [31]. Note that this is excluding heat as often is included in combined heat and power efficiency definitions. Of course, to reach this high efficiency the concept can only be applied if there is a (nearby) market for hydrogen. This could be a local hydrogen filling station for the transport sector, or the fuel cell off gas can be used directly as in gas for the production of chemicals and/or fuel.

Besides its high efficiency the system also allows for very flexible supply of energy. First, the system can be switched from conventional operation as a combined heat and power unit, to the above described tri-generation system. Besides, the ratios between electricity, heat and hydrogen production can be varied within certain technical limits. Simulations have also shown that by combining hydrogen production and efficient use of internally dissipated waste heat, the fuel cell can be operated at double power density. This results in the production of twice the amount of electric power compared to conventional operation and with on top of that an equivalent amount of energy per time unit in the form of hydrogen. Thereby the valuable output of the fuel cell system can be increased by a factor of four [5].

To summarize, HT-IR fuel cells can be operated in tri-generation mode, increasing the system's efficiency by coproducing hydrogen while any waste heat can still be used as in conventional combined heat and power applications. Moreover, they can do so in a flexible way. In the text, we will describe how this flexibility can for example be applied in the built environment or to compensate the fluctuations in electricity production by local renewable energy sources.

4.2.1 Tri-generation in the built environment

In a separate frame on the Superwind concept we have described how HT-IR fuel cells can be used in a Multi-Source Multi-Product energy system. Next we will describe how the concept could be applied in the built environment.

The flexibility of the fuel cell in tri-generation mode can be used to adapt heat production to the dynamic local heat demand. This fuel cell system could supply a domestic area of a few hundred houses with electricity and heat. At the same time it can provide a sufficient and steadily growing amount of hydrogen for the assumed growing number of fuel cell vehicles owned by the inhabitants in this living area. Hydrogen could be produced in times of low heat demand, increasing potential profit and thus overall economic feasibility.

At this moment it is not clear whether hydrogen vehicles will set the standard in future mobility. However, if electric vehicles will rule the market the same Superwind multi-generation system can supply electric power to a (fast) charging station for battery electric vehicles. Also on a local scale transport fuels can be produced from the anode off-gas. [See separate frames on Superwind and micro reactors]. So, this MSMP system can power various potential transport scenarios. Moreover, they can be used to compensate fluctuations in the production of electricity from renewable energy sources on the short timescale and adapt to demand variation or even trends at a larger time scale as well. Contrary to conventional power plants a decrease in production of electricity does not lead to efficiency losses or loss of economic performance. Instead efficiency can even increase and always products with an economic value are produced.

4.3 Industrial ecology applied to distributed generation on a local scale.

Industrial ecology is usually applied on a large scale like in the famous industrial ecology park Kalundborg. But the principle could also function on a smaller local scale, thus contribution to distributed generation. An industrial ecology like development on the local distributed scale is the application of micro reactor technology for distributed fuel generation [see frame 2 on micro reactors]. So it is important not only to think about electricity as being our primary form of energy that we need. We also need other forms of energy like fuel and of course heat.

With the development of micro reactors through process intensification that allow for efficient and intensified local production of chemicals such as hydrocarbons or fuel also the locally generated carbon dioxide can be captured and used meaningful. In present mainstream thinking CCS (carbon capture and storage) can only take place on a large scale with the use of empty gas fields and other means of underground storage. With the development of micro reactors and new technology based on process intensification, distributed and highly efficient systems can be designed and developed that use locally

produced carbon dioxide on a relatively small-scale and convert that with locally available energy sources into meaningful products such as fuel and other higher hydrocarbons. Thereby, at least partly some cycles are closed.

As described in a separate frame locally produced carbon dioxide can be converted back into fuel using renewable energy. In the described case the energy provided to the system is in the form of hydrogen that is produced by electrolysis from wind energy or solar. However we can also think of a combination of Superwind followed by this fuel producing reactor scheme. It has been explained in the separate frame on Superwind that biogas or natural gas is internally reformed in the fuel cell and if hydrogen is not fully consumed by the fuel cell itself some fuel in the form of hydrogen and CO in a mixture with steam and carbon dioxide is leaving the fuel cell. This gas mixture is called syngas and it is ideal for producing fuel, possibly together with additional carbon dioxide if needed. It is an improvement to just using pure hydrogen from electrolysis because the hydrogen does not need to be so pure for this application and can better be used in other applications where a high purity is essential (like PEMFC in fuel cell vehicles) electrolysis is normally very expensive. Electricity from wind and solar can -at least in principle- under most circumstances better be used as electricity, for a better overall system efficiency.

Alternatively Hydrogen can also be converted into ammonia together with nitrogen from the air. In this way also a liquid fuel is obtained. Although ammonia is mostly seen as a chemical and not as a fuel, ammonia can be burned or used in fuel cells directly or indirectly. For example, in the high temperature Solid Oxide Fuel Cells ammonia can directly be used as fuel. But it is also proposed by professor Kordesch and others that decomposition of ammonia is easily achieved by a moderate temperature increase [20, 21]. Therefore, ammonia was and still is seen as a suitable chemical way of storing hydrogen.

Alternatively, methanol is another fuel that can be produced on a local scale from hydrogen and CO₂ from the off-gas of combustion engines or from internal reforming high temperature fuel cells operated at low utilization. New efficient small scale reactors are being developed that can produce valuable chemical products and fuels on a local scale, within the new research area of process intensification. [Also see the article on perfect reactors in this special issue[22]]. For example, also microwave radiation can be applied in these small-scale micro reactors to promote the reaction speed of the reactions and further decrease the volume of these reactors[23]. Microwave technology nowadays is a mass-produced consumer good, so it is very cheap to develop small scale microwave reactors. This can easily be done by small and medium enterprises, but more research is needed to test the feasibility and economic viability of these future concepts.

Microreactor technology for distributed fuel generation

Mitigation of CO₂ emissions is a major concern because of the severe climate changes resulting of uncontrolled GHG emission. In parallel the depletion of fossil fuel reserves are forcing scientists to look for alternative fuel resources if possible with minimal changes and investments in new infrastructure.

Imagine oneself return from college home, plug your car into a socket and produce overnight your 10 liters of fuel for the coming day. This may be not a dream, but one of the option of tomorrows distributed fuel generation. The focus of this approach is:

- on development of the concept of distributed fuel generation technology and
- on parallel utilization of CO₂, which can be derived from thermal combustion, gasification or chemical conversion.

