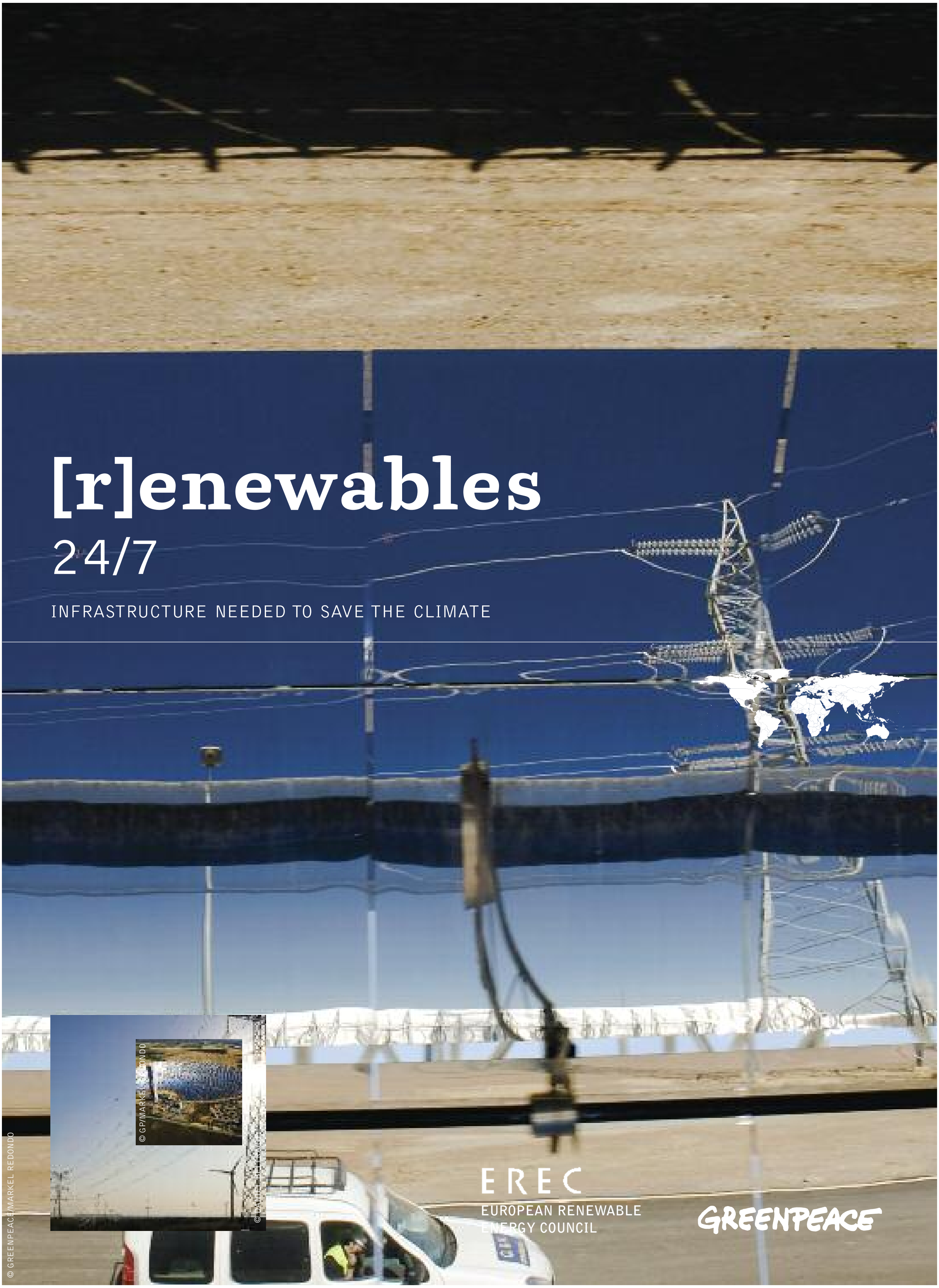

[r]enewables

24/7

INFRASTRUCTURE NEEDED TO SAVE THE CLIMATE

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EREC
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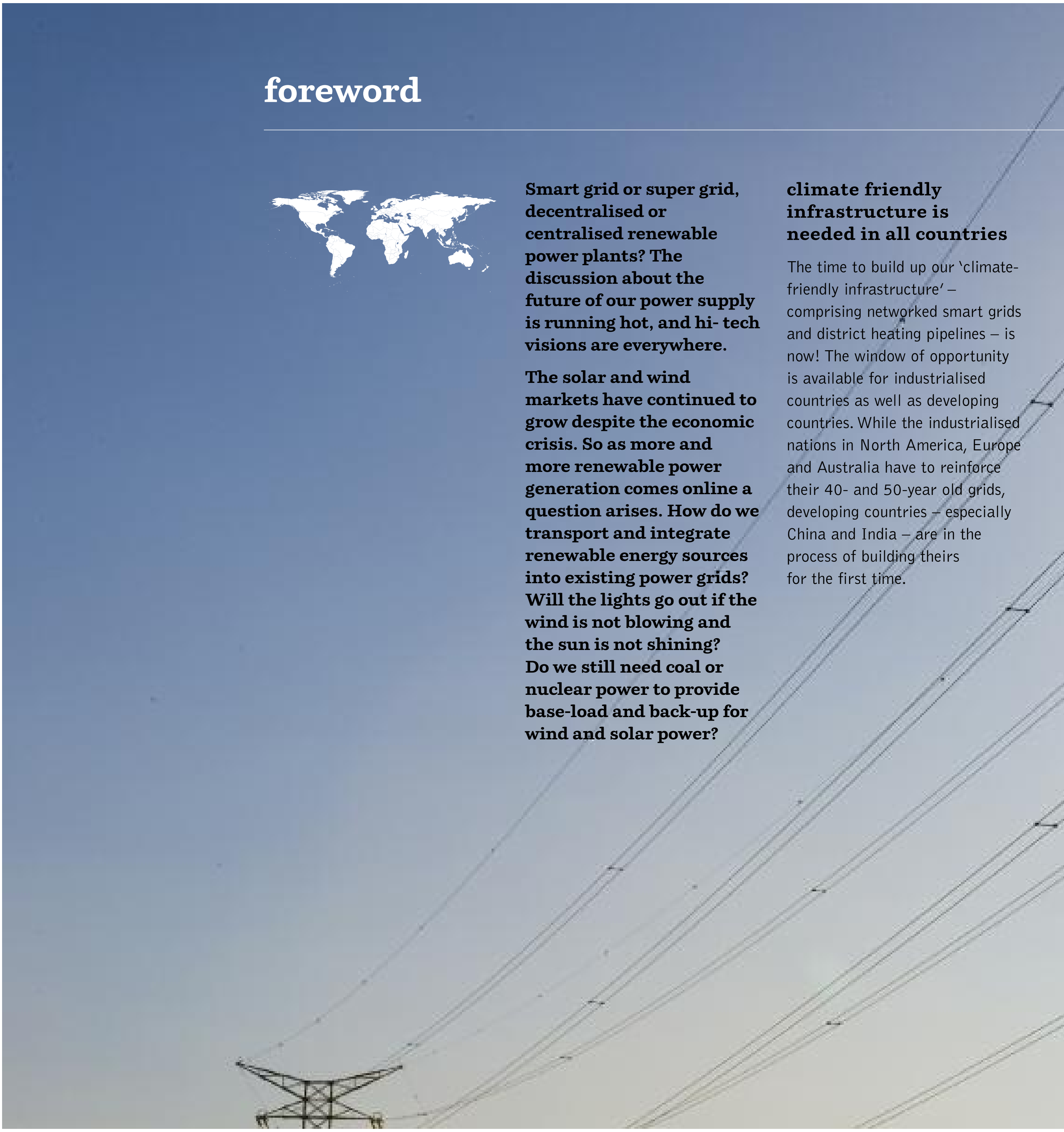
report global energy grid scenario



foreword

Smart grid or super grid, decentralised or centralised renewable power plants? The discussion about the future of our power supply is running hot, and hi- tech visions are everywhere.

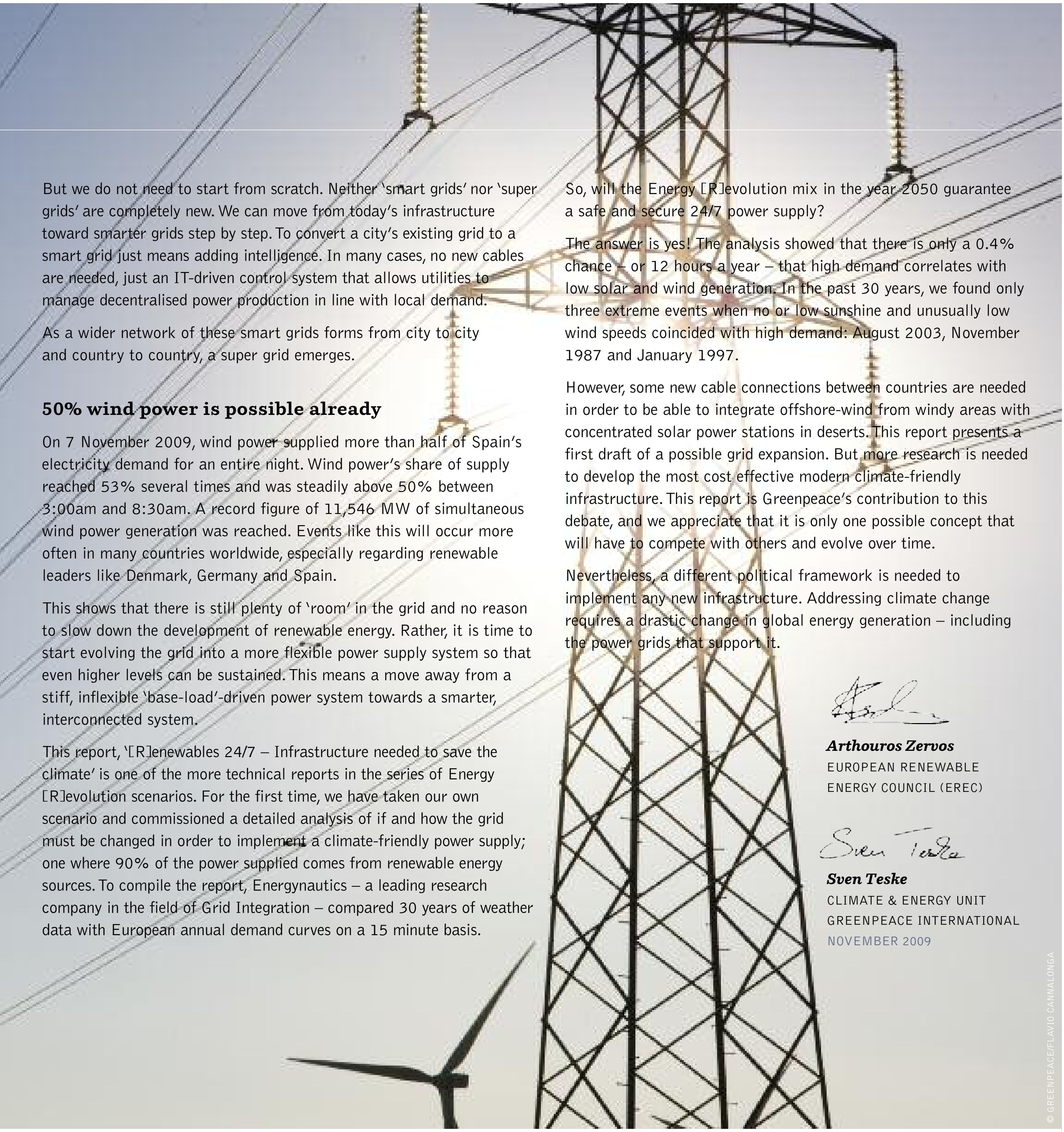
The solar and wind markets have continued to grow despite the economic crisis. So as more and more renewable power generation comes online a question arises. How do we transport and integrate renewable energy sources into existing power grids? Will the lights go out if the wind is not blowing and the sun is not shining? Do we still need coal or nuclear power to provide base-load and back-up for wind and solar power?

climate friendly infrastructure is needed in all countries

The time to build up our 'climate-friendly infrastructure' – comprising networked smart grids and district heating pipelines – is now! The window of opportunity is available for industrialised countries as well as developing countries. While the industrialised nations in North America, Europe and Australia have to reinforce their 40- and 50-year old grids, developing countries – especially China and India – are in the process of building theirs for the first time.

contents

image THE MARANCHON WIND TURBINE FARM IN GUADALAJARA, SPAIN IS THE LARGEST IN EUROPE WITH 104 GENERATORS, WHICH COLLECTIVELY PRODUCE 208 MEGAWATTS OF ELECTRICITY, ENOUGH POWER FOR 590,000 PEOPLE, ANUALLY. **cover image** ANDASOL 1 SOLAR POWER STATION IS EUROPE'S FIRST COMMERCIAL PARABOLIC TROUGH SOLAR POWER PLANT. IT WILL SUPPLY UP TO 200,000 PEOPLE WITH CLIMATE-FRIENDLY ELECTRICITY AND SAVE ABOUT 149,000 TONS OF CARBON DIOXIDE PER YEAR COMPARED WITH A MODERN COAL POWER PLANT.



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But we do not need to start from scratch. Neither 'smart grids' nor 'super grids' are completely new. We can move from today's infrastructure toward smarter grids step by step. To convert a city's existing grid to a smart grid just means adding intelligence. In many cases, no new cables are needed, just an IT-driven control system that allows utilities to manage decentralised power production in line with local demand.

As a wider network of these smart grids forms from city to city and country to country, a super grid emerges.

50% wind power is possible already

On 7 November 2009, wind power supplied more than half of Spain's electricity demand for an entire night. Wind power's share of supply reached 53% several times and was steadily above 50% between 3:00am and 8:30am. A record figure of 11,546 MW of simultaneous wind power generation was reached. Events like this will occur more often in many countries worldwide, especially regarding renewable leaders like Denmark, Germany and Spain.

This shows that there is still plenty of 'room' in the grid and no reason to slow down the development of renewable energy. Rather, it is time to start evolving the grid into a more flexible power supply system so that even higher levels can be sustained. This means a move away from a stiff, inflexible 'base-load'-driven power system towards a smarter, interconnected system.

This report, '[R]enewables 24/7 – Infrastructure needed to save the climate' is one of the more technical reports in the series of Energy [R]evolution scenarios. For the first time, we have taken our own scenario and commissioned a detailed analysis of if and how the grid must be changed in order to implement a climate-friendly power supply; one where 90% of the power supplied comes from renewable energy sources. To compile the report, Energynautics – a leading research company in the field of Grid Integration – compared 30 years of weather data with European annual demand curves on a 15 minute basis.

So, will the Energy [R]evolution mix in the year 2050 guarantee a safe and secure 24/7 power supply?

The answer is yes! The analysis showed that there is only a 0.4% chance – or 12 hours a year – that high demand correlates with low solar and wind generation. In the past 30 years, we found only three extreme events when no or low sunshine and unusually low wind speeds coincided with high demand: August 2003, November 1987 and January 1997.

However, some new cable connections between countries are needed in order to be able to integrate offshore-wind from windy areas with concentrated solar power stations in deserts. This report presents a first draft of a possible grid expansion. But more research is needed to develop the most cost effective modern climate-friendly infrastructure. This report is Greenpeace's contribution to this debate, and we appreciate that it is only one possible concept that will have to compete with others and evolve over time.

Nevertheless, a different political framework is needed to implement any new infrastructure. Addressing climate change requires a drastic change in global energy generation – including the power grids that support it.

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CLIMATE & ENERGY UNIT
GREENPEACE INTERNATIONAL
NOVEMBER 2009

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for further information about the global, regional and national scenarios please visit the energy [r]evolution website: **www.energyblueprint.info/**
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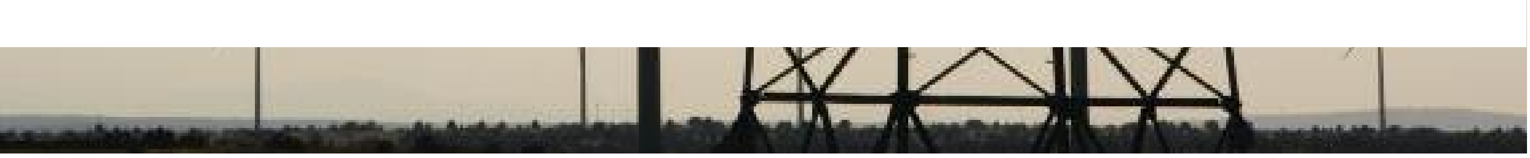

executive summary

“WE HAVE SUN, WIND, GEOTHERMAL SOURCES AND RUNNING RIVERS AVAILABLE RIGHT NOW, AND OCEAN ENERGY, BIOMASS AND EFFICIENT GAS TURBINES SET TO PROVIDE MASSIVE ENERGY SUPPLIES IN THE FUTURE.”

image OFFSHORE WIND FARM, COPENHAGEN, DENMARK.

grids keep power systems working

The grid is the sometimes over-looked part of the electricity system. The developed world has extensive electricity grids supplying power to nearly 100% of the population, but in parts of the developing world, many rural areas get by with unreliable grids or local, dirty electricity - for example from diesel - which is also expensive for small communities.

Our future on this planet depends on a massive shift to clean energy sources worldwide, as outlined in Greenpeace’s Energy [R]evolution. However the grids that bring the electricity to our homes and factories were designed for big, centralised generators, now running at huge loads, providing what is known as ‘base-load’ power. Until now, renewable energy had has to fit in as an extra, small slice of the energy mix and adapt to the conditions the grid currently operates under.

Some critics of renewable energy say it is not ever going to be able to provide enough power for our current energy use, let alone for projected growth of energy demand. This is because it relies mostly on natural resources, like wind and sun, which don’t appear to be available 24/7.

This report shows how that thinking is wrong.

We have sun, wind, geothermal sources and running rivers available right now, and ocean energy, biomass and efficient gas turbines set to provide massive energy supplies in the future. Clever technologies can track and manage energy use patterns, provide flexible power that follows demand through the day, use better storage options and group customers together to form virtual batteries. With all these solutions we can secure the renewable energy future needed to avert catastrophic climate change.

We just need smart grids to put it all together and effectively ‘keep the lights on’.

image WELDER WORKING AT VESTAS WIND TURBINE FACTORY, CAMPBELLTOWN, SCOTLAND.

smart grids can handle renewable energy

A smart grid is an electricity grid that connects decentralised renewable energy sources and co-generation and distributes power in a highly efficient way. It uses distributed energy resources and advanced communication and control technologies to deliver electricity more cost-effectively, with lower greenhouse gas intensity and in response to consumer needs. Typically, smaller forms of electricity generation are combined with energy management to balance out the load of all the users on the system. Small renewable energy generators can be closer to the users, rather than one large centralised source a long way away.

Smart grids are a way to get massive amounts of renewable energy with no greenhouse gas emissions into the system, and to allow decommissioning of older, centralised power sources. Advanced types of control and management technologies for the electricity grid make it run more efficiently overall. This applies whether we are talking about a major, complex system like in Denmark or a small village system in the Pacific Islands.

from little things, big things grow

Hybrid systems, and to some extent micro grids, are concepts for islands and for rural communities, where a number of small generators like wind turbines or PV panels are linked together and controlled centrally, to provide sufficient power to all.

When it comes to these kinds of power supplies, small is beautiful (and cheap to run). Significant savings are possible in remote areas in switching from diesel to renewable energy. Greenpeace outlines a method to bundle up several island power systems to attract more upfront funding from international sources. See Section 1 on hybrid systems and Micro Grids for more.

get smart, manage demand

Smart grids can help to get very large amounts of renewable energy into the system, while keeping a reliable and secure supply. Renewable energy 24/7 is technically and economically possible, it just needs the right policy and the commercial investment to get things moving. Demand management is a crucial part of this, it basically means turning off or down instead of boosting supplies.

Section 2 outlines what demand management means and provides some exciting real-life examples of how it is possible to re-imagine the operation of the grid to use flexible supply. We don't need to be stuck with the model of base-load generation. Electricity users can act together to take the strain out of a system, like the case study where hundreds of cool warehouses or thousands of electric car owners form giant virtual batteries and save power for everyone.

When you look at the real scenarios, for example in Spain, where huge amounts of solar power have been added to the system, large, inflexible fossil and nuclear power plants simply do not fit together with renewable energy.

super grid – connecting the dots intelligently

Smart and super grids are not a science fiction but a further development from today's grids. So we do not need to start from scratch. In fact, various types of high voltage systems suitable for long-distance connections are already under development and deployment. With super grids, we can effectively plug in areas of high demand like Central Europe to areas of high supply, like Northern Africa, and provide a more sustainable energy supply and income to all.

european modelling – the grid can support the energy [r]evolution

This report includes an analysis of the EU 27 Energy [R]evolution[1] scenario showing that extreme weather events where the supplies of naturally occurring sun and wind drop too low for our needs occur rarely, around once a year. The conclusion is that we can develop towards a smarter super grid and expand renewable energy supplies in parallel. There is no reason to stop expansion of renewable energy while we wait for better grids.

policy recommendations

towards a climate-friendly infrastructure: interconnected smart grids It is technically possible to operate a power system with over 90% renewables and guarantee a security of supply 24 hours a day, seven days a week 365 days a year. This is why the title of this report is 'Renewables 24/7'. However the existing grid system in most industrialised countries is over 40 years old. Reinforcement of this important infrastructure is needed, regardless. To prepare for a very high share of renewables, we need to move towards an 'interconnected smart grid'.

This document gives Greenpeace's position on cross-border electrical interconnections and points out the benefits of a more interconnected electrical system and the disadvantages that this represents in a system with a high percentage of dirty energies. Greenpeace calls for an increase in international electrical interconnections and the build-up of 'smart grids' which are needed to operate decentralised renewable energy sources and co-generation power plants. The current grid must be upgraded towards a connected smart grid system in order to implement the Energy [R]evolution – the way out of the climate crisis. The following political changes are needed to implement this very much needed 'climate infrastructure':

the advantages of a more interconnected and smarter system Greenpeace considers that a greater capacity of cross-border electrical interconnection brings advantages in security of supply, energy efficiency and the development of an electrical system based on renewables:

- **security of supply:** An interconnected system allows an increase in the security of supply, since, for the same installed power, there are more options for managing the system assuring the quantity and quality of coverage of demand. For example, in the case of demand peaks, countries could import electricity from other geographic areas when it is necessary and this would reinforce the security of the electrical supply.

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reference

[1] THE ANALYSIS INCLUDES NORWAY, SWITZERLAND AS WELL AS THE EU-27

- **energy efficiency:** A more interconnected system allows better use of the installed power, avoiding the overall need for power production capacity. A similar effect is achieved through demand side management, which means changing demand to meet supply, rather than the other way around. Through exploiting these effects, polluting conventional power production capacity can be reduced substantially.

renewable energies Global emission reductions of at least 30% by 2020 and at least 80% by 2050 are necessary to prevent the most dangerous levels of climate change. In order to reach these objectives renewable energy sources will need to contribute a lot more to our electricity supply - at least 50% by 2030 and close to 100% by 2050.

A large-scale penetration of renewables requires improvements in the infrastructure of the transmission network, both within a national electrical system and in the interconnections between countries, to balance variable power output and demand across regions and to transmit the renewable energy generated by off-shore installations and large-scale solar power stations. Also, the more distributed generation system with small-scale and larger renewable energy installations requires a smarter design and operation of the distribution and transmission system.

Greenpeace demands the development of smart grid technology and the increase of international electrical connections The development of a smart grid will lead to an essential 'climate protection infrastructure' that will get distributed and variable renewable energy sources into the power system and maximise energy efficiency. It should be developed specifically with a view to achieving both these objectives.

In parallel, greater interconnection capacity brings a range of advantages for the security of supply, energy and economic efficiency and the development of an electrical system based on renewable energy. Greenpeace is in favour of a more interconnected grid that is linked to a suitable energy plan focused on ecological sustainability criteria.

However, the present planning system is based on a supply-side approach and not on a demand side management approach and runs on mainly on dirty energies. The opening of new interconnection lines without conditions could favour dirty energies and hinder energy saving.

To promote the development of the grid system, Greenpeace demands the following:

- Governments, as a top priority, should establish by law mandatory energy planning objectives in the medium to long-term, specifically the following:
    - *Increase Energy Efficiency* to reduce the overall demand.
    - Increase contribution of renewables according to the Energy [R]evolution scenarios.
    - A timetable for the gradual but urgent phasing out of nuclear and coal power stations.
- The power system must be flexible to allow the large-scale integration of fluctuating renewable energy. No new, large nuclear or coal power plants should be licensed, and existing plants must be replaced progressively with flexible, highly efficient and more decentralised plants.
- Renewable energy should be guaranteed priority access to the grid. Access to the exchange capacity available at any given moment should be fully transparent and the transmission of energy from renewable sources should always have preference, in both directions.
- The design of distribution and transmission networks, in particular for interconnections, should be guided by the objective of facilitating the integration of renewables and to achieve a system as close as possible to 100% renewable.
- Guarantees should be established that exclude the possibility of transferring electricity from nuclear origin through the new interconnections.
- In planning new interconnections, the existing infrastructure should be exploited as much as possible. Where it is not possible, all environmental considerations should be taken into account, using a global and exhaustive analysis, so that the new installations have the minimum environmental impact. In order to achieve this, the interconnections should have a favourable Environmental Impact Statement in all cases where it is mandatory and should fulfil all the conditions and corrective measures included in the EIS. The Environmental Impact Assessment should include the option of burying the lines, along with all possible alternatives. Environmental criteria must prevail over economic criteria.
- A complete ownership unbundling of electrical grids from power generation and supply companies should be enforced.

  Transmission and distribution system operators must make all relevant grid data accessible so that independent institutions can develop grid optimisation concepts.
- For the construction of new transmission and distribution capacity, preference should be given to ground-based cables, rather than overland high tension lines, as is already done in Denmark.
- Governments should create appropriate framework conditions to support and expand demand side management.
- Regional pilot projects should promote the further optimisation and demonstration of smart grid technology, virtual power stations and highly-developed demand side management.
- The transport sectors (e.g. electric vehicles) should increasingly be integrated into national and regional power supply strategies.
- Communication standards for smart grids should be agreed.

introduction

> "IN THE FUTURE, WE NEED TO CHANGE THE GRIDS SO THEY DO NOT RELY ON LARGE, CENTRAL CONVENTIONAL POWER PLANTS, BUT INSTEAD ON CLEAN ENERGY, FROM SOURCES LIKE WIND, SOLAR, HYDRO AND BIOMASS."


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image THE MARANCHON WIND FARM IS THE LARGEST IN EUROPE WITH 104 GENERATORS WITH A TOTAL CAPACITY OF 208 MW, ENOUGH ANNUAL POWER FOR 590,000 PEOPLE. THE FARM ANNUALLY PRODUCES THE EQUIVALENT ELECTRICITY OF 100,000 TONS OF OIL, THEREBY ELIMINATING 430,000 TONS OF CO$_2$.

The electricity 'grid' is a collective name for all wires, transformers and infrastructure that transport electricity from power plants to users. In all networks, some energy is lost as it travels, making distribution inefficient.

The existing electricity transmission and distribution system was mainly designed and planned 40 to 60 years ago. All over the developed world, the grids were built with large power plants in the middle, with high voltage alternating current (AC) power lines to the areas where the power is being used. A smaller 'distribution network' carries the current to the final consumers. This is known as a centralised grid system and the large power sources are mostly coal and gas power stations. The systems supported massive industrialisation in cities and also brought electricity to rural areas in most developed parts of the world.

In the future, we need to change the grids so they do not rely on large, central conventional power plants, but instead on clean energy, from sources like wind, solar, hydro and biomass. These are typically smaller power generators, and they will be distributed throughout the grid, as well as concentrated in large power plants such as offshore wind power plants. Examples of big generators of the future are the massive wind farms in the North Sea and large areas of land covered in concentrating mirrors to generate energy in Southern Europe or Africa.

The challenge ahead is to integrate new generation sources and at the same time phase out most of the large-scale conventional power plants, while keeping the lights on 24/7. This will need new types of grids and power system architecture. The major new technologies needed are to balance fluctuations in energy demand and supply. Plenty of new measures are available today, like demand-side management, advanced weather forecasting and energy storage; we just need to put them to work.

The key elements of the new power system architecture are micro grids, smart grids and a number of interconnectors for an effective super grid. The first three sections of this report provide information on the technologies and economics of each of these systems. The final section outlines the study which applied the Greenpeace Energy [R]evolution scenario for Europe and worked out how big the onshore super grid would need to be to support it.

definitions

Hybrid system is a term for new electricity supplied on islands or to bring electricity to rural areas, especially in developing countries. In the future, several hybrid systems could be connected and form micro grids which can support the functions of the smart grid by, for instance, enabling virtual power plants which can be used to firm up variable generation. In developing countries, hybrid systems can be built for remote locations or island; they are simpler than micro grids but they can be a step towards a micro grid, when they are upgraded and get integrated to a power system.

Smart grid is an electricity grid that connects decentralised renewable energy sources and co-generation and distributes power highly efficiently. It is an electricity network that uses distributed energy resources and advanced communication and control technologies to deliver electricity more cost-effectively, with lower greenhouse intensity and in response to consumer needs. Typically, smaller forms of electricity generation are combined with energy management to balance out the load of all the users on the system. Small generators include wind turbines, solar panels, micro turbines, fuel cells and co-generation (combined heat and power). These types of energy sources can be closer to the users, rather than one large centralised source a far. Smart grids are a way to get massive amounts of renewable energy with no greenhouse emissions into the system, and to allow decommissioning of older, centralised power sources. Advanced types of control and management technologies for the electricity grid can also make it run more efficiently overall. These include things like smart electricity meters that show real-time use and costs and can respond to remote communication and dynamic electricity pricing.

Super grid is a large interconnection - typically based on HVDC technology - between countries or areas with large supply and large demand. An example would be the interconnection of all the large renewable based power plants in the North Sea or a connection between Southern Europe and Africa where renewable energy could be exported to bigger cities and towns, from places with large locally available resources.

the vision

To create smart grids takes an overall approach; it is not bound to one particular distribution network. Micro grids and therefore also smart grids use new monitoring and control infrastructures embedded in distribution networks, that use local energy generation resources; for example, combinations of solar panels, micro turbines, fuel cells, energy efficiency and information/communication technology to control loads.

The super grid is a concept that helps to guarantee the security of supply at all times. Broadly defined, the concept refers to micro grids supplying local power needs, to smart grids balancing demand out over a region, and to super grids operating to transport large energy loads between regions. The three types of systems support each other and interconnect with each other.

The scenario in Section 4 sets out a way of supplying 90% of European electricity by renewable generation, as part of the global energy mix to meet the tough greenhouse gas reduction requirements needed to avoid dangerous climate change. The study answers the question of 'what super grid infrastructure is needed to keep the lights on 24/7 when 90% of Europe's electricity demand is supplied by renewable generation?' It tracks the extreme weather situations that have occurred in Europe over the last 25 years in order to work out how much capacity the onshore super grid would need, and where it would be located in order to balance the local renewables resources available with big generating potentials like North Sea wind and southern Europe's sun.

image CONSTRUCTION OF THE OFFSHORE WINDFARM AT MIDDELGRUNDEN NEAR COPENHAGEN, DENMARK.

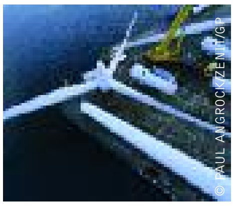
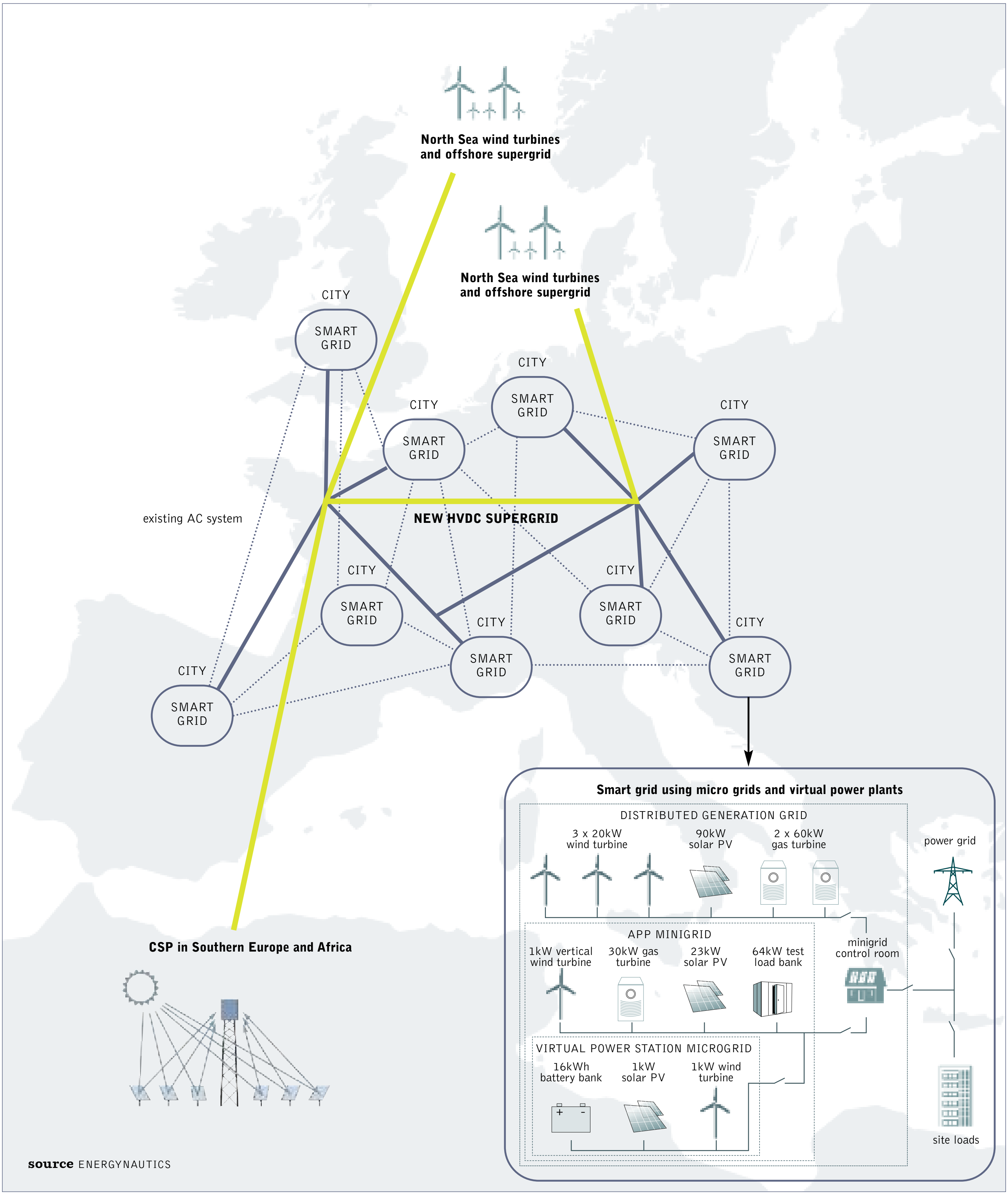


figure 1: overview of the future power system with high penetration of renewables



source ENERGYNAUTICS

a big role for the IT sector

Greenpeace runs the 'Cool IT' campaign to put pressure on the IT sector to make the technologies described in this report a reality. The giants of the telecommunications and technology sector have the power to make the grid smarter, and to get us towards a clean energy future, faster.

There are many opportunities for the ICT sector to help to redefine the power network, which will look a lot different to what we have today. Because a smart grid has power supplied from a diverse range of sources and places it relies on the gathering and analysis of a lot of data. This requires software, hardware and data networks that are capable of delivering data quickly, and of responding to the information that they contain.

