Distributed Generation & System Stability: Learning from the Blackouts

Bachelorthesis

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CONTENT

LIST OF ABBREVIATIONS

DG	Distributed Generation
AC	Alternating Current
DC	Direct Current
NERC	North American Electric Reliability Corporation
TSO	Transmission System Operator
RTO	Regional Transmission Operators
ISO	Independent System Operators
MISO	Midwest Independent System Operator
PJM	Pennsylvania-New Jersey Interconnection
FE	First Energy
AEP	American Electric Power
EDT	Eastern Daylight Time
RTU	Remote Terminal Units
EMS	Electronic Maintenance System
ENTSO-E	European Network for Transmission System Operators for Electricity
UCTE	Union for the Coordination of Transmission of Electricity
DACF	Day Ahead Congestion Forecast
ERGEG	European Regulator's Group for Electricity and Gas
ACER	Agency for the Cooperation of Energy Regulators
IEA	International Energy Agency
CHP	Combined-Heat-And-Power Plants
OECD	Organization for Economic Cooperation and Development

INTRODUCTION

Economies nowadays rely heavily on a ubiquitous supply of energy. The energy needs to always be available. Our Modern society is not thinkable without it. What happens if the supply is cut off? Blackouts expose us to our heavy reliability on energy and also the importance of securing the supply and keeping the grids in stable conditions.

This thesis focuses on two major blackouts that have shown that a reliable energy grid is essential to our economy. The first blackout happened in the United States in August 2003. It was the most severe power outage in North American history. 50 Million People were affected in Canada and the U.S. and the economic loss has been estimated to be between four and ten million US-Dollars. The second blackout in this thesis happened in the European Union and started out in Germany. The effects weren't as severe as in the North American example but the potential for an EU-wide blackout was apparent.

In the first and second chapter both blackouts will be thoroughly analyzed. A detailed rundown of the incidents and their chronological appearance will be given. What were the circumstances of the blackouts? How did the blackouts evolve? Next the reasons for the blackouts will be stated and evaluated. After that the main causes of each blackout will be discussed in order to find out if they could have been averted.

In the third chapter potential causes and their main drivers are identified. After a little introduction into market liberalization, Distributed Generation (DG) will then be presented as the power infrastructure of the future that probably will be able to help to prevent large-scale blackouts from further on.

MOTIVATION AND SCOPE OF THE THESIS

This is a Bachelor thesis in the study program Urban Planning at the HafenCity University Hamburg. Therefore the topic of this thesis is quite off of the regular topic that is to be expected from an urban planning student. Usually this topic would be more suiting for an electrical engineer than for an urban planner. Still much of the content of this thesis is also relevant for the subject of urban planning.

Before I started out on this thesis I already decided to study the masters program "REAP – Resource Efficiency in Architecture and Planning" at the HCU. So I wanted to pick a topic for my thesis that not only is a résumé of my work as an urban planning student but also prepares and enables me for my masters program. During my bachelors degree I worked on subjects related to climate change and I want to stick to that topic in my thesis. Even though this thesis is not mainly about climate change it helped me understand a lot about the energy infrastructure and showed me how much potential there is in the energy sector to work on climate change issues.

Not being an electrical engineer forced me to try to take a slightly different approach than expected. I tried not to focus too much on technical coherences but more on the larger picture as this is more appropriate for an urban planner. There are still technical issues discussed in this thesis but only in very small manageable amounts. The topic of this thesis proved itself to be quite challenging but also worth the effort as I have learned a lot not only about the topic but also about the way to approach a topic that is new to you.

CHARACTERISTICS OF POWER GRIDS

To understand the blackouts you have to understand the characteristics of the power grids first. Therefore this chapter is a small introduction on some of the most important and fundamental concepts of electricity in power grids.

We differentiate two kinds of electricity in power grids.

- Alternating Current (AC)
- Direct Current (DC)

The difference between the two currents is the polarity. In direct currents the polarity always stays the same. In alternating currents the polarity of the electricity is always changing. Most energy today is provided through 50 Hz or 60 Hz alternating current. The power plug in households delivers alternating current. Direct Current is only used in special cases like e.g. in trams or trains, in chemical processes or in High-voltage direct current transmission lines. (Oeding & Oswald, 2011, p. 8)

The distribution of the electricity throughout the power grid is done by many different sub-grids. This is due to the fact that most generation plants produce electricity with a voltage between 10,5 kHz and 21 kHz. (Udo Leuschner) Of course this is too high for household usage. Still the voltage has to be increased even more in order to transport the electricity without too many losses. The different distribution and transport grids in Germany are divided as follows:

- Highest voltage grid (380 to 220 kV)
- High voltage grid (110 kV)

- Middle voltage grid (20 to 10 kV)
- Low voltage grid (400 to 230 V)

The highest voltage grid is responsible for the transport from the generation plants to the lower voltage grids and also takes part in the international power exchanges. The low voltage grid handles the distribution into the individual households. (Udo Leuschner) Bigger industries or businesses sometimes get connected to higher voltage grids like the middle or even the high voltage grid based on their electricity demand. (Oeding & Oswald, 2011, p. 9)

Power grids all around the world are characterized by demand patterns. A day has times when the demand for power is low, for example at night, and there are times when the demand for power is very high, for example in the morning, at noon or in the evening. The power grid needs to suit those disparities. Therefore power generation is divided into three different kinds of power plants:

- Base load → this is the load that is always there. The energy for this load is mainly supplied by brown coal plants and the nuclear power plants in Germany. Base load power plants are usually not very flexible and have to run constantly to maintain a proper and economic generation of power. (Udo Leuschner)

- Medium load → this is the load that is caused by regular variations in the power grid like e.g. the regular variations with peaks in the morning, noon and evening. These variations are predictable and can be accounted for. Medium load is usually provided by stone coal power plants because they are more flexible in generation compared to brown coal power plants or nuclear power plants. (Udo Leuschner)

- Peak load → sometimes there are peak loads even on top of the medium load. These peaks cannot be predicted and have to be dealt with the very second they appear. Gas turbine power plants and also pump storage power plants. These power plants can react on very short notice to supply power immediately (Udo Leuschner)

The generation structure can be displayed in a load curve that shows the demand throughout the day and also which energy resource is covering how much of the demand. The inflexible generation plants like brown coal or nuclear are at the bottom because they are responsible for covering the base load. On the top are the more flexible energy generations like gas turbine or pump storage plants. Also most of the renewable energies can be found here.

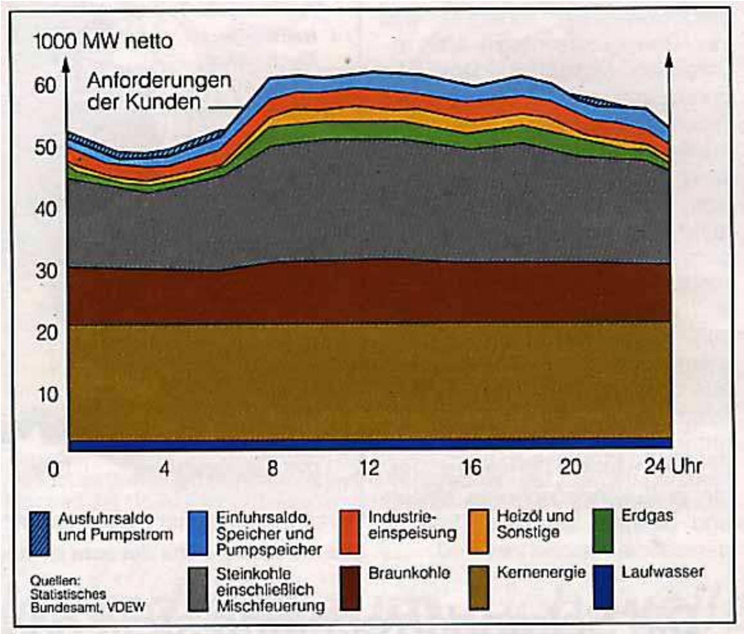

FIGURE 1 LOAD CURVE FOR A DAY IN JANUAR

CHAPTER 1 THE NORTH AMERICAN BLACKOUT

FOREWORD TO CHAPTER 1

In Chapter one, the blackout in the United States and Canada from August 14th 2003 is described. The blackout had massive effects on both of these countries and their power grids. In order to ensure that nothing like that will happen again both countries formed a Joint Task Force to investigate the blackout and also the reasons for the blackout. Also recommendations on how to improve the power grid in the future are made. Most information in this chapter is taken from the final report of the task force. Due to the bi-national background, also with representatives from the power grid itself (NERC), the report can be seen as generally unbiased and objective in its investigations.

THE NORTH AMERICAN POWER GRID

The North-American Power Grid is one of the biggest industrial structures in the world. It is made up of over 320.000 km of transmission lines, 3.500 independent utility organizations and provides electricity for nearly 283 million people. (NERC, 2011) To properly maintain such an enormous and complex structure makes for a great challenge for both, the authorities involved and the independent utility organizations that are working within the power grid.

In order to make that happen there has to be an elaborate organizational scheme that divides the structure of the grid down to a manageable size. In the USA the electric power grid is divided into three major parts, which actually are three power grids in themselves. These are the so-called interconnections. The western interconnection is made up of all the states from the pacific coast to Colorado, including British Columbia, Alberta and the northern part of Baja California in Mexico. The eastern interconnection covers the rest of the USA and the southeastern states of Canada. The third interconnection consists only of the state of Texas. These interconnections are widely independent from each other and are only connected through a few Direct Current (DC) transmission Lines. (U.S.-Canada Power System Outage Task Force, 2004, p. 5)