The background of the actual process is CO₂ capturing and its catalytic conversion back to hydrocarbons. This process includes absorption of CO₂ from the surrounding air or its separation from combustion/pyrolysis/gasification processes followed by Reverse Water Gas Shift process (CO₂ reacts with H₂ to form CO and H₂O - syngas) and Fischer-Tropsch (FTS) process of conversion of syngas (hydrogenation of CO) to a series of hydrocarbons and water. These processes are well-known and well-established. The novelty is to perform these catalytic processes in micro-reactors, while maintaining or even increasing conversion efficiency.

Micro-reactor technology

A micro structured reactor can be described as a chemical reactor, providing pathways for fluid flow whose characteristic dimension, (e.g. channel diameter) is below 1 mm. It is expected that the reactions performed in small volumes are faster and more efficient. The smallest channel would allow molecules of reactants to meet without the need to travel, which translates into instantaneous reaction. A typical micro reactor can consist of several parallel micro channels although the pathways for the fluid flow can also be formed by a catalyst inserted in these micro-channels. The well documented advantages of micro reactors have been thoroughly described by M. Fichtner et al., 1998.[24]

Some of these advantages are:

- Increased reaction rates
- Continuous product formation
- Larger heat transfer rates and simple/precise temperature control
- Simple reactor designs possible although complex systems can be designed (lab-on-a-chip)
- Low-cost reactors
- Simple reaction monitoring
- Reduced scale-up issues
- Safer synthesis.

Some disadvantages also exist such as;

- The difficulty of fabrication,
- lack of straightforward approaches for creating integrated systems,
- Effort involved introducing catalyst.

In a conventional scale reactor the reactants must often travel a substantial distance to contact a catalyst surface. The time to transport reactant material to the catalyst surface limits the potential rate of the reaction. The use of micro channels reduces the average distance a reacting molecule must travel, increases the heat energy flow rate and increases the catalyst surface area to volume ratio. Micro channels encourage immediate contact with the surface of the catalyst and when compared to packed-bed reactors, have a far lower pressure drop in the flow through the reactor.

As well as the above advantages of using micro channel reactor technology, improved selectivity (preferred product reaction) and conversion rates (more product from same reactants) have been repeatedly demonstrated [25, 26].

There are a number of potential advantages of this novel concept for distributed fuel generation:

- utilization of micro-processing advantages, i.e. better heat and mass transfer, higher reaction rates, more controllable product quality, lower temperatures and pressures, better resources management, reduced emissions and cost, enhanced safety and reduced environmental impact.
- Furthermore, the fundamentals for distributed generation of fuel will be developed

Figure 5 presents the block diagram of the process of CO₂ conversion to hydrocarbons. One should note that there are four micro reactors in series attributed to the Reverse Water Gas Shift reaction. The reason is that this reaction is reversible and to secure CO generation and prevent its re-conversion back to CO₂, at least one of the products (here it is the water) has to be removed as soon as it is generated. Therefore each reactor is followed by a cooler/condenser to secure water vapor condensation and separation.

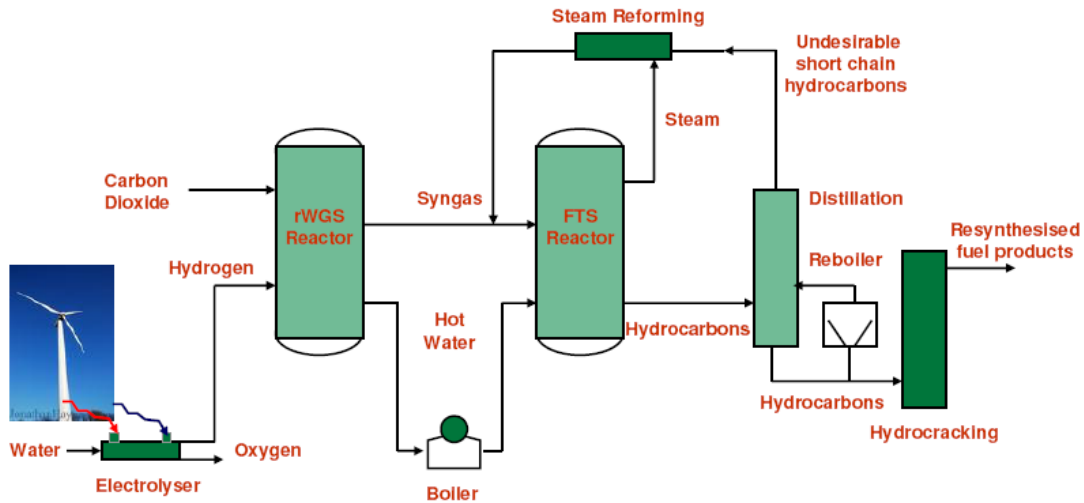
Another important issue is the provision of CO₂ for efficient conversion.

In an earlier paper we proposed to use the off gas from a fossil fuel combustion device to provide CO₂. Pure CO₂ can be extracted from this gas mixture by scrubbing. Here we propose that the hydrogen and carbon dioxide needed as input for the water gas shift reactor [See figure 1] can also be delivered by the anode off gas of the internal reforming fuel cell in the superwind concept. Hereby the need for scrubbing CO₂ is avoided and wind energy [electricity] can directly be used as electricity avoiding conversion losses and capital costs of an electrolyzer. In Figure 5 still the original idea of producing hydrogen by electrolysis from surplus wind energy, with a separate source of carbon dioxide is depicted.

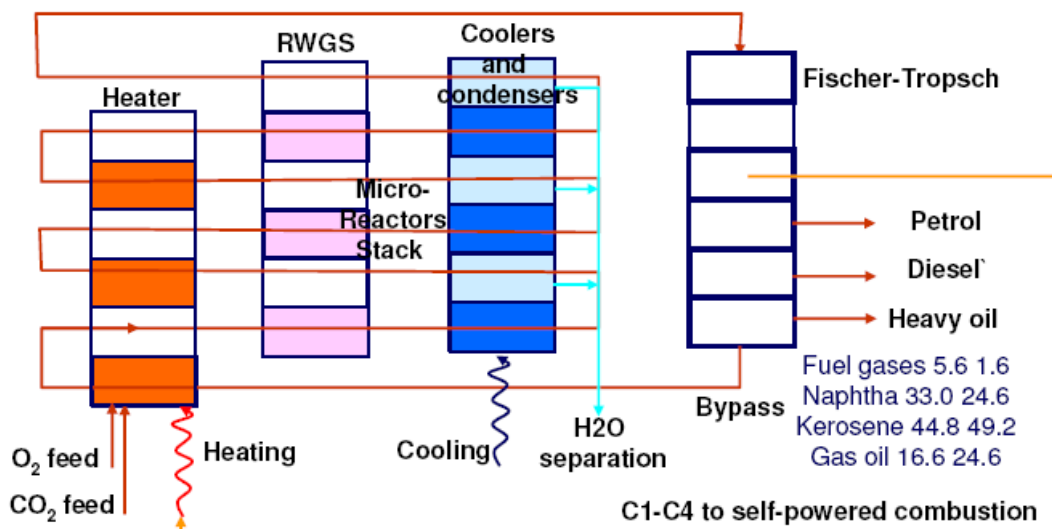
Described ideas provide a radical and promising way for reducing the negative environmental impact of fuel combustion and CO₂ emission generation. It adds the missing link between bio-fuel generation, fuel combustion and CO₂ emission mitigation [25, 26].