Several key IT players are racing to smarten up energy grids across the globe, and there are also hundreds of companies that could potentially be involved with the smart grid, from telecommunications companies, such as Deutsche Telecom, or AT&T; software providers, like Cisco, or Google, and hardware providers, like Fujitsu and IBM; and many more.

figure 2: **ICT solutions opportunities**

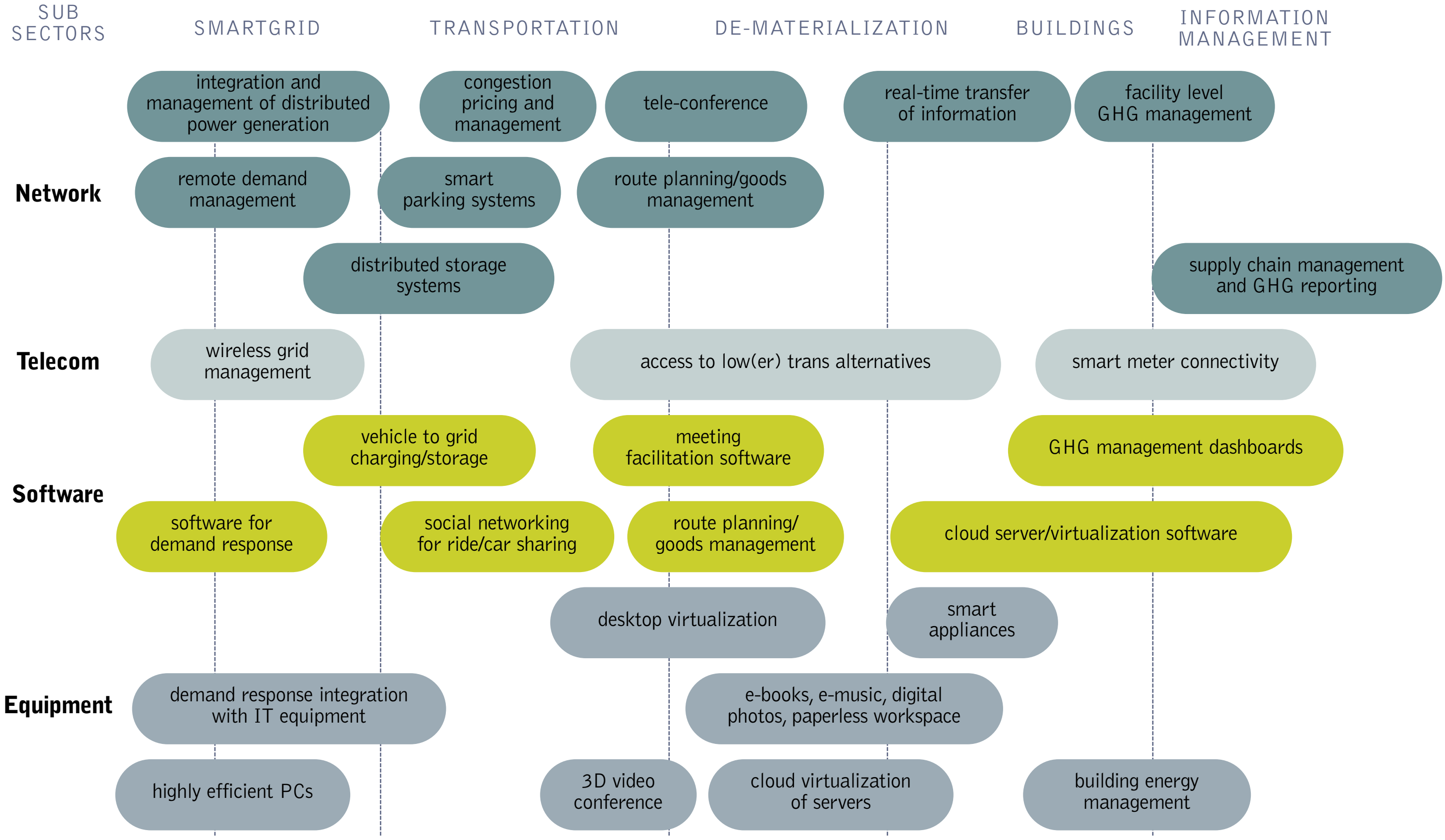


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image ANDASOL 1 SOLAR POWER STATION IS EUROPE'S FIRST COMMERCIAL PARABOLIC TROUGH SOLAR POWER PLANT. IT WILL SUPPLY UP TO 200,000 PEOPLE WITH CLIMATE-FRIENDLY ELECTRICITY AND SAVE ABOUT 149,000 TONS OF CARBON DIOXIDE PER YEAR COMPARED WITH A MODERN COAL POWER PLANT.


© GP/MARKEL REDONDO

Then there is the requirement for smart metering and information systems on the consumer side of the equation. This enhanced energy management information is needed to monitor any local resource, such as a private photovoltaic array, ensuring that this resource is managed and any excess is sold to the grid accurately. Providing energy users with real-time data about their energy consumption patterns and the appliances in their buildings helps them to improve their own energy efficiency, and will allow many energy using appliances to be used at a time when local supply is high, for example, when the wind is blowing. As the grids get smarter still, there will be implications for storage and use in times of low demand, to mop up any excess that may exist.

There are many IT companies offering products and services to manage and monitor energy. The companies are of varying size from small start-ups through to large household names, and other companies that are better known as service providers.

IBM and Fujitsu both provide some hardware solutions to facilitate smart power production and they are involved in producing monitoring equipment for the loads and weather. Google has provided open source software application Powermeter, to help consumers directly leverage their electricity consumption data from their smart meter, providing real-time analysis of energy consumption. Microsoft has also entered the market with its Holm energy meter software. Cisco is looking to duplicate its role in the development of smart grids as they did in building the internet, providing enterprise scale networks for application to energy management. It is rapidly expanding its smart grid product offerings to become a fully vertically integrated smart grid solutions company and are exploring all kinds of solutions in this area.

Technology companies need to be pushing for the development of decentralised smart grids. These companies should be leading the way to a clean technology revolution over vested interests of some energy utilities that use smart grids to refer only to improving the efficiency of centralised fossil fuel based generation. Smart grids have the potential to transform the way that people use energy, and drive the massive global shift away from fossil fuels and towards renewable energy that is required to prevent the worst ravages of climate change. The onus is on leading technology companies to take the bold steps needed to realise this potential.

image THE PS10 CONCENTRATING SOLAR TOWER PLANT IN SEVILLA, SPAIN, USES 624 LARGE MOVABLE MIRRORS CALLED HELIOSTATS. THE MIRRORS CONCENTRATE THE SUN'S RAYS TO THE TOP OF A 115 METER (377 FOOT) HIGH TOWER WHERE A SOLAR RECEIVER AND A STEAM TURBINE ARE LOCATED. THE TURBINE DRIVES A GENERATOR, PRODUCING ELECTRICITY.


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renewable energy and hybrid systems

GLOBAL

RENEWABLE TECHNOLOGIES
HYBRID SYSTEMS DESIGN

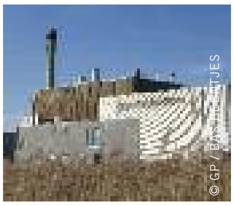
MICRO UTILITY MODEL

1

image SOLAR PANEL. © BERND JUERGENS/DREAMSTIME

> “...more power, at a cheaper rate...”
>
> **GREENPEACE INTERNATIONAL**
> CLIMATE CAMPAIGN

image BIOMASS POWER PLANT IN LELYSTAD, THE NETHERLANDS. BY BURNING WOOD CHIPS THE POWER PLANT GENERATES ELECTRICITY, ENERGY AND HEAT AND PROVIDES FOR 3000 HOUSEHOLDS.



'Hybrid systems' can provide renewable energy solutions on islands or rural electrification in developing countries. This section describes the way that renewable energy technologies can provide more power, at a cheaper rate, with a reliable supply on islands and in rural areas. The 'grid' part of the equation refers to how the technology for interconnection and system control can make renewable energy systems more feasible economically, by connecting several small generators to one integrated system.

Richer countries have more people connected to electricity in their homes and work-place. The percentage of people with access to electricity in a country is also referred to as 'electrification.' Table 1 gives an overview of electricity access in three representative countries: Zambia, a developing economy, India, a rapidly industrialising economy and Germany, a post-industrial country.

In post-industrial countries and regions such as Japan, Europe and North America, the power system essentially reaches everywhere. In these countries each person typically uses 20-25 kWh per day. In developing countries however, the power system does not reach as far, and each person typically uses only 1-2 kWh per day when averaged across a country's entire population.

There are challenges in developing countries to update the electricity system: the existing system is very small, with poor quality of supply and frequent power interruptions and at the same time, there is a rapid increase in demand in the areas that are already connected to the grid. Any solution must address climate change issues; otherwise providing more power in developing countries will have a significant impact on climate change in the future.

In particular, the electrification of rural areas that currently have no access to any power system cannot go ahead as it has in the past. A standard approach in developed countries would be to extend the grid by installing high- or medium-voltage lines, adding new substation(s) and a low-voltage distribution grid. But when there is low potential electricity demand, and long distances between the existing grid and rural areas, this method is often not economically feasible.

Electrification based on renewable energy systems (RES) with hybrid electricity systems is often the cheapest as well as least polluting alternative. Hybrid systems connect renewable energy sources such as wind and solar power to a battery via a charge controller, which stores the generated electricity and acts as the main power supply. They typically have back-up from a fossil fuel, wind-battery-diesel or PV-battery-diesel systems, for instance. Decentralised hybrid systems are more reliable, consumers can be involved in operation through innovative technologies and they can make best use of local resources. Decentralised renewable energy systems are less dependent on larger-scale infrastructure and can be constructed and connected faster, especially in rural areas.

The following sections describe today's state-of-the-art solutions of renewable energy solutions for grid connection and electrification of rural areas in developing countries. The focus is on renewable energy solutions which already exist and have been successfully employed in developing countries.

table 1: electricity access and use in illustrative countries

COUNTRY	CIRCUIT OF > 132 KV TRANSMISSION LINES/SQ KM	PERCENTAGE WITH ACCESS TO ELECTRICITY IN 2000	PER CAPITA KWH USE IN 2000	PER CAPITA KWH USE IN 2003	AVERAGE ANNUAL CHANGE IN PER CAPITA KWH USE IN 2000 - 2003 (%)
Zambia	0.0048	12	582	662	4.6
India	0.021	43	402	435	2.7
Germany	0.234	100	6,682	6,900	1.1

source ENERGY BALANCES OF OECD COUNTRIES (2006 EDITION); ECONOMIC INDICATORS AND ENERGY BALANCES OF NON-OECD COUNTRIES (2006 EDITION);WORLD ENERGY OUTLOOK: ENERGY AND POVERTY (2002), PARIS: IEA; . HTTP://WWW.SAPP.CO.ZW/; HTTP://WWW.POWERGRIDINDIA.COM/POWERGRID/; HTTP://WWW.EON-NETZ.COM/.
graph source HTTP://EETD.LBL.GOV/EA/EMS/REPORTS/MICROGRIDS-LARGER-ROLE.PDF

1.1 renewable technologies

Over the past decade, most renewable energy technologies have become mainstream energy technology and they are applied world-wide where there are sufficient natural resources (Table 2). For example, there is now more than 125 GW of wind energy installed world-wide, from small wind turbines with a few kW to multi-megawatt plants. Approximately 25 GW are added every year, making this a truly established energy technology.

Renewable energy technology is now reliable and economically competitive in many areas around the world, particularly if compared to grid extension. The implications for integrating renewable energy to conventional power grids are discussed in smart grids Section 2.1.

table 2: status of renewable energy technology

TECHNOLOGY	EXPERIENCE WORLDWIDE	COMMERCIAL STATUS
Photovoltaics	Extensive	Fully commercial
Small wind power (electric)	Extensive	Commercial and evolving rapidly
Small modular biopower units (10 kWe to 100+ kWe)	Some	Under development, first commercial products becoming available
Small packaged biopower units (100 - 500 kWe)	Some	Limited but expanding commercial availability; expanded commercialization underway
Bioenergy > 0.5 Mwe	Extensive, in wood and agro industries worldwide	Commercial site-engineered systems
Microhydro electric	Enormous (e.g. China, Nepal, Vietnam)	Fully commercial, with innovative products emerging

source ALLIANCE FOR RURAL ELECTRIFICATION, HTTP://WWW.RURALELEC.ORG/

1.1.1 selecting the right type of renewable energy source

The most appropriate type of renewable energy for any one site, depends on the local conditions, and needs field data to be collected. The best choice of technology will take technical, economic, financial, and socio-cultural considerations into account. The following basic criteria should be considered to design an optimal power solution:[2]

- **location:** The suitability of the site to be electrified, its topographic and geographical characteristics.
- For example, wind turbines should not be installed near buildings, trees and other obstacles to avoid turbulence and loss of energy production. Wind turbines should be at least 2m above any building or obstacles in the area.
- **resource:** Resource evaluation requires data collection and interpretation.

  solar: The solar resource is linked to solar irradiation, latitude, altitude, cloud cover and content of water vapour and dust in the air. Therefore, the essential factors for developing solar energy are the monthly average of daily sunshine hours, site latitude, local average cloudy days, foggy days and rainfall day.

  wind: The power in the wind is directly related to the cube of the wind speed and to the air density, i.e. a 10% higher average wind speed will result in an approximately 30% higher energy yield. Wind resources become exploitable where average annual wind speeds exceed 5 m/s. Essential factors for wind resource evaluation are the yearly average wind speed; height at which wind speeds were measured; site altitude; primary seasonal wind directions; topography of the site and forestry cover at the site.

  small hydro power (SHP): The energy output of a hydro power is determined by flow rate (litres/s) and net head (m) of water. Therefore, the essential factors for evaluating resources for small hydro power are annual flow-rate; monthly distribution of the resource.

- **load analysis:** A load analysis is done to match supply to demand, it typically includes:

  load type: There are three main groups to be considered: domestic loads (lighting, TV, refrigerator, iron, etc), community loads (schools and public lighting and appliances, water pumping, etc) and commercial loads (electric power tools, etc);

  load calculation or how much power is required;

  load growth: A study of the current and future local demand for electricity is needed to match the system size to future use and avoid power shortages. A flexible system design that can be expanded as load demand increases helps to mitigate risks associated with unpredictable load growth rates.

Table 3 provides an overview of average daily working hours for typical loads and their rated power.

table 3: rated power and average daily working hours for typical loads

LOAD / APPLICATION	RATED POWER (W)	AVERAGE DAILY WORKING HOURS (H)
Energy-saving lights	9-30	5
21″ Color TV	70	5
B/W TV	20	5
Cassette recorder	40	2
Washing machine	150	2
Refrigerator	120	10
1/5 HP Water Pump	165	0,5
Radio set	10	1
Dust cleaner	750	1
2 Pair conditioner	2,000	5 (Summer)
Electric fan	50	2 (Summer)
Moveable Electric Heater	1,000	3
Bubble Jet Printer	20	1
Desk computer	400	5
Monitor	200	5
Fax machine	100	30min
Microwave stove	1,000	10min

source ALLIANCE FOR RURAL ELECTRIFICATION, HTTP://WWW.RURALELEC.ORG/, HTTP://WWW.RURALELEC.ORG/8.0.HTML?&L=0,

image WORKERS ON A WIND TURBINE BY THE VILLAGES OF NIEBÜLL AND MARIENKOOG, GERMANY.

© GWEC/WIND POWER WORKS

1.2 hybrid systems design

The electrification of rural areas that have a poor security of supply or are entirely without access to any power system requires new solutions. Often; diesel generators are used for power supply in these areas they may supply just a single load (house or business) or island power systems. Using diesel is expensive for communities and they cause significant emissions. Fuel prices are only going up, so the costs will increase for towns running on diesel. Hybrid systems that use a significant share of renewable power sources are becoming economically competitive and are a lot cleaner. The hybrid system definition for this report is *'a combination of different, but complementary energy supply systems used in the same island power system'.* Hybrid systems are typically designed to balance variable renewable energy resources and other energy supply systems, including storage systems such as battery and flywheel systems. The advantage is being able to supply energy even at times when one part of the hybrid system is not available.

A typical example for a hybrid system is a wind/PV/Battery/Diesel hybrid system. In many places in the world wind and solar resources occur at different times, if solar radiation is high, wind speeds are low and vice versa.

The storage systems within hybrid systems are typically designed to cope with short-term fluctuations; they can store surplus power supply for times when demand is higher than local renewable generation capacity. The storage capacity, however, is typically only enough to provide balancing in the time frame of minutes (5 to 10 minutes). In places where renewable energy does not provide power 100% of the time, diesel gensets are typically used as back-up systems.Hybrid systems can be designed in many different ways, mainly because of great variations in the availability of local natural resources. Often diesel generator sets are already installed in the local area, and hybrid systems are usually developed in two steps:

1. Small amounts of renewable energy sources are added to a diesel island power system, i.e. the renewable energy sources have a rather small influence on the overall island power system operation. In this case, the only impact is the reduction of fuel consumption in the diesel gensets, but the general control scheme is typically not affected.
2. Increasing shares of variable renewable energy sources, which requires adjustment of the overall control scheme and the possible addition of storage systems. One of these control schemes is known under the term micro grid (see also Section 1.3.2 about control approaches for hybrid systems).

Hybrid systems can be designed in a variety of ways, and there are many different combinations in working systems.

A common hybrid system suitable for developing countries consists of:

- A primary source of energy, i.e. renewable such as wind or PV;
- A secondary source of energy for supply in case of shortages e.g. Diesel;
- A storage system to guarantee stable output (battery) during short periods of time and/or to meet peak demands;
- A charge controller which regulates the state-of-load of the battery;
- DC/AC inverters may also be needed.

Some examples of technologies in operation are: PV/Battery, PV/Diesel, PV/Battery/Diesel, PV/Flywheel/Diesel, Wind/Battery; Wind/Diesel; Wind/Battery/Diesel, Wind/Flywheel/Diesel, Wind/PV/Small Hydro; Wind/Small Hydro; Wind/Small Hydro/Battery; Small Hydro/Biomass; Small Hydro/Battery/Biomass; Wind/PV/Biomass.

1.2.1 hybrid systems: main technical design options

There are different principal technical design options for hybrid systems, depending on the overall system demand. A general categorisation of hybrid systems is given in Table 4.

table 4: categorization of hybrid systems

INSTALLED POWER	CATEGORY	DESCRIPTION
< 1kW	Micro systems	Single Point DC-based system
1 – 100kW	Village power systems	Small power system (DC and AC)
100 kW -10MW	Island power systems	Isolated grid systems (AC)
> 10MW	Large interconnected systems	Large remote power system (AC)

source WIND POWER IN POWER SYSTEMS, EDITOR T. ACKERMANN, WILEY & SONS

Examples of these four categories are:

- A micro system is a small PV or wind turbine with a capacity of less than 1kW and a small battery (DC bus system);
- A village home system typically has a load between 1 and 100 kW with a renewable energy generation capacity of 1-50 kW (AC and DC bus possible);
- An island power system typically has a peak load from 100 kW to 10 MW and an installed renewable generation capacity in the range from 100 kW to 1 MW, and
- A large (interconnected) island power system typically is larger than 10 MW with several renewable power plants installed, each typically larger than 1 MW.

reference
2 BASED ON *ALLIANCE FOR RURAL ELECTRIFICATION*,HTTP://WWW.RURALELEC.ORG/.

Wind Energy-diesel systems are the most established hybrid systems, they can provide a model for how much renewable energy can be included in hybrid systems. Figure 3 shows the maximum penetration level of wind power in existing hybrid systems, defined as the ratio between instantaneous wind power output and instantaneous primary electrical load. The real-life conditions in Denmark in 1998 and a projection for Denmark for the year 2030, give an indication of how much wind energy could be included in different power systems of varying sizes.

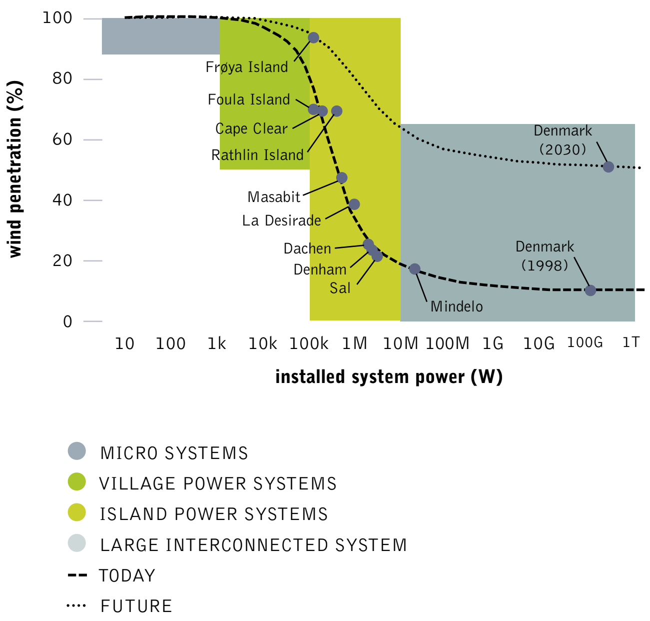
It shows that small hybrid systems can achieve a renewable penetration level of 100%, but with the penetration levels typically lower for systems of greater capacity. However, the reasons are often economic and not technical issues – the increasing price of diesel fuel is likely to raise renewable penetration levels in larger hybrid systems.

In the following, we will briefly describe the principal design options.

DC interconnected hybrid system All electricity generating components are interconnected via a DC (direct current) connection which is used to charge a battery. AC generating components need an AC/DC converter. The battery is typically protected from overcharge and discharge by a charge controller. The battery supplies power to the DC loads in response to the demand. AC loads can be operated via a DC/AC inverter (see Figure 4 for a principal overview).

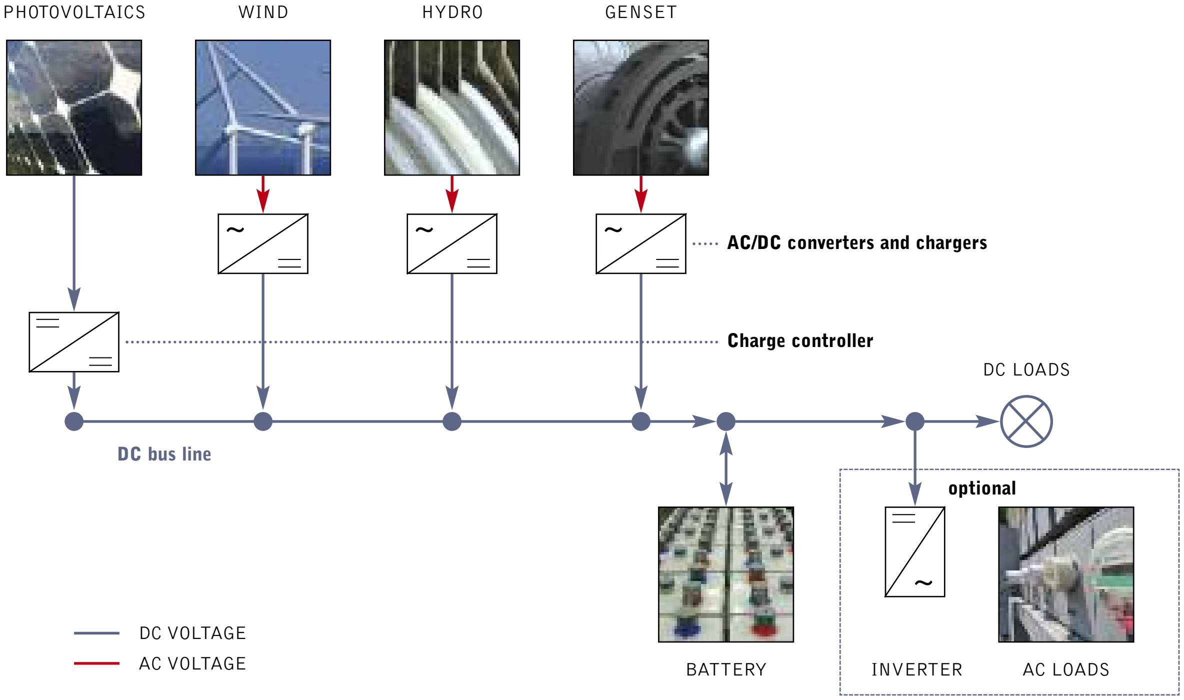
Security of supply is typically limited as no back-up supply is available.

figure 3: present and expected future development of the wind energy penetration vs. the installed system capacity based on lundsager et al. (2001)



source SOURCE: WIND POWER IN POWER SYSTEMS, EDITOR T. ACKERMANN, WILEY & SONS.

figure 4: example for DC interconnected hybrid system



source HYBRID POWER SYSTEMS BASED ON RENEWABLE ENERGIES: A SUITABLE AND COST-COMPETITIVE SOLUTION FOR RURAL ELECTRIFICATION, ALLIANCE FOR RURAL ELECTRIFICATION.

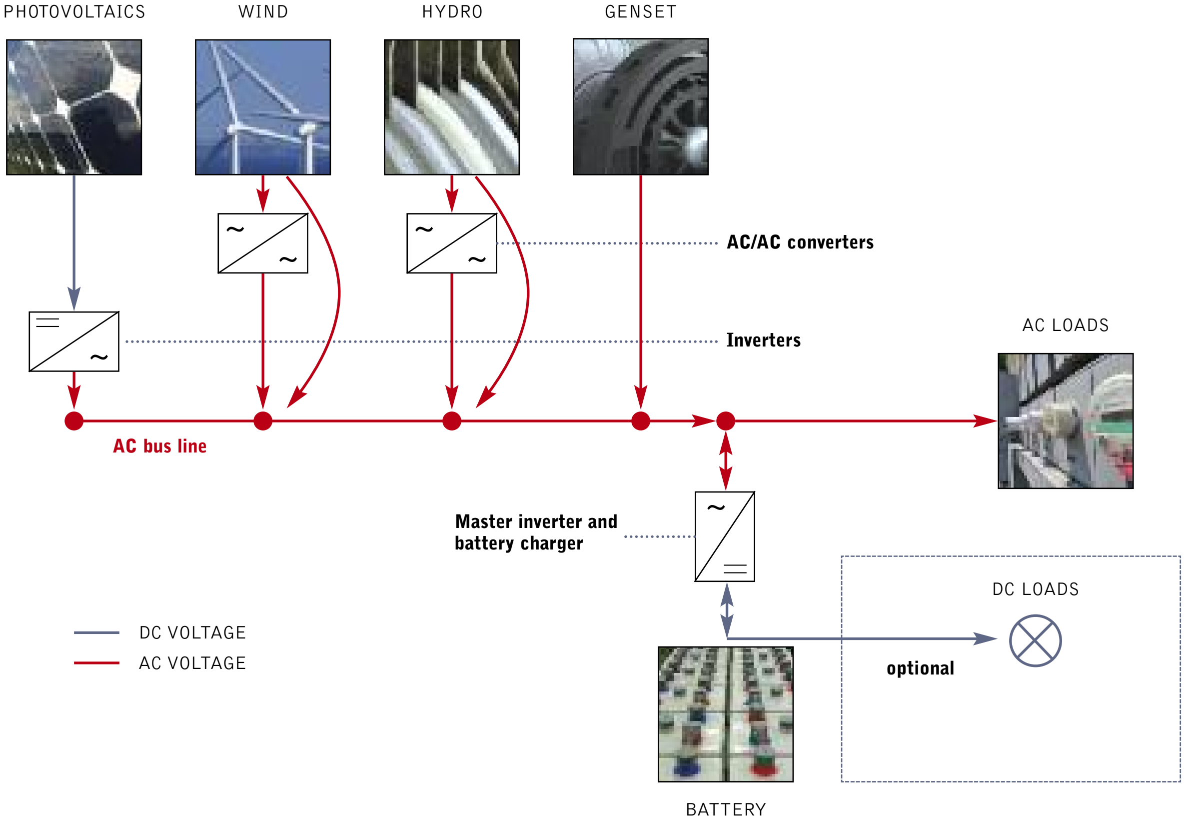
image THE HUGE SHADOW OF A 60-METRE-HIGH WIND TURBINE EXTENDS ACROSS THE GOBI DESERT FLOOR AT THE HE LAN SHAN WIND FARM IN THE NINGXIA PROVINCE, CHINA.

AC interconnected hybrid system All generating components are connected to an AC interconnection and AC generating components may be directly connected to loads via AC connection or via an AC/AC inverter (Option A, see Figure 5). The battery is connected to the AC system via an inverter. The inverter controls the energy supply to the AC loads; and DC loads can optionally be supplied directly via the battery.

In option B (see Figure 6), the DC generation resources are directly connected to the battery via a DC connection.

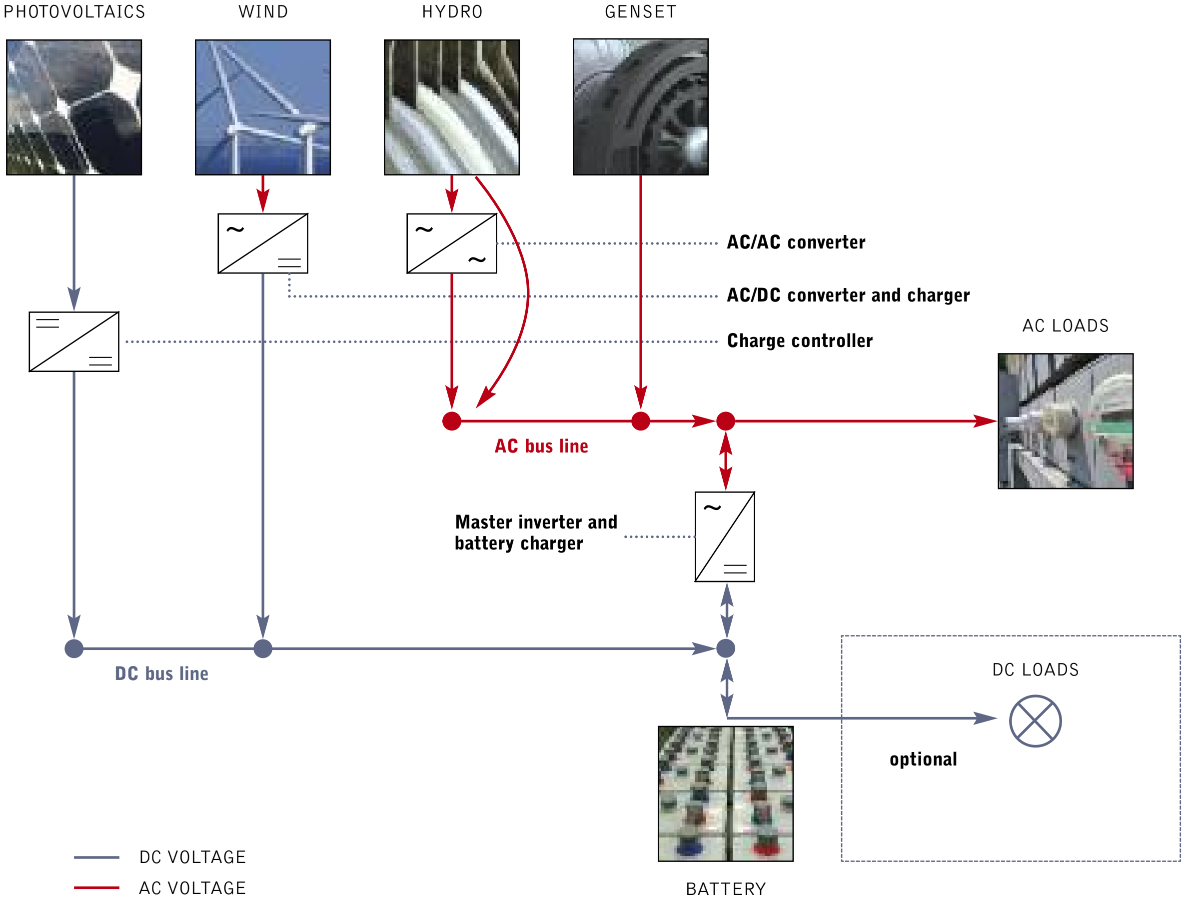
There are different options for the frequency control and voltage control in the AC system, see also section on control for hybrid systems.

figure 5: AC interconnected hybrid system – option A



source HYBRID POWER SYSTEMS BASED ON RENEWABLE ENERGIES: A SUITABLE AND COST-COMPETITIVE SOLUTION FOR RURAL ELECTRIFICATION, ALLIANCE FOR RURAL ELECTRIFICATION.

figure 6: **AC interconnected hybrid system – option B**



source HYBRID POWER SYSTEMS BASED ON RENEWABLE ENERGIES: A SUITABLE AND COST-COMPETITIVE SOLUTION FOR RURAL ELECTRIFICATION, ALLIANCE FOR RURAL ELECTRIFICATION.

1.2.2 hybrid systems: control technologies

In hybrid systems that focus around a DC interconnection, batteries act as a large power resistor, smoothing out any short or long-term fluctuations in the power flow. Hence the control required for DC systems is very simple as it regulates itself based on a few battery-specific parameters.

AC-interconnected hybrid systems have greater control requirements – both for production balancing as well as load and voltage regulation. The simplest control approach is based on 'droop control', a simple proportional control scheme. The big advantage of droop control is that it does not require any complicated communication system.

Droop control is commonly used in diesel-based island systems where several generators are running at once. Because it is simple, and based on inverter technology already used in PV/batteries and wind turbines, island systems now use droop control. Island systems using inverter systems with droop control are often referred to as micro grids.[3] Micro grids typically can also be part of a larger power system.

During a utility-grid disturbance, they can separate and isolate themselves seamlessly from the utility with little or no disruption to the loads within the micro grids. When the utility grid then returns to normal, the micro grid automatically resynchronises and reconnects itself to the grid, in an equally seamless fashion.[4] This is particularly interesting for areas in developing countries which have grid supply, but experience frequent power interruptions. Distributed PV systems and other renewable generation sources can be interconnected to a micro grid and be operated in a micro grid in case the main power supply is interrupted.

In hybrid systems that have more than one-third of variable renewable generation, additional devices will be integrated into the hybrid system to achieve high overall efficiency. This is largely done with the use of synchronous condensers, dispatchable load banks, storage, demand-side management which may require advanced supervisory control systems that carefully monitor the operating conditions of each component to ensure that the result is power with a consistent frequency and voltage. The disadvantage of such a supervisory control system is the need for additional fast communication in the island system.

references

3 MICRO GRIDS – AN OVERVIEW OF ONGOING RESEARCH, DEVELOPMENT AND DEMONSTRATION PROJECTS, SEE HTTP://EETD.LBL.GOV/EA/EMP/REPORTS/62937.PDF, FOR DEMONSTRATION PROJECTS FOR PV BASED MICRO GRID SYSTEMS SEE ALSO HTTP://DOWNLOAD.SMA.DE/SMAPROSA/DATEIEN/1698/REFOCUS_ELECCHINA.PDF

4 HTTP://CERTS.LBL.GOV/CERTS-DER-MICRO.HTML

image CONSTRUCTION OF WIND TURBINES.


© LANGROCK/ZENIT/GP

1.2.3 hybrid systems: design and economic modelling tools

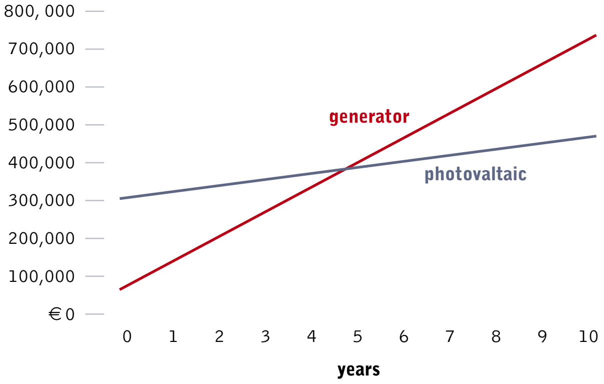
For a principal first evaluation of the economic and technical feasibility of a particular hybrid system the following software tools are useful:

- HOMER is a computer model that simplifies the task of evaluating design options for both off-grid and grid-connected power systems using large shares of renewable generation. HOMER's optimisation and sensitivity analysis algorithms allow the user to evaluate the economic and technical feasibility of a large number of technology options and to account for uncertainty in technology costs, energy resource availability, and other variables. The model is available for free from the National Renewable Energy Laboratory (NREL), https://analysis.nrel.gov/homer/.
- Hybrid2 is a state-of-the-art time series model for the prediction of the technical-economical performance of hybrid wind/PV systems and offers a very high flexibility in specifying the connectivity of systems. Publicly available at http://www.ceere.org/rerl/rerl_hybridpower.html
- RETScreen is a spreadsheet (Microsoft Excel)-based analysis and evaluation tool for the assessment of the cost-effectiveness of potential projects with renewable energy technologies. The software package consists of a series of work sheets with a standardised layout as well as an online manual and a weather and cost database. Publicly available in 34 languages at www.retscreen.net. See the case study below, comparing two types of village power systems.[5]

case study: comparison of PV with diesel or grid connections

Location: Far & Middle East, Africa (>5,000 kWh/ m^2 / year)
Daily energy requirement: 10,000 Wh/day
Maximum peak power of load: <20kW
Power supply of load equipment: 3x230V AC

case study figure 1: economic comparison between diesel / fuel operated power supply and a photovaltaic power supply



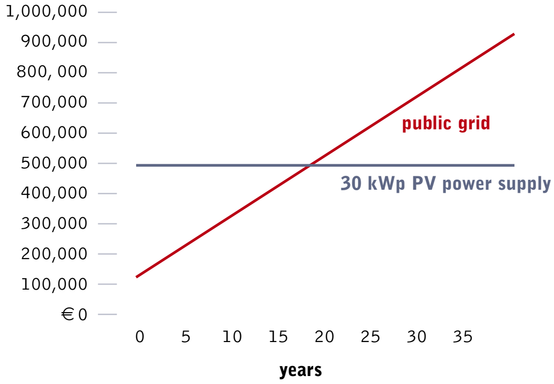
case study table 1: pv power supply

Investment cost of 30 kWp PV village power supply	
PV modules	150,000 Euro
Industrial batteries	80,000 Euro
Electronics	30,000 Euro
Accessories	20,000 Euro
Infrastructure & installation	20,000 Euro
Total	**300,000 Euro**

Annual cost	
Maintenance	2,000 Euro
Interest rate (5%)	15,000 Euro
Total	**17,000 Euro**

Case study Figure 2 shows the investment cost for a public grid extension versus an independent 30kWp photovoltaic power supply system. If we suppose a certain amount for a transformer station and 20,000 Euro per km of grid extension, the initial investment cost for a PV system is cheaper if it is situated further than 17 km away from the public grid.

case study figure 2: village power supply by PV systems: public grid versus 30kWp photovaltaic power supply (VPS)



case study table 2: diesel generator

Investment cost of 20> KWA diesel generator	
Generator	20,000 Euro
20,000 l tank	6,000 Euro
48 V DC supply	10,000 Euro
Accessories	10,000 Euro
Infrastructure & installation	20,000 Euro
Total	**66,000 Euro**

Annual cost	
Maintenance	15,000 Euro
Fuel consumption (15l/h) (131,000 liter / year 0.30 €/ liter)	40,000 Euro
Transport of fuel (9x)	4,500 Euro
Oil consumption	2,000 Euro
Interest rate (5%)	3,300 Euro
Total	**64,800 Euro**

reference

[5] HTTP://WWW.RURALELEC.ORG/INDEX.PHP?ID=118&TYPE=0&JUMPURL=UPLOADS%2FMEDIA%2FECONOMIC_ANALYSIS_COMPARISON_PV-DIESEL_BY_SOLAR_02.PDF&JUSECURE=1&LOCATIONDATA=118%3ATT_CONTENT%3A487&JUHASH=5776920B9D

1.2.4 PV-systems / PV-diesel systems

table 5: current status of pv-diesel systems

TECHNOLOGY	EXPERIENCE WORLDWIDE	COMMERCIAL STATUS
PV/diesel hybrids	Extensive, especially for telecommunications worldwide	Fully commercial and the preferred option for remote telecommunications, commercially evolving for village power

source ALLIANCE FOR RURAL ELECTRIFICATION, HTTP://WWW.RURALELEC.ORG/.