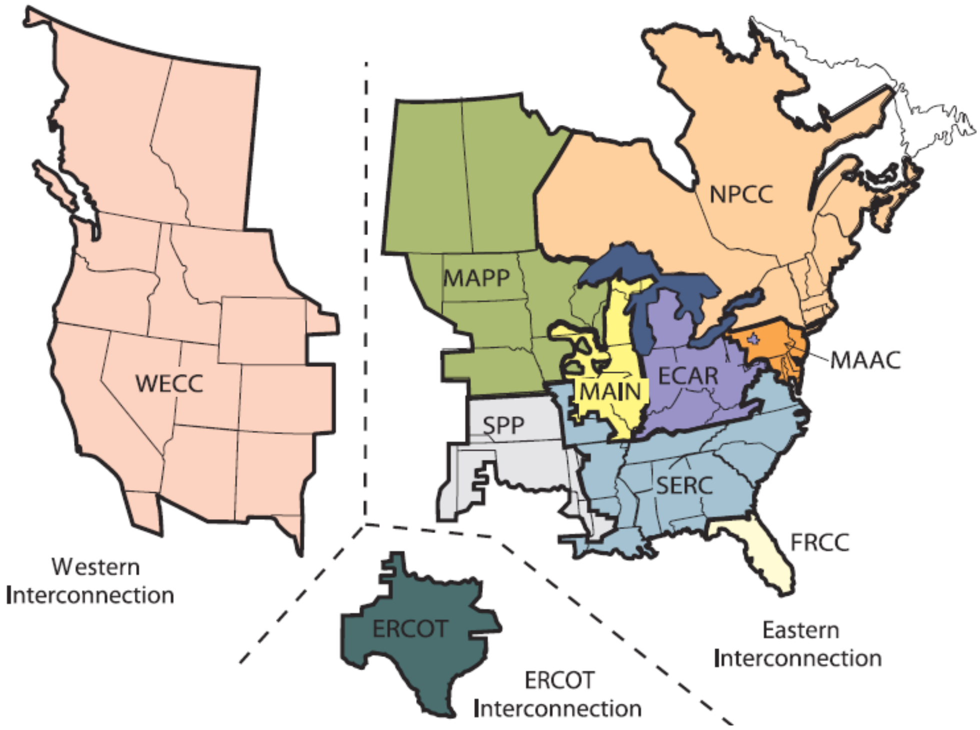

FIGURE 2 MAP OF INTERCONNECTION

The most important attributes for a power grid are reliability and security (of supply and the grid itself). After the big blackout in 1965 the USA founded the North American Electric Reliability Corporation (NERC) in 1968, to ensure these two main attributes are always sufficiently accounted for. The main objective of the NERC is setting industry standards for all utility organizations and transmission system operators (TSO) that are mandatory to comply to and also make sure that these standards are adhered to. These standards are:

- Balance power generation and demand continuously
- Balance reactive power supply and demand to maintain scheduled voltages

The N-1 Criterion

The N-1 Criterion is an operational standard that is supposed to ensure system security. The N-1 Criterion works as follows. In the event of a contingency, a power system is always supposed to keep running properly. The N-1 Criterion ensures that a system will remain operational even after a single failure in the network occurs. A contingency can be the loss of a generator (power plant, etc.), a transformer or a transmission line. This standard has been adopted by system operators all around the world to ensure a secure operational environment. The reason that this standard was adopted was that all power systems are prone to failures because of lightning strikes or mechanical failures. The N-1 Standard is supposed to be applied everywhere with the same standards. In reality, the standard is only applied to manage *credible* contingency events. Therefore the standard is not used for the possibility of multiple independent failures. This is due to financial constraints by the system operators. (IEA/OECD 2005, pp. 31-32)

- Monitor flows over transmission lines and other facilities to ensure that thermal (heating) limits are not exceeded
- Keep the system in a stable condition
- Operate the system so that it remains in a reliable condition even if a contingency occurs, such as the loss of a key generator or a transmission facility (the "N-1 criterion")
- Plan, design, and maintain the system to operate reliably
- Prepare for emergencies
  (U.S.-Canada Power System Outage Task Force, 2004, pp. 6–7)

The other important task for NERC is coordination between the many utility organizations and TSOs. At last NERC is also in charge of the education of personnel to further promote system reliability.

NERC itself is made up of ten regional reliability councils. These councils consist of members that represent the entire electric industry like the different power utilities, power producers and also power customers. During the blackout three regional reliability councils have been affected: the East Central Area Reliability Coordination Agreement (ECAR), the Mid-Atlantic Area Council (MAAC) and the Northeast Power Coordinating Council (NPCC). (U.S.-Canada Power System Outage Task Force, 2004, pp. 10–11)

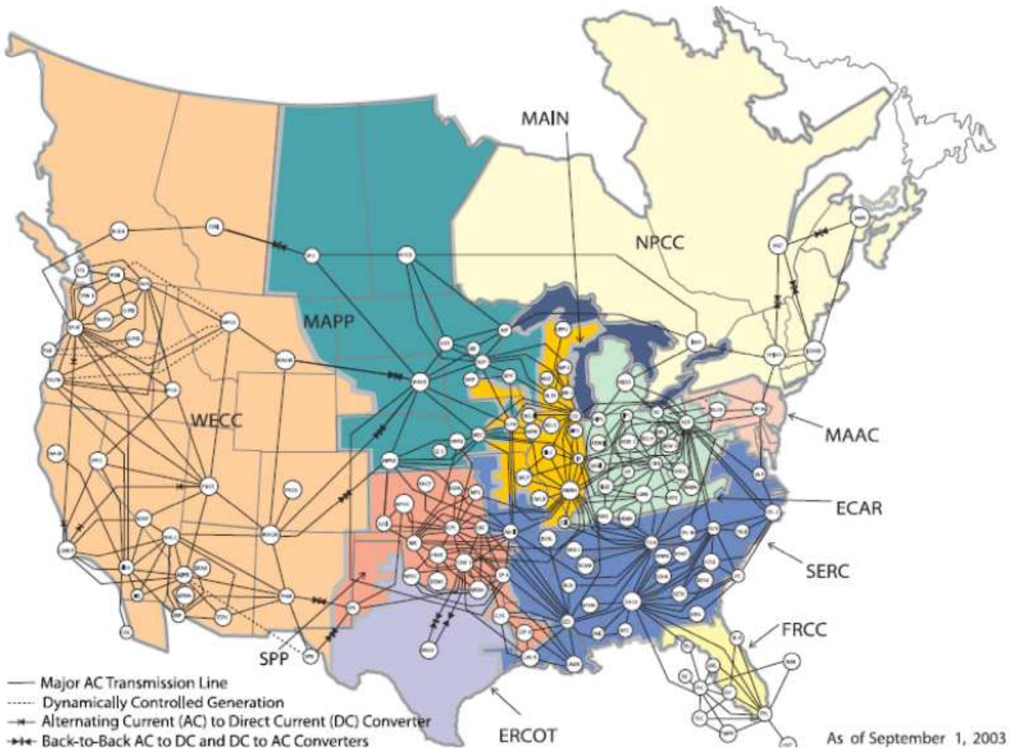

FIGURE 3 MAP OF NERC REGIONS AND CONTROL AREAS

The NERC control areas are then further divided into different Independent system operators (ISO) and Regional Transmission Operators (RTO). This is a result of the restructuring of the utility industry and the resulting unbundling of generation, transmission and distribution. (U.S.-Canada Power System Outage Task Force, 2004, p. 11) The ISOs/RTOs are mainly responsible for securing system reliability in their respective control areas and operate on the wholesale market for energy. They can also be NERC system reliability coordinators. As a reliability coordinator they are responsible for assessing system operation status, securing reliability, and operate (though not actually participate) on the wholesale market. There are five reliability coordinators directly affected by the blackout of August the 14th:

- Midwest Independent System Operator (MISO)
- PJM Interconnection (PJM)
- New York Independent System Operator (NYISO)
- New England Independent System Operator (ISO-NE)
- Ontario Independent Market Operator (IMO)
  (U.S.-Canada Power System Outage Task Force, 2004, p. 11)

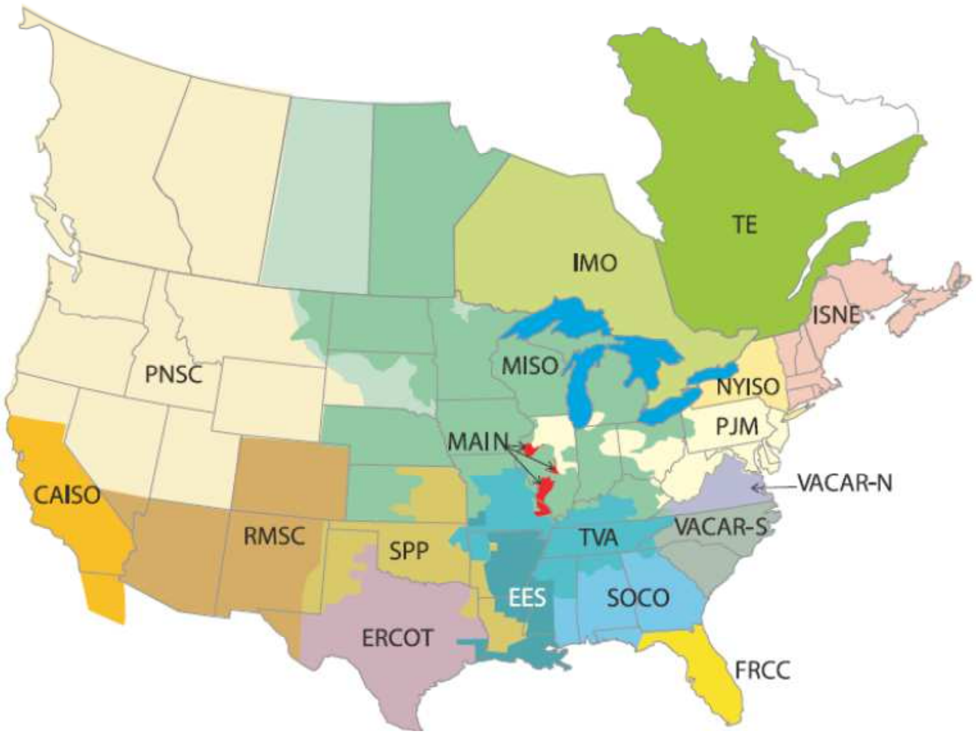

FIGURE 4 MAP OF RELIABILITY COORDINATORS

The reliability coordinators are primarily responsible for the reliability of the system. That means they have to assess the net using the N-1 Criterion, being able to respond properly in emergency situations and train the operating personnel. Also they are to comply with the NERC operating policies. (U.S.-Canada Power System Outage Task Force, 2004, p. 13)

THE PROLOGUE TO THE BLACKOUT

Before looking at the actual events that caused the blackout in the northeastern United States and in Ontario, you have to recognize certain preconditions in the power grid of the regional power utility. The regional power utilities were First Energy (FE) and American Electric Power (AEP). FE coordinates seven electric utility operating companies, mainly at the southern shore of Lake Erie and also around Dayton, while AEP controls the areas south of FE. FE's reliability coordinator is MISO and AEPs reliability coordinator is PJM.