A number of silicone micro reactors were manufactured by Tyndall research institute in Ireland (<http://www.tyndall.ie>). Experimental work is combined with simulations to optimize the performance of

the micro reactors. Flow simulation was performed using CoventorWare™ 2008 package. Detailed work was done on the appropriate design, sizing and connection of the micro reactors. Crucial in this case is the question “How small is small enough”? The flow simulation of micro-channeled reactor at 2 to 10 bars pressure shows that flow rate through even a single micro channel should exceed 10[$\mu\text{L}/\text{min}$] – a flow rate sufficient to allow analysis by a gas chromatography. This is the case for micro channels of 60 to 160 μm of size considered, securing a flow with a Reynolds number (Re) within the range of $100 < Re < 1000$.



(a)



(b)

Figure 5: (a) Block diagram of fuel re-synthesis process (b) micro-reactor system.

4.4 Integration of new technology into existing technology

Integration of new technology into existing technology is a concept that was explained in terms of integration of new technology in large scale existing central power plants or chemical plants[2]. However, the same principle could also be applied by the integration of a new technology into the existing energy system of houses and offices, so without the need for total replacement of the existing system but instead improving the existing system by placing add-ons. Examples may include solar panels (PV) and solar collectors, but also plug-in hybrid cars and micro reactors. Municipal waste is sometimes incinerated under the simultaneous production of power and heat. Thereby an integration of the waste sector and the energy sector has been achieved. This is not trivial because different actors and institutions are operational in the different sectors with different goals and having to comply with different rules and regulations. So a whole range of legal and policy issues had to be solved. The use of waste on a local scale is conceivable with the development of small scale reactors and gasifiers, thereby closing cycles on a smaller scale reducing transport.

4.5 Integration of sectors

Integration of sectors is another form of integration of which the 'vehicle to grid' concept is a nice example that shows that the transport and energy sector can be integrated. Electric vehicles can be used for electricity storage and on the other hand if fuel cell vehicles are developed further they can be used to generate electricity and deliver that to the grid. This is known as the V2G: 'vehicle to grid' concept.

4.6 Integration of functions

Integration of functions is something that is not yet often applied or consciously designed by engineers that are developing distributed generation systems but this aspect should be further taken into account in the development of distributed energy systems. An obvious example is the placement of solar panels on the roof instead of roof tiles hereby the panels also function as protection against the rain. In practice, the solar panels are just place on top of the existing roof tiles. But it must be seen in a wider context, with a lot of creativity. The local distributed generation unit for a community could be the core around which a community building for various activities is built, instead of just the building to house the combined heat and power unit. With this example a connection is made to the last and perhaps most difficult form of integration: integrating sustainability.

4.7 Integration of the broad concept of sustainability in energy systems

Sustainability according to the Brundtland definition puts the issues in a wider context, including the difference between developed and developing countries and our moral obligation to narrow the gap between them. Also in this paper writing about distributed generation is done with an implicit focus on developed countries. However, sustainability, global warming, finite fossil resources, etc. are global issues. Furthermore, if we take into account the number of people and the predictions for the world population in say 2050, the present developed countries will be outnumbered. Electrification of rural areas could or should tie up with local development of rural communities. The systems should preferably provide employment and income for the local community. This imposes different boundary conditions on the systems to be designed, but the topic goes beyond the scope of this paper.

5 The electricity grid.

In this paragraph we will focus on the consequences of increased distributed generation for the design and operation of the electric grid.

5.1 AC/DC

An issue that is back on the agenda again due to the development of distributed generation is the question of AC or DC grids. We have seen that in the early development phases of electricity grids around 1900, AC as well as DC grids were developed. We know now that for several good reasons the AC system is the big winner. However circumstances have changed and with the widespread introduction of solar PV, batteries and fuel cells, many sources of DC electricity to be used locally have become available. From this perspective it does not make sense to convert the DC power first into 230 Volt AC and then convert that back again in our amplifiers, radios and televisions into DC again. Also modern lighting systems such as LEDs do need DC rather than AC current. Is it possible to develop DC systems that are just as efficient as our AC systems and what would be the preferred voltage? Would the losses not increase too much if we go to lower voltage DC grids in our houses and homes?

The energy conversion as it is conceived traditionally is to generate electricity in central power plants, increase the voltage, reducing the current and thus the losses, by means of transformers, to transmit through transmission power lines, and reduce the voltage back again by means of more transformers and distribution lines that connect the transformation points to the consumption points. This way of operation is based on two boundary conditions: the first one is that the transformer can only operate with AC currents, and the second is that there are separate generation and distribution points, so the grid is a unidirectional energy flow conductor. These two conditions can be overcome nowadays by using Power Electronics and will constitute the two antithesis of future common energy concept:

DC transformers can be built by means of power electronics converters that can elevate (boost topologies) or decrease (buck topologies) the voltage. This means that we can take advantage of these topologies to make a "back-to-Edison" (DC -grid) approach feasible.

A lot of research is already performed on the power electronics for the connection of fluctuating renewable energy sources to the grid and on the problems that it gives in terms of its integration and keeping the power balance always correct. But also other issues are at stake, such as active and reactive power and maintaining the power balance on very short time scales. Normally this is done by the inertia of the large generators and energy that is stored in the rotational speed and inertia of these large masses in these generators. If distributed generation is replacing centrally produce electricity this function of the central power system must also be replaced by the distributed sources. The digital control of power electronics is still an area that needs further exploration[27]. A lot of research areas still have to be covered and explored to be able to develop systems that can do the complex and distributed steering of many local distributed production sides and maintain the same integrity and reliability of the existing electricity grid.