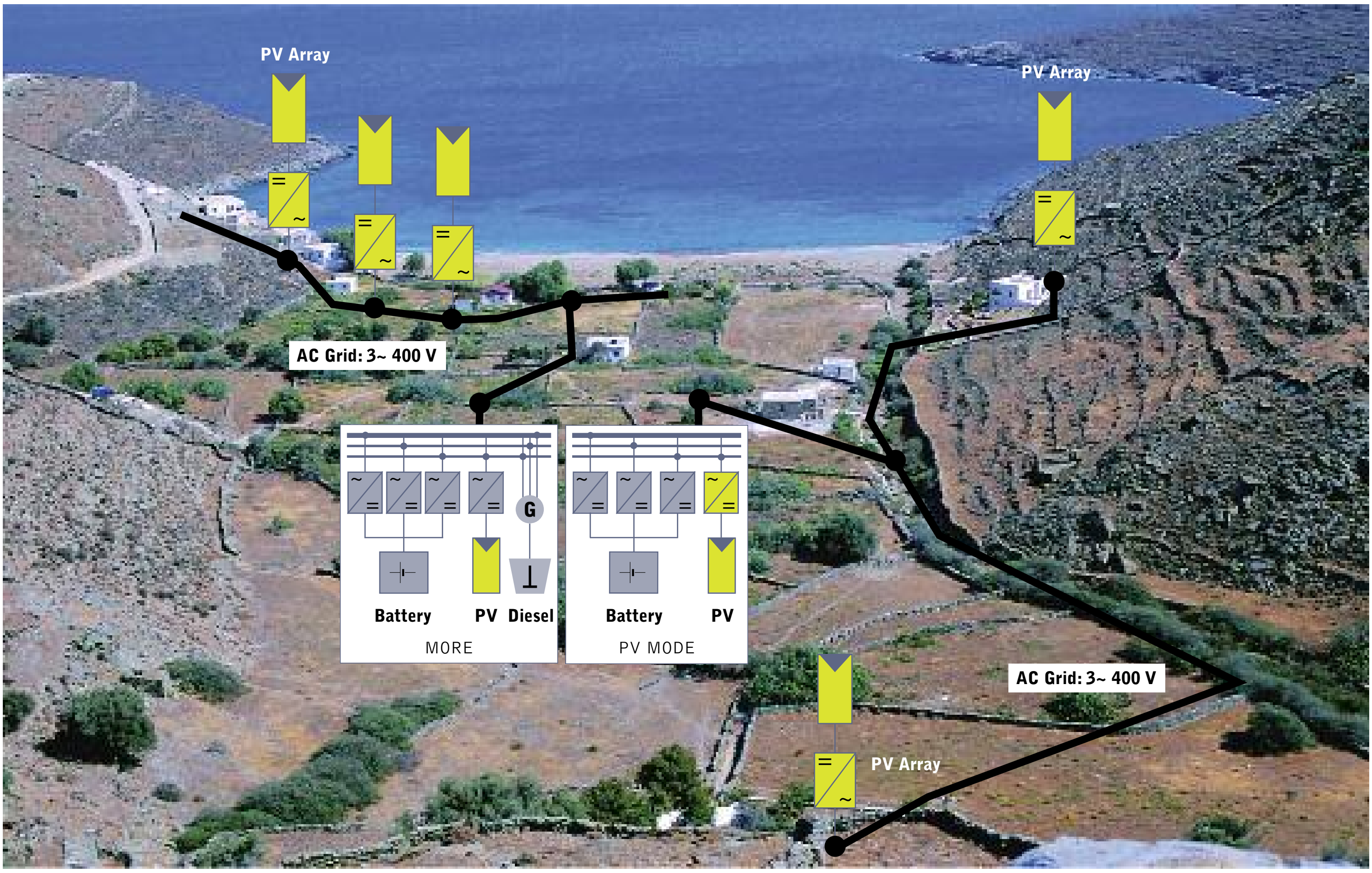
example PV-diesel micro grid: Greek island

The system in Gaidouromantra, Kythnos[6] electrifies 12 houses in a small valley in Kythnos, an island in the cluster of Cyclades situated in the middle of the Aegean Sea. It is a 1-phase hybrid micro grid system composed of overhead power lines and a communication cable running in parallel (see Figure 7). The settlement is situated about 4 km away from the closest pole of the medium voltage line of the island. The system just needed one new building with a surface area of 20 m^2 in the middle of the settlement to house the battery inverters, the battery banks, the diesel genset and its tank, the computer equipment for monitoring and the communication hardware.

The system produces 10kW (peak) and the solar cells are divided into smaller sub-systems and a battery bank with a nominal capacity of 53kWh and a diesel genset with a nominal output of 5kVA. A second system with about 2 kW(peak) mounted on the roof of the system house is connected to a Sunny-island inverter and a 32kWh battery bank. This second system provides the power for the monitoring and communication needs of the systems. The PV modules are integrated as canopies to various houses of the settlements.

The power in each user's house is limited by a 6 Amp fuse. The micro grid is powered by 3 island battery inverters connected in parallel, which means that more than one battery inverter can be used when more power is demanded by the consumers. The battery inverters in the Kythnos system can operate in both isochronous or 'droop' mode. In frequency droop mode the system can pass information on to switching load controllers when the batteries have low charge and can limit the power output of the PV inverters when the battery bank is full.

figure 7: kythnos pv-diesel micro grid



source FRAUNHOFER IWES

reference
6 HTTP://WWW.MICROGRIDS.EU/INDEX.PHP?PAGE=KYTHNOS&ID=2

image THE PS10 CONCENTRATING SOLAR TOWER PLANT IN SEVILLA, SPAIN, USES 624 LARGE MOVABLE MIRRORS CALLED HELIOSTATS. THE MIRRORS CONCENTRATE THE SUN'S RAYS TO THE TOP OF A 115 METER (377 FOOT) HIGH TOWER WHERE A SOLAR RECEIVER AND A STEAM TURBINE ARE LOCATED. THE TURBINE DRIVES A GENERATOR, PRODUCING ELECTRICITY.

1.2.5 wind-diesel systems

table 6: current status of wind-diesel systems

TECHNOLOGY	EXPERIENCE WORLDWIDE	COMMERCIAL STATUS
Wind/diesel hybrids	Significant, not yet extensive	Commercial, competitive, and evolving

source ALLIANCE FOR RURAL ELECTRIFICATION, HTTP://WWW.RURALELEC.ORG/.

The following five case studies show how wind-diesel systems are appropriate for a diverse range of circumstances around the world.

Afghanistan: small wind/PV/battery system The main aim of this system is to supply power to water disinfection/treatment units. Eleven stand-alone systems have been installed in villages, including the districts of Parwan, Wardak and Kapisa. The power system consists of a Bergey 1 1kW wind turbine on a 42 ft tilt-up tower, a 280W PV, a battery bank, and an inverter. The water treatment technology uses a small-scale ozonation system. Ozone is very effective for water treatment and uses minimal amounts of energy. Most communities are using the system to treat around 2,000 to 4,000 litres of drinking water per day.[7]

Guadeloupe Islands: wind/diesel In January 1993 twelve 12 kW wind-powered generators were set up at an altitude of 270 m on the island of La Désirade, on high table-land facing the open sea, swept most of the time by trade winds blowing at an average of 9 to 10 metres a second. Before this, electricity generation on the island was wholly dependent on a 350- kW diesel-driven power plant that consumed nearly 600 tons of oil per year.

Now, the wind farm saves around 220 tons of diesel oil a year and the price of wind-generated electricity per kW/h is now less than that of diesel-generated power. The installed capacity of the wind farm was more than doubled in 1996 and is now rated at 500 kW, and is now producing about 80% of the island's power requirements. When local energy demand is low, La Désirade even exports wind-generated electricity to the neighbouring island of Guadeloupe.

An extra design feature is that the wind turbines on the Guadeloupe islands can be lowered when a hurricane is approaching. On August 16, 2007, for instance, while Hurricane Dean was approaching, local crews lowered the 27 turbines of Guadeloupe securely fastened them to the ground and they survived wind gusts of more than 250 km/h. Once Dean had passed over the islands, the wind farms quickly resumed production.[8]

Bonaire: wind/diesel system A wind-diesel system is currently under construction on the island of Bonaire in the Dutch Carribean. The system has a total capacity of 10.8 MW, made up of connects 14 wind turbines. The turbines are connected to 5 diesel gensets with a total capacity of 14.33 MW and it has a 3 MW battery system, which provides 100 kWh for 3 minutes. The diesel gensets can operate on bio-diesel, so the system can run on 100% renewable energy. The overall hybrid system runs with a 'loss of load' probability of 99.932%, so locals can expect only 6 hours per year when the system might not be able to meet the island's electricity demand. Finally, the system fulfils an advanced grid code which is similar to Western European grid codes for large integrated power systems, so the power quality is equal to large interconnected power systems.

Galapagos: wind/diesel system The wind-diesel hybrid system on San Cristobal Island in Galapagos, Ecuador reduces the amount of diesel fuel used for power generation and promotes new renewable energy on the Galapagos Islands. There are three 800 kW wind turbines coupled to the existing diesel generator system. An electrical collector system gathers the power from each wind turbine through underground cabling and transports the power to the wind farm boundary where it connects to a transmission line via a disconnect switch. Output at the wind farm is 13.8 kV to allow for voltage drop in the transmission line. A new transmission line was installed to transport the power from the wind farm to the existing Elecgalapagos S.A. Diesel Plant substation which was updated with a new control system. The new transmission line connects to the Elecgalapagos distribution substation at the diesel plant.[9]

Alto Baguales: wind-hydro-diesel system This system in Patagonia, Chile, supplies energy to the regional capital of Coyhaique, providing a maximum power of 13.75 MW. The wind turbines are now connected to hydro power, installed in 2003 so the whole load is met by wind and hydropower, completely eliminating diesel production.

Three 660-kW Vestas wind turbines were installed to supplement the diesel and hydro production in 2001. Initially, the Alto Baguales wind energy project was designed to supply more than 16% of the local electric demand and replace about 600,000 litres (158,500 gallons) of diesel fuel per year.

The turbines are operated remotely from the diesel plant with no additional control capabilities; and they operate at capacity factor of approximately 50% due to strong winds at the turbine site. To date, the highest percentage of supply was 22% of total demand based on 15-minute instantaneous readings taken at the power station.

Cape Verde: wind-diesel system The Archipelago of the Republic of Cape Verde consists of 10 major islands off the Western cost of Africa. Three wind-diesel systems have successfully provided power to the three main communities of Cape Verde: Sal, Mindelo, and Praia since the mid-1990s. These power systems are very simple, containing only a dump load and a wind turbine shut-down function to keep minimum diesel load conditions. Three 300-kW wind turbines at each site are connected to the existing diesel distribution grid in a standard grid-connected fashion. The average loads for the communities vary from 1.15 MW for the smallest, Sal, to 4.5 MW for the largest, Praia (the nation's capital).

The power systems operate at monthly wind energy penetrations of up to 25%, depending on the system and time of year. At Sal and Mindelo the wind turbines have provided 14% of the total consumption by wind power each year. The maximum monthly percentage of wind power was of 35% was reached in Sal.

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[7] HTTP://WWW.BERGEY.COM/EXAMPLES/AFGHANISTAN.HTML
[8] HTTP://WWW.VERGNET.FR/IMAGES/STORIES/PDF/EN/DOCUMENTS/PLAQUETTE-GEV_MP275-UK.PDF

reference
[9] HTTP://WWW.EOLICSA.COM.EC/INDEX.PHP?ID=3

1.3 new ownership approaches: the micro-utility model

In many developing countries, communities or individuals cannot afford to install a hybrid system or a PV home system. For this reason, new ownership models are required in developing countries to help the growth of clean energy options.

The power company Grameen Shakti (GS) in Bangladesh[10], for instance, has introduced the idea of micro-utility systems. Under this model, one entrepreneur installs the system at his own premises and shares the load with some of his neighbours. The owner of the system is responsible for making the instalment payments to the power company, but more than 50% is covered by the rents collected from the users of the system. The micro-utility model has become very popular in rural market places in Bangladesh and has helped to increase business turnover by extending business hours. More than 1,000 micro-utility systems are now operating in rural market places.

reference
[10] HTTP://WWW.GSHAKTI.ORG/SOLAR_MICROUTILITY.HTML

case study: solar island states

solar island states – a Greenpeace concept to help island utilities go fossil-free

The 'Solar Island States' idea is a way to get financing from the 'top-down', but planning for the systems from the 'bottom-up', which means that communities are involved in deciding where systems are built and how they are run.

A) top-down financing In remote islands, individual and rural electrification projects are usually too small to be interesting for foreign investors and quality control is difficult. A solution proposed by Greenpeace is to bundle power generation projects from whole islands, the entire island state (such as the Maldives) or even several Island states (such as the 14 Pacific Island States) into one project package. This would make it large enough for funding as an international project, by OECD countries. Funding mechanisms can come from a mix of a feed-in tariff and a fund which covers the extra costs as proposed in the Energy [R]evolution, called FSTM (Feed-in Tariff Support Mechanism).

A bundled project could be worth $US 2 billion or more – that means in the range of an average size power plant investment such as a coal power plant -making it relevant for international finance institutions and for infrastructure projects. A project this size would be too big for a single project developer or an existing small island utility, but it would be interesting for institutional investors. A bigger project also achieves 'economies of scale' so project developers and potential hardware manufacturers can operate with lower costs and centralised quality control and equipment performance guarantees.

B) bottom-up planning A research paper from UNDP[11] and numerous other organisations come to a very clear result: Almost all renewable energy projects in the Pacific have failed because of top-down planning and poor maintenance due to a lack of training of local technicians. Only a few projects – which were planned from the community – were successful. Good planning and a long-term organisation of the maintenance are required to make rural electrification with renewable energy a success.

reference
[11] PACIFIC ISLANDS RENEWABLE SPREP ENERGY PROJECT; A CLIMATE CHANGE PARTNERSHIP OF GEF, UNDP, SPREP AND THE PACIFIC ISLANDS, OCTOBER 2004, PETER JOHNSTON, JOHN VOS, HERBERT WADE

image ELECTRICAL TOWER IN A FLOODED FIELD IN THE SEVERN RIVER VALLEY. GLOUCESTERSHIRE, UK, 2000.

moving from diesel to renewable energies

Currently most islands and island states are powered almost exclusively with diesel generators. In the Pacific for example, Fiji, Papua New Guinea and Samoa are the only pacific island countries with a substantial use of other sources for electricity generation than diesel – mainly hydro. All other pacific islands have 90% to 100% diesel power supply.

This high diesel share in the electricity supply makes the electricity prices very dependent on global oil prices and diesel prices have increased significantly within the past 2 years. The average price per litre diesel increased from around $US 0.80 in 2006 to $US1.70 in 2008 – and the diesel price will almost certainly not drop in the future, but continue to rise.

limited access to diesel

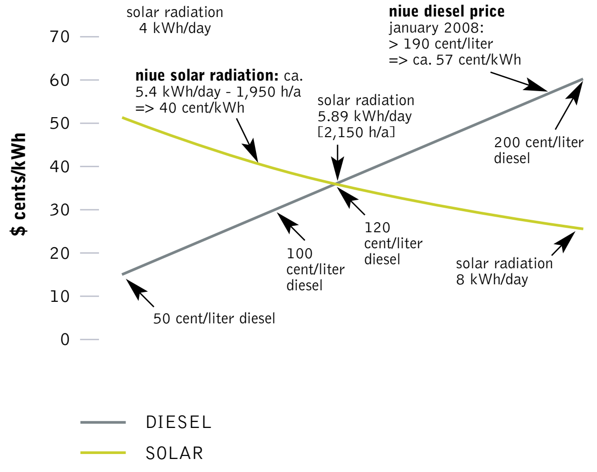
In some cases, the access to diesel is difficult for remote islands and is a constant problem for a reliable electricity supply for these islands. Research on diesel access in Pacific island countries shows problems with access and / or lack of competition, which puts the prices up for the customers.

generation costs for clean energy on island states

Solar electricity systems are in most cases already cheaper than diesel power generation. The graph below shows the fuel costs per kWh for different diesel prices and solar radiation per day (both excluding capital costs):

- Solar PV systems in regions with 5.4 kWh/day annual average solar radiation (like Niue) can produce electricity at a fuel price level of $1.20 per litre diesel.
- If diesel costs are more than $1.20 per litre, solar photovoltaics is cheaper almost everywhere within the Pacific Island region.

case study figure 1: **diesel generator versus solar generator**



source SVEN TESKE / GREENPEACEINTERNATIONAL

financing island utilities

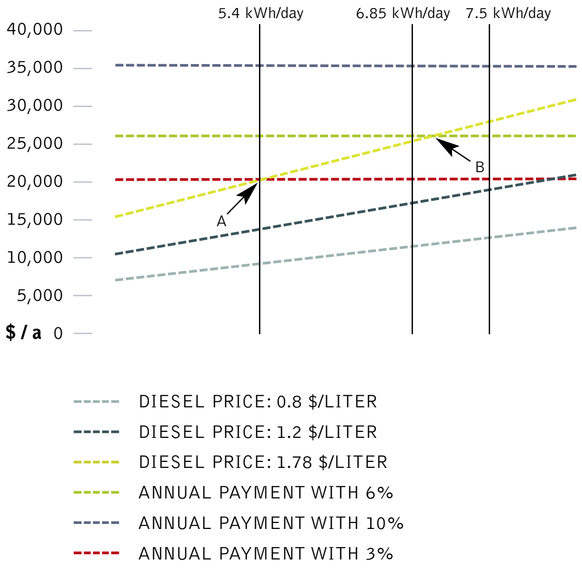
The main obstacles to switching from diesel to solar are the high upfront investment costs, and utilities in Pacific Island countries cannot finance the required new solar capacities. The graph below provides an overview of the annual payment (total payment – including interest) and the interest costs of a 20 kW system which will be completely financed with a 3% soft loan, or 6% and 10% conventional bank credit over 20 years. The Island Utility concept needs to overcome this investment barrier.

how to read the graph - examples:

- In regions with 5.4 kWh/day solar energy, the annual savings on diesel fuel (with a diesel price of $1.78/L) can balance out the average annual interest rates of a soft loan credit with 3% interest & 20 years).
- In regions with 6.95 kWh/day solar energy, the annual diesel fuel savings (with a diesel price of $1.78/L) can balance out the average annual total payment of credit with 10% interest & 20 years.

Example A shows that a solar system could be financed with fuel savings alone if the diesel price is at $ 1.78/L or higher. With an average consumer price of 15 cents/kWh – the break-even point for solar systems operated by a utility will be at around $1.3 /L diesel.

case study figure 2: **annual fuel savings of a 20 kW solar could finance solar systems**



source SVEN TESKE / GREENPEACEINTERNATIONAL

smart grids

2

> "...a vision for better, cleaner future power systems..."
>
> **GREENPEACE INTERNATIONAL**
> CLIMATE CAMPAIGN

image ASSEMBLING SOLAR POWERED PHOTO-VOLTAIC (PV) CELLS IN CHINA. © GREENPEACE/ALEX HOFFORD

image WIND TURBINE WORKER IN MARANCHÓN, GUADALAJARA, SPAIN.

The term 'smart grids' is being used in the media and by politicians, but it is very difficult to find a commonly accepted definition. Typically, the term signifies a vision for better, cleaner future power systems, that will use more information technology than they do today. The section presents more information on the overall system architecture and the smart components in these electric power systems.

Some of the specifics of a smart grid-based power system architecture are still emerging through academic research and industry development. However, there is sufficient knowledge and experience for a sound overall description of future power systems that use smart grids.

For this report we define the term as:

An electricity network that uses distributed energy resources and advanced communication and control technologies to deliver electricity more cost-effectively, with lower greenhouse intensity and in response to consumer needs. Smart grids have smaller forms of electricity generation and high percentages of renewable energy, combined with energy management to balance out the load of all the users on the system. The energy sources are closer to the users, instead of one large centralised source a long distance away.

Genuine smart grids rely on renewable energy with no greenhouse emissions, but control technology can also make more efficient use of conventional fossil fuel power plants and help to integrate more renewables to older-style networks. Today's power systems account for about 41% of world-wide carbon emissions[12] It is a fact that power systems of the future will need a much higher percentage of renewable energy in the mix to help achieve the national and international emission-reduction objectives that will prevent dangerous levels of climate change.

The impact of carbon emissions and other greenhouse gases on climate change was acknowledged in 1992, when 154 governments and the European Community signed the United Nations' Framework Convention on Climate Change at the Rio Earth Summit. Today, there are many national and international targets to reduce these emissions. Denmark, for instance, has a national target of 50% of its national energy consumption from renewables in 2050. The EU has a target of producing 20% of electricity from renewables by 2020, compared to the current level of 8.5%.[13] However, we can only stabilise carbon emission levels in the atmosphere and reduce the impact of climate change with future electric power systems operating with between 80 to 90% renewable energy.

This section lays out the concept of future power systems based on smart grid systems with high levels of renewables which can ensure security of supply at all times. We present technical solutions and existing demonstration projects to illustrate key elements of a future power system that runs on clean sources and is supported by smart grids.

2.1 integrating renewable generation into power systems: it can be done!

The key task of any power system, with or without renewable power generation, is to keep the power available 24 hours a day, 7 days a week. To do this, the system needs to balance electricity consumption and generation at all times, and the network must be designed to cope with different system states.

2.1.1 integration of renewable energy into power systems

The task of integrating renewable energy technologies into existing power systems is similar in all power systems around the world, whether they are large, centralised systems or island systems. The main aim of power system operation is to balance electricity consumption and generation at all times.

Thorough planning ahead is needed to ensure that the available production can match demand at all times. In addition to balancing supply and demand, the power system must also be able to:

- Fulfil defined power quality standards –voltage/frequency- which may require additional technical equipment in the power system and support from different ancillary services (see Appendix 1 for definitions of terms); and
- Survive extreme situations such as sudden interruptions of supply (e.g. a fault at a generation unit) or interruption of the transmission system.

Typically, power systems use cheap power sources as base-load power plants which operate most of the time at rated capacity. These centralised units are often 'inflexible' generation resource, meaning they are quite inefficient and it is expensive to change their output over the day, to match what people actually use (load variation).

> "Smart Grids is a new concept for electricity networks across Europe. ... [It is] a shared vision which enables Europe's electricity grids to meet the challenges and opportunities of the 21st century [and] fulfils the expectations of society."

SMARTGRIDS EUROPEAN TECHNOLOGY PLATFORM FOR ELECTRICITY NETWORKS OF THE FUTURE: VISION AND STRATEGY FOR EUROPE'S ELECTRICITY NETWORKS OF THE FUTURE,
HTTP://WWW.SMARTGRIDS.EU/DOCUMENTS/VISION.PDF

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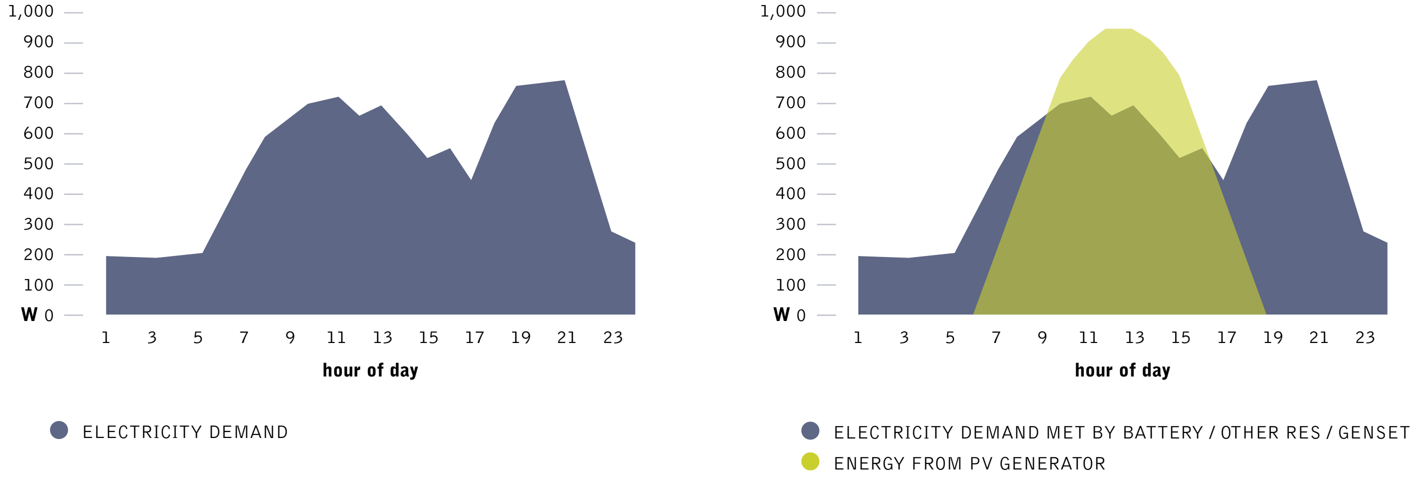
references

[12] HTTP://WWW.IEA.ORG/WEO/DOCS/WEO2009/CLIMATE_CHANGE_EXCERPT.PDF

[13] HTTP://EUR-LEX.EUROPA.EU/LEXURISERV/LEXURISERV.DO?URI=OJ:L:2009:140:0016:0062:EN:PDF

figure 8: **typical load variations over 24 hour and the generation sources supplying the load in a hybrid power system with PV and batteries**



source HYBRID POWER SYSTEMS BASED ON RENEWABLE ENERGIES: A SUITABLE AND COST-COMPETITIVE SOLUTION FOR RURAL ELECTRIFICATION, ALLIANCE FOR RURAL ELECTRIFICATION. ALLIANCE FOR RURAL ELECTRIFICATION, HTTP://WWW.RURALELEC.ORG/.

In reality, load varies over time (see Figure 8) which means that additional flexible power generation resources are required to provide the right amount of power. For larger power systems, typical technologies are combined-cycle gas turbines (CCGT) or hydro-power stations with a sufficient storage capacity to follow the daily load variations. In conventional island power systems, typically a number of small diesel generators (gensets) are used to provide 24/7 supply. Several gensets have to operate continuously at the point of their highest efficiency, while one is used to follow the load variations.

The impact of adding renewable power generation to a conventionally centralised or island power system will affect the way in which a conventionally-designed electricity system runs. The level of impact depends on the renewable energy technology:

- Biomass/geothermal/solar thermal (CSP)/hydro power with storage: power output can be regulated, i.e. they can supply base load as well as peak load;
- Hydro power without storage (run–of-the-river)/photovoltaic/wind power: power output depends on the available natural resources, so the power output is variable.[14]

There are two main types of impact to consider when introducing renewable energy to micro grids, the balancing impact and reliability impact.

Balancing impact relates to the short-term adjustments needed to manage fluctuations over a period ranging from minutes to hours before the time of delivery. In power systems without variable power generation, there can be a mismatch between demand and supply. The reasons could be that the energy load was not forecast correctly, or a conventional power plant is not operating as it is scheduled, for instance a power station has tripped due to a technical problem.

Adding a variable power generation source increases the risk that the forecasted power generation in the power system will not be reached, for instance, due to a weather system moving faster than predicted into the area. The overall impact on the system depends on how large and how widely distributed the variable power sources are. A certain amount of wind power distributed over a larger geographical area will have a lower impact on system balancing than the same amount of wind power concentrated in one single location, as geographical distribution will smoothen out the renewable power generation. System balancing is relevant to:

- **Day-ahead planning**, which needs to make sure that sufficient generation is available to match expected demand taking into account forecasted generation from variable power generation sources (typically 12 to 36 hours ahead);
- **Short-term system balancing**, which allocates balancing resources to cover events such as a mismatch between forecasted generation/demand or sudden loss of generation (typically seconds to hours ahead planning).In island power systems, both aspects must be handled automatically by the system (see Section 1.3.2 on Control Approaches for further details)

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reference

[14] SOMETIMES THESE RENEWABLE ENERGY SOURCES ARE DESCRIBED AS 'INTERMITTENT' POWER SOURCES, HOWEVER, THE TERMINOLOGY IS NOT CORRECT AS INTERMITTENT STANDS FOR UNCONTROLLABLY, I.E. NON-DISPATCHABLE, BUT THE POWER OUTPUT OF THESE GENERATION PLANTS CAN BE FORECASTED, HENCE THEY CAN BE DISPATCHED. FURTHERMORE, THEY CAN ALWAYS BE OPERATED DOWN-REGULATED IF NEEDED.

© GP/RODRIGO BALÉIA

image AS PART OF THE LAUNCHING OF THE BRAZIL ENERGY [R]EVOLUTION REPORT, GREENPEACE INSTALLED 40 PHOTOVOLTAIC SOLAR PANELS THAT SUPPLY THE GREENPEACE OFFICE IN SAO PAULO.

Reliability impact is the extent to which sufficient generation will be available to meet peak demand at all times. No electricity system can be 100% reliable, since there will always be a small chance of major failures in power stations or transmission lines when demand is high. However, renewable power production is often more distributed than conventional large-scale power plants, so it may reduce the risk of sudden drop-outs of major individual production units. On the other hand, variable renewable power generation reduces the probability that generation is available at the time of high demand, and thus adds complexity to system planning.

Reliability is important for long-term system planning, which assesses the system adequacy typically 2 to 10 years ahead. Long-term system planning with variable generation sources is a challenge because of where the resources are located. To get a high level of renewable energy into the system, ideally plants must be situated at some distance from each other, for example using solar power from Southern Europe when there is no or limited wind power available in Northern Europe. These issues are discussed in more detail in Section 3 regarding super grids.

In island power systems, power generators are typically close to each other, which means that there must be a mix of different generation technologies in the island system or that they must be partly over-designed to make sure that there is always sufficient generation capacity available. This is typically done by adding some back-up diesel gensets. In addition, island power systems can adjust power demand to meet power supply, rather than the other way round. This approach is called demand-side management. An example of a 'flexible' load in island systems for demand-side management is water pumps and irrigation pumps which can be turned on and off depending on how much electricity supply there is. The basic planning challenges for integrating renewable energy technology into power systems are not new to power system design, they apply to all power systems around the world regardless of capacity mix, demand levels, and market design. High penetrations of variable renewable generation introduce new challenges, but existing experience shows that renewables penetration can reach significant levels also in island power systems (see Section 4).

In Denmark, for instance, wind power supplied 21.22% of the national consumption in 2007.[15] Many times, for example during nights with high wind speeds and low load, the supplied wind power exceeds local consumption. At those times surplus wind power is exported to the neighbouring countries.

2.1.2 about base-load and system balancing

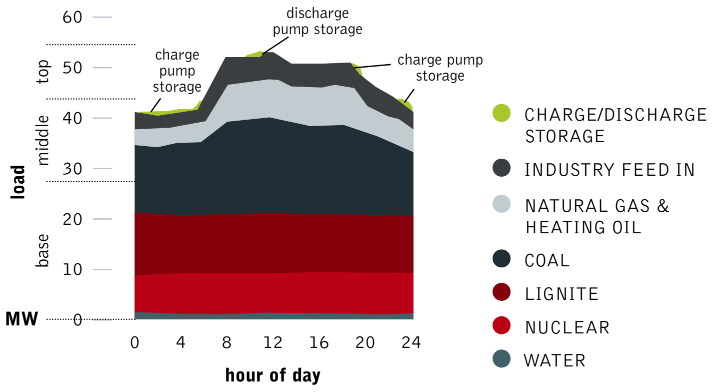
Energy power balance aims to keep frequency in the system consistent. The mains frequency describes the frequency at which AC electricity is delivered from the generator to the end user, and it is measured in Hertz (Hz). Frequency varies in a system as the load (demand) changes. In a power grid operating close to its peak capacity, there can be rapid fluctuations in frequency, and dramatic examples can occur just before a major power outage.

System engineers plan many years ahead so that the available production can match demand at all times and keep frequency variations to a minimum. In the past, generation and power system planning were tasks carried out by a centralised organisation, usually by the company responsible for operating the transmission system (transmission system operator - TSO). Today, generation investment planning is decentralised and influenced by electricity market prices.

The existing power systems around the world have developed certain technologies and generation resources, often influenced by the national energy policy. Typically, power systems were designed around large power stations providing base-load capacity, i.e. base-load power plants of more than 660 MW capacity, operating almost constantly at full output (see also Figure 9).

These centralised units, typically nuclear or coal power plants, are inflexible generation resources – they can't 'follow load', i.e. change their supply to match the changing demand throughout the day. It is inefficient and expensive to change their operating capacity. Furthermore, large, centralised units require significant investment in grid infrastructure.

figure 9: **typical load variations over 24 hours and the generation sources supplying the load in a power system with large centralized units**



In Finland, a planned expansion of the Olkiluoto nuclear power station providing an extra 1,600 MWe was originally scheduled to become operative in 2012. Now it is unclear if and when it will be completed. For the expansion to be feasible it requires an 800 MW undersea transmission line from near Olkiluoto to Sweden to export surplus electricity production. This considerable network upgrade is required in the Scandinavian power system for base-load operation of the expanded Olkiluto nuclear power station.

Load varies over time, see Figure 9, therefore more flexible power generation resources can 'follow the load'. Typical technologies which can do this are combined-cycle gas turbines (CCGT) or hydro power stations because they have significant storage capacity to match the variations over a day. Power systems with large amounts of inflexible generation resources, such as nuclear power stations, also require a significant amount of flexible generation resources.

reference

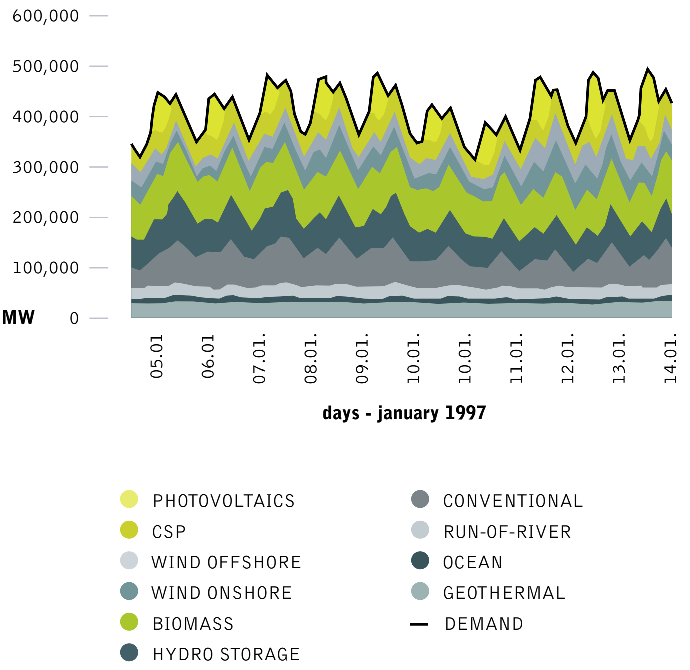
[15] WIND POWER TO COMBAT CLIMATE CHANGE, HOW TO INTEGRATE WIND ENERGY INTO THE POWER SYSTEM, BY ENERGINET.DK, THE DANISH TRANSMISSION SYSTEM OPERATOR, HTTP://WWW.E-PAGES.DK/ENERGINET/126/

2.1.3 base-load versus flexible renewable power generation

Renewable energy integrated into a smart grid changes the need for 'base load' power. In the new energy vision, it is better to think of energy as 'inflexible' or 'flexible'. In countries with good support for renewable energy and natural resources, in Spain for example, the clean, renewable technologies already provide more than 40% of daily demand on certain days. Worldwide, we can bring about an energy switch based on renewables which redefines the need for 'base load' power. Instead, a mix of flexible energy providers can follow the load during the day and night (e.g. solar plus gas, geothermal, wind and demand management), without blackouts.