At 15:05 Eastern Daylight Time (EDT) on August 14th 2003 the power system in the area was completely secure and functional and in absolute compliance to the NERC operating policies. So this rules out any condition that was derived from events before the actual blackout as a cause for the blackout. This also rules out a number of other contingencies as cause for the blackout, as are the following:

- Unavailability of individual generators or transmission lines
- High power flows across the region
- Low voltages earlier in the day or on prior days
- System frequency variations
- Low reactive power output from independent power producers

  (U.S.-Canada Power System Outage Task Force, 2004, p. 23)

Still there was a high vulnerability to voltage instability visible in the Cleveland-Akron area, because the system there was running on the brink of NERC operating policies, and it was clear that any larger contingency could possibly put the whole system at risk. (U.S.-Canada Power System Outage Task Force, 2004, p. 23) FE personnel did not analyze this situation properly because they didn't conduct the necessary long-term planning and thus would

Reactive Power

"Reactive power is a quantity that is normally only defined for alternating current (AC) electrical systems. Our U.S. interconnected grid is almost entirely an AC system where the voltages and currents alternate up and down 60 times per second (not necessarily at the same time). In that sense, these are pulsating quantities. Because of this, the power being transmitted down a single line also "pulsates" - although it goes up and down 120 times per second rather than 60. This power goes up and down around some "average" value - this average value is called the "real" power and over time you pay for this in kilowatt-hours of energy. If this average value is zero, then all of the power being transmitted is called "reactive" power. You would not normally be charged for using reactive power because you are consuming some energy half the time, and giving it all back the other half of the time - for a net use of zero. To distinguish reactive power from real power, we use the reactive power unit called "VAR" - which stands for Volt-Ampere-Reactive. Voltage in an electrical system is analogous to pressure in a water system. Current in an electrical system is analogous to the flow of water in a water system." (Peter W. Sauer, 2003, p. 1) not be able to deal with an emergency the way NERC operating standards demand. (see box N-1 Criterion)

Another precondition to the events of August the 14th 2003 was a seasonal feature. The days before the blackout, and also August the 14th itself, were very hot days. Because of that many people in the Cleveland-Akron area had their air-conditioners running for days. This resulted in a peak load raise by 20% in the area on the 14th. Still this is not an unusual event, and the system operators in the area have faced such peak loads successfully many times in the past. Nonetheless this is substantial to further events because of the massive demand of reactive power that Air-Conditioning appliances require. (see box reactive power) It gets even more remarkable considering that several capacitor banks for reactive power support, that are very important for voltage stability, went out of order on August 14th due to maintenance reasons. FE did not pass this information on to others outside of FE itself because they did not identify this as a problem for system stability. They should have done this though, because reactive power supply can be crucial for the transmission of real power, especially in summer peak load times.

Another important event previous to the blackout was the tripping of FE's Eastlake 5 597 MW generating unit. This was due to the FE system operator trying to raise the reactive power input, in order to react to the higher reactive power demand at that time. The generating unit's protection system identified the raise of Volt-Ampere reactive (VAr) as to high for the generators capabilities and shut down. This significantly increased the risk of transmission line overloads in FE's operating area. Even though this did not jeopardize the systems stability, it did limit the operators maneuvering room, because now FE had to import power to make up for the loss, and therefore made the voltage management in their own system a lot more difficult. (U.S.-Canada Power System Outage Task Force, 2004, p. 25)

THE BLACKOUT

The tripping of Eastlake 5 was a decisive moment for the chronology of the blackout. Even though Eastlake 5 shut down, the loading ratings for the transmission lines were still normal. It was rather a chain of key computer failures, human failures and major transmission lines going down due to overgrown trees, which caused the actual blackout.

Between 12:15 and 15:34 EDT MISO's state estimator was rendered useless. The state estimator is a computer tool that is used to exactly control the loading of the areas transmission lines and the production of generation facilities. It gathers information from field remote terminal units (RTUs) and relays them to the master stations were the information gets processed in order to maintain system reliability. Control areas can't be looked at isolated from their surroundings, so the state estimator has to take into the calculation information from the surrounding control areas. The reason for MISO's state estimator being useless was the tripping of Dayton Power & Lights's (DPL) Stuart-Atlanta 345-kV line in southern Ohio, which had to shut down due to tree contact. (U.S.-Canada Power System Outage Task Force, 2004, p. 45) In no way did this affect the system stability in MISO's control area, but it did affect the calculations of the state estimator. Human failures, like the shutting down of the system estimator for over an hour due to troubleshooting reasons, also attributed to the miscalculations. So in the time frame between 12:15 and 16:04 EDT the MISO's state estimator did not work properly and was not able to foresee that with Eastlake 5 shut down there would be a lot heavier loads on other transmission lines, and that FE's electricity system would not be able to withstand another loss of a major transmission line. (U.S.-Canada Power System Outage Task Force, 2004, pp. 45–46)

Contributing to the computer problems is also the loss of FE's automated alarm in their EMS system. At 14:14 EDT the last valid alarm was recorded. This is a grave incident for FE's operating personnel because they rely heavily on the alarm functions within their system. It was even worse because FE's operators weren't aware of the failing of their alarm system and thus discounted any information from outside that their system might be in jeopardy. (U.S.-Canada Power System Outage Task Force, 2004, p. 59)

The failing of the alarm system and also the loss of a few remote EMS Terminals might have then contributed to the loss of FE's main EMS server, and later of the backup server too. This caused even more problems for FE's operating staff. (U.S.-Canada Power System Outage Task Force, 2004, p. 52)

The next decisive incidents in the blackout were the tripping of three high-voltage 345-kV transmission lines due to tree contact. First, at 15:05 EDT the Harding-Chamberlin line tripped. This caused other lines in the area to pick up higher loads, especially for the Hanna-Juniper line. This was apparently not discovered by FE or MISO until after the Blackout. At 15:31 DPL's Stuart-Atlanta line also tripped, which can be neglected concerning system stability, but had a major impact on the calculations of MISO's state estimator. (as mentioned above) Next the Hanna-Juniper line tripped due to a tree contact. After the tripping of the Harding-Chamberlin line, Hanna-Juniper had to pick up much of the load. Now with this line out too, more of the energy had to be transported by the remaining two lines, Star-Juniper and Star-South Canton, and also by the underlying 138-kV system. At last, the Star-South Canton line tripped, also due to tree contact. This now caused the flows in the 138-kV system and also the 69-kV system to increase even more. Also the power flows of the Sammis-Star line increased. (U.S.-Canada Power System Outage Task Force, 2004, pp. 57–58) The reason for the tree contacts here are in general a combination of not proper trimming the trees in the rights-of-passage of the responsible utility and the sagging of the transmission lines due to overheating caused by higher loads. Both these reasons are not uncommon at all, but in combination resulted in the tripping of the three 345-kV lines.

After the loss of three 345-kV transmission lines in northern Ohio, much of the increasing loads hat to be relayed to the 138-kV system. This pushed these lines quickly into an overload status that ended with sixteen 138-kV lines tripping.

THE CASCADE

The vital incident for the start of the cascade was the tripping of the Sammis-Star 345-kV transmission line at 16:05 EDT. This triggered lots of interruptions on the high-voltage system and in the end led to the loss of over 508 generating units and 265 power plants spread out all across the northeastern United States and southeastern Canada. Millions of people in this area were without electrical power. All of this took only three minutes. (U.S.-Canada Power System Outage Task Force, 2004, p. 74)

The reason for the tripping of the Sammis-Star 345-kV Line, compared to the tripping of the other lines in FE's electrical power system, was **not** due to a tree contact. The tripping here was a result of a protective relay which treated the high power flows as a short circuit and therefore tripped the line automatically. (OECD/IEA, 2005, p. 59)

Massive power surges, resulting from the interruptions in FE's power system caused many neighboring power systems to overload and shut down. This chain reaction (or Cascade) went on so quickly that it wasn't possible to intervene in any way once it started. In a counter-clockwise motion the power surge took out electrical power systems around Lake Erie. This caused the whole area to split from the rest of the Eastern Interconnection and therefore the cascade was then isolated and stopped. (U.S.-Canada Power System Outage Task Force, 2004, p. 75)

We will not further go into detail on the full cascade in the different regions because that would be too extensive. The most important part of the cascade is the beginning and the events that triggered the cascade.

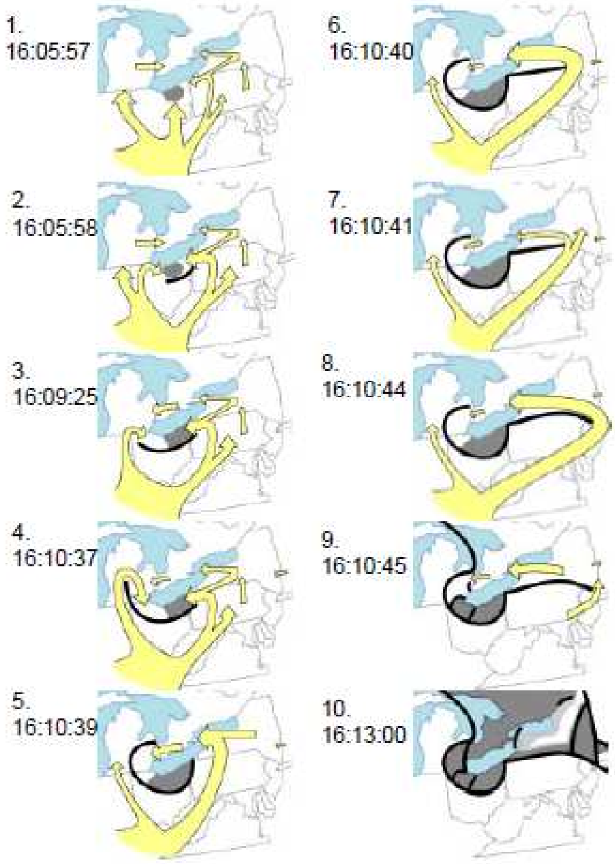

FIGURE 5 SEQUENCE OF THE CASCADE

THE AFTERMATH OF THE BLACKOUT

The blackout of August 14th 2003 was the most sever power outage in the history of the United States and Canada. About 50 million people in two countries were affected by it. The economic cost of the blackout has been estimated to between four and ten Million US-Dollars. (OECD/IEA, 2005, p. 55-56) Most of the electrical services in the United States have been restored within two days, while the whole system took four days to be fully restored. In Ontario there was a provincial state of emergency declared and the wholesale electricity market was suspended. The government of Ontario even appealed to their people to reduce energy consumption by 50% to attribute to the very low generating capabilities during the restoration process. (OECD/IEA, 2005, p. 64)

Shortly after the blackout, the then-President of the United States George W. Bush and the then-Prime Minister of Canada Jean Chrétien, ordered a task force to fully investigate the causes for the blackout and develop recommendations to further avoid any risks of similar events in the future. In this report the following key groups of causes for the blackout have been identified:

- Inadequate System Understanding
- Inadequate Situational Awareness
- Inadequate Tree Trimming
- Inadequate Diagnostic Support from Reliability Coordination
  (U.S.-Canada Power System Outage Task Force, 2004, p. 19)

In addition to that the Task Force also found out that security relays responsible for the safety of the electrical power system contributed heavily to the spreading of the outage in the cascade phase. The security relays are programmed to trip the lines if currents are high and voltages low, normally a sign for a fault in the system. Also multiple contingencies can send transient oscillations through the system that can easily be misinterpreted as system faults. The security relays on the crucial Sammis-Star 345-kV line did just that during the blackout, triggering the cascade phase. These security relays also work so quickly that it is virtually impossible to intervene after the triggering of the cascade. (OECD/IEA, 2005, p. 71)

In the report of the task force there are 46 recommendations on how to regain the proper structural, organizational and legal standards for a reliable and robust bulk electrical power system in northern America. These 46 recommendations are then again divided into the four groups of causes as mentioned above.