The dominant role of central power generation plants, imply significant power losses in the transport of electricity in the electrical distribution lines. In addition, if there is a single fault in those lines, a black out can result causing a series of problems due to our strong dependence on the electricity. These black outs, also results in distributed generators (DG) to remain disconnected for safety reasons, so that technical staff can work on the grids to resolve the problems. As a consequence, major parts of grid codes do not allow islanded operation, i.e. if there is a blackout it is mandatory to disconnect the DG generators. This means for instance that, if we have installed photovoltaic panels on the roof that are connected to the grid, and there is some fault in the external grid, it is mandatory to stop the electricity generation and to disconnect the panels. The scenario of one sunny day with a blackout, and the sudden interruption of electricity is something that from the point of view of the user is unconceivable. On the other hand, the user is allowed to operate in autonomous way but only if they always remain disconnected from the grid. Further, no interaction with the grid is allowed when using storage energy elements. In the last years a change in the government and regulators points of view can be observed, promoting experimental projects to test the technical viability of micro grids or mini grids, i.e. parts of the commercial electrical grid, able to operate in island as well as grid connected modes, using distributed generation systems, energy storage elements, and local smart loads, together working like an autonomous but also grid-interactive small electrical grid. These kinds of smart elements (micro-grids) will become possible due to the integration of different technologies like power electronics, communication systems, distributed control systems, and intelligent agents. Besides this concept, it is necessary to explore the bi-directional interconnection of these micro grids to reduce the need for electrical transport lines. They will become

just tie lines of electrical energy interchange. In this sense, the future electrical grid, also called smart grid should be more intelligent, flexible and distributed to accommodate the user needs. This is a change of paradigm, since the user is not only a consumer, but will become part of the grid in terms of generation and storage.

The evolution of this change can be seen as a 3-G concept: DG distributed generation, MG micro grids, SG smart grids:

1. Distributed generation coincides with an increased penetration of renewable energy into the grid, which can be done near the demand side.
2. Micro grids allow for island operation; grid interactivity and small grids that provide autonomous electricity supply.
3. Smart grid is a grid with a computer and telecommunication infrastructure (ICT), including forecast of generation and demand, reducing the need for massive energy storage systems, and also providing energy interchange, which reduces the losses and optimizes the energy balance in real-time.

These three concepts, have a different development pace, but are sometimes mixed up. Next we will address these concepts to clarify them further.

5.2 Smart Grids

Small generators can be connected to the grid by means of Power Electronics interfaces that can perform two functionalities: optimize the operation of the generation as well as provide power quality to the grid. Distributed generation also implies that the grid should become bidirectional. The electrical grid is developing into a more distributed, intelligent and flexible grid. New power electronic and ICT equipment will be applied in the electric infrastructure in the next decades. The energy generation and consumption areas cannot be conceived separately. Nowadays electrical and energy engineering have to face a new scenario in which small distributed power generators and dispersed energy storage devices have to be integrated into the grid. The new electrical grid, also named smart-grid (SG), will deliver electricity from suppliers to consumers using digital technology to control appliances at consumer's homes to save energy, reducing cost and increase reliability and transparency.

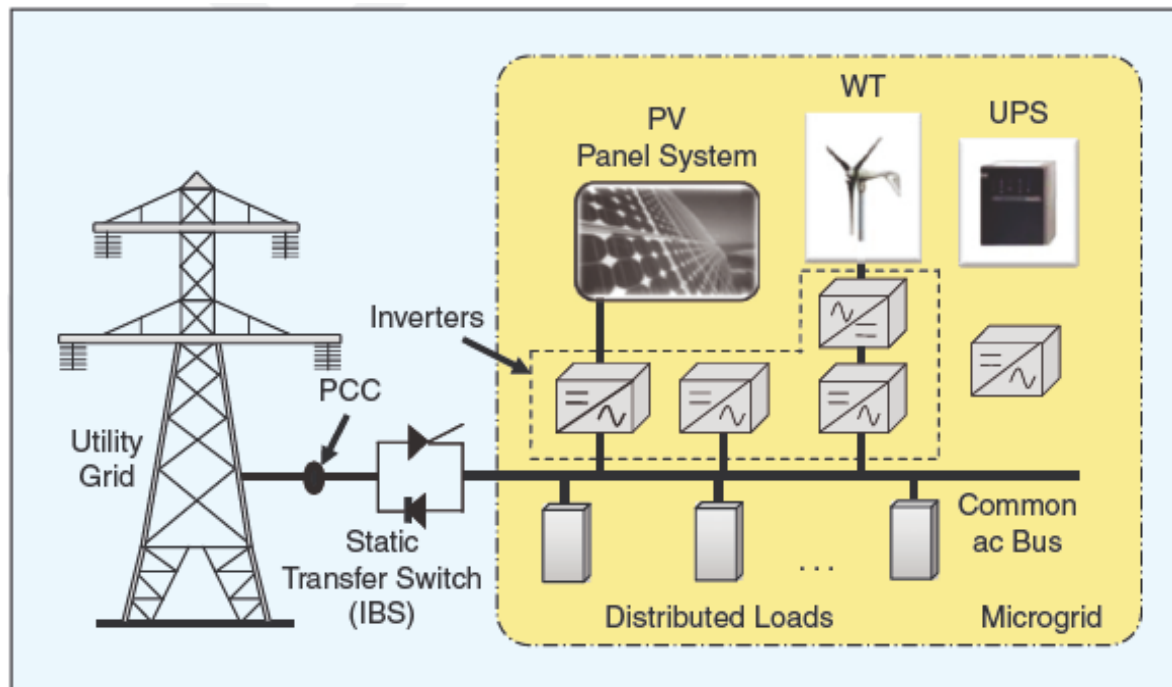


Figure 6. Typical structure of a flexible micro grid.

Micro grids (MG), also named mini grids, are becoming an important concept to integrate DG and energy storage systems. The concept has been developed to cope with the penetration of renewable energy systems, which can be realistic if the final user is able to generate, store, control, and manage part of the energy that will be consumed. This change of paradigm, allows the final user to be not only a passive independent consumer but also an active part of the grid.

DC- and AC-micro grids have been proposed for different applications, and also hybrid solutions have been developed. Islanded micro grids, in which storage is inevitable, have been used in applications like avionic, automotive and marine and in rural areas. The interfaces between the prime movers and the micro grids are often based on power electronics converters acting as voltage sources (voltage source inverters, VSI, in case of AC-micro grids). These power electronics converters are parallel connected through the micro grid. In order coordinate the operation of each individual converter when there is no critical communication between them, the droop control method is often applied.