Figure 10 shows a typical situation with significant variable renewable generation – in this case mainly PV- in the European power system. Here, geothermal, ocean and run-of-the-river power plants are operated in base-load and conventional plants – in this case gas-fired- and biomass plants are used to follow the variations caused by demand changes and changes in renewable generation such as PV and wind power.[16]

figure 10: power production (in MW) from different sources and overall demand in europe during extreme january event



source ENERGYNAUTICS

technical or economic barriers?

In the example of Spain, renewable power supply already exceeds 40% of the daily demand on certain days. The power system is able to cope with this, there have been no black-outs or major technical problems. However, the renewable industry now faces an economic barrier, because Spain now has an overcapacity of supply. Effectively, Spain has much more generation capacity than demand, and the gap is exacerbated because of the economic crisis. The reason is that extra renewable capacity (and combined-cycle gas turbines) was built with the intention to move Spain to a clean renewable energy future, however no conventional capacity has been decommissioned so far.

Now renewable generation takes an increasing market share in the electricity supply, taking it away from conventional fossil power plants. The conventional power plants sell less kWh than originally planned, and they cannot run power plants in base-load mode anymore, which increases costs of operation and lowers the profit on each kWh sold. In Spain, the operators of conventional power plants have begun to lobby against renewable power generation because renewable generation impacts their business plans. They are typically providers of base-load power, which is less and less needed with larger amounts of renewable in the power system. Instead more flexible and fast controllable generation assets are needed. In this case, the integration of large-scale renewable energy is becoming less of a technical issue, but more of an economic one. The barriers are from companies reluctant to abandon their economic investment in conventional base-load power plants.

Decommissioned power plants, or 'stranded assets', for certain companies are not a sufficiently strong reason for holding up the development of a massive renewable energy infrastructure. Greenpeace campaigns to dramatically reduce our reliance on coal and nuclear power in order to halt climate change and its devastating impact on the planet. Our energy options are advanced enough for conventional base units to become redundant in the future renewable-based power system. However, the power industry is planning more and more coal and nuclear power plants in Europe, which do not fit into a future renewable-based system. They are not clean enough and they cannot be operated flexibly enough to fit into the future power system.

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reference

[16] IN PRINCIPAL ALSO GEOTHERMAL COULD BE USED TO PROVIDE LOAD FOLLOWING CAPABILITIES.

image BERLINER GEOSOL INSTALLING THE SOLAR ENERGY PLANT (PHOTOVOLTAIK) "LEIPZIGER LAND" OWNED BY SHELL SOLAR IN A FORMER BROWN COAL AREA NEAR LEIPZIG, SACHSEN, GERMANY.

© LANGROCK/ZENIT/GP

2.2 why do we need smart grids for high penetration of renewables?

The future power systems around the world will need to be based on renewable generation with up to 90% of the consumption supplied by renewable energy technologies such as wind, solar, biomass or hydro power.

Until now renewable power technology development has put much effort into adjusting the technical performance to the needs of the power system, mainly by complying with grid codes (See Appendix 2 on Grid Codes). For this reason, most large wind turbines comply with the same grid codes as conventional power stations and wind farms have become wind power plants. However, the time has come for the power systems themselves to better adjust to the needs of variable power generation, i.e. the power system has to become more flexible and less reliant on large, inflexible conventional power plants.

The Danish example of integrating significant shares of wind power into the power system was mainly possible because of the availability of very flexible hydro power from Scandinavia, which is used to balance wind power variations. Similar resources are not available everywhere, therefore the power system has to become more flexible in other ways. Smart grid technology will play a significant role in achieving this, in particular by integrating demand-side management into power system operation.

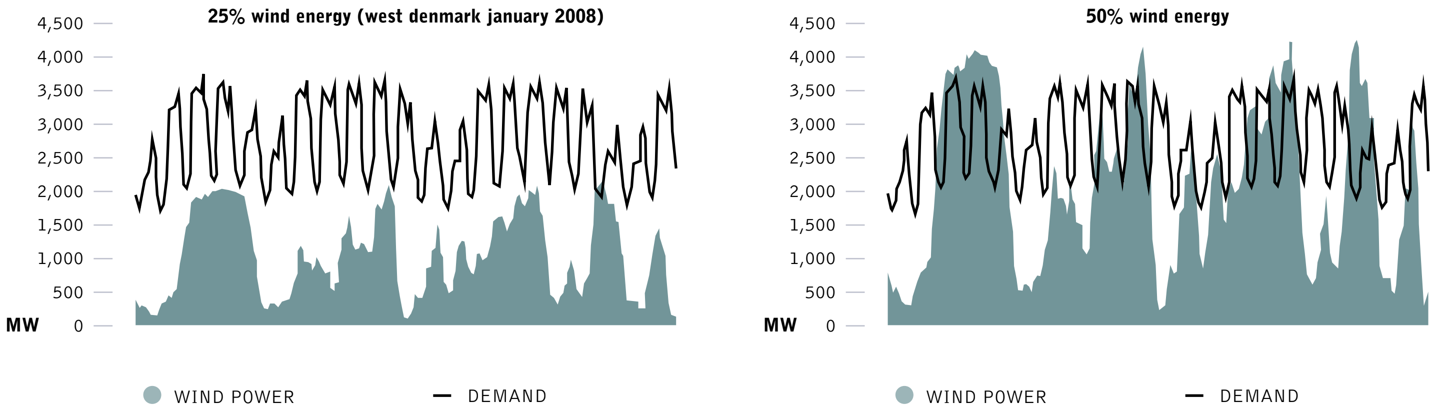
The future power system will not consist of a few centralised power plants but of tens of thousands generation units such as solar panels, wind turbines and other renewable generation, partly distributed in the distribution network, partly concentrated in large power plants, like offshore wind power plants. Smart grid solutions will help to monitor and integrate this diversity into power system operation and at the same time will make interconnection simpler.

The trade-off is that power system planning will become more complex due to the larger number of generation assets and the significant share of variable power generation causing constantly changing power flows in the power systems. Smart grid technology will be needed to support power system planning, i.e. actively support day-ahead planning and power system balancing by providing real-time information about the status of the network and the generation units in combination with weather forecasts. Smart grid technology will also play a significant role in making sure systems can meet the peak demand at all times. Smart grid technology will make better use of distribution and transmission assets thereby limiting the need for transmission network extension to the absolute minimum.

Smart grids use information and communication technology (ICT) to enable a power system based on renewable energy sources. ICT in smart grids is used to:

- easily interconnect a large number of renewable generation assets into the power system (plug and play);
- create a more flexible power system through large-scale demand-side management and integrating storage to balance the impact of variable renewable generation resources;
- provide the system operator with better information about the state of the system, which so they can operate the system more efficiently;
- minimise network upgrades by using network assets efficiently and supporting an efficient coordination of power generation over very large geographic areas needed for renewable energy generation.

figure 11: **wind energy in the western danish power system.**



The left picture shows 25% wind energy in the Western Danish power system while the left picture shows 50% wind penetration (wind in grey/demand as orange line). It can be seen that with increasing penetration levels surplus wind power might be available at certain times, while at other times, it will be not sufficient to supply the load. Hence, the power system must become more flexible to follow the variable renewable power generation, for example by adjusting demand via demand-side management and/or by deploying storage systems.

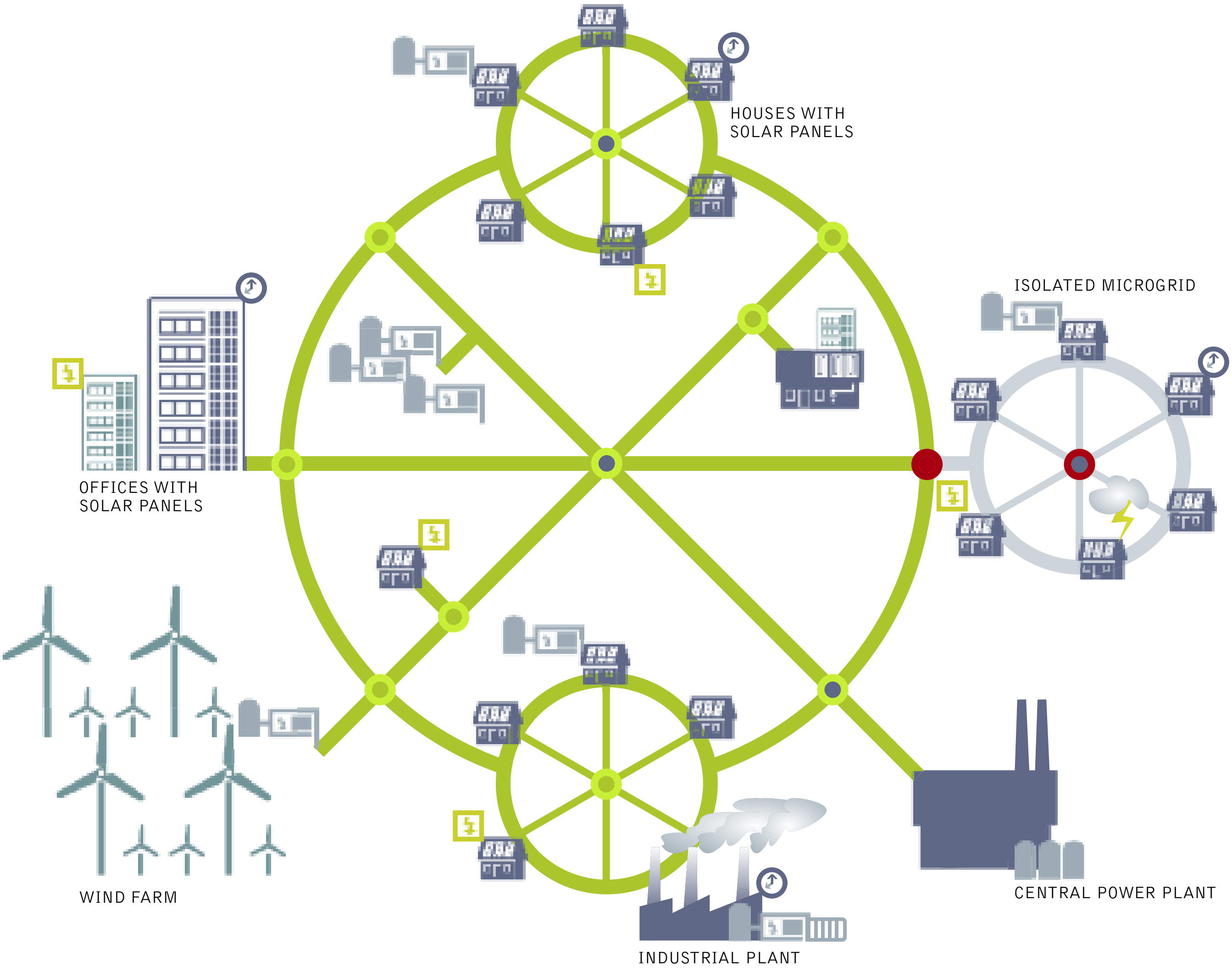
source ECOGRID PHASE 1 SUMMARY REPORT, AVAILABLE AT: HTTP://WWW.ENERGINET.DK/NR/RDONLYRES/8B1A4A06-CBA3-41DA-9402-B56C2C288FB0/0/ECOGRIDDK_PHASE1_SUMMARYREPORT.PDF.

2.4 the smart grid vision for the energy [r]evolution

To develop a power system based almost entirely on renewable energy sources will require a new overall power system architecture –including smart grid technology, which will need substantial amounts of work to emerge.[17] Figure 12 shows a very basic graphic representation of the key elements of future, renewable-based power systems using smart grid technology.

figure 12: the smart-grid vision for the energy [r]evolution

A VISION FOR THE FUTURE – A NETWORK OF INTEGRATED MICROGRIDS THAT CAN MONITOR AND HEAL ITSELF.



- ● **PROCESSORS** EXECUTE SPECIAL PROTECTION SCHEMES IN MICROSECONDS
- ● **SENSORS** ON 'STANDBY' – DETECT FLUCTUATIONS AND DISTURBANCES, AND CAN SIGNAL FOR AREAS TO BE ISOLATED
- ● **SENSORS** 'ACTIVATED' – DETECT FLUCTUATIONS AND DISTURBANCES, AND CAN SIGNAL FOR AREAS TO BE ISOLATED
- ▣ **SMART APPLIANCES** CAN SHUT OFF IN RESPONSE TO FREQUENCY FLUCTUATIONS
- ◷ **DEMAND MANAGEMENT** USE CAN BE SHIFTED TO OFF-PEAK TIMES TO SAVE MONEY
- ▥ **GENERATORS** ENERGY FROM SMALL GENERATORS AND SOLAR PANELS CAN REDUCE OVERALL DEMAND ON THE GRID
- ▭ **STORAGE** ENERGY GENERATED AT OFF-PEAK TIMES COULD BE STORED IN BATTERIES FOR LATER USE
- ⚡ **DISTURBANCE IN THE GRID**

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reference

17 SEE ALSO ECOGRID PHASE 1 SUMMARY REPORT, AVAILABLE AT: HTTP://WWW.ENERGINET.DK/NR/RDONLYRES/8B1A4A06-CBA3-41DA-9402-B56C2C288FB0/0/ECOGRIDDK_PHASE1_SUMMARYREPORT.PDF

image THE PS10 SOLAR TOWER PLANT AT SAN LUCAR LA MAYOR OUTSIDE SEVILLE, SPAIN, APRIL 29, 2008.

A more detailed outline of the system architecture of the smart grid vision will be defined through ongoing research and dynamic technology developments. The first steps in the transition process towards a new, renewable-based power system using smart grid technology have already been taken in some countries. This section presents innovative demonstration projects based on smart grid technology.

The examples show that smart grid technology is much more than just smart metering and that technology development does not need to start from scratch. In many cases there is already enough experience available to move from demonstration projects to a large-scale deployment. The largest problem the power system industry currently faces is not the lack of ideas or possible solutions, but the lack of incentives to test and implement the solutions in real power systems. Testing and real-life examples are essential for gaining additional knowledge with the thousands or even tens of thousands of electrical devices in the real world compared to often only a few dozen devices used in demonstration projects. Incentives help apply new technology to existing electric power systems. However, transmission systems are classical monopolies and so they have little incentive to innovate to gain greater market shares.

The smart grid concept typically focuses on applications connected to the medium or low voltage network, using IT technologies to monitor and control different applications such as small generation technologies (PV, Wind), and storage systems or demand technologies such electric; cars or heat pumps. However, the smart grid vision, is an overall power system approach and is not bound to one particular distribution network. Smart grids, micro grids and super grids will all be needed to work in harmony to provide day-to-day system balancing and also transport power from areas with large amounts of renewable resource to areas with high electricity demand.

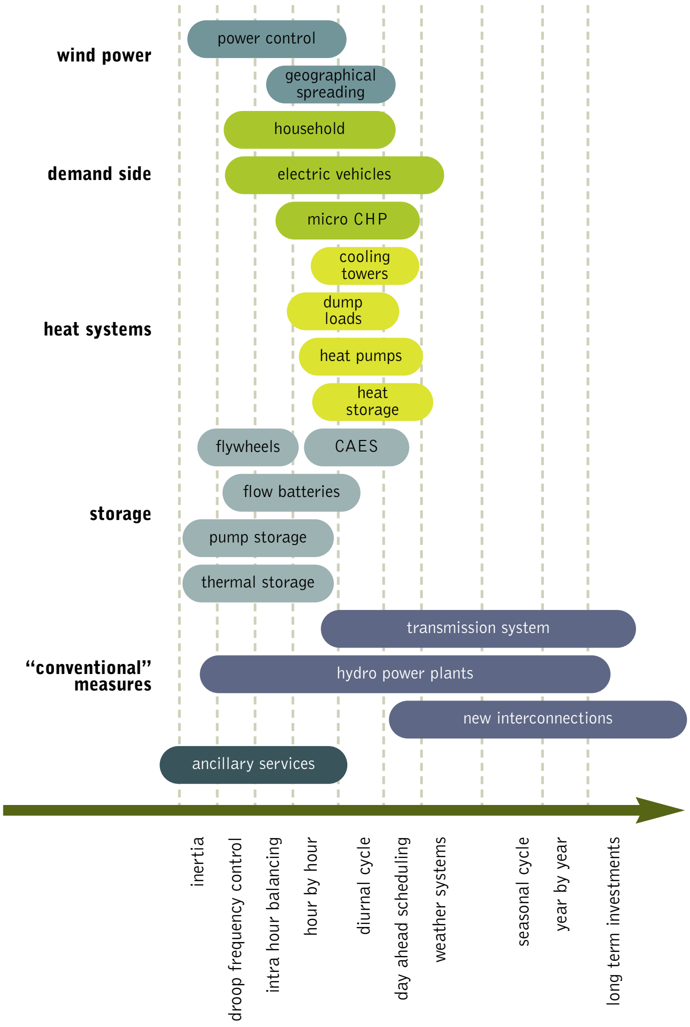
2.4.1 smart grid solutions for the integration of renewables using micro grids

The large-scale integration of variable renewable energy resources into the power system will require new measures to make the power system more flexible on several time scales. Figure 10 provides an overview of selected new measures in relation to their time impact in the balancing process. The integration of these new measures into power system operation will require new ICT solutions, which can be considered part of the smart grid vision for Energy [R]evolution.

Figure 13 shows that there is a large range of possible options to make the power system more flexible for supporting balancing from a very short time frame (seconds) to approximately day-ahead balancing (day-ahead planning). Long-term aspects are related to seasonal weather cycles and the need to meet peak demand at all times, so power system planning must includes large geographic areas. This is the point where the smart grid vision meets the super grid vision. For smart grids to work, micro grids are needed on the distribution network level. Examples of island and rural micro grids are provided in section 1. More broadly, the term micro grid refers to the IT monitoring and control infrastructure on the distribution level. Each distribution level will represent one unique micro grid enabling selected functions based on the available resources or technologies in the distribution network. The key tasks of micro grids in a smart grid system are to:

- enable informed participation by customers to ultimately support demand side management;

figure 13: **overview of new and conventional measures in relation to the time impact in the balancing process**



source ECOGRID PHASE 1 SUMMARY REPORT, AVAILABLE AT: HTTP://WWW.ENERGINET.DK/NR/RDONLYRES/8B1A4A06-CBA3-41DA-9402-B56C2C288FB0/0/ECOGRIDDK_PHASE1_SUMMARYREPORT.PDF.

- monitor and control all generation and storage options in the distribution network;
- enable new products and services such as demand side management and virtual power plants;
- address disturbances in the power system locally, e.g. by automated prevention or containment of faults in the power system or by automated restoration in case of a black-start.

In the following, we will present selected examples of existing smart grid applications focusing mainly on day-ahead planning and balancing support. The main focus here is on how micro grid and smart grid technologies work together to achieve a certain functionality, less emphasis is given to the overall control and information structure. The following examples are only a selection of possible smart grid applications for the large integration of renewables into the power system; many more are currently under investigation/development.

2.4.2 management of power generation

The virtual power plant A virtual power plant interconnects different real power plants (of different nature such as solar, wind and hydro) as well as storage devices distributed in the power system via information technology. This virtual power plant (VPP) can be designed / operated so that it can always comply with a given schedule. From the perspective of the overall power system, a VPP is similar to a conventional power plant and will simplify day-ahead scheduling. The variability of certain renewable energy technologies is taken care of within the VPP and does not need to be dealt with in the power system's day-ahead planning.

A real-world example is the *Combined Renewable Energy Power Plant* that was developed by three German companies and is now operating in Germany.[18] The VPP interconnects and controls eleven wind power plants, twenty solar power plants, four combined heat-and-power plants based on biomass, plus a pump storage unit, all of them spread throughout Germany. The VPP thereby combines the advantages of various renewable energy sources. Wind turbines and solar modules help generate electricity in accordance with how much wind and sun is available. Biogas and the pump storage units are used to make up the difference: they are converted into electricity as needed in order to balance short-term fluctuations, or are temporarily stored.[19] Together they ensure sufficient electricity supply to cover the demand.

The function of the renewable VPP can be divided into two stages:

- anticipatory control similar to day-ahead planning, and
- fine-tuning similar to final system balancing at the time of delivery.

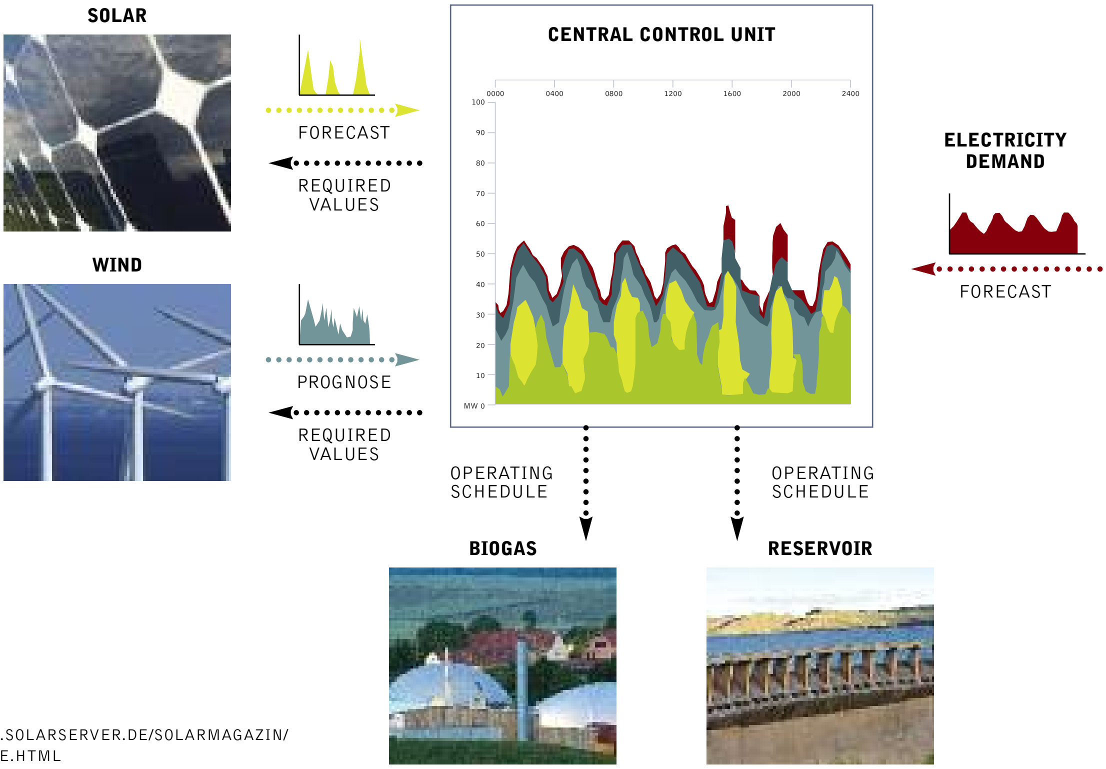
The actual forecasted demand is the central starting point for the day-ahead planning. The forecast of the electricity demand, the 'load profile', is communicated to the central control unit. The central control unit also has access to a wind and solar production forecast for the different power plants, delivered by the German Weather Service (DWD). Because wind and solar energy cannot precisely meet a given electricity demand, oversupplies and shortages need to be compensated by the biomass and pump storage unit to ensure security of supply and grid stability.

There are the following options to balance wind and solar generation:

- Firstly, combined heat–and-power (CHP) plants are used to produce electricity and heat from biogas.
- Secondly, energy can be stored temporarily in a pumped storage power plant and can be quickly made available again.

Forecasts of the expected solar and wind production makes it possible to plan ahead for the operation of combined heat-and-power plants and storage systems. If the amount of electricity produced by wind and solar power installations exceeds demand, the surplus of energy is used for filling up storage reservoirs. Another option would be to use surplus electricity to charge batteries in electrical cars. If maximum storage capacity is reached, wind and solar power plants can be curtailed.

figure 14: **principle of a VPP: stage 1 – day-ahead planning.**



source HTTP://WWW.SOLARSERVER.DE/SOLARMAGAZIN/ANLAGEJANUAR2008_E.HTML


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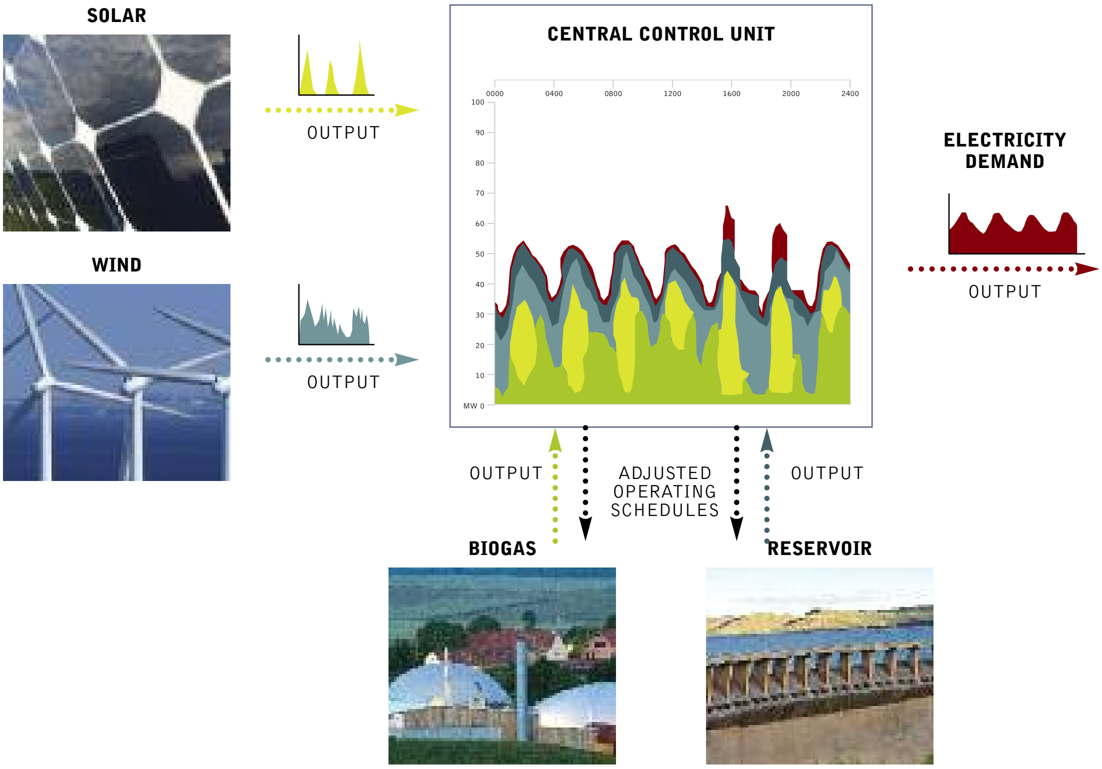
image SOLAR POWERED PHOTO-VOLTAIC (PV) CELLS ARE ASSEMBLED BY WORKERS AT A FACTORY OWNED BY THE HIMIN GROUP, THE WORLD'S LARGEST MANUFACTURER OF SOLAR THERMAL WATER HEATERS. THE CITY OF DEZHOU IS LEADING THE WAY IN ADOPTING SOLAR ENERGY AND HAS BECOME KNOWN AS THE SOLAR VALLEY OF CHINA.

Even with good weather forecasts the actual electricity production of solar and wind power can be different to predictions. To deal with this, the operating schedules need to be fine-tuned and adjusted based on the actually measured values, see also Figure 15.

figure 15: **principle of a VPP: stage 2 – fine tuning or balancing in real time.**



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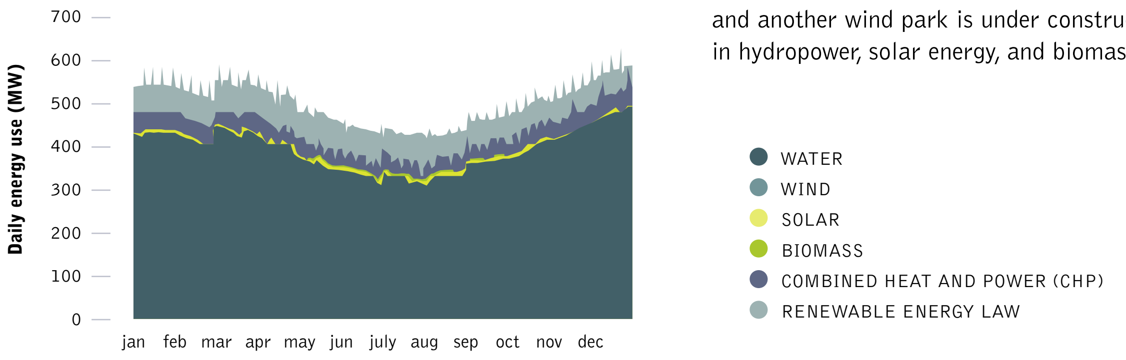
references
18 SEE ALSO HTTP://WWW.KOMBIKRAFTWERK.DE/INDEX.PHP?ID=27
19 SEE ALSO HTTP://WWW.SOLARSERVER.DE/SOLARMAGAZIN/ANLAGEJANUAR2008_E.HTML

case study: greenpeace energy eG - the consumer cooperative for clean electricity

In Germany, as of April 2009 about 91,000 households and about 5,000 companies from all over the country are being supplied by Greenpeace Energy. They operate under a cooperative model, with 18,000 members. Apart from providing customers with a guarantee that they are getting power with dramatically less greenhouse gas, and no nuclear power, the cooperative employs both demand management and supports development of new renewable and CHP plants. Electricity prices are approx 1.5 or 2 cents higher, at 21.40 cent per kilowatt-hour plus a basic charge of 8.90 euro per month, but there is a large market willing to pay the premium for a safe future. The consumer cooperative effectively gathers up consumer power and makes it possible to ensure monitoring of the quality of the electricity supplied, customers care and the finances.

case study figure 1: **daily generation mix of Greenpeace energy over the entire year**



source SVEN TESKE / GREENPEACEINTERNATIONAL

real-time monitoring and demand management

With the Greenpeace eG, the production of electricity fits the customer's consumption in real time, using a computerised control station. Every generating facility is monitored by remote inquiry. BET, an independent engineering office in Aachen, has access to all the data and regularly checks that composition of electricity is being kept and random checks are made by facility operators.

helping to build new renewable energy

Clean power from Greenpeace Energy is at least 50% from renewable sources (hydro, wind, biomass), with a maximum of 50% of combined heat and power plants (natural gas only). The supplier guarantees no nuclear, coal or oil-based power. The eG cooperative has also established a business for planning, financing and operating green power installations so Greenpeace can supply its members and customers with green energy from own power plants. These tasks are done by Planet energy Ltd., which is a 100% daughter company of Greenpeace Energy eG. Three wind parks and three PV-installations have been built already and another wind park is under construction. Further investments in hydropower, solar energy, and biomass are in planning.

Ancillary services from a wind power plant To ensure availability, quality and safety of power supply at all locations in the overall system, some plants must provide ancillary services. One of the key ancillary services is called Frequency Control Ancillary Services (FCAS) and combines the medium-term energy balancing. Sometimes this is called secondary control and the short-term, minute-by-minute control of the power system frequency is also known as primary control. The balancing service is required to adjust generation (and load, if applicable) continuously until minutes before delivery when frequency regulation service (primary control) takes over to maintain a minute-to minute generation-load balance.

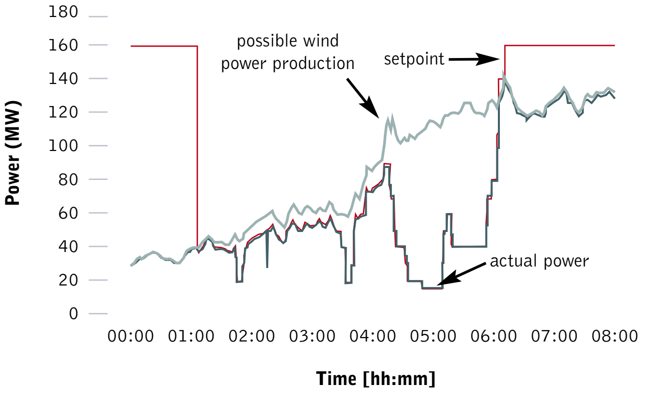
Historically, such ancillary services were only supplied by conventional power plants, but nowadays also wind farms are able to provide this service. Therefore they should be better referred to as wind power plants as they can fulfil now the same ancillary services as conventional power plants. Renewable energy must be able to work as 'power plant' to achieve very high penetration levels in the power system.

For wind power, several new features are now integrated into the plant operation to support the operation of the power system. The most significant step in this direction is the wind farm controller for the first large offshore wind farm, the Danish Horns Rev offshore wind farm. The Horns Rev wind farm consists of 80 Vestas V80 (2 MW) wind turbines with double-fed induction generators (DFIG).

To illustrate the performance of wind power at this scale, a 'normal' day of operation at the Horns Rev wind farm is explained below. At about 4:00 am, the mode to provide frequency control ancillary services is activated. This causes the actual power generation of the wind farm to decrease below the theoretically possible power production. This makes the difference between actual power generation and theoretically possible power production available as spinning reserve which can be used in case of under-frequency. For about two hours the power output of the wind power plant is reduced significantly because of overproduction in the grid. Then the balance control and frequency control are cancelled, and the wind farm returns to normal operation, just as day starts and demand increases.

image LOADING SUBMARINE SEA CABLES.

figure 16: balance control and reservation for frequency control at the same time



source IEEE.

Another important development is that wind turbines can have now fault-ride-through control capabilities that enable the wind turbines to stay connected during and after grid faults in the power system, a capability that most conventional power plants have (see also Appendix 3 on Wind Turbine Control Functions). The fault-ride-through capability is an important feature to secure stable operation in case of a voltage or frequency distortion.

2.4.3 demand-side management (DSM)

Demand-Side Management (DSM) means taking active control of the demand by the electricity industry, including customers, to influence the amount and timing of electricity use. It can be done either by industrial or residential customers, but usually involves some advanced information technology so that load changes can be communicated to those controlling the grid, in order to regulate demand as well as supply. This is a new paradigm for many grid operators. A full definition and detailed information is given in Appendix 4 on DSM.

DSM in the Norwegian balancing market The idea of a market for ancillary services is for other players besides the central power plants to provide the necessary ancillary services and to make the power system more flexible. The easiest market for ancillary services is a real-power balancing market (real-time frequency regulation). Those who can participate in an ancillary service market should be generation units as those who are creating the demand, hence the term 'demand-side participation'. Demand-side participation increases competition in electricity markets and gives great potential to regulate resources. Information and communication technology in a smart grid is typically used to bring together a number of electricity users so they can bid together in the market for their services. The basic concept is that they can increase or decrease demand after an order from the market operator is released, and that this is cheaper than for the generators to alter supply.

In Norway, the national transmission system operator (TSO) Statnett developed an 'options' market to secure sufficient fast operating reserves in high-demand periods. This Regulating Capacity Option Market was launched in 2000. From the beginning, Statnett has encouraged the demand side (electricity users) to participate in this market. Offers are based on area, option price, and size (a minimum of 25 MW). The basic concept is that users can offer to 'switch off' in times of high demand, and that this gives them a cheaper electricity price. In the Norwegian market this has meant demand measures can compete with generation for ancillary services to the grid. A number of consumers have prepared for demand disconnection on short notice, in return for the financial reward of lower prices. Mainly big industries (aluminium industry, steal industry, oil industry) have participated, though there is a potential for smaller demand to participate.

The maximum purchase from the demand side so far has been 1,300 MW (mainly from the power-intensive industry). The offered volume is even higher. In addition, up to 1000 MW of electric boilers have been made available. This potential depends on temperature and the price ratio between oil (or other fuels) and average daily or weekly electricity prices.

DSM using virtual power plant of cold storage warehouses
The EU research project Night Wind has investigated the possibilities of using Cold Store Warehouses for DSM to balance variability from wind generation.[20] Cold Store Warehouses are large facilities for storing refrigerated and frozen products. The total capacity of cold stores in the EU 27 is estimated at 4,300 MW (installed electrical maximum capacity).[21] Typically cold stores do not operate at maximum capacity during normal operation, but actually at about 60-70% of maximum capacity.