There is also a general appeal from the task force towards the governments of both the United States and Canada. In this appeal, the members of the task force strongly suggest that the mentioned recommendations are to be implemented as quickly as possible. Furthermore, the task force appeals to the governments to show a lot more engagement into the problems of the reliability of the bulk electrical power system. The task force is sure that neglecting the reliability of the bulk electrical power system will in the end be a lot more expensive than investing into it now. The task force also demands that the costs for the reliability of the system should be recognized as necessary by the regulators as well as the consumers and therefore be included in electricity prices from here on out. Also the imminent importance of immediately implementing the recommendations is stressed again considering the always rising demand for energy while at the same time no investment in new lines is done. This leads to utilities trying to operate their lines at the absolute maximum possible loads, heavily increasing the risk for contingencies. (U.S.-Canada Power System Outage Task Force, 2004, pp. 139–140)

SOLUTIONS TO THE BLACKOUT

The blackout from August 14th 2003 left over 50 million people in two countries for a time span of over 31 hours without electrical power. This estimated economic loss for this is between four and ten million US-Dollars. There is no doubt that any steps or precautions that can be taken to ensure that this won't happen again have to be taken immediately. But what are the proper precautions? How can be ensured that the reliability of the bulk electrical system is not jeopardized again? After the blackout, long before the results of the task force and the actual causes for the blackout were made public, many different voices asked for different solutions.

One of the most common demands after such a power outage is for new generating units, meaning more power-plants. This is supposed to relieve the pressure from consumer demand on the power grid. The lack of power was in fact not in any way related to the blackouts. The power reserves in the region affected by the blackout were at about 30% for the time period in question. They actually had the highest power reserves all across the United States due to recent adding of generation capabilities. So this clearly shows that there was no lack of power generation. In fact, any more power generation unit in the area would have also been affected by the same instabilities. (White et al., pp. 45–46)

The next demand after the blackout was the creation of new transmission lines. The task force called for new transmission lines as one of many recommendations to ensure system reliability in the future. (U.S.-Canada Power System Outage Task Force, 2004, p. 140) When looking at the blackout thoroughly, one can see that there wasn't a problem with the amount of transmission lines. More important was the maintenance, like proper tree-trimming. Still, the call for investment into the transmission grid is not generally wrong. There certainly are selective areas around the United States that after close examination could possibly need more transmission lines. But this does not stand as the patented solution for the entire transmission grid. In most cases the improvement of the existing transmission grid can emerge as a lot less cost-intensive and even more efficient. There are technical solutions available to increase the load of power that a line can carry. Applying those will definitely show to be less expensive. (White et al., pp. 46–47)

While new generation capabilities and strong investment in the transmission lines are usually called upon right away, distributed generation (DG) is usually not so commonly mentioned. DG means to use small power generating units within the low-voltage local power grids. These can be small power generators, or renewable energies like photovoltaic, even fuel cells. These decentralized power generators can greatly help improving the reliability of the grid because they are not connected to the large scale transmission grid. Because of more and more energy trading the high-voltage transmission lines become congested. DG units could help unclog those lines too, which also helps to prevent “bottlenecks” in the transmission system. During the blackout, those areas and islands that were using DG units were little islands of light because they almost did not get affected by the blackout. This fact makes them also very usable for critical infrastructures like hospitals, telephone centers or banking centers because they are disjointed from the rest of the generation system. (White et al., p. 48)

At last, demand response programs and efficiency programs could have helped to avoid the blackout. Demand response programs are supposed to give an incentive to the consumers to “power off” during peak times. Practically speaking, this means that during peak energy demand times the prices per kWh go up, and the prices fall during low energy demand times. This gives the consumer a reason to use energy in times when the demand is low and save money. For the power grid, demand response programs can help relieve the transmission system during peak times. This can effectively help to use the transmission system more efficiently and also raises the reliability of the grid because transmission systems don’t have to be operated at the threshold of their capabilities during peak times anymore. During the blackout on August the 14th the New England ISO ISO-NE actually used a demand response reserve to help out the local power grid. So, if used on a larger scale, demand response could have possibly helped to avoid the blackout, or at least mitigate the constraints on the power system. (White et al., pp. 48–49)

Another way to help out the reliability of the system in the long run is efficiency programs. These programs are able to generally relieve the power system of some of the congestion. Unfortunately, so far there haven’t been enough incentives for efficiency programs to really have an effect. Naturally, most of the big energy suppliers are not really in favor of these programs because it would mean a loss of retail value for them. In the future, if combined with working incentive mechanisms, efficiency programs can help out the reliability of the power grid. (White et al., 48-49)

CHAPTER 2 THE EUROPEAN BLACKOUT

THE EUROPEAN POWER GRID

The European power grid is the biggest infrastructural entity in Europe. With over 305,000 km of transmission lines it is only slightly smaller than the North American power grid. But compared to the North American power grid, the European power grid serves nearly twice as many people with about 532 million customers. The grid has a net generation capacity of 880 GW and a consumption of nearly 3200 TWh. Where the North American power grid stretches only over two countries the European power grid assembles the power grids of 34 countries. (Entso-E, 2011) This is of course a very big organizational challenge that has to be operated with great care. In order to assure the maximum of stability and reliability, the 41 responsible transmission system operators (TSO) in 2009 formed together the European Network for Transmission System Operators for Electricity (ENTSO-E), which is now the organization that represents the interests of all the TSOs throughout Europe. (Entso-E, 2011) ENTSO-Es predecessor was the Union for the Coordination of Transmission of Electricity (UCTE). During the events of the blackout of 4th of November 2006 UCTE was still the organization in place and will therefore be referred to in the text.

The European power grid cannot be seen as one power grid. It actually consists of seven different power grids. This is due to technical differences in the power grids that only allow a connection between each other through direct current high-voltage transmission lines. The seven different power grids are:

- Continental European Synchronous Area
- Baltic Synchronous Area
- Nordic Synchronous Area
- British Synchronous Area
- Irish Synchronous Area
- Isolated System of Iceland
- Isolated System of Cyprus

  (Entso-E, 2011)

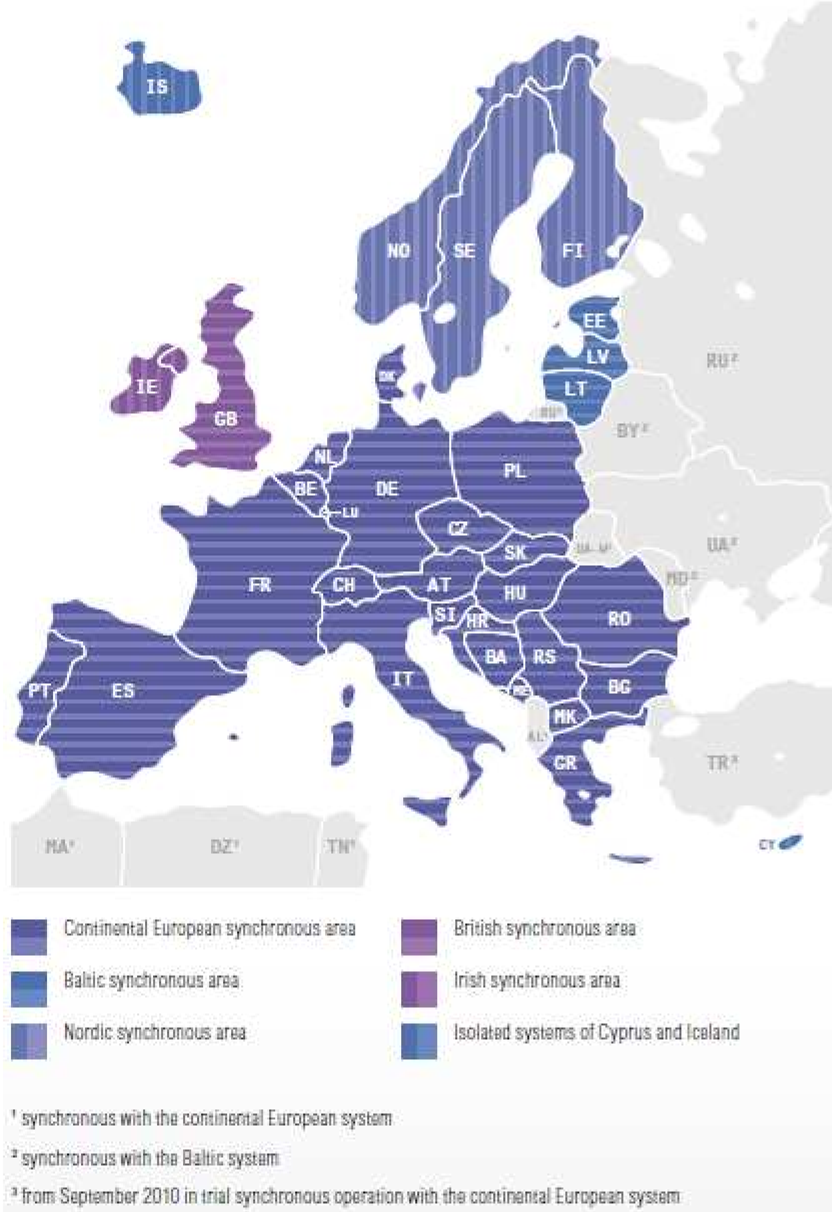

FIGURE 6 MAP OF INTERCONNECTED SYSTEMS

ENTSO-Es goals and duties are:

In line with Regulation (EC) 714 / 2009, ENTSO-E aims and mission is to promote important aspects of the EU's energy policy in view of significant challenges:

– **Security** – it pursues coordinated, reliable and secure operations of the electricity transmission network.

– **Adequacy** – it promotes the development of the interconnected European grid and investments for a sustainable power system.

– **Market** – it offers a platform for the market by proposing and implementing standardized market integration and transparency frameworks that facilitate competitive and truly integrated continental-scale wholesale and retail markets.