In case of parallel inverters, the droop method consist of subtracting proportional parts of the output average active and reactive powers to the frequency and amplitude of each module to emulate virtual inertias. Hence the inverters will behave like a synchronous machine, allowing the active and reactive power sharing autonomously. However, the inherent trade-off of this method between frequency and amplitude regulation in front of active and reactive power sharing accuracy cannot be avoided in islanded mode. To solve this problem, the use of ICT technology seems unavoidable and it is very desirable to implement a low-bandwidth noncritical communication system next to the distributed generation and

interconnecting (micro) grid infrastructure. We need a low bandwidth communication system, since we do not want to rely on the speed of the communication in case of disturbing events and we want the DG equipment to run autonomously as much as possible.

Hierarchical control applied to power dispatching in AC power systems is well known and it has been used extensively for decades. Nowadays, these concepts are starting to be applied to wind power parks and were proposed for isolated photovoltaic systems. However, with the development of power electronic based MGs, which are able to operate both in grid connected and island mode, hierarchical control and energy management systems become necessary. Some researchers proposed secondary and tertiary controllers. The main problem to be solved is the frequency control of the system. However, voltage stability and synchronization issues are also important to achieve enough flexibility to operate in both modes. Only few approaches published in literature conceived the MG as a whole problem taking into account the different control levels [28].

MGs can be conceived to use DC or AC voltage in the local grid. Also, there are AC sources or MGs interconnected by means of power electronic interfaces to a DC micro grid. Thus hybrid DC-AC micro grids are often implemented, introducing the necessity to control the power flow between DC and AC parts. In this sense, it seems reasonable that the DC-micro grid area can be connected to energy storage systems like batteries, supercapacitors or hydrogen-based fuel cells. Although DC transmission and distribution systems for high voltage applications are well established, and there is a notable increase of DC-micro grid projects, there are just a few studies about the overall control of these systems [29].

The need for standards in micro grid control is related to the new grid codes that are expected to appear in the near future. The ANSI/ISA-95, or just ISA-95 as it is more commonly referred to, is an international standard for developing an automated interface between enterprise and control systems. This standard has been developed for global manufacturers to be applied in all industries, and in all sorts of processes, like batch processes, continuous and repetitive processes. The objectives of ISA-95 are to provide consistent terminology that is a foundation for supplier and manufacturer communications to provide consistent information and operations models. This is essential for clarifying application functionality and how information is to be used. In this standard a multilevel hierarchical control is proposed, with the following levels:

Level 5: Enterprise. The enterprise level comprises the superior management policies of a commercial entity. This level has operational and development responsibility for the entire enterprise, including all of its plants and their respective production lines.

Level 4: Campus/Plant. The campus or plant level comprises superior management policies of a branch or operational division of an enterprise, usually including the elements of the enterprise financials that are directly associated with that business entity.

Level 3: Building/Production. The building or production level comprises the management and control policies required to administer the states and behaviors of a building and its environmental and production systems

Level 2: Area/Line. The area or production line level comprises the management and control policies required to administer states and behaviors of a specific area or production line.

Level 1: Unit/Cell. The unit or cell level comprises the management and control policies required to govern the states and behaviors of a unit of automation or a manufacturing cell.

Level 0: Device. The device level comprises the set of field devices that sense and provide actuation of physical processes within the environmental and production systems.

Each level has the duty of the command level and provides supervisory control over lower level systems.

In this sense, it is necessary to ensure that the command and reference signals from one level to the lower levels will have low impact on the stability and robustness of the lower-level. Thus as is well know from control theory, the bandwidth must be decreased when increasing the control level. For instance, in order to control a DC-AC inverter, two control loops are normally used: an inner current control loop and an outer voltage loop. The voltage loop will be always designed to have lower bandwidth (e.g. 500 Hz) than the current control loop (e.g. 5 kHz), therefor its dynamics is also slower allowing time for the lower level to finish a control loop based on a control signal of a higher level. In case of a micro grid, the primary control loop will control active and reactive power, which will adjust the reference for the voltage loop. Thus, this primary control has to be designed with lower bandwidth than 50 Hz, taking into account that active and reactive powers are calculated in every line cycle of the grid (50 Hz or 60 Hz, depending on the country).

In order to adapt ISA-95 to the control of a micro grid, levels zero to three can be adapted as follows:

- Level 3 (tertiary control): This energy production level controls the power flow between the micro grid and the main grid.
- Level 2 (secondary control): Ensures that the electrical parameters in the micro grid are within the required range. In addition, it can include a synchronization control loop to seamlessly connect or disconnect the micro grid to the main grid.
- Level 1 (primary control): The droop control method is often used in this level to emulate physical behaviors that makes the system stable and more damped. It can include a virtual impedance control loop to emulate physical output impedance.
- Level 0 (inner control loops): Regulation issues of each module are integrated in this level.

Current and voltage, feedback and feedforward, and linear and nonlinear control loops can be performed to regulate the output voltage and to control the current of each unit, while maintaining the stability of the system.

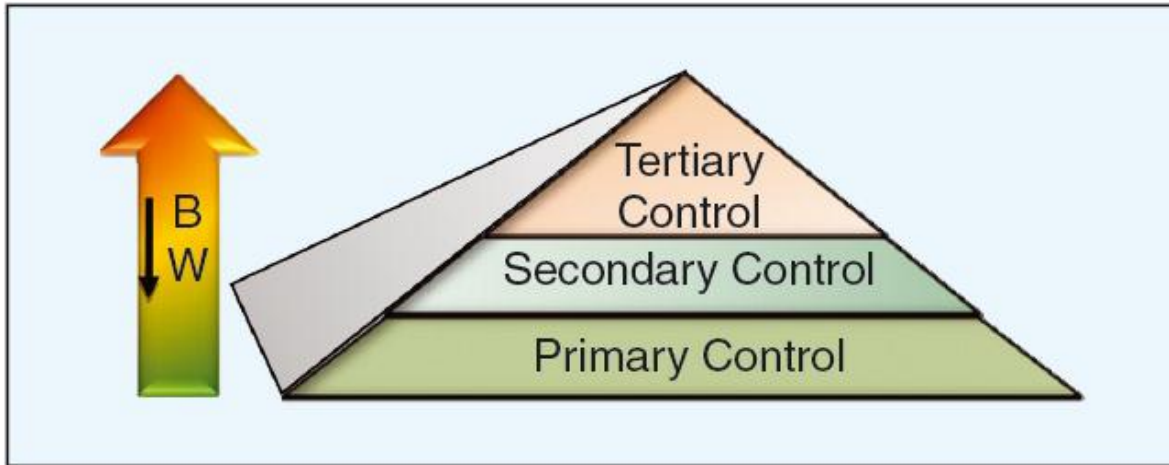


Figure 7. Hierarchical control levels of the flexible microgrid.