When the cold store operates above average capacity, the temperature in the cold store drops and the products are cooled down. In other words, the additional energy supplied to the cold store is transformed into thermal energy (lower product temperatures). The 'battery' is being charged.

When the cold store operates below average capacity, the temperature of the products rises. The thermal 'battery' is discharged. There is no 'real' electricity produced in this discharging process. More precisely, the electricity that would have been required to keep the cold store at constant temperature is now available for other purposes, and is thus virtually produced.

The process of charging and discharging the cold store 'battery' is almost free of losses. For example you could run the refrigeration machine for half an hour at -16 °C plus half an hour at –20 °C, instead of for one hour at -18 °C. Doing this, you would lose less than 1%, efficiency – the overall efficiency is above 99%. For comparison, storing energy in heat pumps has an overall efficiency of approximately 70 to 85%.

Thus, these cold storage warehouses can become part of the system voluntarily 'charging' and 'discharging' to help deal with oversupply and keeping the temperature in the warehouses at the right level. To do this, they would become part of the Virtual Power Plant, requiring two-way communication systems and software that aggregates the warehouses so they can take part in the electricity market as ancillary services.

references
[20] SEE HTTP://WWW.NIGHTWIND.EU/.
[21] SOURCE: HTTP://WWW.NIGHTWIND.EU/MEDIAPOOL/48/485045/DATA/COLD_STORAGE_OF_WIND_ENERGY.PDF

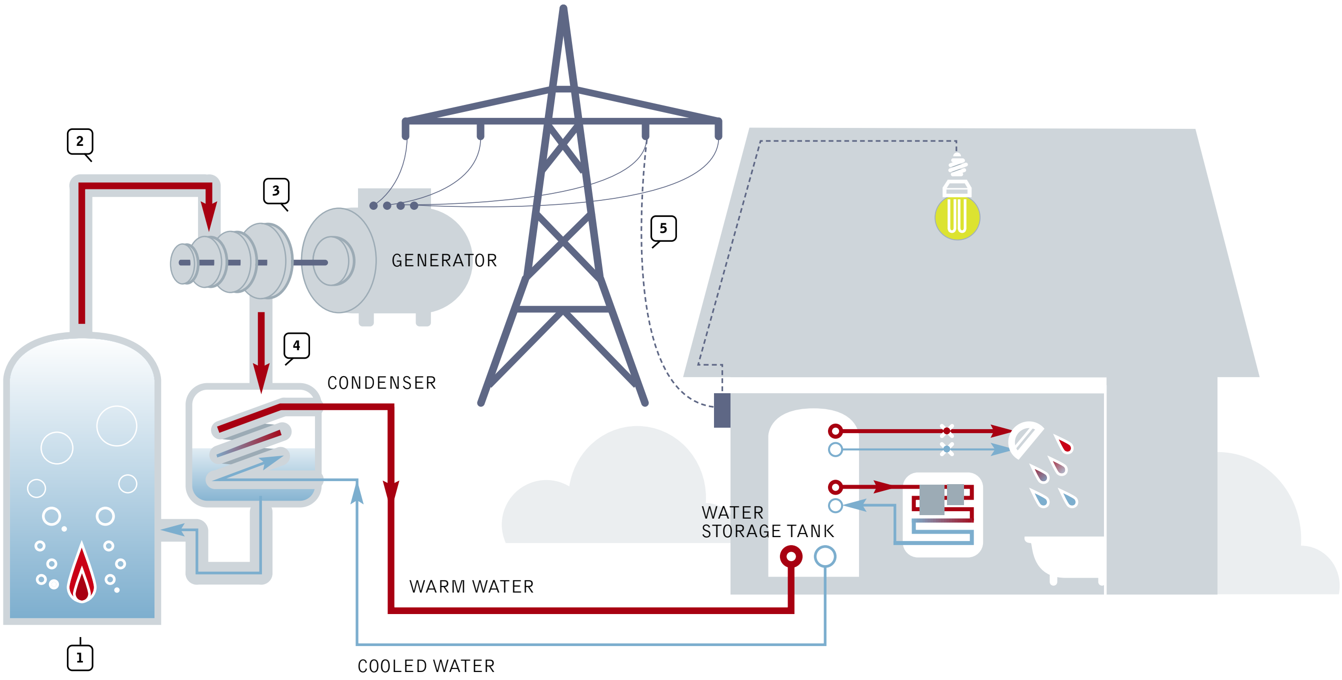
DSM with combined heat and power plants A combined heat and power (CHP) plant is a plant where both heat and electricity are produced from one fuel source, see Figure 17. The heat can be used to heat up water which is distributed via a district heating system, i.e. a pipe system in the ground, to the customers which use the water to heat buildings, for instance. The cold water is then returned to the CHP plant via additional return pipes.

Denmark's major cities, for instance, have city-wide district heating schemes where most of the heat (95%-98%) is produced in large coal- or gas-fired CHP plants. Smaller cities in Denmark, communities and even small villages typically also have a district heating system powered by a small-scale CHP plant, utilising typically natural gas and operated with rather high power-to-heat ratio. The size of the CHP plants varies from around a few 100 MWe in larger cities to 0.5-10 MWe in small communities and villages.

The CHP systems combined with a district heating system installed all over Denmark are unique in their design because almost all district heating systems are equipped with a hot water storage tank which is, if filled completely, typically capable of supplying the heat demand in the district heating system without any support of the CHP plant for at least 48 hours.

In addition, most CHP systems are also equipped with boilers, so electricity supplied via the Danish power system can be converted to heat which can be stored and distributed via the exiting infrastructure of the district heating systems. At times when there is surplus electricity generated by wind power, for example when there is high wind speeds and low loads, it can easily be converted to heat and stored in the existing heat storage tanks. Hence, instead of 'spilling' power when it is in oversupply it can be used to replace natural gas usually used in CHP stations for producing heat.

figure 17: **example for a district heating system based on a CHP plant**



1. BIOFUEL OR NATURAL GAS FIRED CHP PLANT.
2. STEAM IS LED TO THE TURBINE.
3. THE TURBINE PRODUCES ELECTRICITY WITH THE HELP OF A GENERATOR.
4. THE STEAM (RESIDUAL HEAT) FROM THE TURBINE, CONDENSES AND IS TRANSFERRED TO THE DISTRICT HEATING NETWORK.
5. ELECTRICITY FOR LIGHTING ETC.

source HTTP://WWW.KRISTIANSTAD.SE/SV/KRISTIANSTADS-KOMMUN/SPRAK/ENGLISH/ENVIRONMENT/DISTRICT-HEATING/WHAT-IS-DISTRICT-HEATING/

image ANDASOL 1 SOLAR POWER STATION IS EUROPE'S FIRST COMMERCIAL PARABOLIC TROUGH SOLAR POWER PLANT. IT WILL SUPPLY UP TO 200,000 PEOPLE WITH CLIMATE-FRIENDLY ELECTRICITY AND SAVE ABOUT 149,000 TONS OF CARBON DIOXIDE PER YEAR COMPARED WITH A MODERN COAL POWER PLANT.

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2.4.3 storage technologies

A number of mature and emerging technologies are viable options for electrical energy storage. Each has benefits and drawbacks in terms of energy storage capacity, peak power capability, and response time among other variables. Therefore, each technology will be most viable for a particular energy storage application, such as peak load shaving, or local voltage control. Appendix 5 provides a detailed overview of the newest storage options available and under development for renewable energy sources.

Storage with vehicle-to-grid The idea of the Vehicle-to-Grid (V2G) concept is based on electric cars equipped with batteries that could be used to make the power system more flexible, i.e. they can be charged during times with surplus renewable generation and can be discharged to supply peaking capacity or ancillary services to the power system while they are parked. Investment costs would be considered zero and the power supply to the market would be an opportunity for an additional income for the car owner. Most important, during peak times cars are often parked close to main load centres, e.g. outside factories, so there would be no network issues.

Within the V2G concept a Virtual Power Plant would be built using ICT technology to aggregate the electric cars for participating in the relevant electricity markets and to meter the charging/de-charging activities. The V2G concept is probably the VPP concept that will include the largest number of devices, i.e. electric cars, easily amounting to several hundred thousand units. In addition, the VPP has to take into account the preference of the car owner, so the system has to know when each owner wants to use the car.

The Danish EDISON demonstration project started 2009 to develop and test the infrastructure for integrating electric cars into the electric power system of the Danish island of Bornholm.

Storage with pump storage Pumped storage can be considered a traditional technology because it has been in operation for more than 100 years. Pump storage can be compared to a normal hydro power station[22] - it is a type of hydroelectric power generation that can store energy. Water is pumped from a lower elevation reservoir to a higher elevation during times of low-cost, off-peak electricity. During periods of high electrical demand, the stored water is released through turbines. Losses in the pumping process make the plant a net consumer of energy overall, however the system makes income by selling more electricity during periods of peak demand, when electricity prices are highest.

Pumped storage is the largest capacity form of grid energy storage now available. The technology is currently the most cost-effective means of storing large amounts of electrical energy on an operating basis, but capital costs and appropriate geography are critical decision factors for building new infrastructure. Taking into account evaporation losses from the exposed water surface and conversion losses, approximately 70% to 85% of the electrical energy used to pump the water into the elevated reservoir can be regained when it is released. The technology has been successfully used for many decades all over the world. In 2007 the EU had 38. 3 GW net capacity of pumped storage out of a total of 140 GW of hydropower, representing 5% of total net electrical capacity in the EU (Eurostat, consulted August 2009)

Along with energy management, i.e. smart grids, pumped storage systems help control electrical network frequency and provide reserve generation. Thermal plants are much less able to respond to sudden changes in electrical demand, potentially causing frequency and voltage instability. Pumped storage plants, like other hydroelectric plants, can respond to load changes within seconds.

2.4.4 other power system integration services

Black-start In a power system with large amounts of renewable generation, centralised generation units will no longer be available to re-start the power after a black-out (called 'black-start' by system engineers). This has already become an issue in the Danish power system which has one of the highest wind penetration levels in the world. During times of high wind production only a limited number of conventional centralised generation units are online, which might not be enough to black-start the power system in an emergency situation.

The so-called 'Cell Project' is investigating 'black-start' options and was initiated by the Danish TSO Energinet.dk. Within this project, the power system is divided into cells, each cell consisting of a 10-60kV distribution network. In the Danish case, there are a large number of wind turbines and to a lesser extent combined heat–and-power (CHP) units scattered all over the distribution network. The aim of the Cell Project is to use these local generation assets to either:

- transfers the local distribution network to controlled island operation supplied by the local generators, or
- after a total black-out, to use the local generators to black-start the cell to a state of controlled island operation.

For this purpose, an ICT-based communication system was implemented in a demonstration cell in the Danish network. In addition, a control software, known as the cell controller, was developed to control and coordinate the operation of generators, load feeders and main power circuit breakers. The first successful tests were performed in November 2008.[23] The project is currently extended to a larger cell area and more tests are scheduled for 2011.

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references

[22] CONVENTIONAL HYDROELECTRIC PLANTS THAT HAVE SIGNIFICANT STORAGE CAPACITY MAY BE ABLE TO PLAY A SIMILAR ROLE IN THE ELECTRICAL GRID AS PUMPED STORAGE, BY DEFERRING OUTPUT UNTIL NEEDED.

[23] HTTP://WWW.ENERGINET.DK/EN/MENU/NEWS/NEWSARTICLES/ENERGINET.DK+IN+FRONT+WITH+SMARTGRID+CONCEPT.HTM

New operation tools The development of smart grids will create a whole set of new tools for the companies that operate the power system. New operation tools will mean operators can better understand the status of the power system and control will be faster and more sophisticated.

One example is the Renewable Energies Control Centre (CECRE) at the Spanish system operator (see also Figure 18) which was commissioned in June 2006. The aim of the control centre is to give greater supervision and control of renewable energy generation so more renewable sources can be integrated to the system. CECRE's main function is to manage and integrate the special regime production depending on the needs of the electrical system.

In Spain, all renewable production facilities with a total installed power greater than 10 MW must be controlled by a control centre that is directly connected to the CECRE. These local renewable generation control centres (RESCCs) must have enough control over the plants in order to be able to execute CECRE's orders within 15 minutes at all times This advanced system information sharing allows for a fast and reliable control of the renewable generation assets.

In addition, the Spanish TSO has developed special computer tools such as GEMAS, which use the data from the control centres to study possible operation scenarios, power system failures in particular, to determine the best strategies to keep the system secure.

figure 18: **the Renewable Energies Control Centre (CECRE)**

source RED ELÉCTRICA DE ESPAÑA. WWW.REE.ES.

3

image PRODUCING WIND ROTORS FOR OFFSHORE WIND ENERGY IN RINGKOBING, DENMARK.
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> “super grids provide a solution to transfer energy over large distances”

GREENPEACE INTERNATIONAL
CLIMATE CAMPAIGN

In a power system electricity demand and supply must be equalised at all times to keep supply flowing to where it is needed. To guarantee this, sufficient generation capacity must be available at all times and network capacity must be adequate and operational when needed. Adding large shares of –partly variable- renewable generation to a power system does not change this criteria. The concept of super grids provides a solution to transferring energy supply between areas of large resources and areas of large demand.

The Greenpeace simulation study (Section 4) shows that in a largely renewables-based power system, extreme situations can occur. Essentially, during two successive weeks of low solar radiation and little wind most of the European electricity would have to be filled by other sources. Although these cases are not frequent, the power system must be adequately designed to cope with such extreme situations.

Based on the current technology development of energy storage technologies, it is difficult to envision that energy storage could provide a comprehensive solution to this challenge. While different storage technologies such as electrochemical batteries are already available today, it is not clear whether large-scale electricity storage, other than hydro power described in the previous section, will become technically and economically viable.

Feasible storage systems would have to cover most of the European electricity supply during up to two successive weeks of low solar radiation and little wind – this is difficult to envision based on current technology development. The Greenpeace simulation study shows (Section 4) that extreme situations with low solar radiation and little wind in many parts of Europe are not frequent, but they can occur. The power system, even with massive amounts of renewable energy, must be adequately designed to cope with such extreme situations.

To design a power system that can adequately react to such extreme situations a substantial amount of planning ahead is needed in order to ensure that available generation capacity together with sufficient network capacity can match demand. In order to do so, different timescales must be considered:

- Long-term system plans to assess the system adequacy over the coming years (typically a time horizon of 2 to 10 years ahead is considered).
- Day-ahead planning, making sure that sufficient generation is available to match expected demand (typically 12 to 36 hours ahead)
- Short-term balancing, covering events such as a mismatch between forecasted generation/demand or sudden loss of generation (typically seconds to hours ahead planning).

Small changes in the power system – such as a small addition of solar or wind generation to an existing power system - will have little impact on the overall design of the system design. The E[R] energy mix proposed by Greenpeace, however, results in a major change in the generation structure, hence the network structure must be adopted to the new generation structure in order to be able to 'keep the lights on' even in extreme situations such as low solar radiation and little wind in many parts of Europe. A key element of this new network structure will be the onshore and offshore super grid, discussed in more detail in the following.

3.1 benefits of a super grid

From around 1920 each load centre in Europe had its own isolated power system. With the development of transmission lines using higher voltages, the transport of power over larger distances became feasible, and soon the different power systems were interconnected. In the beginning, only stations in the same region were interconnected. Over the years, technology developed further and maximum possible transmission line voltage increased step by step.

The main driver of extending network structure had two main reasons:

- Larger transmission networks and high voltage lines meant suppliers could follow the aggregated demand of a large number of customers, instead of the demand variation of one customer - which can change significantly over time- with one generation resource. The demand of those aggregated customers became easier to predict and generation scheduling therefore significantly easier (see Figure 19);
- The larger transmission networks created economies of scale by installing larger generation units. In the 1930s, the most cost-effective size of thermal power stations was about 60 MW. In the 1950s, it was 180 MW, and by the 1980s about 1,000 MW. This approach made only economic sense because extending the power system was cheaper than adding local generation capacity.

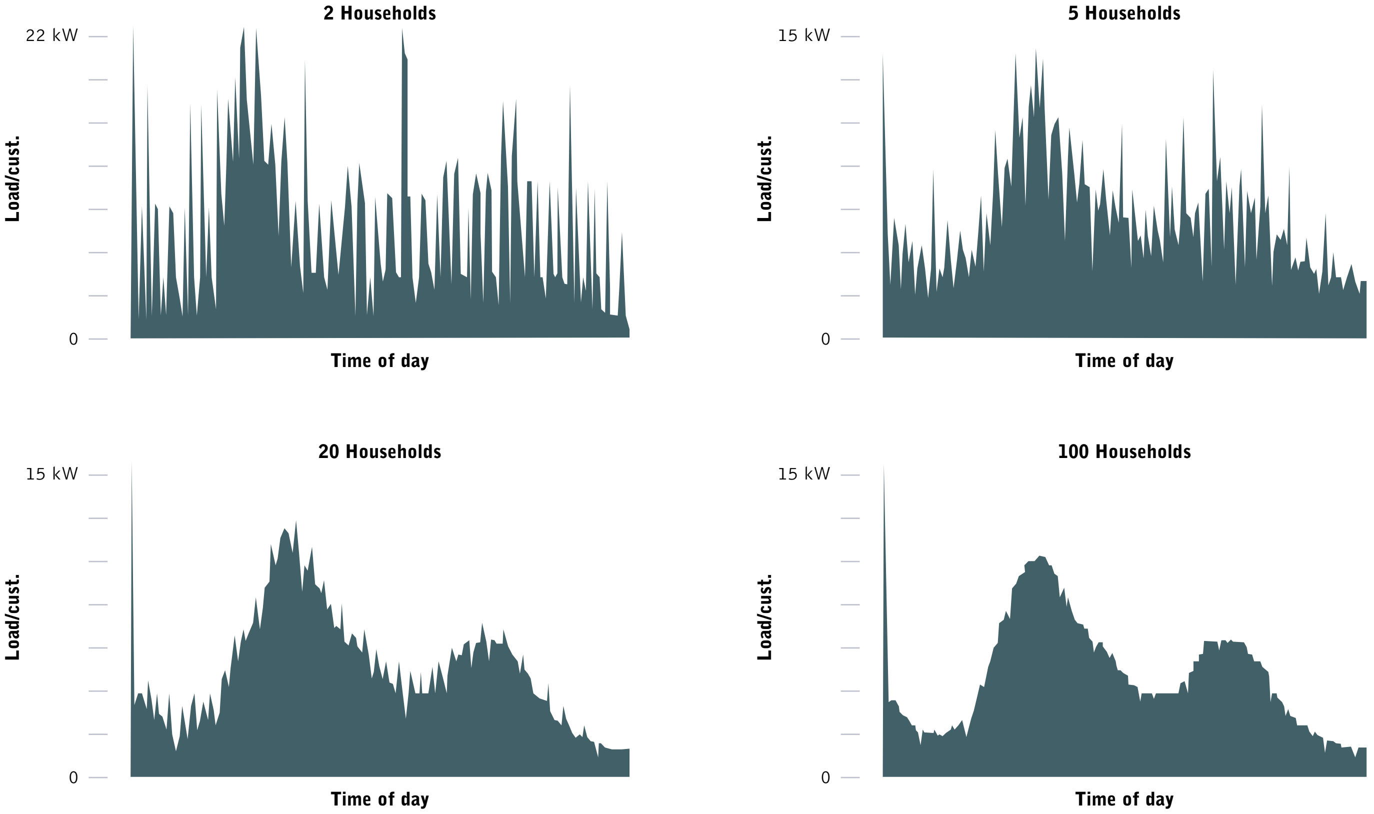
This approach includes some major risks, like the break-down of a large power station or the interruption of a major transmission line, which can interrupt the power system over a large area. To be better prepared for such situations national transmission systems in Europe and elsewhere were interconnected across borders. Countries can help each other in case of emergency situations by cooperating in the organisation of spinning reserve, reserve capacity and frequency control.

Transmission network expansion has always played a key role in developing a reliable and economic power supply. Now, shifting to the Energy [R]evolution energy mix with approximately 90% of the electricity supply coming from renewable energy sources will also require a significant redesign of the transmission network to adapt to the needs of the new generation structure. The right kind of grid gives us an economic, reliable and sustainable energy supply.

In the E[R] energy mix, distributed generation that is close to the actual demand, plays a key role (about 70% of all generation is located close to the load centres). Biomass, pump storage systems as well as large-scale renewable power plants, such as offshore wind farms in the North Sea and CSP in North Africa are used to compensate the variations in local supply caused by the variability of the demand and the local renewable energy sources. In addition, the E[R] assumes that customers become more flexible in their demand; that about 20% of the local demand can be reduced for 3-4 hours by demand-side management and/or local storage options.

image GEOTHERMAL POWER STATION,TUSCANY, ITALY.

figure 19: customer aggregation in a power system



In principal, oversizing local generation would reduce the need for large-scale renewable generation elsewhere as well as upgrading the transmission network.[24] However, making local plants bigger (oversized) is less economic compared to installing large-scale renewable energy plants at a regional scale integrating them into the power system via extending the transmission system. The allocation of 70% distributed renewable generation and 30% large-scale renewable generation is not based on a detailed technical or economic optimisation – in each location the optimum mix is specific to local conditions. Further detailed studies on regional levels will be needed to better quantify the split between distributed and large-scale renewable generation.

The main aim of the transmission system redesign under the E[R] energy mix scenario is to keep the lights on 24/7, even in extreme situations. Such extreme situations are, for instance:

- Less than average wind production over main parts of Europe during the winter, when solar radiation is low;
- An unscheduled interruption of supply, for instance, of a major interconnection to a large offshore wind farm (n-1 criteria). The impact of such a sudden interruption will be within milliseconds.

An appropriately designed transmission system is the solution in both cases as it can be used to transmit the required electricity from areas with surplus of generation to areas that have an electricity deficit.

In general, the transmission system must be designed to cope with:

1) Long-term issues:

- Extreme variations in the availability of natural resources from one year to another, e.g. the output of wind turbines in any given area can vary by up to 30% from one year to the next, for hydro power the variations can be even larger.

2) Medium-term issues:

- Extreme combinations in the availability of natural resources, e.g. less than average wind production over main parts of Europe during the winter, when solar radiation is low.

3) Short-term issues:

- Significant mismatch between forecasted wind or solar production and actual production with significant impact on power system operation in the range of 15 minutes to 3 hours;

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reference

[24] IN THIS CASE THE LOCAL POWER SYSTEM WILL EVOLVE INTO A HYBRID SYSTEM THAT CAN OPERATE WITHOUT ANY OUTSIDE SUPPORT.

- Loss of a significant amount of generation due to unscheduled break-down or network interruption, impact within milliseconds. The mainland European power system is currently designed to cope with a maximum sudden loss of generation of 3000 MW. If this is sufficient for the future depends, for example, on the maximum transmission capacity of a single transmission line. Most likely the maximum transmission capacity of a single transmission line in the future HVDC super grid will exceed a capacity of 3000 MW, hence sufficient spare generation and/or network capacity must be considered when redesigning the power system (considered in the simulation report (Section 4) by loading the super grid to a maximum of 70%).

Section 4 aims to determine the appropriate transmission capacity between key regions based on extreme combinations in the availability of natural resources (medium-term issues). The medium-term issues are most critical for the design of the transmission system, i.e. as long as the transmission system is appropriately designed to cope with the medium-term issues, it will most likely also be able to cope with the long-term and short-term issues. The model focuses on determining the transmission capacity between different European regions, but no power system dynamic issues were investigated.

3.2 super grid transmission options

In principle, there are different technical options for the redesign of the onshore transmission network. In the following, the technical options are briefly presented, followed by a general comparison.

- HVAC (High Voltage Alternating Current);
- HVDC LCC (High voltage direct current system using line commutated converter);
- HVDC VSC (High voltage direct current system using voltage source converter);
- Other technical solutions

3.2.1 HVAC

A high voltage AC transmission (HVAC) using overhead line has become a leading technology in electrical networks.[25] Its advantage is in using transformers to increase the typical, rather low voltage at the generators to higher voltage levels, which is a significantly cheaper approach than the AC/DC converter stations for the HVDC technologies. Transmission over long distances with low or medium voltage will result in high and prohibitively expensive losses, so high voltage AC (400 kV or more) over medium distance (a few hundred kilometres) is typically the most cost-effective solution. As AC systems develop, there are increases in transmission voltage. Typically, doubling the voltage quadruples the power transfer capability. Consequently, the evolution of grids in most countries is characterised by the addition of network layers of higher and higher voltages.

Today, the highest HVAC voltage used is around 800 kV for overhead lines. The Canadian company Hydro Quebec, for instance, operates a massive 735 kV transmission system using overhead lines, the first line was put into operation in 1965. 1000 kV and 1200 kV AC has been tested in several test-installations and even short-term commercial applications but is not currently used in any commercial application.[26] There are several challenges involved in building such lines and new equipment to be developed includes transformers, breakers, transformers, and switches.

The major advantage of an AC-based system is the flexibility with which loads and generation along the route can be connected. This is especially important if the transmission route passes through a highly populated area and if many local generation facilities are located at many places along the route. The disadvantage of HVAC systems are the comparatively high costs for transmission of large capacity (> 1000 MW) over very long distances (> 1000 km) due to the additional equipment required for keeping the voltage level on the overhead lines, for instance.

3.2.2 HVDC LCC

The advantage of line commutated converter (LCC) based high voltage DC (HVDC) connections is certainly its proven track record. The first commercial LCC HVDC link was installed in 1954 between the island of Gotland and the Swedish mainland. The link was 96 km long, 20 MW rated and used a 100 kV submarine cable. Since then, LCC based HVDC technology has been installed in many locations in the world, primarily for bulk power transmission over long geographical distances and for interconnecting power systems, e.g. the different island systems in Japan or New Zealand. Other well-known examples for conventional HVDC technology are:

- The 1,354 km Pacific Interie DC link with a rating of 3,100 MW at a DC voltage of ± 500 kV;
- The Itaipu link between Brazil and Paraguay, rated at 6,300 MW at a DC voltage of ± 600 kV (2 bipoles x 3,150 MW).

The total conversion efficiency from AC to DC and back to AC using the two converters lies in the range of 97 to 98% and depends on design details of the converter stations. A system design with a 98% efficiency will have higher investment costs compared to a design with lower efficiency. The advantages of an LCC HVDC solution are comparatively low losses – in the order of 2-3% for a 500 MW transmission over 100 km, including losses in converters and transmission. In addition, the higher transmission capacity of a single cable compared to the HVAC transmission or the voltage source converter based transmission can be an advantage when transmitting large capacities. The disadvantage of the HVDC LCC design is the lack of power system support capability. Typically, a strong HVAC network is required on both sites of the HVDC LCC connection. Hence, to build an entire HVDC back-bone network using HVDC LCC technology that has to support the underlaying HVAC network is technically challenging and only possible with the installation of additional equipment such as Statcoms.[27]

references

25 HVAC CABLE SYSTEMS ARE CURRENTLY LESS ATTRACTIVE AS CABLE LOSSES ARE HIGHER AND TRANSMISSION CAPACITY IS LESS THAN WITH HVAC OVERHEAD LINES.
26 IN 1986 A 1200 KV AC TRANSMISSION LINE, CONNECTING RUSSIA AND KAZAKHSTAN, WAS PUT INTO OPERATION. THE LINE, HOWEVER, WAS TAKEN OUT OF OPERATION IN 1996.
27 STATCOM = STATIC SYNCHRONOUS COMPENSATOR.
28 ALSO KNOWN AS FORCED COMMUTATED CONVERTER.

image ELECTRICITY STATION PYLONS.


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3.2.3 HVDC VSC

The voltage source converter (VSC)[28] based HVDC technology is capturing more and more attention. This comparatively new technology has only become possible due to advances in high power electronics, namely Insulated Gate Bipolar Transistors (IGBTs). This way Pulse Width Modulation (PWM) can be used for the VSC converter, as opposed to thyristor based line-commutated converters used in the conventional HVDC technology.

The first commercial VSC-based HVDC link was installed by ABB on the Swedish island of Gotland in 1999. It is 70 km long, with 60 MVA at ± 80 kV. The link was mainly built in order to provide voltage support for the large amount of wind power installed in the South of Gotland.

Today about 10 VSC-based HVDC links are in operation world-wide. Key projects are:

- In 2000, the Murraylink was built in Australia with a length of almost 180 km. This connection was the longest VSC-based HVDC link in the world until 2009. It has a capacity of 220 MVA at a DC voltage of ±150 kV.
- The Bard Offshore 1 Project BorWind in Germany connects a 400 MW offshore wind farm to the onshore grid using a 203 km long cable, operating at a DC voltage of ±150 kV.
- The longest HVDC VSC project is the Caprivi link in Namibia. It is 970 km long and operates at ±350 kV, which is the highest voltage level used so far for HVDC VSC projects, to transmit a capacity of 300 MW.

The total efficiency of a VSC-based HVDC system is slightly less than that of a LCC HVDC system, but it is expected that the efficiency will improve in the future due to future technical development. Also, rating per converter is presently limited to approximately 400-500 MW, while the cable rating at +/-150 kV is 600 MW. More cable and converter stations are required for a VSC based HVDC solution compared to a LCC based HVDC solution, however, manufacturers are already working on converter stations with higher ratings and increased cable ratings. The significant advantages of VSC-based HVDC solutions are its power system support capabilities such as independent control of active and reactive power. In addition, a VSC-based HVDC link does not require a strong AC network, it can even start up against a non-load network. Building up a VSC based HVDC back-bone network will be technically easier than using LCC based HVDC technology. However, Multi-terminal VSC HVDC systems are also new for the power system industry, so there will be a learning curve to achieve that.

3.2.4 other technical solutions

In principal other technical transmission solutions are possible, for instance, using

- Gas insulated transmission lines (GIL), or
- AC transmission systems with lower network frequency, or
- Four or six-phase bipolar HVAC systems.

The development of these transmission technologies is, however less advanced than the three technologies described in the previous sections. In the long-run, some of those technologies might become an important option when replacing overhead lines with cable systems (hence reduced environmental impact).

table 7: overview of the three main transmission solutions

	HVAC	LCC HVDC	VSC HVDC
Maximum available capacity per system	Cable system: • 200 MW at 150 KV; • 350 MW at 245 KV; Overhead lines: • 2000 MW at 800 KV • 4000 MW at 1000 kV (under development)	Cable system: • ~ 1200 MW Overhead lines: • 3150 MW at ± 600 kV • 6400 MW at ± 800 kV (under development)	Cable/Overhead: • 400 MW • 500 - 800 MW announced
Voltage level	Cable system: • Up to 245 kV realistic, short cables up to 400 kV possible Overhead lines: • Up to 800 kV • 1000 kV under Development	Cable system: • Up to ± 500 kV Overhead lines: • Up to ± 600 kV • ± 800 kV under development	Cable:Up to ± 150 kV, higher voltages announced Overhead lines:Up to ± 350 kV
Transmission capacity distance depending?	Yes	No	No
Total system losses	Distance depending	2 - 3%	5 – 10%
Black start capability	(Yes)	No	Yes
Technical capability for network support	Limited	Limited	Large range of possibilities.
Space requirements for substation.	Small	Depending on capacity. Converter larger than VSC.	Depending on capacity. Converter smaller than LCC but larger than HVAC substation.

source ENERGYNAUTICS

3.3 comparison of transmission solutions

Table 7 compares the three standard transmission solutions. The technical capabilities of each system can probably be improved by adding additional equipment to the overall system solution.

The cost of transmitting electricity is dominated by the investment cost of the transmission lines and by the electricity losses during transmission. At present, overhead lines are predominant since costs of overhead lines are about 20% of that for underground cables. The transmission losses of HVAC overhead lines are roughly twice as high as those of HVDC. On the one hand, the cost of overhead lines is similar for the lower voltage level, but at 800 kV HVDC lines are much less expensive than comparable AC lines. On the other hand, AC/DC converter stations for HVDC technology are considerably more expensive than the transformer stations of AC systems. Therefore, for shorter distances and lower voltages AC is typically the most economic solution, while HVDC lines are applied at distances well over 500 km (see Figure 20).

The most economic system design is typically a combination of HVAC and HVDC technology. HVAC is a cost-effective and flexible solution over medium distances (up to 1000 km), for instance to distribute power along the route to different load centres or to collect locally distributed generation and transmit the surplus electricity to other regions. HVDC technology can be used as an overlaying network structure to transmit bulk power, i.e. large capacity, over long distances to the areas where the energy is needed. An HVDC super grid will have only a very limited number of connection points, because the substation (converter station) costs are significant.

In addition, an HVAC solution will require significantly more lines than HVDC solutions. The transmission of 10,000 MW or 10 GW, for instance, can be achieved with two lines using 800 kV and applying LCC HVDC technology, while transmitting the same power with 800 kV AC would require five lines. For a given transmission capacity of 10 GW, the space requirement of HVDC overhead lines can be four times lower than that of HVAC lines (Figure 21). While an 800 kV HVAC line would require a width of 425 metres over the total length of a power link of 10 GW, a HVDC line of the same capacity would only require a band of 100 metres width. This leads to considerable differences in the environmental impact of both technologies.

A final advantage of using HVDC technology is that it is easier to move the entire HVDC super grid underground by using HVDC cables. This approach will be more costly, but following existing transporting routes, e.g. laying the cables along motorways, railway tracks or even in rivers will allow a fast roll-out of the HVDC super grid infrastructure and reduce the visual impact of the installation.

3.4 regulatory and energy policy issues / policy recommendations

The planning, design, realisation and operation of a European super grid requires a European-wide effort with close coordination between the various connected power systems. In addition, the onshore super grid must be coordinated with the development of the offshore super grid as well as the developments in North Africa and the ongoing electricity market harmonisation in Europe. To quickly achieve and develop this infrastructure, a European-wide regulatory authority is required to moderate between and coordinate the different European transmission system operators (TSOs), national governments as well the different electricity markets. The regulatory authority must also develop economic incentives so that the electricity industry undertakes the relevant investments in the upgrade of the HVAC system and the construction of the HVDC super grid.

figure 20: comparison of AC and DC investment costs using overhead lines. BREAK EVEN POINT IS TYPICALLY BETWEEN 500 TO 1000 KM.

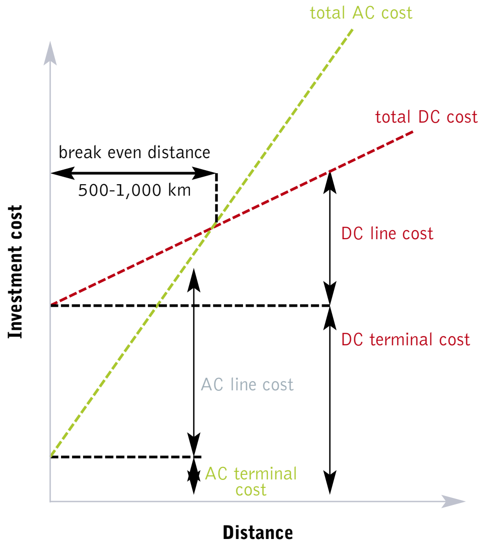
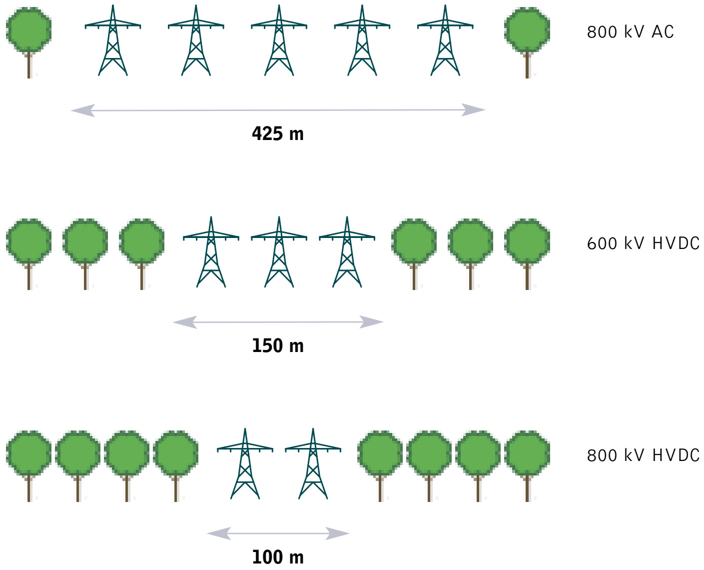


figure 21: comparison of the required number of parallel pylons and space to transfer 10 GW of electric capacity



4

"we know that there are enough resources to power the whole continent with renewables."