– **Sustainability** – it facilitates secure integration of new generation sources, particularly growing amounts of renewable energy and thus the achievement of the EU's greenhouse gases reduction goals.

(Entso-E, 2011, p. 4)

THE PROLOGUE TO THE BLACKOUT

The substantial events that initiated the blackout took place in northern Germany. On the 18th of September 2006 the shipyard "Meyerwerft" located in Papenburg on the Ems River requested from the local TSO, E.ON Netz, to switch off the double circuit 380-kV Conneforde-Diele transmission line on the 5th of November at about 1:00 hrs.. The request was done because the shipyard wanted to transport the ship "Norwegian Pearl" through the Ems River into the northern sea. The 380-kV Conneforde-Diele transmission line spans over the Ems River and therefore needed to be shut down, because the distance between the transmission line and the structure of the ship is too close to securely avoid contact with the ship. (Bundesnetzagentur, 2007, p. 5) It was also not possible to keep the line running because if powered on, transmission lines tend to sag down due to overheating because of the electrical load. (see page 5 "The Blackout") This was not the first request by the shipyard to shut down the transmission line in order to transport a ship through the Ems River. In fact, there have been 14 occasions in the past where this has been done without any problems. (UCTE, 2007, p. 17)

The next step for the local TSO E.ON Netz was to calculate if the N-1 criterion (see box above) is still fulfilled when the Conneforde-Diele transmission line is shut down. The standardized calculations of E.ON Netz showed that this will be the case. Next E.ON Netz provisionally agreed to the shutting down and informed the neighboring TSOs RWE TSO in the south and TenneT west in the Netherlands about this agreement in order for them to also check their systems for reliability and the fulfillment of the N-1 Criterion. This also turned up to be the case in both TSOs systems, even though the grid would be highly loaded. (Bundesnetzagentur, 2007, p. 5) In order to maintain absolute reliability standards TenneT and E.ON Netz still agreed on reducing the cross-border exchange by 350 MW from 0:00 hrs. until 6:00 hrs.. (UCTE, 2007, p. 17) Still the agreement to shut down the line stayed provisional because at the time of the request it was not possible for E.ON Netz to safely predict the system conditions for the 5th of November 2006 in advance. Therefore the final agreement had to be the substance of further analysis closer to the actual shutting down, which is standard procedure according to E.ON Netz. (Bundesnetzagentur, 2007, p. 5)

On the 4th of November 2006 TenneT further reduced the transmission capacity from Germany to the Netherlands because there was no feed-in from wind energy expected. (Bundesnetzagentur, 2007, p. 5) On the 3rd of November the shipyard asked E.ON Netz to advance the shutting down of the Conneforde-Diele transmission line by three hours to 22:00 hrs. on the 4th of November. E.ON Netz agreed to that because from their position this would fit in easier with predicted conditions on the grid. E.ON Netz then immediately did a calculation to ensure N-1 Criterion security, which came out positive. E.ON Netz then did not inform RWE TSO or TenneT about the new time for shutting down the Conneforde-Diele Transmission line. This meant they also weren't able to perform any kind of N-1 Criterion check. (UCTE, 2007, p. 18)

The first time E.ON Netz informed the other TSOs about the advanced timing for the shutting down was on the 4th of November between 18:00 and 19:00 hrs.. The then established cross-border exchange by TenneT could not be reverted by that time because of the auction rules for international energy trading. (Bundesnetzagentur, 2007, p. 6) The three TSOs decided to prepare for the heightened power flows that were expected, by changing the tap position on the phase shifter in Meeden which is part of the TenneT grid. (Bundesnetzagentur, 2007, p. 6) Additionally, there was no clue in the planning data of E.ON Netz that had been distributed to the other TSOs through the DACF. "DACF (Day Ahead Congestion Forecast) data and files are prepared by each TSO every day at around 18:00 for the coming day. UCTE is requiring 4 time stamps per day. E.ON Netz is providing 24 time stamps data for each hour and a half. These DACF files can be used by all UCTE TSOs to make security analyses on a larger basis than their "home" grid." (UCTE, 2007, p. 18)

Another important precondition is the construction work on the Borken substation by E.ON Netz that resulted in shutting down any east to west transmission in the region for the time being. The frequency in the area right before the start of the blackout was close to the nominal 50 Hz. (Bundesnetzagentur, 2007, p. 6)

Shortly before shutting down the Conneforde-Diele 380-kV transmission line E.ON Netz made an empirical evaluation that led them to assume that N-1 Criterion safety is fulfilled. They did not do a numerical calculation, even though this is mandatory for TSOs according to the UCTE operation handbook. The other TSOs, RWE TSO and TenneT, then agreed to shut down the Conneforde-Diele line, because as far as their calculations went they were safe, even though power flows are expected to be very high. (UCTE, 2007, p. 18)

THE BLACKOUT

On the 4th of November 2006 at 21:38 hrs., E.ON Netz switched off the first circuit of the Conneforde-Diele 380-kV transmission line. The power flows that were cut off now had to take a different route to the south. (UCTE, 2007, p. 19) A minute later they shut down the second circuit. Shortly after that E.ON Netz received several warning messages from the Elsen-Twistetal transmission line and the Elsen-Bechterdissen transmission line about too high power flows. Next, RWE TSO informed E.ON Netz about the safety limit value on the Landesbergen-Wehrendorf line, which serves as an interconnection between the RWE TSO area and the E.ON Netz area. The safety limit wasn't reached, but in jeopardy. (UCTE, 2007, p. 19) At 21:41 hrs. E.ON Netz issued the passage approval to the ship "Norwegian Pearl".

At 22:05 hrs. the Landesbergen-Wehrendorf line suddenly had to deal with a load increased by 100 MW. This also raised the current intensity by 160 Ampere (A), which led to breach RWE TSOs security limit value of the line. Shortly after that RWE TSO urgently demanded from E.ON Netz to take action to avert any further destabilization. E.ON Netz then decided to couple the busbars at the Landesbergen station in order to reduce the load by about 50 MW and 80 A of current intensity. Again they did not commit any type of N-1 Criterion analysis before this and also did not communicate any of this to RWE TSO. Against the expectations of the control staff at E.ON Netz this in fact did not decrease but increase the current intensity on the line by 67 A. This led to the tripping of the line by the distance relays due to overloading. (UCTE, 2007, p. 20) The tripping of the Landesbergen-Wehrendorf transmission line then led to a cascade of line-trippings all across Germany and Europe.

THE CASCADE

The cascade phase of the blackout started with the tripping of the Landesbergen-Wehrendorf transmission line at 22:05 hrs.. This initiated a chain-reaction of line trippings from the north to the south of Germany and then across Austria, Hungary, Croatia and other countries. In the end even the interconnection between Morocco and Spain was affected. The loss of these lines had a massive impact on the entire European grid of the UCTE. At 22:10hrs. it split the grid into three parts with different frequencies. (UCTE, 2007, p. 21)

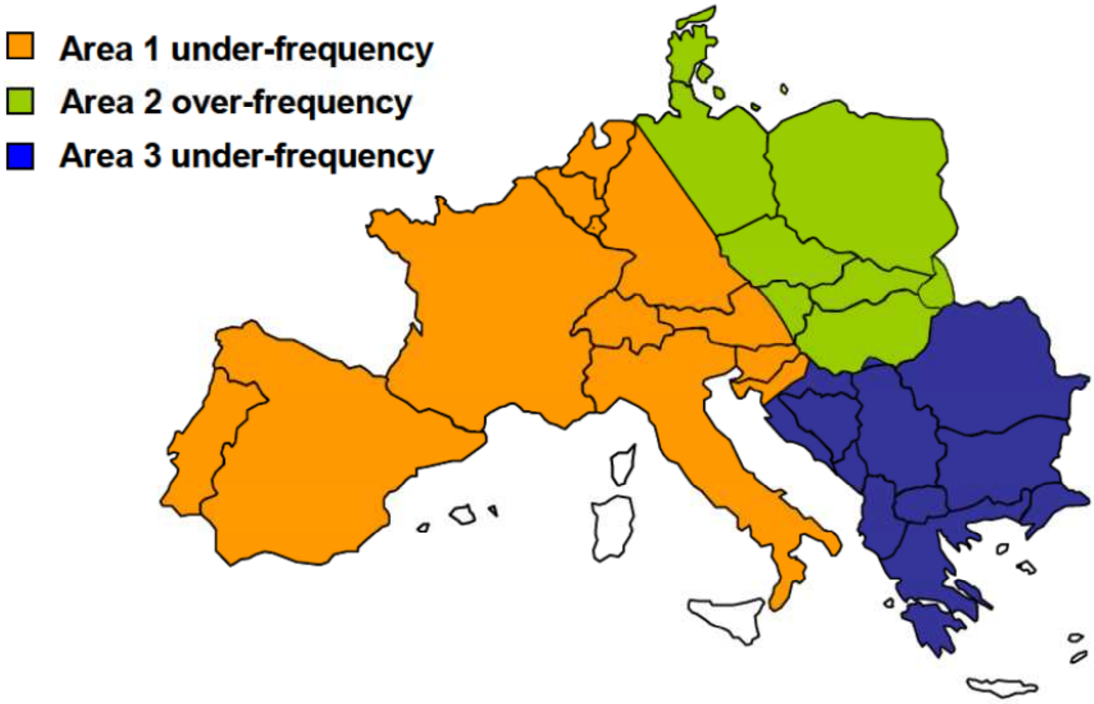

FIGURE 7 MAP OF THREE FREQUENCIES

Western Europe, from Portugal, Spain and Italy, over to the Alps and the Benelux countries, as well as half of Germany had an under-frequency in the power grid. In the northeast of Germany, an over-frequency was measured. This area stretched over Poland and the Czech Republic, to Slovakia and Hungary as well as Denmark. The third resulting area, also with an under-frequency, was the whole southeast of Europe with Greece, Bulgaria, Romania, Serbia, Bosnia, Albania, Croatia and Macedonia. (UCTE, 2007, p. 21)

The manual switching of the Landesbergen substation by E.ON Netz induced frequency oscillations that kept growing with each consecutive line-tripping. This then caused an imbalance in the power that was available in each of the three areas. The cutting off of the western area left that part with a lack of 9500 MW which was supposed to come from the eastern part. This caused a frequency decline to about 49 Hz. The missing 9500 MW, that weren't possible to be transmitted to the western part, caused the eastern part to suffer from a sudden big surplus in power, resulting in a very high over-frequency of about 51.4 Hz. The situation in the southeast was a little less dramatic, just a slight under-frequency, because of 800 MW of power missing, of 49.7 Hz was induced. (UCTE, 2007, pp. 22–23)

After the event many actions were undertaken to get the power grid under control again in the three different areas. This was done through load-shedding and generation tripping and the restarting or stopping of generation processes. (UCTE, 2007, p. 23) This process will not be described in detail in this thesis. Anyway it is important to mention that at about 22:47hrs. the transmission tie between area 1 and area 2 has been re-established and two minutes later at 22:49hrs. these two areas also reconnected to area 3. The re-synchronization took about 38 min. The full interconnection of the entire European power grid was done at about 23:57 hrs.. (UCTE, 2007, p. 45)

THE AFTERMATH OF THE BLACKOUT

The blackout from the European power grid on the 4th of November 2006 affected more than 15 million people all across Europe. (UCTE, 2007, p. 11) Compared to other European blackouts, for example in Italy in 2003 with more than 57 million people affected, the blackout from the 4th of November 2006 does not seem as grave. This is only because of the quick and successful handling of the situation from the affected TSOs after the cascade. The potential impacts of the blackout, considering that pretty much all of central Europe was affected, could have been horrific. Seen in that light, 15 million people affected for, at the most two hours, is a manageable figure.