On the other hand, AC-micro grids should be able to operate both in grid connected and islanded modes. The intelligent bypass switch (IBS, see Fig. 5) is responsible for connecting the micro grid to the main grid. This bypass switch is designed to meet grid interconnection standards, e.g IEEE 1547 and UL 1541 in North America. Now the IEEE P1547.4 Draft Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems is already approved as a standard. It covers MGs and intentional islands that contain distributed energy resources with utility electric power systems. The standard provides alternative approaches for the design, integration, and operation of MGs, and includes the ability of connection and disconnection to/from the grid.

In grid-connected mode, the micro grid operates in accordance with the IEEE 1547-2003 standard. The transition to islanded mode is done by intentional or unintentional events, e.g. grid failures. Thus, proper islanding detection algorithms must be implemented. In islanded mode, the MG must supply the required active and reactive powers, as well as provide frequency stability and operate within the specified voltage ranges. The reconnection of the MG to the grid will be done when the grid voltage is within acceptable limits and phasing is correct. Active synchronization is required to match the voltage, frequency, and phase angle of the MG.

Although AC-MGs are now in the cutting edge of the state of the art, the control and management of such a system needs further investigation. MGs for standalone and grid-connected applications have been considered in the past as two separated approaches. Nowadays, it is necessary to design flexible micro grids able to operate in both grid-connected and islanded modes.

The hierarchical control of AC-micro grids consists of the same control levels as presented before. UCTE (Union for the Co-ordination of Transmission of Electricity, Continental Europe) has defined a hierarchical control for large power systems. In these power systems large synchronous machines with high inertias

and inductive networks are present. However, in power electronic based MGs there are no inertias and the nature of the networks is mainly resistive. Consequently there are important differences between both systems that we have to take into account when designing their control schemes. A multilevel hierarchical control is organized as follows. The primary control deals with the inner control of the DG units adding virtual inertias and controlling their output impedances. The secondary control is designed to restore frequency and amplitude deviations, inside the micro grid, by adding virtual inertias and virtual output impedances. The tertiary control regulates the power flows between the main grid and the micro grid at the point of common coupling (PCC), or between two micro grids. Several interconnected micro grids in one area can interoperate forming micro grid clusters controlled by hierarchical controllers of upper levels. The interconnection of micro grid clusters with different energy services may suggest a smart grid configuration, as shown in Figure 8.

Further studies of topologies, architectures, planning, and configurations of micro grids are necessary. This is a great challenge due to the need of integrating different technologies such as power electronics, telecommunications, energy generation and storage systems, etc. In addition, islanding detection algorithms for MGs are necessary for ensuring a smooth transition between grid-connected and islanded modes. Furthermore, security issues such as fault monitoring, predictive maintenance and protection are very important with respect to the feasibility of micro grids.

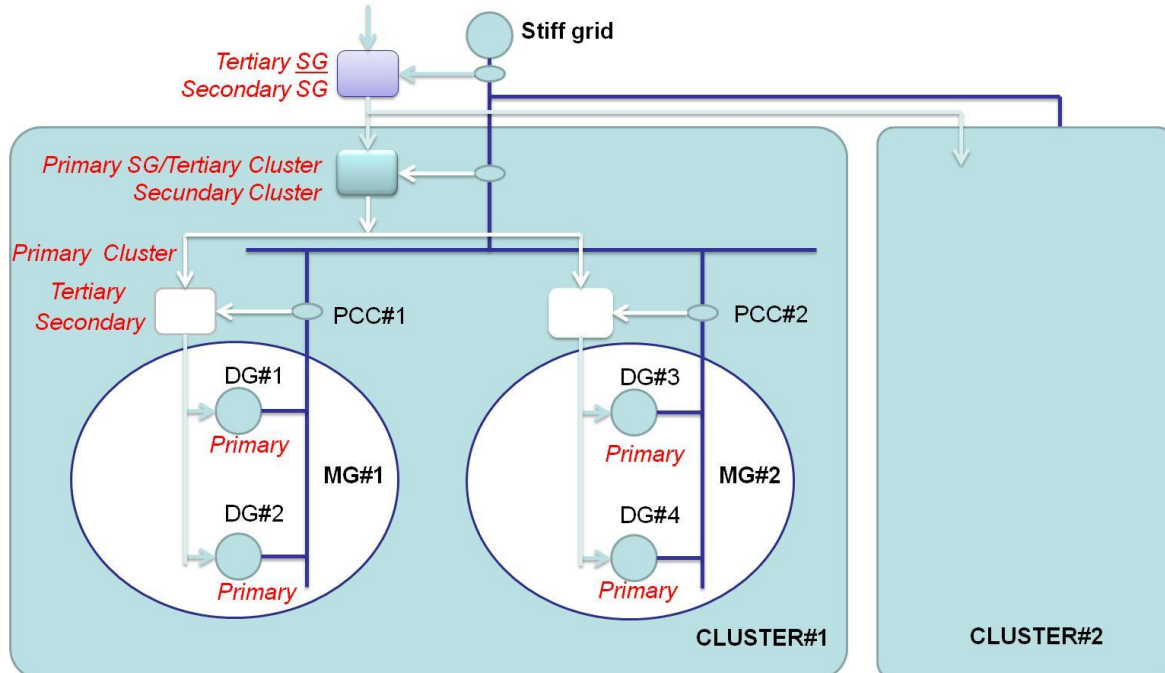


Figure 8. Multiple micro grid clustering – towards a Smart Grid concept.

6 Storage

6.1 Storage of electricity and alternatives.

In order to maintain the power balance; i.e. the balance between the energy generated and consumed at each point in time, the main grid could supply or absorb the difference between generation and consumption in the micro grid. If the main grid is not present, we could use electricity storage systems. The storage of electricity in the form of electricity can only be achieved in (super)capacitors. However, even using super capacitors the storage capacity is very limited. Energy conversion has to take place as is done for example in batteries. For real large scale storage matching the order of magnitudes needed in large scale power supply CAES (compressed air energy storage) and hydro power are suitable. It is not the purpose of this paper to extensively review all storage options, but to provide an outlook for alternatives. In order to be able to 'always' deliver electricity the use of massive and over-dimensioned energy storage systems can hardly be avoided if conventional storage would be the only option. Battery electrical vehicles connected to the grid (V2G concept) is an interesting alternative solution providing flexible storage capacity not only dedicated to one single function, with a reasonable large scale capacity due to the large number of vehicles potentially available.