GREENPEACE INTERNATIONAL
CLIMATE CAMPAIGN

image BIOGAS FACILITY "SCHRADEN BIOGAS" IN GROEDEN NEAR DRESDEN, GERMANY.
© LANGROCK/ZENIT/GP

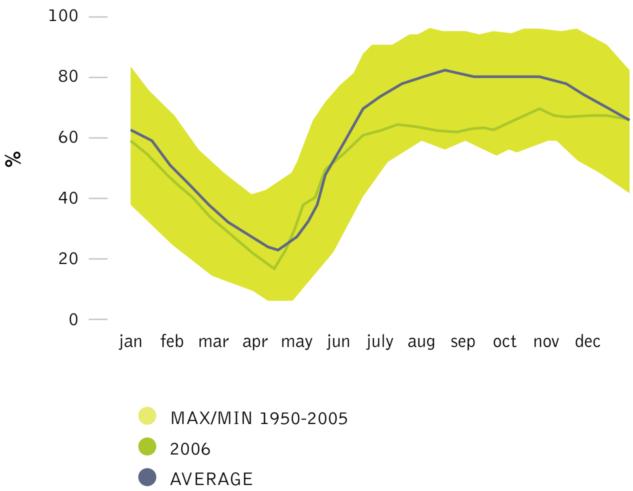
The following case study looks at extreme weather events to work out what kind of grid technology is needed to achieve a secure power supply based on the Energy [R]evolution energy mix in Europe. Technically, we know that there are enough resources to power the whole continent with renewables – solar in the Southern nations, wind in the North, and geothermal, biomass, and combined heat and power making up the bulk of the energy needed. Smart grids will connect distributed energy sources and consumers with the forward-looking use of information and communications technology, virtual power plants, and control technology that helps the system to follow the load. The technical design aspects needs to account for the rare events when weather-based renewable energy in certain geographic areas drops below the supply capacity needed. Interconnections of smart grid systems will add up to a 'super grid' which provides more transport capacity for large-scale renewables such as offshore wind and concentrated solar power stations.

4.1 introduction

Extreme situations in power systems can happen for a variety of reasons, independent of the actual power generation resources or the power system design.

The Swedish power system, for instance, is based on hydro and nuclear power generation. Hydro power generation depends mainly on the water inflow into the water reservoirs. The inflow in a dry year can be 40% lower than in a wet year, causing significant changes in hydro power generation from one year to another, see also Figure 22.

figure 22: storage levels in the regulating reservoirs



source HTTP://WWW.SVENSKENERGI.SE/UPLOAD/OM%20EL/EL%C3%A5RET/FILER/ELARET%202006_ENGLISH.PDF, PAGE 18.

In 2006, water levels in the water reservoirs were rather low (see Figure 22). In addition, in August 2006 three out of ten Swedish nuclear reactors were shut down due to safety concerns following an incident at Forsmark Nuclear Power Plant. Another reactor in Forsmark and a fifth at Ringhals nuclear power plant were offline due to planned maintenance work. Hence suddenly five of the ten Swedish reactors were not in operation (about 5100 MW out of 8961 MW of nuclear generation capacity), reducing the Swedish generation capacity significantly (nuclear power typically generates between 45 to 50% of the Swedish demand). Because the levels in the water reservoirs were also very low, Swedish electricity security of supply relied heavily on foreign imports, a situation which continued for almost two months until the safety concerns were removed.

But also fast demand changes can be a challenge for a power system. For instance, the first game of the Brazil national soccer team at the 2006 FIFA World Champion Cup caused a major drop in electricity demand because all industrial activities went to a virtual standstill. After the game, the demand increased rapidly, from approximately 43.5 GW nation-wide to 55 GW in 15 minutes (11.5 GW in 15 minutes). Even though these are extreme cases, the power system must be designed to cope with such events. This document describes the model as well as its basic assumptions and data, which have been derived from different sources. The results identify the necessary actions to strengthen the existing interconnections.

4.1.1 summary of results

To evaluate the frequency of occurrences of extreme events, the study analysed the wind data of the last 30 years for all Europe. As simulations showed, the extreme events can be expected during winter time, when electricity demand is high and solar production low.

During the last 30 years, the potential power production from wind during winter time throughout Europe in the Energy [R]evolution scenario would have only dropped below 50GW 0.4% of the time, equivalent to once a year if the average duration of the event is 12 hours.

This study selected key 'extreme events', with regard to balance of wind and solar power production on the one hand, and high demand on the other hand, and created a model of power supply based on the E[R] energy mix. The results were:

- In an extreme summer event of high demand and extremely low wind (as in August 2003), the available power from locally distributed PV is enough to compensate for the lack of wind power; therefore no change to the existing grid would be needed under a renewable energy scenario.

image CONSTRUCTING WINDTURBINES IN HÉTOMESNIL, PICARDIE, FRANCE.


© GWEC/WIND POWER WORKS

- In an extreme winter event of high demand, low solar power production in most parts of Europe due to low solar radiation combined with low wind power production in Central and Northern Europe (as in January 1997), Central-Europe and Great Britain have a higher demand than they can supply whereas North and South of Europe have higher productions than demand. In this situation electricity has to be transported from Northern Europe (mainly hydro power) and from Southern-Europe (mainly solar power) to Central-Europe. For this to be achieved by renewable energy, the interconnections between Spain and France, Italy and France, Romania and Poland, Sweden and Poland, and Ireland and Great Britain have to be strengthened (see Figure 45) and a super grid must be built (Figure 48).
- In an extreme autumn event (as in November 1987) with very low sun radiation and low wind production, the reinforcement of the HVAC grid as well as the installation of the super grid as proposed would be sufficient to also cope with this event.

4.1.2 recommendations for grid improvements

To be able to provide reliable, secure power supply to Europe, taking into account extreme weather and high demand scenarios, this study proposes:

- Strengthening 34 HVAC interconnections between neighbouring countries in Europe: 5,347 km of upgrades at a cost of approximately 3 billion.
- 17 new or strengthened HVDC interconnections within Europe : 5, 125 km of upgrades at a cost of approximately €16 billion (see Figure 45).
- Up to15 new HVDC 'super grid' connections,

  - Within Europe: up to 11 connections with a total of up to 6,000 km at a cost approximately €100 billion

  - Between Europe and Africa: The capacity of interconnections needed depends largely on the amount of imported CSP electricity and on the availability of storage capacity within Europe. Without further optimisation and storage capacity, 4 HVDC connections with a total length of 5,500 to 6,000 km at a cost of approximately €90 billion

All together the proposal would cost around €209 billion or €5.225 billion per year till 2050. Assuming the level of electricity consumption in Greenpeace's Energy [R]evolution, this would increase costs of every kWh by 0.15 cent over 40 years. However, the real costs for the required grid need further research, especially the availability of storage capacity within Europe, e.g. from electric vehicles. To exploit further optimisation potential in the energy generation mix can significantly reduce grid expansion costs and could reduce the links needed between North Africa and Europe.

4.1.3 assumptions

The study is based on a given E[R] energy mix provided by Greenpeace and doesn't look at economic optimisation between local and large-scale generation. It was assumed that High Voltage Direct Current (HVDC) technology was used for the transmission over long distance and HVAC for medium distances (outlined in Section 3).

The simulation is a first indication of the possible design and costs of the required transmission network redesign, but further studies will be required to identify the economic optimal design. We did not look at overall economic optimisation between upgrading the existing HVAC system and building a new HVDC system.

Greenpeace and energynautics recommend further research to optimise this concept economically and technically via the use of advanced storage technologies or slight changes in the energy mix.

The simulation study focuses on the redesign of the onshore grid. The offshore super grid connecting the offshore wind farms in the North Sea using HVDC technology is based on the results of the Greenpeace report 'A-North-Sea-electricity-grid-(r)evolution'.[29]

4.2 grid model

The model to do the load flow calculations has been built in DIgSILENT PowerFactory. It is a simplification of the European power system and comprises Central, East and Southern Europe (UCTE) as well as Scandinavia (Nordel), Britain (UKTSOA), and Ireland (ATSOI). The following figure shows the map of the grid model for Europe and represents the situation today.

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reference

[29] SOURCE: HTTP://WWW.GREENPEACE.ORG/RAW/CONTENT/EU-UNIT/PRESS-CENTRE/REPORTS/A-NORTH-SEA-ELECTRICITY-GRID-%28R%29EVOLUTION.PDF, A SUMMARY OF DIFFERENT PROPOSALS FOR THE OFFSHORE SUPER GRID IS GIVEN IN THE EWEA REPORT: "OCEANS OF OPPORTUNITIES" AVAILABLE AT: HTTP://WWW.EWEA.ORG/FILEADMIN/EWEA_DOCUMENTS/DOCUMENTS/PUBLICATIONS/REPORTS/OFFSHORE_REPORT_2009.PDF

figure 23: map of the high voltage network of europe with the overlaying simplification of the european power system

source UCTE, NORDEL & ENERGYNAUTICS

image GREENPEACE DONATES A SOLAR POWER SYSTEM TO A COASTAL VILLAGE IN ACEH, INDONESIA, ONE OF THE WORST HIT AREAS BY THE TSUNAMI IN DECEMBER 2004.

4.2.1 modelling generation

The generation scenario is based on the energy mix presented by Greenpeace in the Energy [R]evolution[30] report. However, this report does not show how the different energy resources are allocated to each region or country within Europe. Energy [R]evolution reports have been available individually for some countries. This has been taken into account when distributing the renewable resources within Europe.

A detailed split up of different renewable sources within Europe can be found in the MED-CSP[31] study conducted by the German Aerospace Centre (DLR). However, this study is much more focused on concentrating solar power (CSP), whereas in the E[R] scenario photovoltaics play a major role. Thus, the MED-CSP scenario has been scaled to match the figures provided in the E[R] report. Further adjustment has been carried out by including the results of the TradeWind[32] study as well as performing a reasonability check (e.g., the share of solar power has been reduced in Scandinavia and increased in the Mediterranean area).

The following table gives an overview over the resources in each country as it was used for this study.

In the following sections, each resource will be described in detail.

table 8: installed capacity and maximum demand (both in GW) based on E[R] scenario for 2050

COUNTRY	WIND	PHOTOVOLTAICS	GEOTHERMAL	BIOMASS	CSP PLANTS	WAVE/TIDAL	HYDROPOWER	GAS	COAL	TOTAL	MAX DEMAND
Europe	**378.1**	**383.3**	**38.5**	**115.7**	**31.0**	**27.3**	**190.8**	**113.8**	**3.6**	**1282.2**	**545.1**
Slovenia	0.9	4.0	0.1	0.7	0.0	0.0	1.4	0.0	0.0	**7.2**	**2.2**
Ireland	6.2	10.0	0.0	1.4	0.0	0.8	0.5	1.8	0.0	**20.8**	**4.8**
Greece	12.5	16.1	1.7	0.8	2.3	0.8	2.8	1.0	0.0	**38.0**	**9.8**
Finland	6.5	3.0	0.0	4.0	0.0	0.4	3.4	3.3	0.0	**20.6**	**13.8**
Netherlands	8.5	6.5	0.4	2.9	0.0	0.2	0.0	6.6	0.1	**25.2**	**17.8**
United Kingdom	53.6	36.3	0.1	7.1	0.0	12.5	3.9	22.0	0.3	**135.8**	**59.2**
Denmark	6.3	5.5	0.0	1.4	0.0	0.5	0.0	3.8	0.1	**17.5**	**6.4**
Slovak Republic	0.6	7.0	0.9	1.2	0.0	0.0	2.6	0.9	0.0	**13.2**	**4.4**
Czech Republic	1.9	7.0	0.0	2.1	0.0	0.0	2.2	1.2	0.1	**14.5**	**10.0**
Portugal	9.0	12.0	1.6	2.6	2.9	1.5	5.6	1.7	0.0	**36.9**	**9.1**
Hungary	2.4	7.3	5.3	1.2	0.0	0.0	0.0	0.9	0.0	**17.0**	**6.5**
Bulgaria	1.6	11.0	0.2	1.0	0.0	0.0	2.9	1.5	0.0	**18.2**	**6.8**
Belgium	5.7	5.0	0.0	2.2	0.0	0.0	0.1	1.4	0.1	**14.5**	**13.8**
Poland	40.8	29.0	0.5	10.4	0.0	0.2	1.0	2.3	0.2	**84.4**	**22.6**
Romania	4.0	11.0	0.2	5.5	0.0	0.0	5.3	5.9	0.0	**31.9**	**8.7**
Austria	2.3	10.9	1.1	2.8	0.0	0.0	11.7	0.7	0.0	**29.4**	**9.3**
Italy	18.0	40.0	6.8	11.0	13.0	2.0	21.0	11.0	0.0	**122.9**	**55.9**
Germany	62.1	50.0	8.2	21.8	0.0	1.5	6.5	15.1	0.7	**165.9**	**82.8**
France	49.7	40.0	4.1	6.3	0.0	2.5	29.4	15.6	0.3	**147.9**	**87.9**
Spain	45.3	49.5	6.6	12.0	12.8	2.7	19.0	5.7	0.1	**153.6**	**43.4**
Sweden	21.0	7.0	0.4	11.5	0.0	0.4	16.4	2.8	0.0	**59.4**	**24.5**
Macedonia	0.0	2.1	0.0	0.3	0.0	0.0	1.0	0.7	0.6	**4.8**	**1.6**
Serbia & Montenegro	0.5	3.2	0.4	1.4	0.0	0.3	5.0	4.6	1.0	**16.4**	**7.2**
Bosnia-Herzegovina	0.0	2.1	0.0	0.9	0.0	0.0	3.9	0.3	0.0	**7.2**	**2.0**
Croatia	5.6	2.9	0.1	1.0	0.0	0.4	2.5	0.8	0.0	**13.2**	**3.0**
Switzerland	1.1	3.7	0.0	0.8	0.0	0.0	13.2	0.0	0.0	**18.8**	**10.0**
Norway	12.0	1.3	0.0	1.4	0.0	0.6	29.3	2.4	0.0	**47.1**	**21.6**

source GREENPEACE

references
[30] HTTP://WWW.ENERGYBLUEPRINT.INFO/
[31] HTTP://WWW.DLR.DE/TT/MED-CSP
[32] HTTP://WWW.TRADE-WIND.EU/

wind power

Besides PV, wind power has the highest share of installed capacity within this study and by far the highest share of energy produced, thus wind power plays a major role in the scenario.

To determine the amount of wind power produced during the time frame of investigated scenarios, the approach described in the TradeWind study has applied. For each region the wind speed is taken from the reanalysis data source from the National Centre for Environmental Prediction (NCEP).[33]

Figure 24 shows the wind speed from the reanalysis source in comparison to the measured site data. A good match can be observed.

The wind speed has to be further processed to calculate the relevant power output of all wind turbines within each region. This is done according to the equivalent regional power curves in Figure 25.

photovoltaics (PV)

PV has along with wind power the highest share of installed capacity in Europe. However, due to its production characteristic, i.e., no production at night, partial production in the morning and evening, the amount of energy produced is only one third of the energy generated by wind power.

Due to its highly fluctuating characteristics, it is important to have a higher sampling rate than wind power. Although NCEP-2 reanalysis data provide solar data, the time resolution is with 6 hour values not sufficient. A better data set is provided by S@tel-Light.[34] This source provides half hour values for all over Europe. However, it is limited to the years 1996 to 2000.

geothermal

Geothermal power does not have the highest share of capacity due to limited resources in Europe. Typically, geothermal power plants always run at full load, because there is no heat storage included (like CSP) or fuel to be saved (like Biomass). To account for maintenance work and failures in geothermal power plants, the power output is set to 90% of rated capacity.

concentrating solar power (CSP)

CSP plays an important role within this study, as it is to a certain extent a controllable source, due to its heat storage. The calculation of the available power is done according to the approach described for PV, but taking only direct sunlight into account. In addition to the installed capacity within Europe, another 60 GW will be installed in North Africa for power export to Europe via HVDC lines.

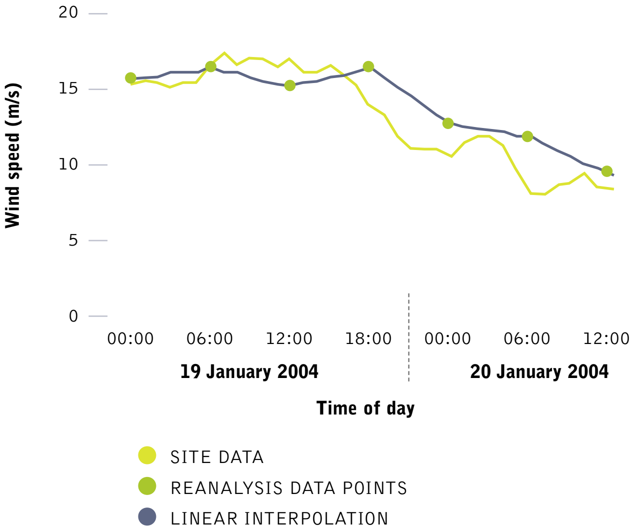
ocean energy

Wave and tidal power has only a small share within the E[R] scenario, thus a detailed analysis of the prevailing waves or tides during the time frame of the event has not been carried out. Instead a typical mean value of 30% of the installed capacity is taken.

hydropower

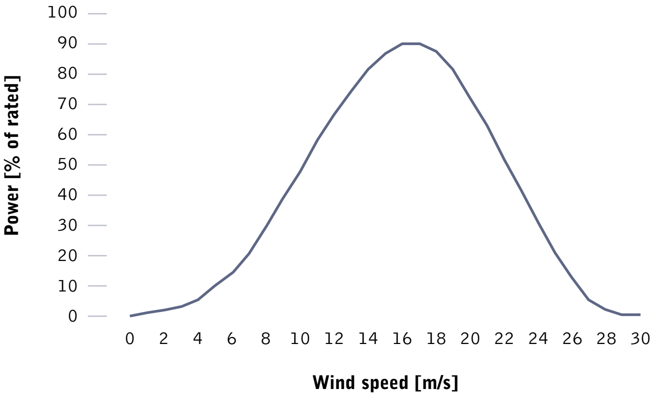
Hydropower has to be divided into power plants with and without a reservoir. Run-of-river power plants typically do not have a capacity for energy storage and are therefore not controllable; whereas those with reservoir can be considered controllable. The power output of run-of-river power plants can vary; depending on the region, the river has either more water in summer due to melting snow (e.g. the Alps) or less in summer, especially when it is a dry summer and there is no rainfall (e.g. Spain).

figure 24: comparison of NCEP-2 reanalysis data and site data, 19th and 20th january, 2004.



source TRADEWIND

figure 25: equivalent regional power curve



source TRADEWIND

references

[33] NCEP-2 REANALYSIS DATA PROVIDED BY NOAA/OAR/ESRL PSD, BOULDER, COLORADO, USA, HTTP://WWW.CDC.NOAA.GOV

[34] HTTP://WWW.SATELLIGHT.COM

image WORKERS EXAMINE PARABOLIC TROUGH COLLECTORS IN THE PS10 CONCENTRATING SOLAR TOWER PLANT. EACH TROUGH HAS A LENGTH OF 150 METERS AND CONCENTRATES SOLAR RADIATION INTO A HEAT-ABSORBING PIPE IN WHICH A HEAT-BEARING FLUID FLOWS THAT IS THEN USED TO HEAT STEAM IN A STANDARD TURBINE GENERATOR.

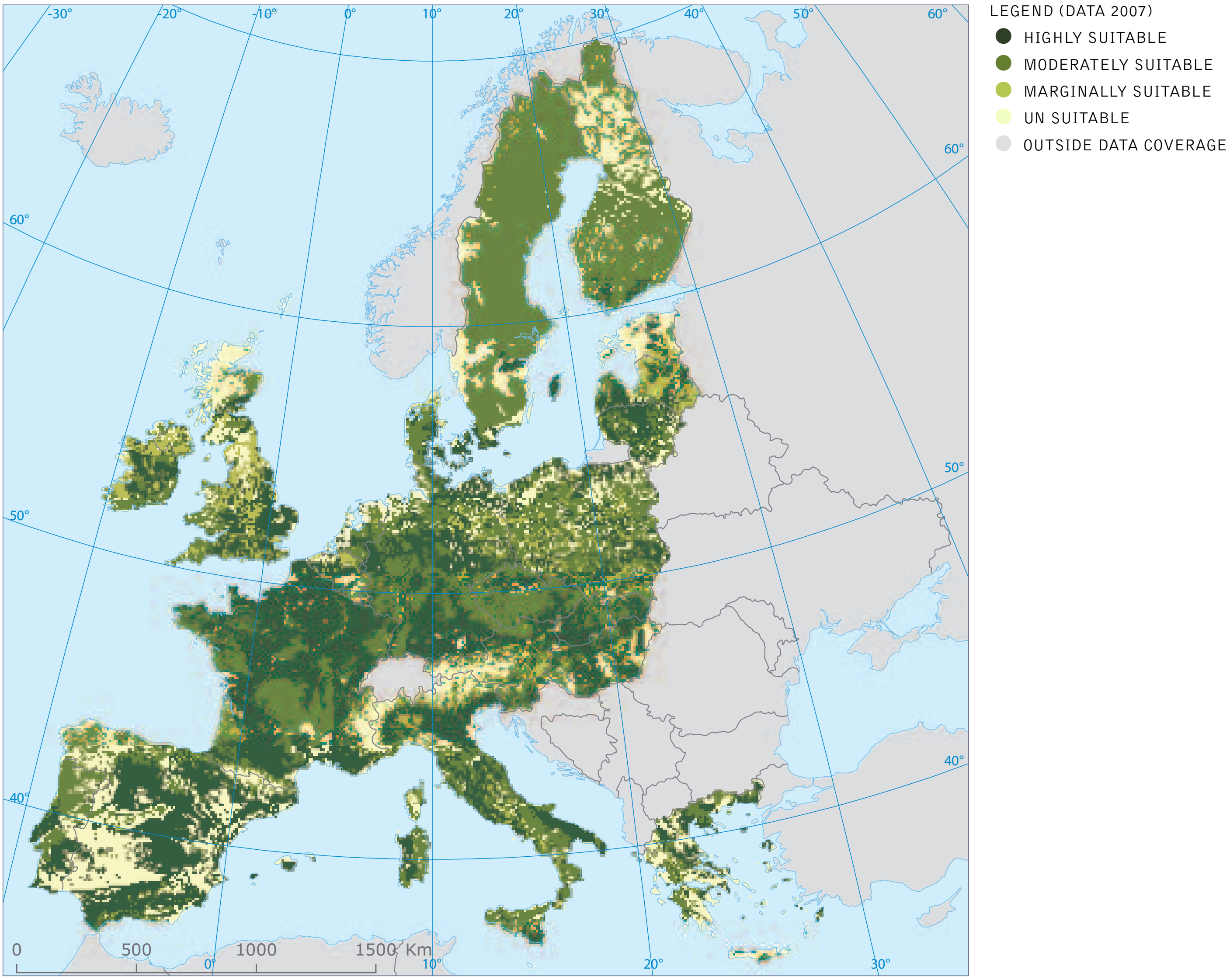
biomass

Biomass can be considered as power on demand, therefore it plays an important role in the study. These power plants are applicable almost all over Europe, as the following map shows. The availability of biomass power plants has been taken into account with a share of 95%.

natural gas

Gas power plants can be used for control purposes. In the study, the non renewable plants are strategically placed where there is a high demand and low amount of renewable sources. These plants are only used as backup system in times when the amount of renewable power production is too low.

figure 26: biomass potential in europe



source EUROPEAN ENVIRONMENT AGENCY - 2008[35]

reference
35 HTTP://WWW.EEA.EUROPA.EU/

4.2.2 modelling demand

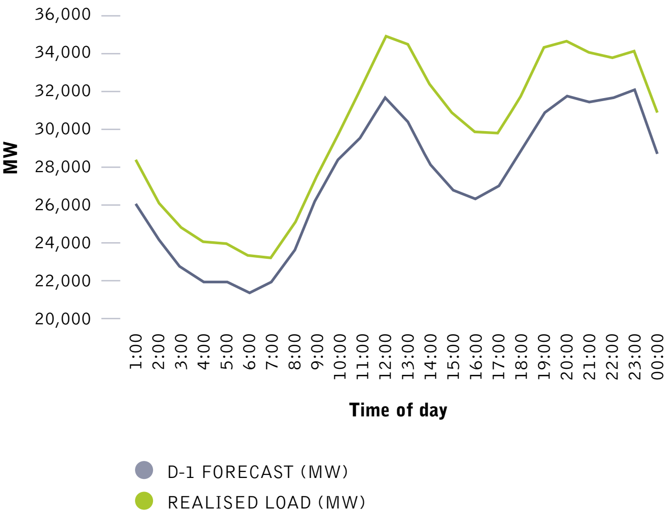
According to the E[R] report, the energy demand in 2050 within Europe will not increase in comparison to today's demand, due to higher efficiency in energy use required to keep greenhouse gas emissions stable. In the model, the power demand of today is used as input. To determine the amount of power demand of each country, the so called 'vertical load' is taken. The European Network of Transmission System Operators for Electricity (entso-e[36]) provides hourly values of the vertical load in each country (Figure 27).

To further allocate the load to each node within the model, the population density is taken. According to Zhou and Bialek[37] there is a good correlation between consumption and population density, as in most cases a high population is where there is employment and thus industry.

The population density can be found in the statistics database of the European Commission (Eurostat[38]). The following map shows the population density within Europe.

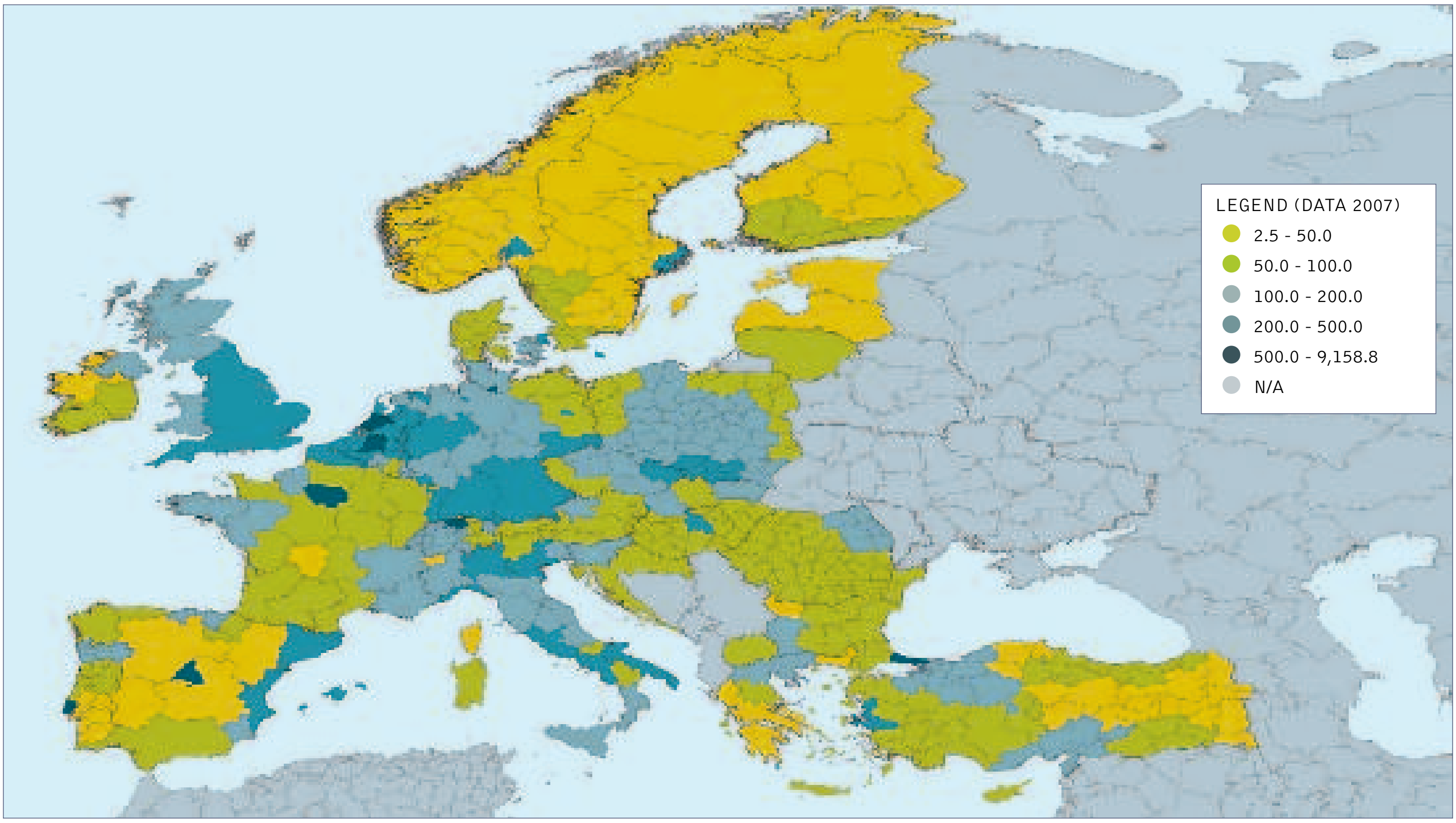
As it is expected that there will be higher use of demand-side management and local storage (see smart grid report) in the future power system with high amounts of fluctuating sources, this is taken into account by adapting the load to a certain extent to the available power production.

figure 27: vertical load in germany on 7 june 2009



source ENTSO-E

figure 28: map of the population density by regions in 2007 INHABITENTS PER KM²



source EUROSTAT

references

[36] HTTPS://WWW.ETSOVISTA.ORG/

[37] ZHOU, BIALEK "APPROXIMATION MODEL OF EUROPEAN INTERCONNECTED SYSTEM AS A BENCHMARK SYSTEM TO STUDY EFFECTS OF CROSS-BORDER TRADES", IEEE TRANSACTIONS ON POWER SYSTEMS, MAI 2005

[38] HTTP://EPP.EUROSTAT.EC.EUROPA.EU/PORTAL/PAGE/PORTAL/POPULATION/INTRODUCTION

image OCEANLINX IS COMMERCIALISING WAVE POWER TECHNOLOGY WHICH USES A COLUMN OF WATER TO DRIVE A TURBINE, PRODUCING ZERO EMISSIONS.

© GP/DEAN SEWELL

4.3 approach

The following approach has been taken to determine the needs of a future power grid with a high share of renewable energies.

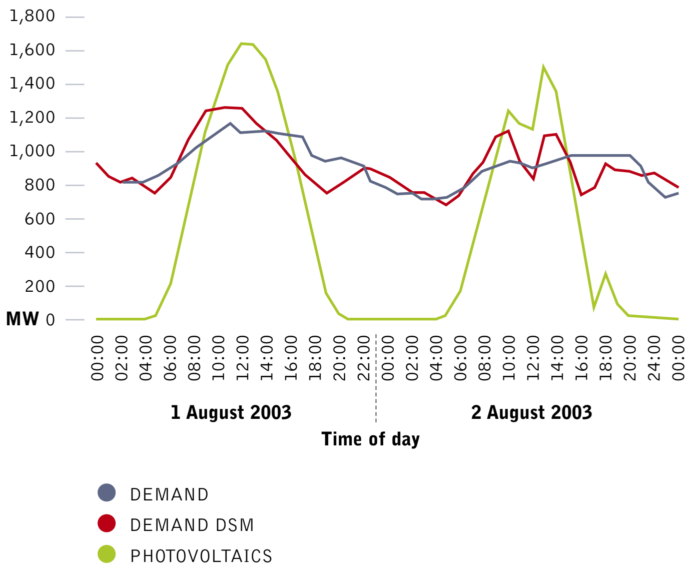
4.3.1 non-controllable renewable energy source

In the model, priority is given to electrical power from sources that can only be controlled by not using the available power to the full extent (e.g. by pitch control of wind turbines). These sources are 'downward controllable' – as compared to fossil fuels where production can be 'ramped up' to meet demand. They are fluctuating sources like wind, PV and ocean but also run-of-river as well as geothermal power plants. The amount of power produced by these sources at each node of the model is used first to meet the demand at each node.

4.3.2 demand-side management

To take advantage of demand-side management and local storage the resulting power difference between production and generation is smoothed over the time. The following figure shows the operation of such a demand-side management: depending on the available local source, in this case PV, the demand is increased or decreased.

figure 29: **operation of demand-side management and local storage**



source ENERGYNAUTICS

4.3.3 optimal power flow

The next step is to perform a DC load flow calculation and power flow optimisation. The result of this calculation is the necessary amount of additional power (within given limits) at each node to keep the high voltage network within allowed operation limits. This additional power is provided by controllable sources such as:

- CSP
- Hydropower (storage)
- Biomass
- Natural gas

Renewable sources are prioritised.

In case there is a surplus of power, the power will be fed into the high voltage grid, in case there is a lack of power, it will be withdrawn from the grid.

Definition of N-1 security: A system is N-1 secure if any element in the system may fail without overloading any other element.[39] As the model does not represent exactly each physical HVAC line in the network, but instead aggregates a number of lines, the N-1 security cannot be assured by evaluating each single line. Instead, a maximum loading of 80% on the lines has been allowed to account for N-1 security. On the other hand, the HVDC lines and thus the super grid are represented by physical lines, thus each HVDC connection has been evaluated for N-1 security.

4.3.4 evaluation

With the help of the load flow calculations described in the previous section it can be determined where the grid will be overloaded due to high production at one point and high demand at another point of the network. Depending on the distance between these points, it is either reasonable to strengthen the HVAC grid in between or in case the distance is too high to build an HVDC line or even a super grid consisting of several HVDC lines.

In case there is no further demand but still excessive amount of variable power, there are two options, either to store the available power and to use it at another time or to curtail it. From an economic point of view it might be more economic to oversize and occasionally regulate down the wind farms than to build expensive electric storage systems.

This study was done to find out how the electrical network has to be strengthened to allow 24/7 power supply with a very high share of renewables also in extreme situations as described in the next section. More information on super grids is provided in Section 3 of this report.

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reference
[39] HTTP://WWW.ENTSOE.EU/_LIBRARY/PUBLICATIONS/CE/OH/POLICY3_FINAL.PDF

4.4 extreme events

Several extreme events on a short, medium and long-term basis have been investigated to determine the necessary layout of a future power system with a high share of renewable energy sources.

4.4.1 long-term issues

As renewable resources can vary from year to year, this study focuses on extreme events on a long-term basis. In effect this study evaluates the Energy [R]evolution Scenario to see whether it would have an impact on the security of supply.

The variation of different sources from year to year has been analysed. As wind energy has by far the highest share in energy production in the E[R] Scenario, it has been chosen for further investigations.

The lowest values found were around 20% below the long-term average (An example for Germany can be found in Figure 30), this is an amount the portfolio in the E[R] Scenario can easily cope with and will not influence the layout of the future power system.

4.4.2 medium-term issues

Variable renewable energy sources like wind and solar power as well as the demand vary within the range of minutes to hours, and generation and consumption has to be balanced at all times, while electrical storages are limited and expensive. For these reasons the medium-term issues are the most critical and dimensioning situation for the power system.

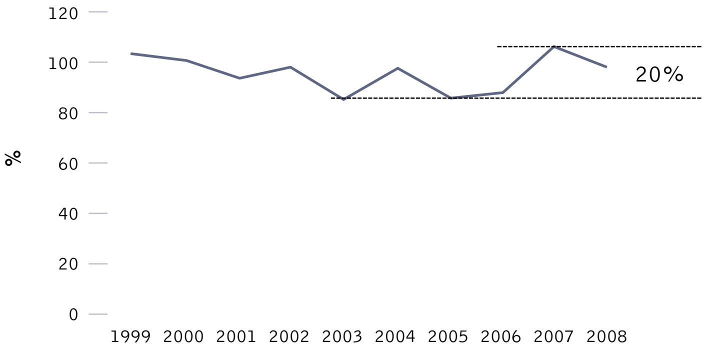
For this purpose three extreme events have been identified and analysed:

- Extreme summer event in August 2003
- Extreme winter event in January 1997
- Extreme autumn event in November 1987

4.4.3 evaluation of occurrences of extreme events

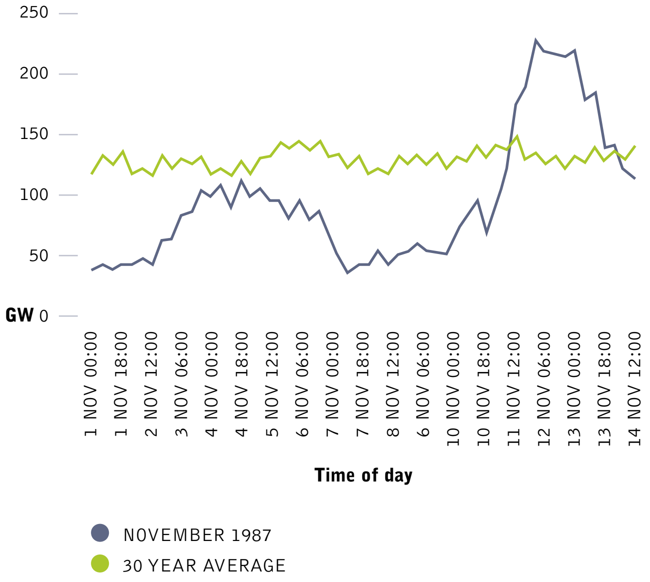
Renewables 24/7: A mix of different renewable energy sources such as solar PV, wind, biomass, geothermal, hydro – and ocean energy in the future – guarantees a secure around the clock power supply – even though the wind is sometimes not blowing or the sun won't shine! The extreme weather event as described here appear very seldom and last only for a short period.

figure 30: **yearly wind energy yield in comparison to long-term average; example germany**



source WINDMONITOR / ISET

figure 31: **available wind power (in GW) according to energy [r]evolution scenario in november 1987 compared to 30 years average (6 hour values)**



source ENERGYNAUTICS


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image PUBLIC BATH HOUSE THAT USES SOLAR THERMAL TECHNOLOGY IS SEEN BESIDE A FARM. THE CITY OF DEZHOU IS LEADING THE WAY IN ADOPTING SOLAR ENERGY AND HAS BECOME KNOWN AS THE SOLAR VALLEY OF CHINA.