SOLUTIONS TO THE BLACKOUT

Regarding the reasons for the blackout, the UCTE (respectively the ENTSO-E now) compiled a set of recommendations in order to avert future blackouts. These recommendations are strongly tied to the results of the investigation of the blackout from the 4th of November 2006. Another report that deals with the blackout and also gives recommendations for the future is the final report by the European Regulator's Group for Electricity and Gas (ERGEG). This is a former advisory group to the European commission that advised the commission on matters of energy regulation. The group was dissolved in the summer of 2011 and followed up by the Agency for the Cooperation of Energy Regulators (ACER).

The first recommendation that both reports give is that the not-fulfilling of the N-1 Criterion by E.ON Netz was key in the initiation of the events of the blackout. This of course resembles a human error in the control center of E.ON Netz. Instead of doing an N-1 analysis the staff at their control center did an "empirical" analysis in order to ensure the safety of the power grid. If they would have done a proper N-1 analysis, the insecurity of the system would have been uncovered and the transport of the "Norwegian Pearl" from the shipyard could have been delayed, ultimately resulting in the avoidance of the blackout. The UCTE Operational Handbook states "TSOs perform N-1 security analysis on a regular basis either automatically or manually and always when topology changes are planned or take place." (ERGEG, 2007, p. 8) This guideline is mandatory for all TSOs though not legally binding. Only national law is legally binding. For ERGEG this also implies that "“TSOs monitor at any time the N-1 criterion for their own system” (Policy 3, chapter A, requirement 1)" (ERGEG, 2007, p. 8). Still they see that this is an area in the UCTE operational Handbook that needs to be looked at. ERGEG demands that a regular analysis of the N-1 Criterion, and also stated how regular precisely, must be mandatory for all the TSOs.

Closely connected is also the need for a mandatory data exchange between TSOs in order to ensure that every N-1 Criterion analysis is carried out with the most up-to-date data on hand. This also needs to be put in to the UCTE Operational Handbook. (ERGEG, 2007, p. 9)

The next key miscue was the lack of proper communication between the TSOs. E.ON Netz communicated before the event with neighboring TSOs, RWE TSO and TenneT, about the situation. After the switching off of the Conneforde-Diele 380-kV transmission line, and the subsequent warning messages in the E.ON Netz control center about the reaching of the limit values for current on several lines, E.ON Netz had an exchange of information with RWE TSO. In this exchange RWE TSO did inform E.ON Netz about the reaching of the current limit on the Landesbergen-Wehrendorf transmission line. E.ON Netz did not take this information into further consideration when they decided on what actions to take in order to avert the tripping of the line. This is also a major cause for the blackout. Also TSOs should in general be informed about the different limit values on interconnecting lines between the areas of two TSOs. (ERGEG, 2007, p. 10)

The exchange of information and data about the systems of neighboring TSOs is also one of the recommendations by the UCTE: "UCTE has to develop standard criteria for regional and inter-regional TSOs co-ordination approach aiming at regional security management, from operational planning to real time, in terms of joint training, enhancement of exchanges of data, results of security analyses and foreseen remedial actions." (UCTE, 2007, p. 10)

Another important issue brought up by ERGEG is the lack of an information structure throughout Europe during the course of the blackout. Most affected TSOs were not aware about the origin or cause of the disturbance. "During the disturbance information about the reason for the disconnections and the consequences were scarce for TSOs. Many TSOs were not aware about the separation of the UCTE system into three areas, neither about the place of the disconnection, the borders of the areas formed, nor about the start and place of the recovery of the synchronous operation. Generally, however, the local information available to TSOs allowed for actions to limit the effects of the disturbance during the recovery time." (ERGEG, 2007, p. 10)

The third major complex of issues was the lack of control over the behavior of the generation of power by the TSOs. This is especially the case for decentralized power generation on the DSO level. Incentives are in place in order to help renewable energies to enter the market without too many barriers. Especially energy generated through wind mills is critical because of the unpredictable generation. This is in general a very strongly growing market that plays a more important role now. In this case, the TSOs need to have more information and also data about these decentralized generators so they can help them contribute to system security instead of hampering the system security through uncontrolled and unpredictable power generation. During the blackout, the uncontrolled generation of wind energy in the northeastern part with its high frequency resulted in an even more difficult situation for the TSOs than necessary. (ERGEG, 2007, pp. 11–12)

The UCTE indentified the same problem and also indicated that with wind power and also combined-heat-and-power-units generation increasing significantly, the problem of imbalance due to uncontrolled energy generation is growing. Therefore they also recommend that TSOs have control over these generators and that TSOs also should be regularly be informed about the generation schedules and changes. This can be found in one of their recommendations: "The regulatory or legal framework has to be adapted in terms of the following aspects:

• TSOs should have the control over generation output (changes of schedules, ability to start/stop the units)

• Requirements to be fulfilled by generation units connected to the distribution grid should be the same in terms of behavior during frequency and voltage variations as for the units connected to the transmission network. These requirements should be applied also to units already connected to transmission and distribution grids.

• Operators of generation units connected to the transmission grid must be obliged to inform the TSO about their generation schedules and intra-day changes of programs prior to their implementation.

• TSOs should receive on-line data of generation connected to DSOs grids (at least 1-minute data)" (UCTE, 2007)

CHAPTER 3 - COMPARISON OF THE CAUSES OF THE TWO BLACKOUTS

Both blackouts described earlier had (potentially) devastating outcomes for the countries involved. And in both cases the blackout could have been avoided if handled properly. This is truer for the European blackout than for the one in the USA and Canada.

The blackout in North America was caused by a mixture of computer failures, line tripping due to overgrown trees and human error. All of these causes could have been handled if there was a proper regulation in place that observes these contingencies. The key factor here was that all these causes happened at the same time, whereas a single contingency could have been dealt with, all three of them at the same time could not be dealt with.

Line tripping due to overgrown trees is a very common theme for TSOs. They have been granted the right-of-passage and to cut down any trees that intrude this space. Considering the many thousand kilometers of transmission lines in North America this seems like a very difficult situation to handle. FE, the responsible TSO here, uses a 5-year vegetation management plan. This means that they use a 5 year cycle to complete all relevant work that has to be done. This is the industry standard in North America. The vegetation management for TSOs around transmission lines is in most cases the highest recurring cost. (OECD/IEA, 2005, p. 155) This means that often, when TSOs have to cut back on their expenses, they are swift to lower the budget spend on vegetation management. This is of great concern considering that the lack of vegetation management was a main cause for the blackout. NERC did not offer any kind of standards or requirements for vegetation management at the time. After the blackout though, the Task Force identified several best practice examples for the vegetation management that included the implementation of a management framework, better operational practices, qualifications and education and also research and development. (OECD/IEA, 2005, p. 156)

The other technical cause was the failure of the computer system. Right before the start of the blackout the staff at FE's control room lost their computerized alarm system. This was even more crucial because they weren't aware of this loss. That a computerized system can be lost due to many reasons is something that everybody who is working with a computer knows. The actual problem here was the lack of communication in FE's staff. The IT personnel were already working on fixing the system, but did not inform operating personnel about that or even that the system was offline in the first place. So this cause is more about human error and miscommunication then about the loss of a computerized alarm system.

At last the most important failure was the lack of an adequate system understanding and the lack of situational awareness. FE did not perform any long-term planning studies of their system and did not show that they knew about their system and the weaknesses of their system. They did not have the tools to mitigate the events. Neither did they communicate well with the other neighboring TSOs nor with the responsible reliability coordinator (MISO).

The causes for the European blackout are not as spread out as the ones of the North American blackout. Here the causes can be pinpointed quite exactly on the mishandling of the situation in the control room of E.ON Netz. Especially the lack of communication with the neighboring TSOs is to be mentioned. E.ON Netz informed the neighboring TSOs too late about the change of time for shutting down the Conneforde-Diele transmission line, so that the neighboring TSOs couldn't react to the changed parameters. Also when RWE TSO informed E.ON Netz about the reaching of the security limit value for electrical current on the connecting Landesbergen-Wehrendorf transmission line, E.ON Netz did not inform RWE TSO about the further steps they were taking to avert an overloading of the line.

In both cases human error or the proper understanding of the grid played a major role. This is not supposed to show the lack of capable personnel in TSOs but the lack of a proper regulation framework to support the personnel. In North America this lack was also supported by other contingencies (tree trimming/computer failures) which then lead to the blackout. In Europe the blackout did not coincide with any other contingencies and could therefore be resolved fairly quick. Even though both events weren't similar they both showed similar causes and also similar weaknesses in today's multinational power grids.

CHAPTER 4 - DISCUSSION OF PROBLEMS AND SOLUTIONS

The next chapter will deal with the potential causes for the blackouts and their backgrounds. First, the impact of market liberalization will be discussed. Market liberalization is often referred to as potentially the reason for the blackouts. This accusation is going to be looked at in more detail. Next the emergence of renewable energies in Germany is shown. After that we will discuss Distributed Generation (DG) as a future concept for the structure of the power grid. Also DG, with the further emergence of renewable energy sources, is a concept that will probably gain a lot more importance in the near future. At last the lack of communication is going to be reviewed and recommendations on how to improve this in the future are made.