Nevertheless, the real challenge is to consume the energy at the time it is produced, thereby we can reduce the energy storage need, and increase the efficiency and flexibility of the system while reducing cost. This can be achieved by demand side management. Some consumers are willing to consume electricity at another time certainly if they are compensated by a lower price for electricity. For example cooling warehouses for storage of fruit and vegetables etc. can be done a few degrees colder when there is a surplus of electricity and postpone the consumption until periods of shortage of electricity with (high prices) have passed and prices have lowered again, or of course when the inside temperature becomes too high and they have no other option then to consume electricity to cool the warehouse.¹ Since large industrial warehouses consume a significant amount of electricity (tens of MW) their contribution to maintaining the power balance can be significant.

Another alternative as already mentioned is flexible coproduction [See separate frame on the superwind concept]. The Superwind concept can function as it does, because large scale storage of energy is already there, namely in the form of fossil energy reserves. Also if there is a surplus of electricity (locally) and we convert that into a fuel or chemical, while it is not absolutely necessary to convert that same fuel back into electricity again when more electricity is needed, as would be the case in the strict definition of a storage system. In supplied by the gas network. Even if they are the same form -say methanol- it need not be the same methanol that is converted back into electricity; it may come from another stream of methanol as well. This resembles the case of dynamic storage of hydrogen as will be further explained in the next section.

¹ http://www.tno.nl/content.cfm?context=thema&content=inno_case&laag1=896&laag2=916&item_id=247&Taal=2

Figure 9 the alternative 'storage system' is depicted and two sorts of fuel are indicated in which energy is stored. They need not be the same fuel, for example they can be methanol produced from surplus wind energy and natural gas supplied by the gas network. Even if they are the same form -say methanol- it need not be the same methanol that is converted back into electricity; it may come from another stream of methanol as well. This resembles the case of dynamic storage of hydrogen as will be further explained in the next section.

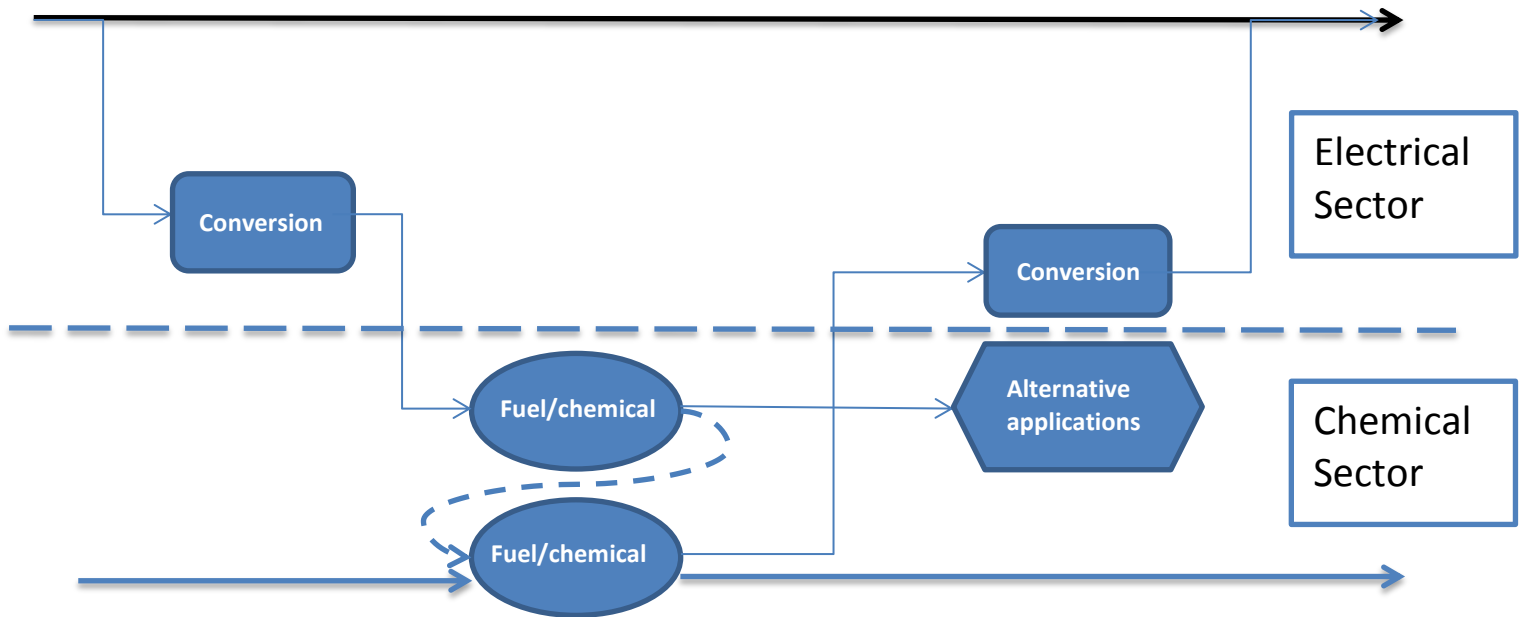


Figure 9. By coupling of two sectors and an overflow of energy from one sector to the other 'virtual' storage can be obtained.

6.2 Dynamic storage of hydrogen

An often proposed chemical/fuel for temporarily storing a surplus of electricity is hydrogen. With this solution immediately the problem of storage is shifted to the problem of storing hydrogen. Several options are available but again it is not the purpose of this paper to provide a review of electricity storage nor that of hydrogen storage options. We hope to provide another way of thinking about storage and thereby enlarge the solution space.