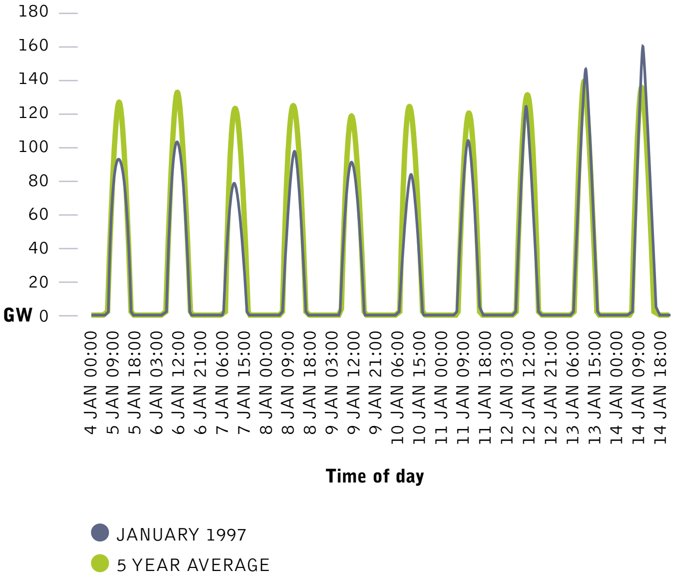
To evaluate the frequency of occurrences of extreme events, we have analysed the wind data of the last 30 years. As simulations showed, the extreme events can be expected during winter time, when the electricity demand is high and the solar production low.

During the last 30 years the potential power production from wind during the winter time within Europe in the E[R] Scenario would have been only dropped below 50GW 0.4% of the time. Taking an average duration of an extreme event of 12 hours, this is equivalent to once a year.

The following two figures show the wind power production in Europe during the two simulated extreme winter events: November 1987 and January 1997

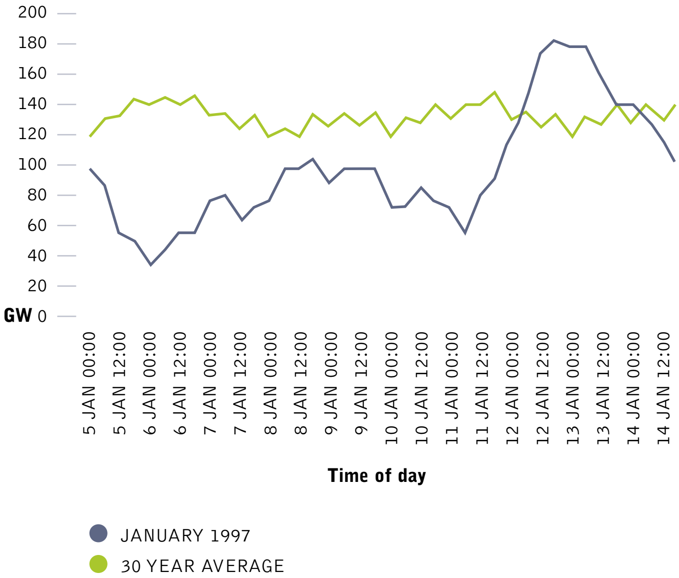
The next figure shows the PV production during the extreme January event. During January 1997 there are some days (5th to 10th), where the production is considerably lower than the long-term average. Together with a high demand (Figure 34) and low wind power production (Figure 32), this is a critical situation for the European power system. (see also Figure 35)

figure 33: available solar pv power (in GW) according to energy [r]evolution scenario in january 1997 compared to 5 years average (1 hour values)



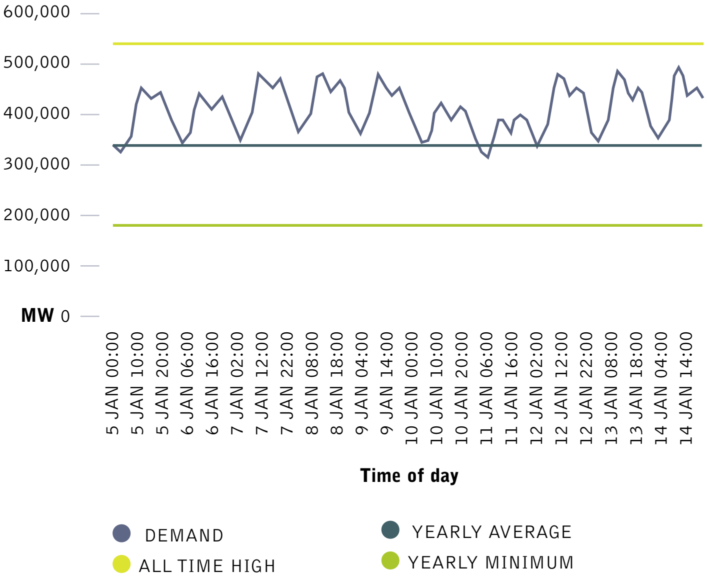
source ENERGYNAUTICS

figure 32: available wind power (in GW) according to energy [r]evolution scenario in january 1997 compared to 30 years average (6 hour values)



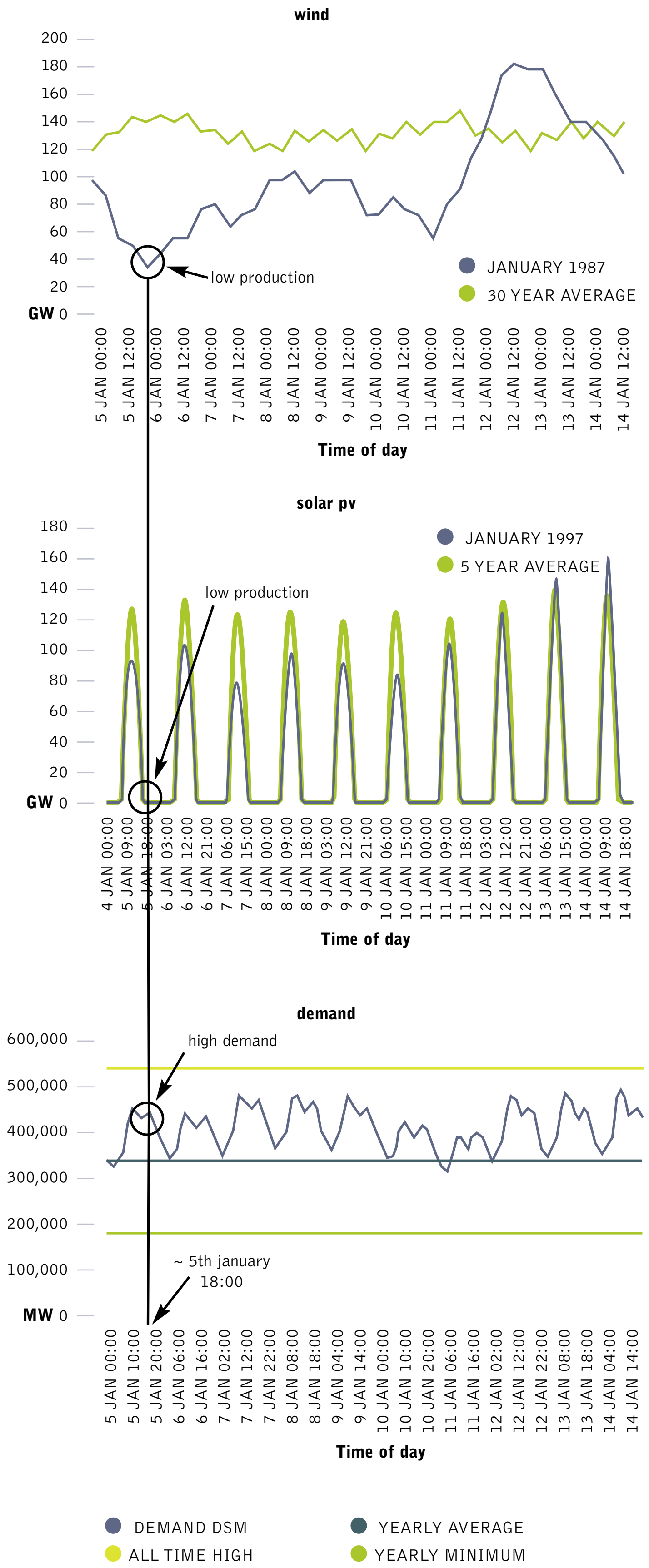
source ENERGYNAUTICS

figure 34: demand (in MW) during january 1997 event compared to all time high, yearly average and minimum (1 hour values)



source ENERGYNAUTICS

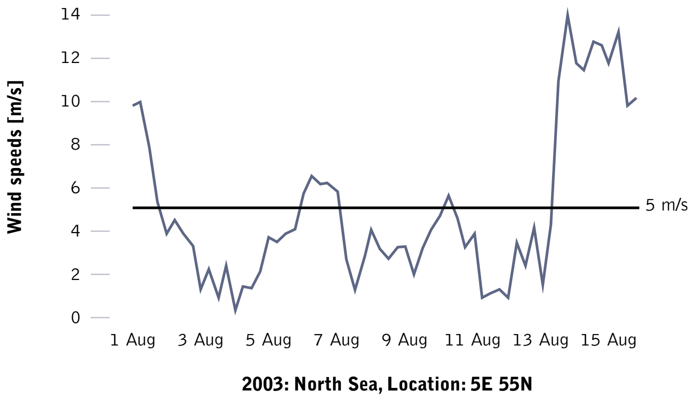
figure 35: overview extreme january event: wind and solar production as well as demand (in MW) during january



extreme summer event (august 2003)

This extreme event is characterised by two weeks of no or very little wind in the North Sea (Figure 36).

figure 36: wind speed in the north sea during august 2003 (extreme summer event)



source NCEP-2

As the following table shows, the highest demand is around 68% of the all time high, which is typical for the load during summer. The amount of PV power produced is very high due to lots of sunshine during August. Further characteristics are presented in the following table.

table 9: characteristic of extreme summer event (available power in MW)

	HIGH	AVERAGE	LOW
Demand % of all time high	366,959 68%	287,666 53%	203,092 38%
Non Contr. RES % of inst. cap	408,570 45%	193,881 21%	82,743 9%
Windpower % of inst. cap	119,603 31%	43,661 11%	17,538 5%
Photovoltaics % of inst. cap	296,661 77%	91,130 24%	0 0%

source ENERGYNAUTICS

image A WORKER ENTERS A TURBINE TOWER FOR MAINTENANCE AT DABANCHENG WIND FARM. CHINA HAS HUGE WIND RESOURCES, WHICH COULD BE EASILY AND PROFITABLY EXPLOITED BY SWITCHING INVESTMENT FROM CLIMATE DESTROYING FOSSIL FUELS INTO HARVESTING THIS CLEAN, ABUNDANT ENERGY RESOURCE.

results

Results of load flow calculations show that during an extreme summer event, the available power from PV is enough to compensate for the lack of wind power. Therefore it is not necessary to improve the current design of the European grid or to install additional HVDC lines. The necessary power is mainly provided by distributed PV, which is well available during August.

The following table gives an overview over the share of different sources during the event. The amount of wind power and run-of-river is obviously fairly small whereas the amount of PV and Biomass is high. Only 10% have to be provided by conventional power plants.

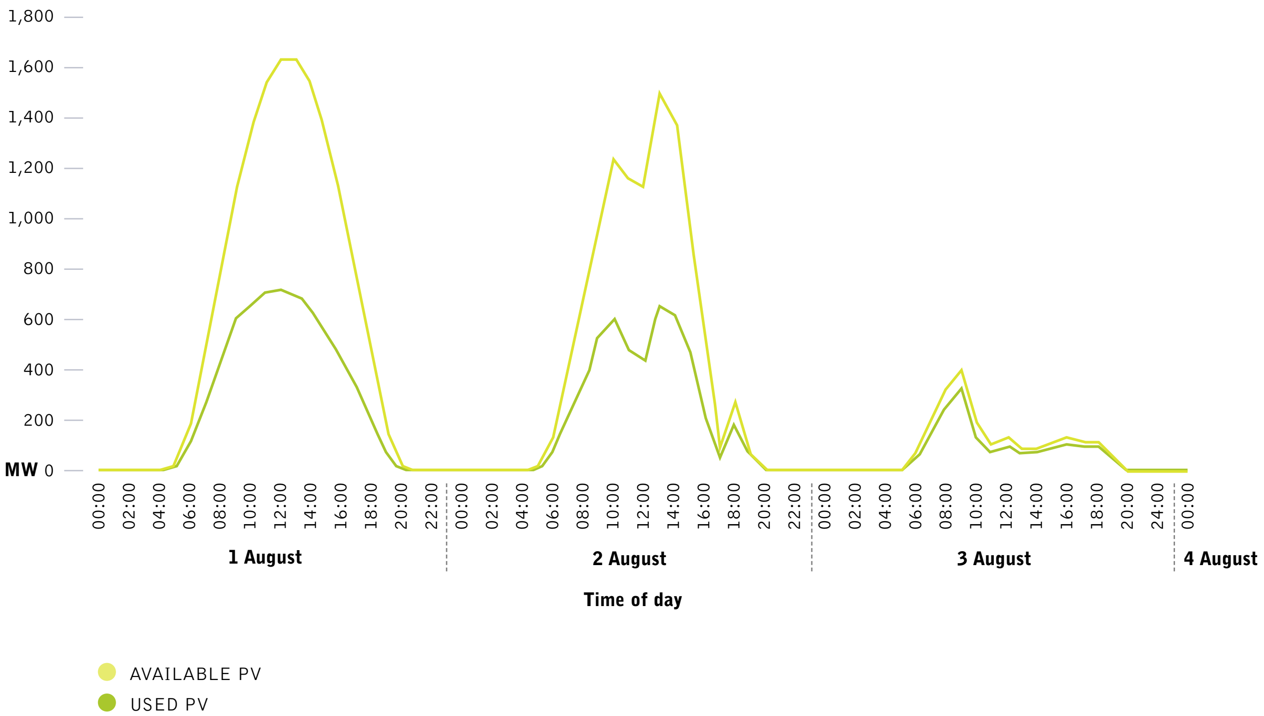
There was almost no storage included in the study, and an analysis of the calculation results reveals a high amount of renewable energy supplies has to be curtailed – or better – is available for storage to be used e.g. in electric vehicles, this is mainly PV. For this we use the term 'surplus power' for power generation which must be 'curtailed' if there is no storage capacity available. Figure 37 shows the used versus the available PV power.

table 10: (medium) generated power in MW and share of different sources during extreme summer event

Wind Onshore	14,558	5%
Wind Offshore	14,232	5%
Photovoltaics	65,914	23%
Geothermal	32,208	11%
Biomass	60,561	21%
CSP Plants	17,549	6%
Wave / Tidal	6,604	2%
Hydro run-of-river	11,425	4%
Hydro Storage	36,976	13%
Conventional	30,299	10%
Total	**290,327**	**100%**

source ENERGYNAUTICS

figure 37: surplus PV capacity available for storage (sample for a region in austria, august 2003)



source ENERGYNAUTICS

table 11: maximum of surplus power in MW during different hours of the extreme event in august 2003

Max Wind Onshore	19,469
Max Wind Offshore	44,866
Max Photovoltaics	117,474
Max Total	161,749

source ENERGYNAUTICS

extreme winter event (january 1997)

This event is characterised by a very high demand on one hand and a low solar power and medium to low wind power production on the other hand (Table 12).

It is typical to have the highest demands of electricity in Europe during winter. Sunlight in the daytime is reduced and the angle of incident is low, thus the amount of solar power is also low during winter time. Together with these two facts, there were also times when there was hardly any wind during January 1997 making this a critical situation for proposed future power supply.

table 12: characteristic of extreme winter event january 1997 (available power in MW)

	HIGH	AVERAGE	LOW
Demand % of all time high	491,064 91%	406,098 75%	311,837 58%
Non Contr. RES % of inst. cap	378,419 42%	195,426 22%	108,067 12%
Windpower % of inst. cap	200,795 53%	96,818 25%	32,533 9%
Photovoltaics % of inst. cap	197,032 51%	33,313 9%	0 0%

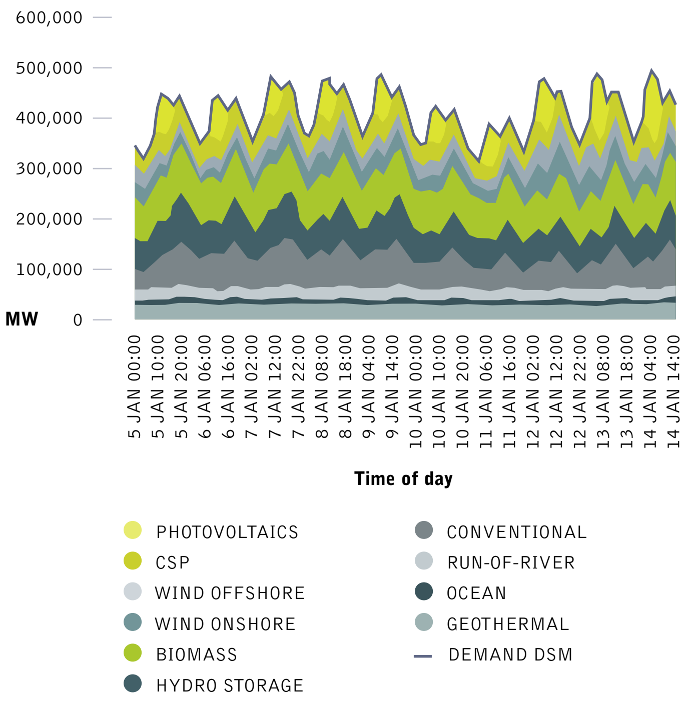
source ENERGYNAUTICS

energy production during extreme january event

Figure 38 gives an overview on the different sources during this extreme January event. To keep the lights on, the demand has to be met at all times.

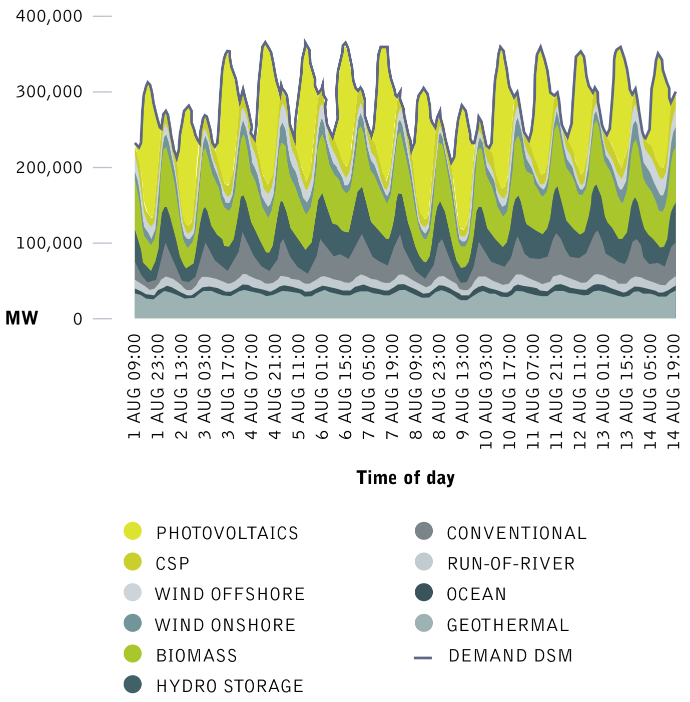
For comparison, the power production for August 2003 is shown in the Figure 39. During summer there is a lower demand than in winter and far more PV production.

figure 38: power production (in MW) from different sources and overall demand in europe during extreme january event, 1997



source ENERGYNAUTICS

figure 39: power production (in MW) from different sources and overall demand in europe during extreme august event, 2003



source ENERGYNAUTICS

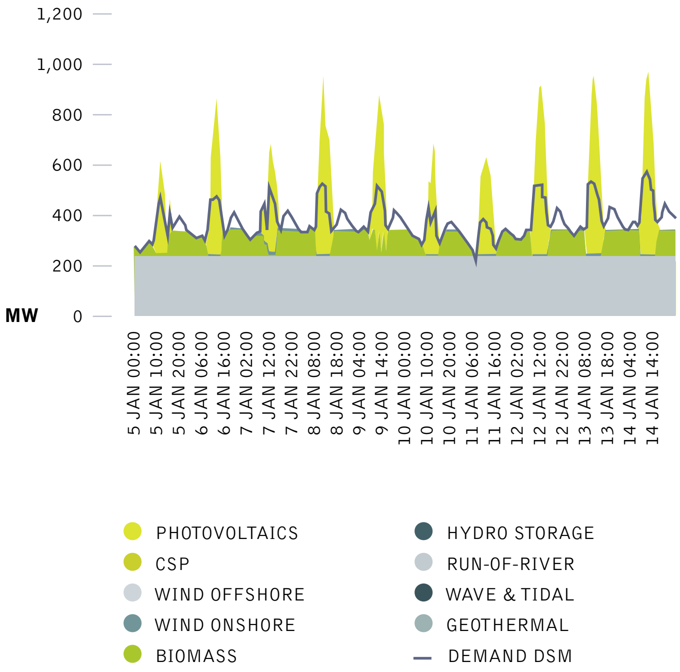
image WORKERS IN THAILAND INSTALL A WIND TURBINE IN THEIR COMMUNITY. THE IMPACTS OF SEA-LEVEL RISE DUE TO CLIMATE CHANGE ARE PREDICTED TO HIT HARD ON COASTAL COUNTRIES IN ASIA, AND CLEAN RENEWABLE ENERGY IS A SOLUTION.

© GP/VINAI DITHAJOHN

As the power production and demand is not balanced at each location at all times, the electrical network has to transport the energy from one location to another.

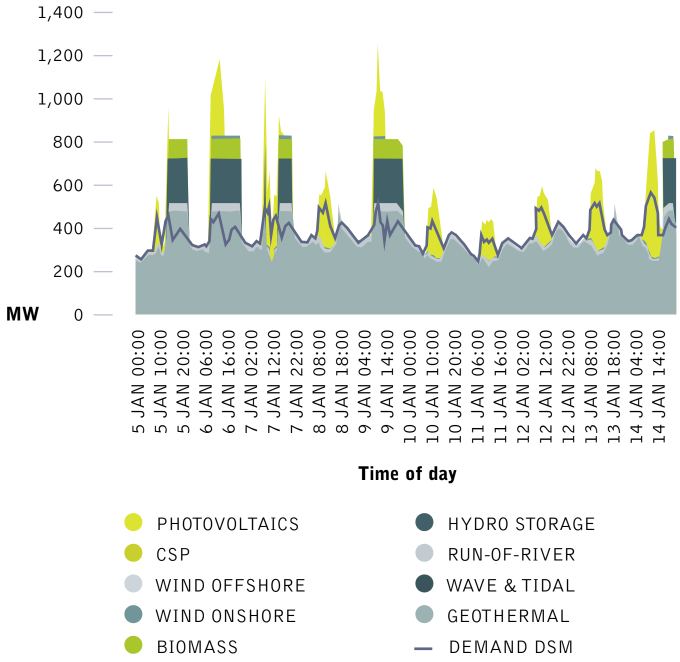
The following figures show the power production from different sources during the extreme January event at three different locations. Depending on the available renewable energy supply, the power can both be exported and transported via the grid to other locations or has to be imported. (See also Figure 43)

figure 41: **power production (in MW) from different sources and local demand during extreme january event at a second location in south germany, 1997. there are times with surplus of power production and times with lack of power**



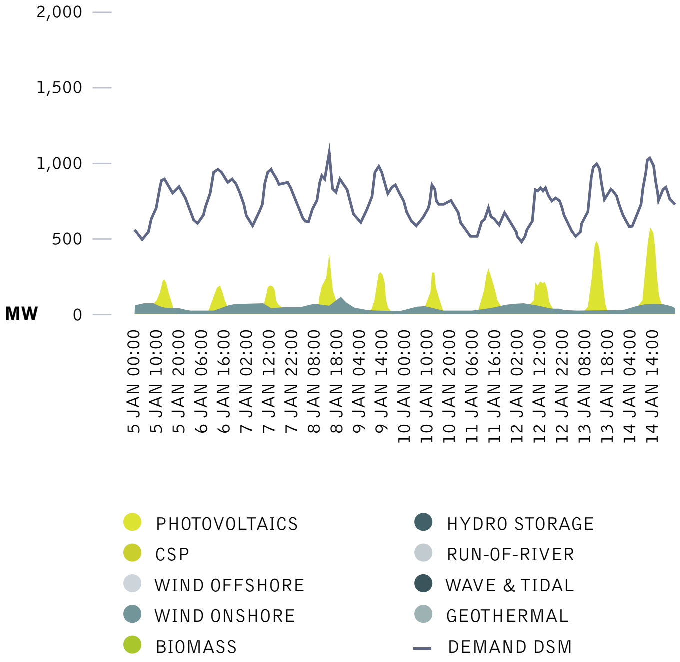
source ENERGYNAUTICS

figure 40: **power production (in MW) from different sources and local demand during extreme january event at a location in south germany, 1997. there is a surplus of power production, so power can be exported**



source ENERGYNAUTICS

figure 42: **power production (in MW) from different sources and local demand during extreme january event at a location in the netherlands, 1997. this location has to import power at all times during the event**



source ENERGYNAUTICS

The following figure demonstrates the necessary transport between the different locations within the power system

figure 43: power production (in MW) at three different locations. demonstration of necessary transport of power between the locations

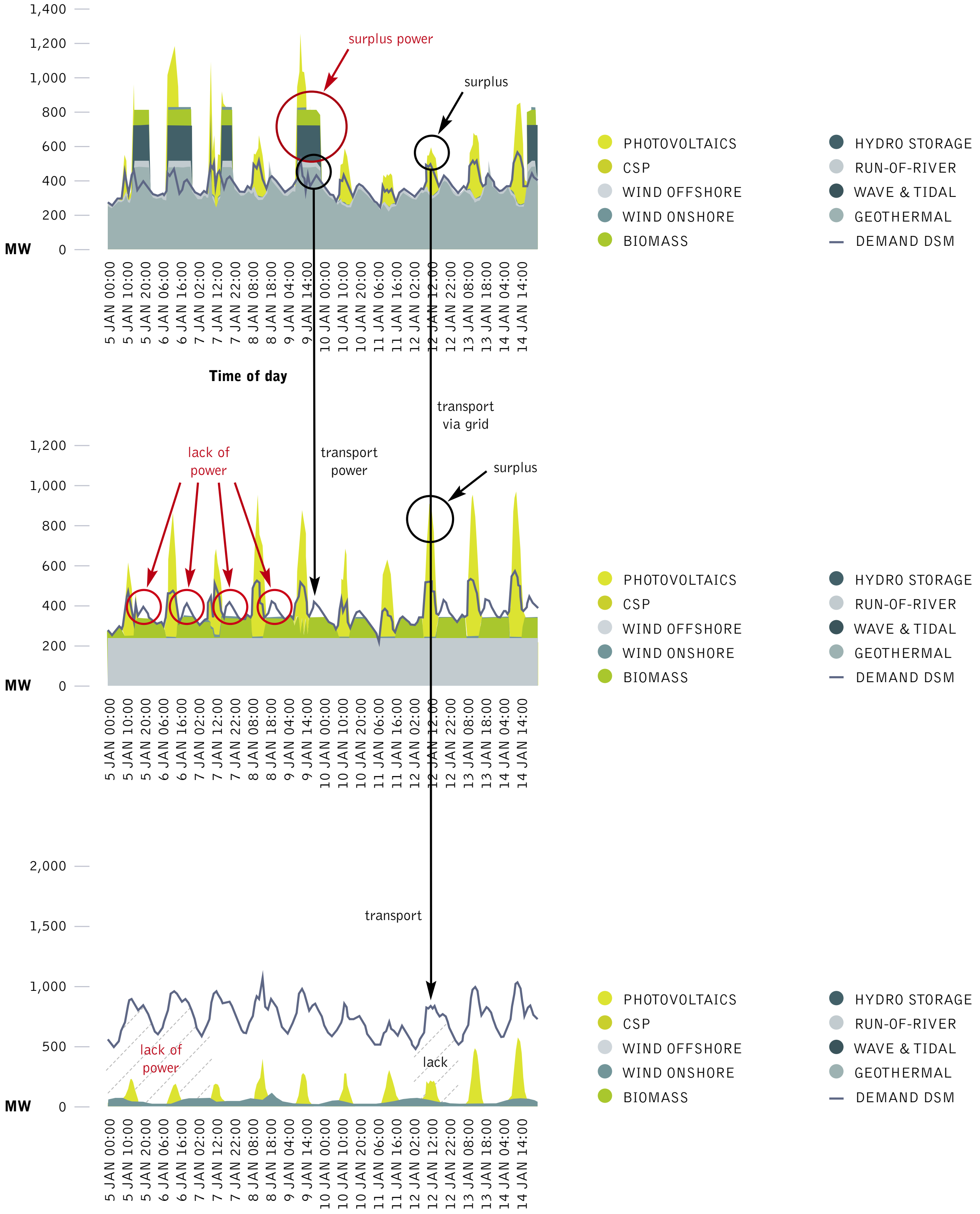


image CONSTRUCTION OF OFFSHORE WIND TURBINES.

results

The simulations of this event show that the currently installed grid and the available power during this event make it necessary:

- to strengthen the grid in certain parts of Europe and
- to transport further power (from e.g. CSP or Hydro) via HVDC lines directly to the centres of highest demand

The following figure shows which regions would supply excess power and which region would lack power (have excess demand) during the January event. Arrows indicate the resulting load flow.

figure 44: areas of lack and surplus of power during extreme january event

source UCTE, NORDEL AND ENERGYNAUTICS

During this event, Central-Europe and Great Britain would have a higher demand than they can supply whereas Northern and Southern Europe would have higher production than demand. Thus the load-flow is mainly from Northern Europe (mainly hydro power) and from Southern Europe (mainly solar power) to Central Europe. Due to this load flow, the interconnections between Spain and France, Italy and France, Romania and Poland, Sweden and Poland, and Ireland and Great Britain would have to be strengthened (Figure 45).

figure 45: european high voltage network with marked reinforcements of interconnections

source UCTE, NORDEL AND ENERGYNAUTICS

© PAUL LANGROCK/ZENIT/GP

image GEO-THERMAL RESEARCH DRILLING IN THE SCHORFHEIDE DONE BY THE GEOFORSCHUNGSZENTRUM POTSDAM IN COOPERATION WITH THE GERMAN MINISTRY OF ENVIRONMENT AND VATTENFALL.

Due to the widespread lack of power within Central Europe, a further reinforcement of the HVAC grid seems not to be the best solution; instead the power should be transported directly from the source to the centres of demand via HVDC lines. This is the basis of the super grid, described in Section 3, with connections to sources in North Africa (Concentrating Solar Power) and Scandinavia (Hydro).

The following table gives an overview over the medium generated power of different sources during the extreme January event. Wind power and PV have a fairly low proportion. Still 84% are provided by renewable energy supplies with a high share of biomass and hydro power. Only 16% has to be provided by conventional power.

table 13: (medium) generated power in MW and share of different sources during extreme event

Wind Onshore	36,260	9%
Wind Offshore	30,469	7%
Photovoltaics	22,220	5%
Geothermal	32,469	8%
Biomass	83,510	21%
CSP Plants	38,592	9%
Wave / Tidal	7,214	2%
Hydro run-of-river	24,020	6%
Hydro Storage	65,295	16%
Conventional	66,313	16%
Total	**406,362**	**100%**

source ENERGYNAUTICS

Again there is some surplus power which is available for storage. The following table gives an overview of maximum surplus power during this event. This time the amount of surplus PV power is lower in comparison to the previous investigated events.

table 14: maximum of surplus power in MW during different hours of the extreme event

Max Wind Onshore	30,856
Max Wind Offshore	58,049
Max Photovoltaics	28,695
Max Total	**117,600**

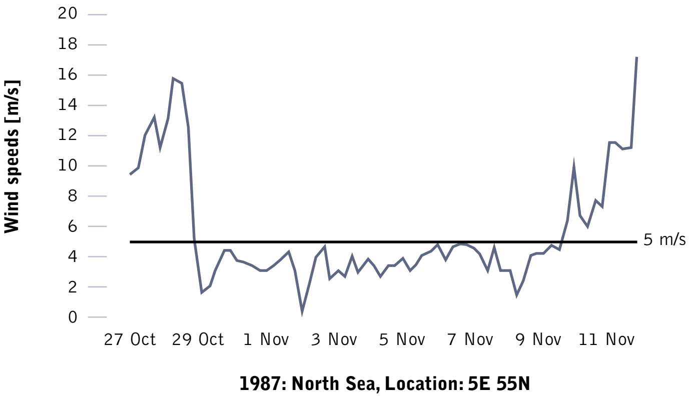
source ENERGYNAUTICS

extreme autumn event (november 1987)

The proposed improved grid is tested in a third extreme event, which has been identified for November 1987.

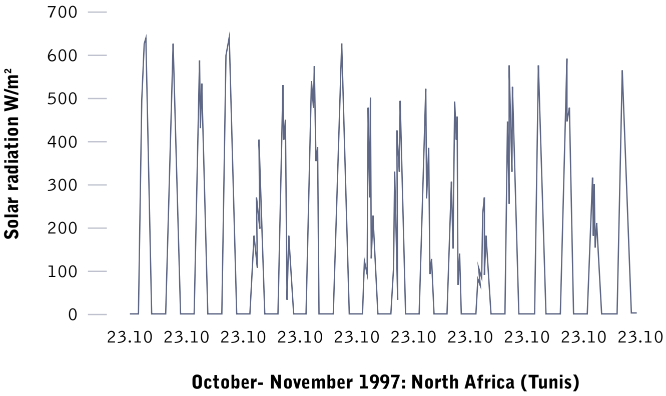
In November solar power is considerably reduced due to the low path of the sun in the sky. During this event in November 1987, there was also a period of over twelve days, where there was hardly any wind. Both energy sources form the backbone of the E[R] scenario, therefore this is a critical situation for the whole power supply proposed.

figure 46: wind speed in the north sea during oct/nov 1987 (extreme winter event)



source NCEP

figure 47: solar radiation in north africa (tunis) during oct/nov 1997 (extreme winter event)



source SATEL-LIGHT

Further characteristics are presented in the following table.

table 15: characteristic of extreme november event (available power in MW)

	HIGH	AVERAGE	LOW
Demand % of all time high	441,199 82%	358,810 67%	257,437 48%
Non Contr. RES % of inst. cap	444,999 49%	212,189 24%	112,415 12%
Windpower % of inst. cap	236,075 62%	94,871 25%	34,910 9%
Photovoltaics % of inst. cap	200,106 52%	44,264 12%	0 0%

source ENERGYNAUTICS

results

The reinforcement of the HVAC grid as well as the installation of the super grid as proposed in the previous section are sufficient to also cope with this event. No further actions have to be taken to keep the lights on during this extreme event.

The following table gives an overview over the share of different sources during the event. The amount of wind power and PV is obviously fairly small whereas the amount of biomass is high. In this case 17% of the power is provided by conventional power plants.

table 16: (medium) generated power in MW and share of different sources during extreme november event

Wind Onshore	34,508	10%
Wind Offshore	26,654	8%
Photovoltaics	33,130	10%
Geothermal	29,166	8%
Biomass	73,670	21%
CSP Plants	9,284	3%
Wave / Tidal	6,803	2%
Hydro run-of-river	22,057	6%
Hydro Storage	50,709	15%
Conventional	58,394	17%
Total	**344,375**	**100%**

source ENERGYNAUTICS

Although there are regions with lack of power, in other regions there is a power surplus. The following table gives an overview over the maximum surplus power of different sources.

table 17: maximum of surplus power in MW during different hours of the extreme november event

Max Wind Onshore	42,922
Max Wind Offshore	69,541
Max Photovoltaics	66,400
Max Total	**153,253**

source ENERGYNAUTICS

image HIGH VOLTAGE ELECTRICAL PYLON OVER CHAMPAGNE VINEYARDS. IF TEMPERATURES INCREASE BEYOND 2°C, FRANCE WILL BE FACED WITH A RUNAWAY GEOGRAPHICAL DISPLACEMENT OF BOTH ITS NATURAL AND CULTIVATED ECOSYSTEMS, AND THE EFFECTS ON THE SUSTAINABILITY OF WINE PRODUCTION WILL BE CATASTROPHIC FOR THE LOCAL INDUSTRY.