THE IMPACT OF MARKET LIBERALIZATION

Electricity markets have undergone fundamental changes in the last 25 years. They went from state-owned vertically integrated power utilities to privatized independent regionally active power utilities. Virtually all members of the International Energy Agency (IEA) have committed themselves to market liberalization until now. (Stridbaek, 2005, p. 27) In the traditionally federal U.S. there has never been a nation-wide regulatory framework for liberalization, so the decision whether or not to introduce market liberalization has been delegated to the states. This led to many states introducing limited liberalization reforms. (Paul L. Joskow, 2008) Generally, it can be said that the market liberalization has brought on many benefits for the countries committed to it. The economic benefits of market liberalization across all sectors has been recently assessed by the Organization for Economic Cooperation and Development (OECD) to between 1% and 3% of GDP in the United States and 2% to 3.5% of GDP in the European Union. (Stridbaek, 2005, p. 28) And this assessment doesn't even involve the dynamic gains from increased innovations. (Stridbaek, 2005, p. 28) Still, in many countries market liberalization reforms are incomplete and are not moving forward at the pace that was expected. (Paul L. Joskow, 2008) For the member countries of the IEA, the IEA emphasizes that the development towards complete and successful market liberalization is a work still in progress that will not be finished anywhere in the near future. Positive impacts are observed nonetheless. For example, in traditionally state-owned vertically integrated utilities there were always substantially high over-capacities. In liberalized markets this trend was reduced greatly due to greater efficiency. (Stridbaek, 2005, p. 29) Also the electricity prices for industrial customers in countries with a liberalized energy market have fallen as predicted. Same cannot be said for household customers. (Stridbaek, 2005, p. 29)

The blackouts in North America and Europe have raised a lot of questions about the reliability of supply in liberalized energy markets. After each blackout in recent years voices emerged that were skeptical about the liberalization and the benefits of it. In the minds of the skeptics a vertically integrated utility that handles all parts of the production chain, from generation to transmission to distribution, could have handled the situation better. The unbundling of the market through market liberalization has changed the decision-making. Decisions that were once done by single vertically integrated utilities are now done by many independent market participants. (OECD/IEA, 2005, p. 38)

With this unbundling and the installment of a liberalized market new usage of the transmission systems have emerged. Most important is the increase in long-distance transportation through inter-regional trade and cross-border exchanges.

Cross-border exchanges can also contribute to system stability and reliability. Through cross-border exchange utilities are enabled to share the reserves of adjacent utilities and therefore increase reliability. This is particularly important during emergencies with frequency issues and to reestablish a supply-demand balance. (OECD/IEA, 2005, p. 39) Issues that were both apparent in the two examples presented in this thesis.

Market forces in a competitive market also increased the efficiency of the involved utilities. Participants are held on to be very efficient in their behavior in order to stay competitive. This, and also the long-distance transportation of power due to the cross-border exchange, does have setbacks though. They force utilities to work closer to the limits of their capabilities. This is especially true for the loads transported on transmission lines. The margin for error grows a lot smaller because of the more efficient use. This is underlined by studies conducted by NERC and the UCTE in the recent history, showing that with further growth of inter-regional trade and low expansion of transmission capacity, systems will have to be operated even closer to the edge than before. This loss of a security margin has been a contributing factor to the situations that led to the blackouts. Still, the handling of the situation by the involved TSOs is what ultimately caused the blackouts. So it is clear that the operating environment for participants of power systems has to face new and different challenges since the market liberalization.

In both blackouts discussed in this thesis, no clear evidence shows that the liberalization of markets itself was the reason for the blackouts. Official investigative studies after the blackout by the North American Task Force and by the UCTE show that the reasons can be contributed more to the regulatory framework that is supposed to support the systems reliability. They definitely show that the need for better coordination and better cooperation between the many market participants is the pressing matter. After the blackouts in North America and in Europe, changes were made to attribute to this. The U.S. implemented legislative changes and the UCTE in Europe made their operational handbook now binding. Prior to this, agreements on both sides of the Atlantic have been only voluntary. (Stridbaek, 2005, p. 157) The question now is whether the monitoring of these new "rules" is enough or if the need arises to make the compliance legally binding. In both, the U.S. and Europe, the law in question is state, respectively country, law.

RENEWABLE ENERGIES

Renewable energies are taking up bigger and bigger pieces of the total energy generation in Germany. In 2011 renewable energies for the first time became the second biggest source of energy in Germany. (spiegel.de, 2012) The most power from renewable energies comes from wind generation, followed by biomass and hydropower. In 2010 the total amount of energy produced from renewable energies was at about 1.322 PJ. (BMWi, 2011) Renewable energies in 2011 have taken on a big role in the German energy mix.

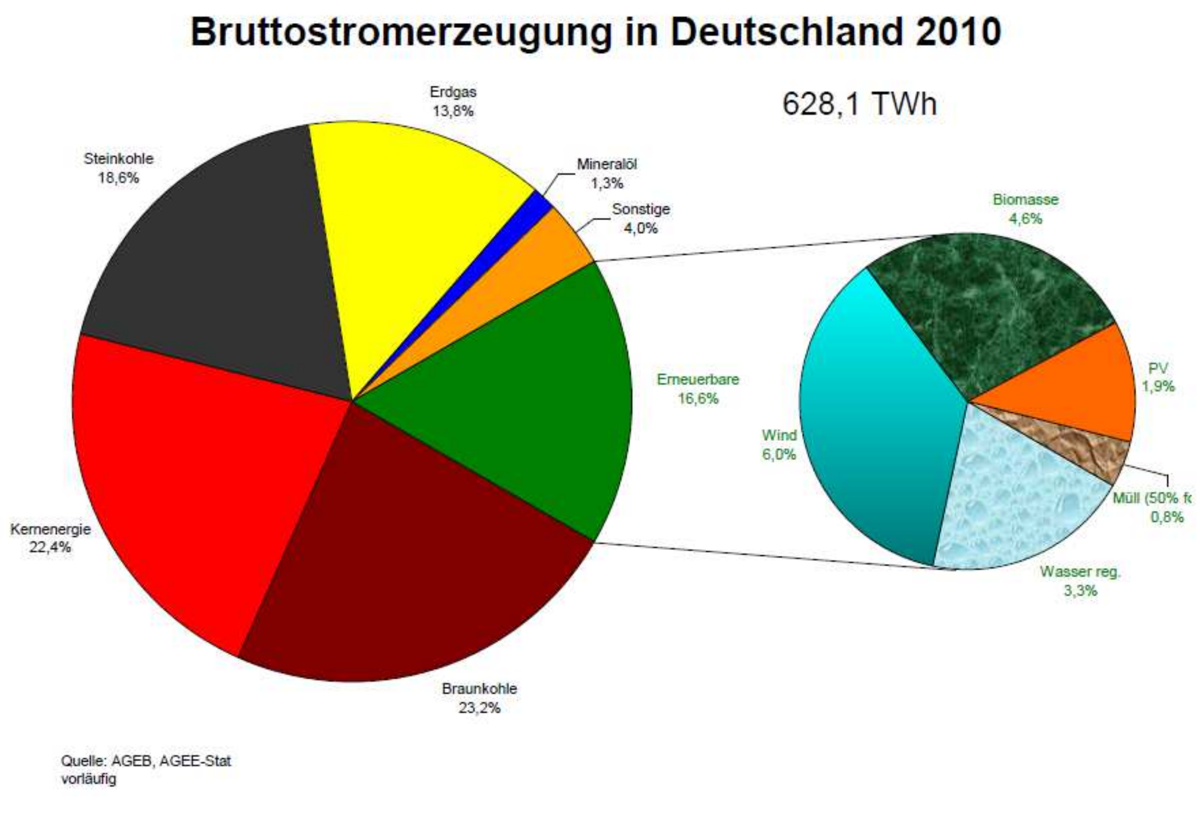

FIGURE 8 RENEWABLE ENERGIES IN GERMANY

There are also issues relating to this increase of renewable energies. The most important issue is the high volatility of power generation. (Boyle, 2009, pp. 5–6) This means that the generation of power from these sources is not predictable in terms of when and how much energy will be produced. The power and the time when winds occur for the generation of power from a wind turbine cannot be calculated sufficiently in advance. So the issue of high volatility is true for wind power but also for photovoltaic. The radiation from the sun is not as unpredictable as wind power but also a volatile power generation. The only steady power is coming from biomass and hydropower.

As said before, renewable energies, especially wind and photovoltaic are subject to high fluctuations in power generation. The energy laws in Germany state that the feed-in of renewable energies regardless of price or the time of generation is mandatory. Usually conventional plants like stone coal plants are used to equalize this. Volatile wind power is also often times generated in times when there is no need for more power e.g. at night. The power then cannot be used unless it gets stored.

Another general problem, especially for wind power generation in northern Germany, is that the points of consumption are usually far away from the point of generation. This results in a big issue because it puts a lot of pressure on the transmission system to distribute the power. Therefore, power grid operators need to find other ways to manage the load. In order to maintain system security load shedding is usually used. That means that they just dump power in order to avert system instability. Wind power, because of its volatile nature, gets shed a lot by system operators. In this case, potential renewable energies get wasted. (Schönfelder et al., 2009, p. 374)

The load shedding of power from renewable energy sources needs to be minimized in the future. New distribution systems like distributed generation and smart grids will be able to make more efficient use of the renewable energy sources that are available today.

DISTRIBUTED GENERATION

This chapter will introduce Distributed Generation (DG) as a possible mean to further increase system stability and reliability while at the same time increase the level of input from renewable energy sources. Before that we need to define specifically what is understood under the term distributed generation in this paper, because the definitions can vary strongly. In some cases only small CHP-plants that are right next to the source of consumption are counted as DG. (ETG-

Taskforce Dezentrale Energieversorgung 2020, 2007, pp. 11–12) The IEA defines DG as "Distributed Generation is a generating plant serving a customer on-site or providing support to a distribution network, connected to the grid at distribution-level voltages. It generally excludes wind power, since that is mostly produced on wind farms rather than for on-site requirements." (International Energy Agency, 2002) This definition also excludes large wind generation. The US Department of Energy has another definition, "Distributed Generation – small and modular electricity generators sited close to the customer load – can enable utilities to deter or eliminate costly investments in transmission and distribution system upgrades, and provide customers with better quality, more reliable energy supplies and a cleaner environment." (US Department of Energy, 2012) For this paper the combined definition from Manuel Sanchez Jimenez is used, "DG is the integrated or stand-alone use of small, modular electricity generation sources, installed within the distribution system or a customer's site by utilities, customers or any other third parties to meet specific capacity and reliability needs in applications that benefit the electricity system, specific end-use customers, or both." (Manuel Sánchez Jiménez, 2006, p. 67)

Distributed Generation is also known as "cogeneration" or "small power production". The basic principle of DG is to install small power generating units on site near the point of consumption, for example photovoltaic panels on the roof of a house. Also a combined heat and power unit in a hospital for emergency supply is DG. DG can be split up into three groups:

"• On-site DG includes photovoltaic solar arrays, micro-turbines, and fuel cells, as well as CHP, which are installed on-site, and owned and operated by customers themselves to reduce energy costs, boost on-site power reliability, and improve power quality.