An interesting possibility for hydrogen storage could be envisioned when natural gas as we know it has been partly replaced by hydrogen. In a large European research program (NATURALHY) this has for example extensively been studied. If this is realised in the future and if we allow for a fluctuation of the hydrogen content in the natural gas/hydrogen blend (relative to a fixed nominal H₂ percentage of say 10% by volume). For the Netherlands, at the current rate of natural gas consumption of $40 \cdot 10^9 \text{ Nm}^3/\text{y}$ (or $1.3 \cdot 10^3 \text{ Nm}^3/\text{s}$), allowing for a fluctuation of ± 1 point % H₂ implies that on average, $130 \text{ Nm}^3/\text{s}$ of hydrogen can be put into or extracted from the grid. In other words at any point in the grid it is allowed to input or extract hydrogen at a rate of 1% of the local flow. At a constant rate and for the whole of the Netherlands this would be equivalent to $0.4 \cdot 10^9 \text{ Nm}^3/\text{y}$. This method of using the natural gas grid could be termed as 'dynamic storage'. The term 'dynamic' refers to the non-steady-state character of the storage (namely it decays) as is also indicated by the unit of time in the storage capacity (volume per second) and the proportionality of the storage capacity with the (local) flow. Although it is an unconventional way of thinking about storage, it presents storage possibilities for hydrogen that are not

easily achieved otherwise. However, since the hydrogen is not stored in a pure form, the drawback of this method is linked to the costs and difficulties in the extraction of hydrogen from the mixture and, in some cases, to the costs of increasing its pressure from the partial pressure of the mixture to consumer pressure. That is, if we introduce a surplus amount of hydrogen at atmospheric pressure into the grid than the partial pressure of this hydrogen is reduced to around 0.1 atm., which represents a loss. To get it out via a hydrogen membrane for example we would have to reduce the pressure at the outward side of the membrane by means of a vacuum pump for example and pump up the pressure to atmospheric pressure or higher for use in our application, which requires energy.

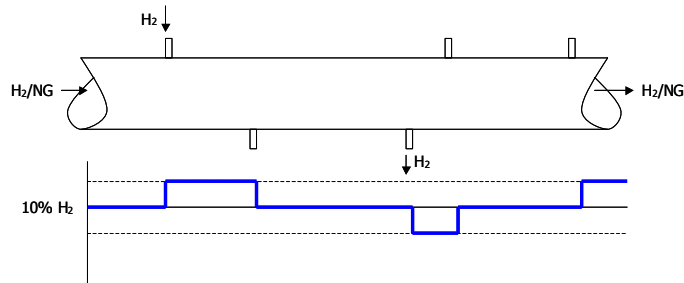


Figure 10. Illustration of the concept of dynamic storage of hydrogen in the natural gas grid containing nominal 10% of hydrogen with an allowed bandwidth of +/- 1%.

Alternatively we can choose to store hydrogen in the high pressure net. If this pressure is higher than 10 bar than the stored hydrogen is at a partial pressure of 1 bar or higher and can be filtered out by a membrane to applications without the use of a pump. In this case however we have to bring the hydrogen to a pressure of 10 bar or higher to be able to introduce it into the pressurised grid. The higher the nominal hydrogen concentration in the natural gas the lower is the energy loss in the storage and 'taking out' process. At 100% hydrogen more or less normal storage is obtained except for the fact that not the same hydrogen molecules are coming out as were put in. Also in the case of nominal 10% hydrogen in the grid storage is dynamic in the sense that hydrogen that has been put in is consumed downstream in end use appliances and the higher amount of hydrogen decreases over time. However there is a continuous new supply of hydrogen upstream to maintain the nominal value of 10%. Furthermore it is possible to take out hydrogen downstream an injection point and thus restore the composition to nominal value up on which further down again hydrogen can be injected as shown in Figure 10. Thus an even larger effective storage capacity can be obtained than just indicated by the allowed bandwidth and flow.

However, technical merits of this unconventional storage option have to be investigated further in order to determine its feasibility in practice.

7 Innovation and R&D policy implications

7.1 Innovation

The example of combining superwind with the ideas of local production of chemicals from hydrogen produced by electrolysis does show that sometimes two innovations can be put together to obtain a better and more feasible solution, whereas each of the separate inventions can have serious drawbacks. It is all about innovation. Innovation leads to things we cannot think of ahead. But we should allow for these developments to take place and allow innovations to build on top of each other. If we do not provide such a research and development ambience with proper R&D funding schemes to allow for this unknown 'innovation on top of innovation' and if we continue to prescribe and describe the type of innovation and developments that we expect from the funded research [sometimes in dreadful detail] we have little chance of bringing about real innovation. This is all in spite of the fact that all policy documents speak of innovation as the motor of economic development. So innovation and R&D directed towards innovation should be driven by a general consensus of the direction in which we should go and not on the exact topics what should be researched and innovated. Or at least room should be provided for this type of 'innovation on top of innovation' next to the more focused R&D we see as meaningful today. Such a meaningful direction certainly is distributed generation and we plea for an R&D program that allows for distributed generation of different forms of energy and not just electricity and definitely going beyond the concept of combined heat and power production.. We are standing at the beginning of these new developments. A research program that allows for unexpected ideas and combinations of technologies and developments is necessary. Many possible new ideas and inventions will develop, if R&D in this direction is stimulated and ample funds are provided. But maybe it is more important to provide ample room for innovation in the R&D funding programs.

One important characteristic of distributed generation is very different from central power production. Distributed generation takes place on a local scale whereas locally many variables and circumstances may differ, such as the availability of solar or wind, or local heat sources or the availability of existing combined heat and power installations. They all can differ very significantly so the design and the development of new distributed energy conversion devices must be adopted to local circumstances and take advantage as much as possible of these local circumstances also including industrial ecology type of interactions. Therefore it cannot be described and prescribed by central funding programs what kind of distributed generation should be developed. More innovation and more freedom of R&D is essential for the development of efficient and effective systems that are highly adapted to local circumstances and take most advantage of these circumstances.

7.2 Institutional change

With the developments of distributed generation also the management and institutional arrangements around these new systems must be designed and thought of in advance in order to prevent unwanted side effects of this development. Is it true like Jeremy Rifkin is stating that with the development of distributed generation we have the concept of power to the people made real [30]? Or will it be that institutions are developing and fully controlling all these distributed generation units and providing the services to consumers so that they do not have to bother about the operation and maintenance of the (or maybe their?) local energy system.

When crossing sectors different rules and regulations apply. Even the culture can differ enormously between sectors. For example comparing the agricultural sector with its farmers operating on a local scale in local communities, with the international and strongly business oriented energy and transport (fuel) sector.

8 Conclusion

Providing a suitable infrastructure for distributed generation of electricity will promote the introduction of renewable energy. The electricity grid has to be updated to accommodate multiple sources of electricity distributed in space and we have to find ways to manage these more complicated systems. In order to develop the new and future oriented vision on distributed generation and the accompanying challenges that integrative approach as proposed by the Dutch Royal Academy of science foresight committee on the renewable energy has been applied to distributed generation. This approach leads to several suggestions such as broadening the forms of energy and the interactions between them: so, not just look at that generation of electricity but also include the local production of chemicals and fuel possibly in multisource multiproduct entity systems. Looking at storage from this broader perspective also yields new approaches for the problem of fluctuating energy sources and the mismatch in time between supply and demand of electricity, such as flexible coproduction of hydrogen and power.

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