4.5 additional simulations with reduced PV (2030 scenario) with no storage capacity available

Additional to the 2050 scenario, the extreme events have been simulated with a reduced installation capacity of PV (2030 scenario) from 383GW down to 211GW in order to reduce the amount of surplus PV power if there is no further storage capacity available. By systematic reduction at certain locations, where there are enough other renewable energy supplies available, the proposed power system including reinforcements and super grid can still cope with this situation during the extreme events.

Simulation results show that further increasing PV installations above 211GW only makes sense if large-scale storage is available. These should be sized for about 12 hours' storage to shift the power production during the day into evening and night hours. The usage of storages to this extent lies not within the scope of this study but should be investigated together with optimal placements of renewable energy generators and grid enhancements in further studies.

extreme january event (1997) – reduced PV

To further test the function of the grid, we took the extreme winter event described in Section 6 and modelled the available power with reduced PV (a small percentage of installed capacity operating).

table 18: characteristic of extreme winter event january 1997 – reduced PV (available power in MW)

	HIGH	AVERAGE	LOW
Demand	491,064	406,098	311,837
% of all time high	91%	75%	58%
Non Contr. RES	304,312	180,864	108,067
% of inst. cap	42%	25%	15%
Windpower	184,042	96,236	34,407
% of inst. cap	48%	25%	9%
Photovoltaics	81,909	11,435	0
% of inst. cap	39%	5%	0%

source ENERGYNAUTICS

In comparison to the base simulation (Table 12) with 191GW there is at maximum 82GW PV available during this event.

The following table gives an overview over the medium generated power of different sources during the extreme January event.

table 19: (medium) generated power in MW and share of different sources during extreme event

Wind Onshore	36,954	9%
Wind Offshore	30,394	7%
Photovoltaics	11,129	3%
Geothermal	33,220	8%
Biomass	85,930	21%
CSP Plants	41,427	10%
Wave / Tidal	7,266	2%
Hydro run-of-river	24,557	6%
Hydro Storage	68,362	17%
Conventional	67,172	17%
Total	**406,412**	**100%**

source ENERGYNAUTICS

The following table gives an overview of maximum surplus power during this event. The amount of surplus PV is in comparison to the non-reduced scenario reduced from 27GW to only 5GW.

table 20: maximum of surplus power in MW during different hours of the extreme event

Max Wind Onshore	31,112
Max Wind Offshore	58,265
Max Photovoltaics	4,909
Max Total	**102,414**

source ENERGYNAUTICS

extreme august event (2003) – reduced PV

This extreme event has been described in the main document. For this simulation the installed PV capacity has been reduced from 383GW to 211GW.

The following table shows the characteristic of this event with reduced PV.

table 21: characteristic of extreme summer event august 2003– reduced PV (available power) in MW

	HIGH	AVERAGE	LOW
Demand	355,584	207,067	0
% of all time high	66%	38%	0%
Non Contr. RES	271,333	148,631	82,709
% of inst. cap	37%	20%	11%
Windpower	119,603	43,661	17,538
% of inst. cap	81%	29%	12%
Photovoltaics	146,509	45,881	0
% of inst. cap	69%	22%	0%

source ENERGYNAUTICS

The following table gives an overview over the medium generated power of different sources during the extreme August event.

table 22: (medium) generated power in MW and share of different sources during extreme event

Wind Onshore	14,606	4%
Wind Offshore	13,253	4%
Photovoltaics	36,586	10%
Geothermal	31,404	9%
Biomass	67,751	19%
CSP Plants	13,459	4%
Wave / Tidal	22,315	6%
Hydro run-of-river	62,012	18%
Hydro Storage	51,232	15%
Conventional	40,077	11%
Total	**352,696**	**100%**

source ENERGYNAUTICS

The following table gives an overview of maximum surplus power during this event. The amount of surplus PV is in comparison to the non-reduced scenario reduced from 117GW to 51GW. As described in the beginning of this section, a high amount of this power could be fed into storage systems and used at a later time. Doing this, the amount of conventional power can be further reduced.

table 23: maximum of surplus power in MW during different hours of the extreme event

Max Wind Onshore	19,954
Max Wind Offshore	44,479
Max Photovoltaics	51,394
Max Total	**102,317**

source ENERGYNAUTICS

short-term issues

The proposed super grid would be designed so that the interruption of one onshore interconnection (onshore super grid) or loss of a 5,000 MW wind farm (offshore super grid partially down) can be compensated by the other interconnections within the super grid (N-1). That means that in such a situation, energy supply will continue. Besides the (N-1)-security, the super grid will continue to function for an extreme event described in the previous sections which is likely to happen only once every 40 years. To have a situation with both an extreme event and an interruption of an interconnection is very unlikely.

4.6 the super grid proposal

The scenarios modelled in this report lead to a proposal for strengthening existing European grid interconnections (HVAC) and creating a new super grid of HDVC that takes power straight from its source to the population centres, without having to travel via existing networks.

Interconnections to be strengthened are those between Spain and France, Italy and France, Romania and Poland, Sweden and Poland, and Ireland and Great Britain (Figure 45). A full list and costs are provided in Section 4.7.

image SUBMARINE CABLE WITH OPTICAL FIBRE.

The super grid is an HVDC grid in Central-Europe with connections to sources in North Africa (Concentrating Solar Power) and Scandinavia (Hydro). The following figure shows the proposed super grid, which includes the North Sea offshore grid proposed by Greenpeace in an earlier study.[40] A full list of new HDVC connections and costs are provided in the following section.

figure 48: **map of the proposed super grid**

source UCTE, NORDEL ENERGYNAUTICS

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reference

[40] HTTP://WWW.GREENPEACE.DE/FILEADMIN/GPD/USER_UPLOAD/THEMEN/ENERGIE/OFFSHOREWINDGRID_FINAL.PDF

4.7 estimation of costs

The following table lists the interconnections which have to be strengthened (see also Figure 42) and gives an overview over the necessary additional capacity and distance.

The overall costs of the reinforced interconnections are approximately €3 billion.

table 24: strengthened HVAC interconnections

	ADD CAPACITIY / MW	DISTANCE / KM
Austria – Czech Republic	3,400	131
Belgium – The Netherlands	1,700	100
Czech Republic - Poland	1,700	118
France – Spain (1)	5,100	450
France – Spain (2)	3,400	312
Germany – The Netherlands	1,700	93
Inside Czech Republic	1,700	125
Inside France (1)	3,400	237
Inside France (2)	3,400	250
Inside France (3)	1,700	175
Inside France (4)	3,400	325
Inside Italy (1)	1,700	250
Inside Italy (2)	5,100	531
Inside Italy (3)	1,700	250
Inside Romania	1,700	250
Inside Slovakia	1,700	93
Italy – France	5,100	260
Italy - Switzerland	1,700	218
Norway - Sweden	1,700	218
Norway- Finland	500	562
Romania – Ukraine	1,700	106
Slovakia - Poland	1,700	125
Slovakia - Ukraine	1,700	75
Switzerland – France	1,700	93
	58,300	**5,347**

source ENERGYNAUTICS

The next table gives an overview over the necessary additional capacity and distances of the North Sea Offshore grid plus some selected HVDC connections (Table 23). The total costs have been estimated at approximately €16 billion, which is in line with the E[R] offshore grid study by Greenpeace.

The overall costs of the new or strengthened HVDC connections are approximately €15.9 billion.

table 25: new or strengthened HVDC Connections

	ADD CAPACITIY / MW	DISTANCE / KM
Belgium - France	1,000	200
Belgium - GB	1,000	250
Belgium – The Netherlands	1,500	125
Denmark – Germany	2,500	200
East West Interconnector	500	250
GB – Germany	3,500	375
GB – Norway (1)	3,000	675
GB – Norway (2)	3,000	875
Germany – Norway	1,000	550
Germany – The Netherlands	1,500	325
Inside GB (1)	1,000	200
Inside GB (2)	3,500	125
Inside Germany (1)	1,000	250
Inside Germany (2)	1,000	225
Inside Germany (3)	600	125
Moyle Interconnector	760	125
SwePol	1,200	250
	27,560	**5,125**

source ENERGYNAUTICS

image WINDTURBINES AND ELECTRICITY CABLES.


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The capacity and distances of the European super grid togetherwith the estimated costs are given below. The costs are calculated for HVDC VSC (also referred to as HVDC light or HVDC plus), this technology is slightly more expensive but has the main advantage that it can contribute to system stability by providing reactive power to the HVAC grid and is more applicable for an HVDC grid. However, more research is needed to determine the real costs for the needed grid. Especially the availability of storage capacity within Europe, e.g. from electric vehicles. Further optimisation potential in the energy generation mix can significantly reduce grid expansion costs and could reduce the needed links between North Africa and Europe. An optimisation study would be required to find out if some money would be better invested in additional storage capacity or additional HVDC connections.

Without further optimisation, the maximum transport capacity from North Africa to Central Europe is 55GW. This is slightly lower than the 60GW mentioned in the Energy [R]evolution scenario. During the extreme event a maximum of 35GW CSP power from Africa is used. Part of the surplus production has to be provided to compensate for the losses on the lines and in the converters. Part of the installed capacity will not produce at rated capacity due to maintenance and cloudy weather. An estimation of the necessary installed CSP power can be done by evaluating the n-1-security: There are three major HVDC interconnections (Spain, Italy, Greece) and three major production areas (Morocco, Tunisia, Egypt).

- Up to 15 new HVDC 'super grid' connections,
- Within Europe: up to 11 connections with a total of up to 6000 km at a cost approximately €100 billion.
- Between Europe and Africa: The capacity of the required interconnections depends largely on the amount of imported CSP electricity and on the availability of storage capacity within Europe. Without further optimisation and storage capacity, 4 HVDC Connections with a total length of 5,500 to 6,000 km at a cost of approximately €90 billion.

or €5,225 billion per year till 2050. Assuming the level of electricity consumption in Greenpeace's Energy [R]evolution, this would cost about 0.15 c/ kWh over 40 years.

The costs are more like to be the maximum of the needed investments. With an optimisation process via a slight change of the overall energy mix and/or the use of more storage capacity, the need for grid expansion can go down.

4.8 literature

1 energy [r]evolution report 2009, www.energyblueprint.info/fileadmin/media/documents/energy_revolution2009.pdf

2 MED-CSP report, www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/system/projects/MED-CSP_Full_report_final.pdf

3 Trade-Wind: Integrating Wind - Developing Europe's power market for the large-scale integration of wind power, www.trade-wind.eu/fileadmin/documents/publications/Final_Report.pdf

4 NCEP-2 Reanalysis data provided by NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, www.cdc.noaa.gov

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6 Biomass potential in Europe, http://dataservice.eea.europa.eu/atlas/viewdata/viewpub.asp?id=2132

7 ETSOVista: ENTSO-E - European Network of Transmission System Operators for Electricity, www.etsovista.org

8 Zhou, Bialek 'Approximation Model of European Interconnected System as a Benchmark System to Study Effects of Cross-Border Trades', IEEE Transactions on Power Systems, Mai 2005

9 European Commission: Eurostat - Population, http://epp.eurostat.ec.europa.eu/portal/page/portal/population/introduction

10 Operational Security, www.entsoe.eu/_library/publications/ce/oh/Policy3_final.pdf

11 energy [r]evolution: a north sea electricity grid report, www.greenpeace.de/fileadmin/gpd/user_upload/themen/energie/offshorewindgrid_final.pdf

12 Wind power to combat climate change - How to integrate wind energy into the power system, published by Energinet.dk, the Danish TSO, www.energinet.dk/NR/rdonlyres/3097FD4E-F82A-43D0-BBD9-8BF07C349474/0/Windpowermagazine.pdf

13 Wind Power in Power Systems, Editor: Thomas Ackermann, Wiley & Sons, 2005. www.windpowerinpowersystems.info

5

> “the largest potential for demand-side control is in heat or cooling activities within households and industry.”

GREENPEACE INTERNATIONAL
CLIMATE CAMPAIGN


image WINDTURBINE CONSTRUCTION YARD, UK.

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appendix 1: definitions

Power System Control and Power system Operation: Control generally means the process of maintaining the instantaneous balance of a power system, keeping the system balance. Operation is typically a set of short-term actions taken by power system equipment aimed at reducing internal and external disturbances affecting the desired operating point. Examples. A voltage regular takes a control action by adjusting the output voltage in order for the terminal voltage to equal the desirable value, in response to a deviation at the terminal of a synchronous generator. A typical operational aspect of the power system would be to deliberately change the set point of a generator.

Power quality is a measure of how well the available supply serves the connected premises. It is commonly measured by harmonic oscillations, voltage fluctuations, supply frequency, power surges, voltage dips or interruptions.

Electricity system reliability has two components, adequacy and security. Adequacy is the ability of the system to supply the energy requirements of the customers at all times, taking into account scheduled and unscheduled outages of system facilities. Security is the ability of the system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system facilities. Reliability is commonly measured in terms of duration and frequency of sustained outages experienced in a year.

Security of supply resembles system reliability and usually consists of the same two aspects: Operational security of the power system, i.e. ensuring a secure day-to-day operation and long-term security of supply, which mainly aims at securing an adequate long-term generation and transmission capacity.

Ancillary services maintain the physical balance and safeguard the quality of electricity in a power system at all times. There are three categories of ancillary services:

Frequency Control Ancillary Services (FCAS) maintain power system frequency, keeping supply and demand in balance.

Normal operation reserves are a type of FCAS used to maintain normal operation at all times. Used, for instance, to balance the difference between forecasted wind power production and the actual wind power production. Typically normal operation reserves must be operating at full capacity after 15 to 30 minutes of order.

Operational disturbance reserves, are a type of FCAS used in emergency situations to restore the electricity system to a secure state of operation within a reasonable time after a disturbance such as a trip of a power line or power plant. The amount of operational disturbance reserves is based on the worst-case fault e.g. loss of one of the largest production units. Typically operational disturbance reserves are always spinning so they are immediately available after a system disturbance.

Network Control Ancillary Services (NCAS) is related to aspects of quality of supply other than frequency, e.g. voltage control. Most of NCAS is a service that can only be supplied locally. In distribution systems, this service is typically performed entirely by specific equipment, e.g. voltage control by special transformer or capacity banks, as local generation and local customers seldom are able to perform this service. In the transmission systems, currently large conventional power plants provide the NCAS.

System Restoration Ancillary Services (SRAS), are related to system restoration or re-starts following major blackouts. Currently, mainly large conventional power plants are used to provide the SRAS.

appendix 2: grid codes

The relationship of transmission system operators (TSOs) and/or distribution network operators (DSOs) with their customer (generators, consumers, etc.) is outlined in different grid codes. The objectives of the grid codes are to secure efficient and reliable power generation, distribution and transmission, and regulate rights and responsibilities of the entities acting in the electricity sector.

Grid codes for generators typically include:

- Control of ramp rates, i.e. generators should not ramp up or down too fast;
- Support the restoration of frequency in case of a system imbalance between demand and supply;
- Fulfil certain power quality standards, e.g. keep given voltage levels;
- Support voltage control to keep the system voltage within predefined standards;
- Stay connected to the power system in case of a fault (fault-ride-through).

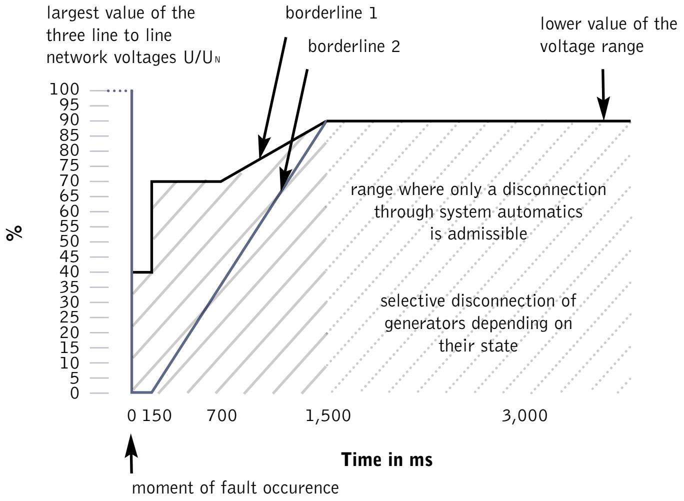
For wind power plants, such requirements were introduced in most countries over the past five to ten years and today new wind power plants can typically comply with these requirements. A key element for compliance with some of the grid codes requirements are the new control functions presented listed in Appendix 1.

One of the key issues related to wind power plants and grid codes is the fault-ride-through requirement. Fault ride-through is the ability of a generator to stay connected to the grid even when the grid is experiencing a fault condition so that once the fault is cleared (which is normally done in less than 400 milliseconds) the wind power plant will resume the delivery of power. Similar requirements exist in most countries for conventional power plants. This requirement is extremely important for power systems with high shares of wind power, otherwise a small fault in the power system causing a regional voltage drop could result in the disconnection of all wind turbines in a large area.

The following figure shows the fault-ride-through requirement for the German high-voltage network, which basically means:

- A voltage drop due to a disturbances in the network, which is in depth and duration above borderline 1 (Figure 49) must not lead to a disconnection of the wind turbine from the grid.
- In case a voltage drop happens, which is located between borderline 1 and borderline 2, a short-time disconnection from the network is permitted by agreement with the network operator.
- Below borderline 2 a short-time disconnection of the wind turbine from the grid is always permitted.

figure 49: fault-ride-through requirements for wind turbines for the German high-voltage network



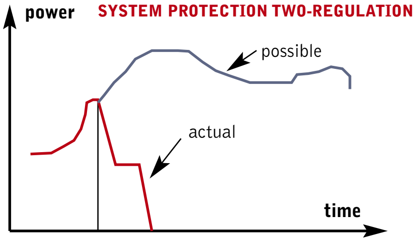
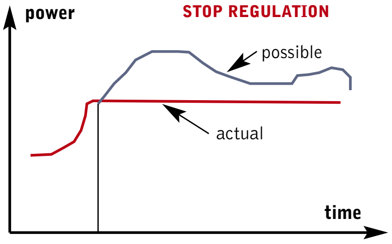
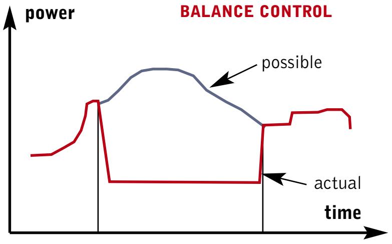
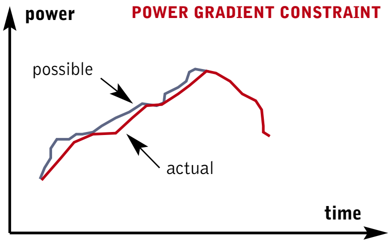
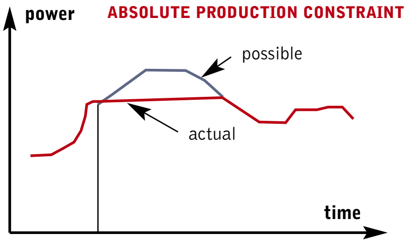
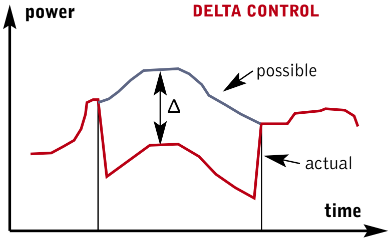
source TRANSMISSION CODE 2007, NETWORK AND SYSTEM RULES OF THE GERMAN TRANSMISSION SYSTEM OPERATORS, VDN, AUGUST 2007

appendix 3: new wind turbine control functions

New wind turbine control functions mean that wind turbines can operate with a certain constant reserve capacity in relation to their momentarily possible power production capacity. The advantage of such control is that reserve capacity is available and can be used very quickly for ramping up in order to provide balancing or frequency control action (see also Figure 50 on the following page). Using pitch control, wind power becomes one of the fastest regulating generating resources currently available. The 160 MW Horns Rev offshore wind farm in , for instance, can ramp up from zero production to 160 MW in approximately 8 seconds, assuming sufficient wind conditions. Such ramp rates are similar to - if not faster than - most conventional gas power stations. on the following page). Using pitch control, wind power becomes one of the fastest regulating generating resources currently available. The 160 MW Horns Rev offshore wind farm in Denmark, for instance, can ramp up from zero production to 160 MW in approximately 8 seconds, assuming sufficient wind conditions. Such ramp rates are similar to - if not faster than - most conventional gas power stations.

The advantage of this approach is that wind power plants gain similar technical characteristics as conventional power plants. The drawback is reduced efficiency because up-regulation can only be achieved if wind is spilled before the actual ramping situation.

figure 50: new wind turbine control schemes

CONTROL TYPE	OBJECTIVE	PRIMARY CONTROL OBJECTIVE
System protection	Protection function that shall be able to perform automatic down-regulation of the power production to an acceptable level for electrical network. In order to avoid system collapse it should act fast.	
Frequency control	All production units shall contribute to the frequency control.	Automatic control of power production based on frequency measurement to re-establish the rated frequency.
Stop control	Wind farm shall keep the production on the actual level even if it is an increase in the wind speed.	
Balance control	The power production shall be adjusted downwards or upwards in steps at constant levels.	
Production rate	Sets how fast the power production can be adjusted upwards on downwards.	
Absolute production limit	Limit the maximum production level in the PCC in order to avoid the overloading of the system.	
Delta control	The wind farm shall operate with a certain constant reserve capacity in relation to its momentary possible power production capacity.	

source ECOGRID WP4 REPORT, PAGE 219, HTTP://WWW.ENERGINET.DK/NR/RDONLYRES/B57A4B4A-AC10-41C4-AB31-AFA55634FD31/0/WP4REPORTMEASURES_2009.PDF. PERMISSION TO USE THE FIGURE NEEDED, SUGGEST THAT ORDER OF CONTROL TYPES SHOULD BE CHANGED, DELTA CONTROL SHOULD BE FIRST).

appendix 4: demand-side management

Demand-Side Management (DSM) means taking active control of the demand by the electricity industry, including customers, to influence the amount and timing of electricity use. However, DSM usually does not include interruptible loads used for example, in an emergency situation for system balancing. DSM is usually driven by economic reasons and not controlled by the independent System Operator (ISO) or transmission system operator (TSO).

DSM can be used by industrial and residential customers. The main aim is to make the consumption more flexible to be able to better react to what the power system is doing. DSM can help balance the power system, for instance in case of forecast errors for variable renewable power generation, but also for providing ancillary services such as spinning reserve (switching on/off electrical devices is the fastest way of balancing the power system in case of a frequency deviation).

The largest potential for demand-side control is in heat or cooling activities within households and industry. In effect, the devices can be operated as short-term thermal storage devices. For instance, a freezer or large industrial cold storage building can be cooled down several degrees more in the morning to avoid operation during times with reduced availability of variable renewable energy sources (which will result in high electricity prices in a market-based electricity system).

For room heating or cooling there is some degree of flexibility in operations, as long as the room temperature and humidity stays within a human comfort zone. For instance, air-conditioning units within a building can be coordinated so that total demand from a building is reduced during certain times. These two examples would rely on a central control unit that could turn adjust heating or cooling up and down by degrees, depending on conditions in the grid. Not all devices in homes and offices can be operated depending on the availability of renewable energy resources, but the potential is still very high.

Table 26 presents an overview of the residential electricity consumption in the US, Japan and Germany as well as the share of that consumption that could be controlled. Between 28.5% and 55% of the installed capacity could be controlled, which represents about 7.6% to 19.2% of the total consumption. The significant difference between the countries is due to different local effects, for example, in Japan electric heating is not as common as in the US or Germany. While in the US electric heating might also be used during peak times, Germany already uses mainly night storage heating systems which therefore cannot be used for load shifting to reduce the peak demand.

presents an overview of the residential electricity consumption in the US, Japan and Germany as well as the share of that consumption that could be controlled. Between 28.5% and 55% of the installed capacity could be controlled, which represents about 7.6% to 19.2% of the total consumption. The significant difference between the countries is due to different local effects, for example, in Japan electric heating is not as common as in the US or Germany. While in the US electric heating might also be used during peak times, Germany already uses mainly night storage heating systems which therefore cannot be used for load shifting to reduce the peak demand.

table 26: overview of potential residential electricity consumption

	USA	JAPAN	GERMANY
Residential share of total electricity consumption	35% (1,124 TWh)	26.9% (252 TWh)	26.7% (130 TWh)
Not controllable:[a]	***Share of residential consumption:***		
Electric kotatsu	-	3.8%	-
Cooking	3%	3.1%	7.9%
Vacuum cleaner	-	2.6%	3%
Heated toilet seats	-	3.8%	-
Electronics	-	2.9%	-
TV, audio, video, PC	11%	1.9%	-
Television			5.9%
Light	3%	9.4%	
Furnace fans	9%	15.5%	7.1%
Motor	2%	-	-
Fans	9%	-	-
Other	-	11.9%	20%
Sum not controllable:	37%	54.9%	44.2%
Limited controllable:[b]	***Share of residential consumption:***		
Water boiler kitchen	-	-	2.7%
Washing machine	1%	1%	3.6%
Dryer	6%	2.5%	2.4%
Dishwasher	1%	0.9%	2.8%
Night Electric heating	-	-	14.8%
Sum limited control:	8%	4.4%	26.3%
Controllable:[c]	***Share of residential consumption:***		
Refrigerator	11%	17.2%	8.1%
Freezer	3%	-	8.8%
Water boiler bath	-	-	8.8%
Water heating	10%	-	-
Air conditioning	13%	23.5%	-
Electric heating	18%	-	2.8%
Sum controllable:	55%	40.7%	28.5%
Sum control in % of total consumption	19.2%	10.9%	7.6%
Controllable plus limited controllable load in % of total consumption	22%	12.1%	14.6%

notes

a. CONSUMERS WILL MOST LIKELY NOT ACCEPT ANY DEMAND-SIDE CONTROL FOR THOSE APPLIANCES.
b. CONSUMERS WILL SOMETIMES ACCEPT DEMAND-SIDE CONTROLFOR THOSE APPLIANCES.
c. CONSUMERS WILL ACCEPT DEMAND-SIDE CONTROL FOR THOSE APPLIANCES IF INTERRUPTION IS WITHIN THE STORAGE CAPACITY.

source DISTRIBUTED RESOURCES IN A REREGULATED MARKET ENVIRONMENT, PH.D. THESIS T. ACKERMANN, ROYAL INSTITUTE OF TECHNOLOGY, STOCKHOLM, SWEDEN 2004.

image HELIOSTATS MIRRORS AT THE PS10 CONCENTRATING SOLAR TOWER PLANT IN SPAIN.

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appendix 5: overview of new electric energy storage options

Among the technologies available for electrical energy storage, the relationship between peak power and energy is critical. Figure 49 shows the types of energy storage devices available, and their typical energy volume indicated by the time to completely fill the empty storage device as well as the typical power ratings. For flow batteries, the energy volume and the time can be designed independently of the power capacity, but for economic reasons, the typical time is limited to a maximum of one day. Table 27 provides a more detailed comparison of storage technology including current cost levels. With a wider implementation of storage technology, the costs would drop significantly. shows the types of energy storage devices available, and their typical energy volume indicated by the time to completely fill the empty storage device as well as the typical power ratings. For flow batteries, the energy volume and the time can be designed independently of the power capacity, but for economic reasons, the typical time is limited to a maximum of one day. Table 28 provides a more detailed comparison of storage technology including current cost levels. With a wider implementation of storage technology, the costs would drop significantly. provides a more detailed comparison of storage technology including current cost levels. With a wider implementation of storage technology, the costs would drop significantly.

Figure 51 also shows that electrical energy storage will only be suitable for balancing variable generation for a day or so, i.e. by "moving" surplus wind energy generated during a storm to a day without wind. However, the electrical energy storage technologies listed here would not be able to store surplus wind energy generated in the winter for compensating long periods with low or no wind in the summer. also shows that electrical energy storage will only be suitable for balancing variable generation for a day or so, i.e. by "moving" surplus wind energy generated during a storm to a day without wind. However, the electrical energy storage technologies listed here would not be able to store surplus wind energy generated in the winter for compensating long periods with low or no wind in the summer. Currently, such storage is only possible using a large number of hydro dams with significant water storage capacity. The Scandinavian hydro-power system, for instance, can store sufficient water to cover total electricity demand in Scandinavia for 6 months. However, this requires significant changes in the water level of the hydro reservoirs. In some cases the difference between a full and empty reservoir would amount to 15 meters causing severe environmental issues.

figure 51: overview of operation range of different energy storage technologies. SMES = superconducting magnetic energy storage

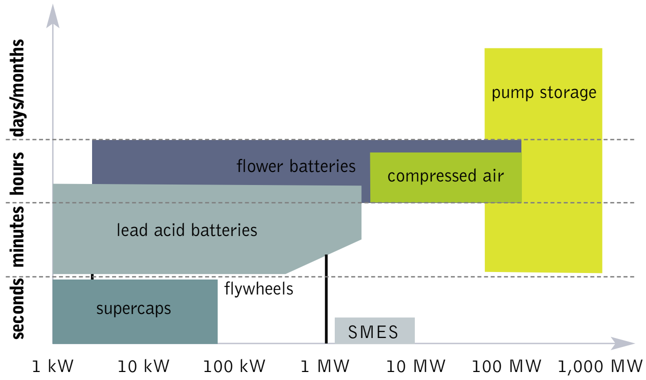

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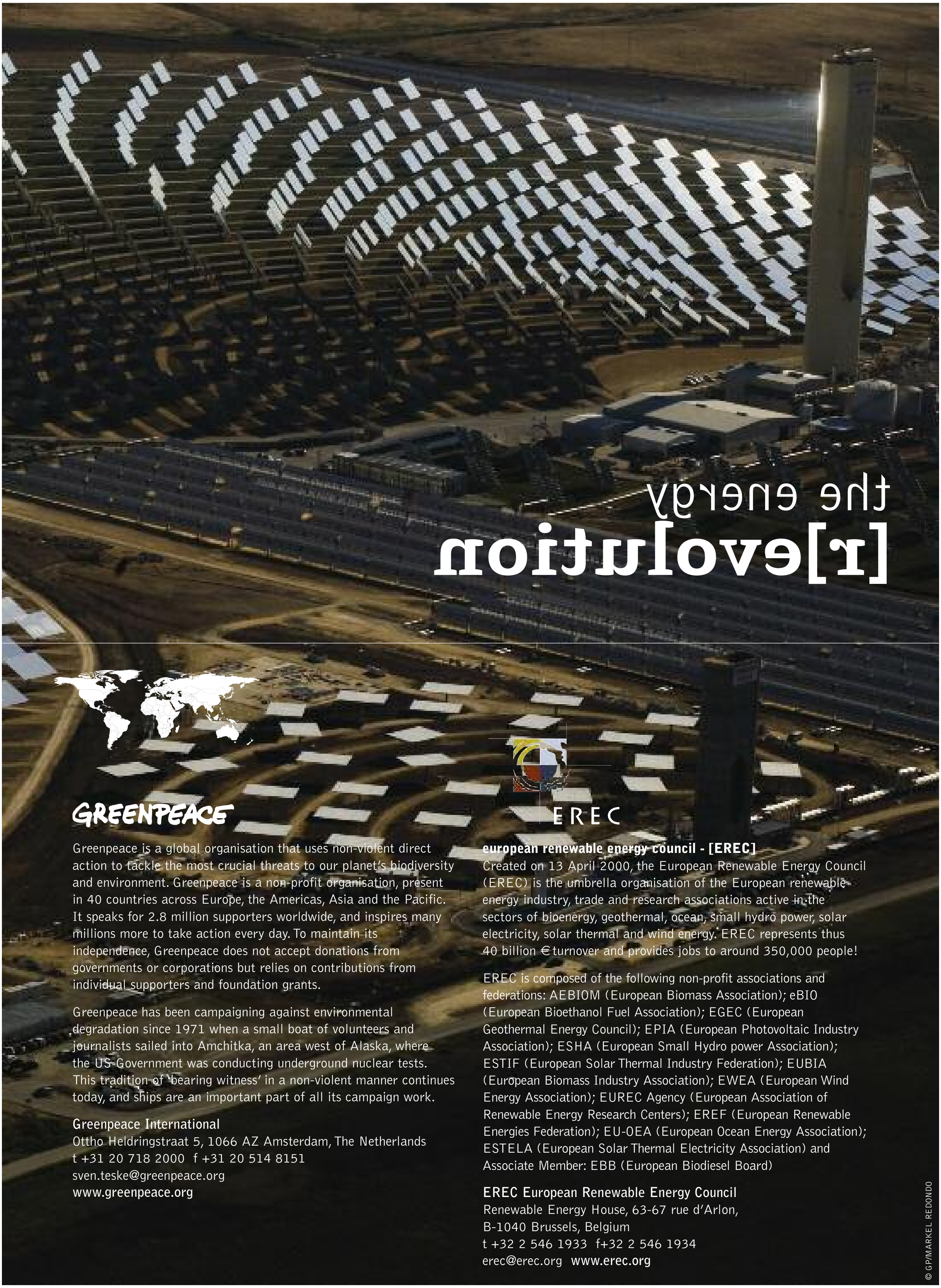
table 27: short comparison of different energy storage technologies

ENERGY STORAGE TECHNOLOGY	POWER CAPACITY (MW)	ENERGY CAPACITY (MW)	ELECTRICICAL EFFICIENCY	ENERGY COST (€/KWH/YR)	POWER COST (€/KWH/YR)
Flywheel	< 10	< 250	80+	77	0.88
Compressed air	5 - 400	2,600,000+	55 - 75	1.5-3	34.16
Conventional battery	4	40,000	75 - 85	24-117	73 - 351
Redox flow battery	0.005 - 500	400,000	65 - 75	9.4-12.5	70 - 144
Superconducting magnetic energy storage (SMES)	2	< 5	95	3x10^{5}	47
Supercapacitors	< 20	< 5	85 - 98	570	4.8
Hydrogen	0.2 - 4	n/a	75 - 80	6.8	128

source ECOGRID PHASE 1 WP4 REPORT, AVAILABLE AT: HTTP://WWW.ENERGINET.DK/NR/RDONLYRES/B57A4B4A-AC10-41C4-AB31-AFA55634FD31/0/WP4REPORTMEASURES_2009.PDF, PAGE 20



GREENPEACE

Greenpeace is a global organisation that uses non-violent direct action to tackle the most crucial threats to our planet's biodiversity and environment. Greenpeace is a non-profit organisation, present in 40 countries across Europe, the Americas, Asia and the Pacific. It speaks for 2.8 million supporters worldwide, and inspires many millions more to take action every day. To maintain its independence, Greenpeace does not accept donations from governments or corporations but relies on contributions from individual supporters and foundation grants.

Greenpeace has been campaigning against environmental degradation since 1971 when a small boat of volunteers and journalists sailed into Amchitka, an area west of Alaska, where the US Government was conducting underground nuclear tests. This tradition of 'bearing witness' in a non-violent manner continues today, and ships are an important part of all its campaign work.

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EREC

european renewable energy council - [EREC]
Created on 13 April 2000, the European Renewable Energy Council (EREC) is the umbrella organisation of the European renewable energy industry, trade and research associations active in the sectors of bioenergy, geothermal, ocean, small hydro power, solar electricity, solar thermal and wind energy. EREC represents thus 40 billion € turnover and provides jobs to around 350,000 people!

EREC is composed of the following non-profit associations and federations: AEBIOM (European Biomass Association); eBIO (European Bioethanol Fuel Association); EGEC (European Geothermal Energy Council); EPIA (European Photovoltaic Industry Association); ESHA (European Small Hydro power Association); ESTIF (European Solar Thermal Industry Federation); EUBIA (European Biomass Industry Association); EWEA (European Wind Energy Association); EUREC Agency (European Association of Renewable Energy Research Centers); EREF (European Renewable Energies Federation); EU-OEA (European Ocean Energy Association); ESTELA (European Solar Thermal Electricity Association) and Associate Member: EBB (European Biodiesel Board)

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image AERIAL PHOTO OF THE PS10 CONCENTRATING SOLAR THERMAL POWER PLANT OUTSIDE SEVILLA, SPAIN. THE 11 MEGAWATT SOLAR POWER TOWER PRODUCES ELECTRICITY WITH 624 LARGE MOVABLE MIRRORS CALLED HELIOSTATS. THE SOLAR RADIATION, MIRROR DESIGN PLANT IS CAPABLE OF PRODUCING 23 GWH OF ELECTRICITY WHICH IS ENOUGH TO SUPPLY POWER TO A POPULATION OF 10,000.