• Emergency power units are installed, owned, and operated by customers themselves in the event of emergency power loss or outages. These units are normally diesel generation units that operate for a small number of hours per year, and have access to fuel supplies that are meant to last hours, not days.

• District energy systems are installed, owned, and operated by third parties, utility companies, or customers. These systems are often used in municipal areas or on college campuses. They provide electricity and thermal energy (heat/hot water) to groups of closely located buildings." (FERC, 2007, p. 33)

In the U.S. over 12 Million DG units were installed in 2005 with a total capacity of over 200 GW. (FERC, 2007, p. 5) Nearly all of these 12 Million DG Units are emergency generators in critical infrastructures like hospitals or photovoltaic arrays. None of these are connected directly to the distribution grid. (FERC, 2007, p. 6) The share of DG around the world in 2006 has risen to over

10 % of the total power generation according to the World Alliance for Decentralized Energy (WADE). (McConnico & Moore, 2006)

DG resembles a real opportunity for more stability in the power grid. The use of DG can have many benefits for the stability of the grid. One of the most important benefits of the DG is the ability to reduce the peak load. This means that structures that are equipped with a DG system can rely on those during peak times in order mitigate congestion on the large-scale transmission system. This also works perfectly together with the use of demand – response programs. This benefit is very important considering the fact that both of the blackouts displayed in this thesis showed that most of the transmission lines on the power grids are already running very close to their limits due to increased inter-regional power trade and other structural changes that came with the market liberalization. (FERC, 2007) So far DG has not been used much in a way that it also contributes to system stability and control. This is more due to administrative problems than to the ability of DG to do it. With a bigger share of DG connected to power grids, this situation has to change. Not only transmission system operators but also distribution system operators have to participate now actively in maintaining system stability. (Nick Jenkins, 2009, pp. 8–9)

To a certain degree, DG can replace new investments into transmission and distribution. This of course implies that the needed resources for DG systems are all locally available. "On-site production could result in cost savings in transmission and distribution of about 30% of electrical energy costs." (K. Purchala, Belmans, Exarchakos, & Hawkes, 2007, p. 4). This is also due to the savings in transmission and distribution losses that occur during long-distance transport of energy through transmission lines.

The integration of renewable energies and the end of nuclear energy in Germany is a complete reset of the entire energy infrastructure. At the heart of this are the climate change and the need to change the way we deal with energy, especially fossil energy sources. The reduction of fossil fuels in Germany can be supported by DG because many of the generators in DG are small Combined-Heat-and-Power (CHP) plants. These plants are very efficient and while producing power through burning gas also produce heat and therefore lower the need for additional house heating. The next step then is the connection of many of these micro-generation units to create a Microgrid for small settlements or suburban areas. (Chowdhury et al., 2009, p. 12) These are some of the advantages in Microgrids:

- Reduction in gaseous and particulate emissions due to close control of the combustion process

- Physical proximity of customers to the sources which increases awareness towards a more judicious energy usage
- Improvement of reactive support of the whole system
- Improvement of power quality due to
  - Decentralization of supply
  - Better match of supply and demand
  - **Reduction of the impact of large-scale transmission and generation outages**
  - Minimization of downtimes and enhancement of the restoration process through black start operations of micro sources
    (Chowdhury et al., 2009, p. 9)

These are only some of the advantages. For the topic of this paper the reduction of the impact of large-scale transmission and generation outages definitely stands out.

Another important benefit that could be derived from the use of DG is providing ancillary services. These services are the provision of reactive power as well as voltage support. Both these services were lacking in the blackouts. In the North American blackout there was a very high need for reactive power that could not be sufficiently granted. In the European blackout voltage support might have been able to avert the events. (FERC, 2007)

The last benefit mentioned here is the fact that for example in the North American blackout no DG systems were affected. They were actually islands of light during the hours of the blackout. This unaffectedness by large-scale blackouts is a great benefit. This makes DG especially important to critical infrastructures.

There are many other benefits with the use of DG that are not going to be mentioned in this thesis because of constraints of the scale of the thesis.

No doubt there are also many difficulties with the use of DG. The most important and most mentioned difficulty is of course the significantly higher cost of DG use compared to centralized power generation. "Moreover, different DG technologies differ from each other in that respect quite significantly, ranging from 1000 €/kW[3] for combustion turbines to over 20,000 €/kW for fuel cells. If these numbers are compare with the capital costs of large centrally managed power plants, 750 €/kW for gas-fired, 1300 €/kW for Integrated Gasification Combined Cycle (IGCC) and 1600 €/kW for nuclear, it can be noticed that the DG technology is quite expensive." (K. Purchala et al., 2007, p. 4). Higher prices in DG are also the case for the supply of fuel, if needed.

In order to be connected to the power grid, DG systems have to abide to some rules. One of these rules is that you always have to withdraw as much power from the grid as you want to inject into the grid in order to maintain the balance on the grid. If failed to adhere to this rule penalties will be enforced. This rule is especially difficult for DG systems that rely on renewable energies. These energies (e.g. wind energy) are very unpredictable in their power generation and therefore have many difficulties to maintain their balance. (K. Purchala et al., 2007, pp. 2–3)

The key for a better use of DG in the power grid lies in the integration of DG systems. Often times the TSOs do not have the ability to control DG systems. This can have negative effects on the whole system when DG units are not detachable. (FERC, 2007) Many TSOs have therefore tried to create incentives for DG system owners to allow the TSOs to control and operate the DG systems during peak load and also emergency times. If integrated properly DG systems can greatly affect the reliability of the power grid in a very positive way. So far power utilities are not using DG systems in any relevant way. This has to change in order for them to gather the know-how required for them to integrate DG in a beneficial way. The next steps in achieving this are outlined by FERC (2007):

"There are several potential “paths forward” for achieving this outcome. Among them are the following:

• State and regional electric resource planning processes, models, and tools could be modified to include DG as potential resource options, and thus provide a mechanism for identifying opportunities for DG to play a greater role in the electric system.

• Accomplishing this will require development of better data on the operating characteristics, costs, and the full range of benefits of various DG systems, so that they are comparable – on an equal and consistent basis – with central generation and other conventional electric resource options.

• This task is complicated somewhat because calculating DG benefits requires a complete dataset of the operational characteristics for a specific site, rendering the possibility of a single, comprehensive analysis tool, model, or methodology to estimate national or regional benefits highly improbable.

• Efforts by the States to implement the requirements posed by Subtitle E – Amendments to PURPA of the Energy Policy Act of 2005 will likely affect the consideration of DG by the electric power industry, particularly those provisions that promote smart metering, time-based rates, DG interconnection, demand response, net metering, and fossil fuel generation efficiency." (FERC, 2007, p. 7)

Distributed Generation is already part of the energy infrastructure for some time now. Climate Change and the connected issues like the consumption of fossil fuels have pressured countries to introduce a far bigger percentage of renewable energies into their energy mix. In Germany the dynamic of the change is even greater because of Germanys exit out of nuclear energy. Renewable energy sources usually do not get generated in large plants but in small decentralized units. Therefore DG systems are lying at the heart of the future development of energy distribution and generation not only in Germany but all around the world.

INFORMATION AND COORDINATION

The energy market changed a lot over the last 25 years. The market liberalization had many impacts on the structure of the energy market. Especially the unbundling of formerly vertically integrated utilities created many new challenges. Power grids are now divided into many parts, each part controlled by a different utility. The former agglomeration of power within the system to only a few utilities has now diverted into a widespread collection of very different players. With that comes also the spreading of responsibilities. This inherits some serious issues for the reliability of the power grid as a whole. The blackouts described in this thesis both show that the failure of one utility can within seconds become the problem of neighboring utilities or for the entire power grid. Therefore the key for a reliable operation of the power grid is coordination and the exchange of information.

Especially the exchange of information will play a key role in the future. The successful management of an electricity grid is a very demanding task. Information about the status of different grid operations pours in on system operators from all sides. This big load of information has to be managed correctly at all times because even slight miscues can have enormous effects on the grid. This was the case in the European example when the lack of information, resulting from insufficient communication from a TSO (E.ON Netz), resulted in a major Europe-wide blackout. So the availability of grid information is crucial for the reliability of the power grid. The information situation gets even more complicated when you introduce renewable energy sources into the picture. This is due to the unpredictable power generation from wind and solar energy. Both sources are not entirely predictable. The German "Erneuerbare-Energien-Gesetz" (EEG) makes the feed-in of power generated from renewable energy sources mandatory. Therefore, the system operators have to manage the load on the grid through real-time assessment of the energy generation at any time. This is most of the time done by IT-supported assessment systems. These systems can only function properly when they are supported by the best available information.

CONCLUSION

For the economies of the world to function properly it is very important that the needed energy is always available and ready to be served. The power grids do that. Therefore they are a very crucial infrastructure that needs to be working at any times with absolute reliability and stability. As both of the examples in this thesis show, this is a very challenging task for the system operators. Many different influences can jeopardize the integrity of the power grids. As the case studies show, this can be overgrowing trees as well as the failure of automated computer systems, or just simply a lack of communication. These difficulties get even more amplified if you take the market liberalization into the equation. Market liberalization in general, brought many benefits for the customers. It also put a great burden on the power grids. The exchange of power between countries increased greatly. Due to the unbundling of former vertically integrated utilities there was also a large increase in the players involved in the power grids. Both these changes consequently started to push the transmission loads closer to the maximum capacities. Even though there was also a lot of investment into new transmission capacities they still had to operate their lines even closer to their capabilities. The existing power grid was never laid out to cope with these challenges.

The inherent complexities of the power grid together with the requirements of the market liberalization lead to a lot of possible areas of failure.

In times of a big surge towards renewable energies the power infrastructures need to accompany that. Old-fashioned power systems infrastructures with big generation plants and no active management plans for the distribution networks are not only out of fashion but simply cannot handle the expectations that are put on them through these new generation possibilities. The concept of distributed generation can no longer be only understood as a little generation extra to the rest of the network but as an integral part of the network. DG is not yet ready to lift the burden of system stability, e.g. providing voltage and frequency control, but starts to contribute to that. This has to be acknowledged by all connected players. Certainly this cannot change overnight.

The mid-term future will be a hybrid energy grid that uses large centralized energy plants and decentralized energy systems in a balanced system that is strongly interspersed with renewable energy generation on the local DG level as well as on the level of medium-sized generation plants (e.g. offshore wind parks).

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TABLE FOR FIGURES