MSc Program
Renewable Energy Systems

Renewable Energy Microgrids - Enhancing the Resilience of Critical Infrastructure through Microgrid Facilities and Renewable Energy Systems

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Vienna, 15.10.2018

Affidavit

I, **MAG. MARKUS AMATSCHEK, MBA**, hereby declare

1. that I am the sole author of the present Master's Thesis, "RENEWABLE ENERGY MICROGRIDS - ENHANCING THE RESILIENCE OF CRITICAL INFRASTRUCTURE THROUGH MICROGRID FACILITIES AND RENEWABLE ENERGY SYSTEMS", 99 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Abstract

The risk of electricity outages caused by natural disasters, cyberattacks, or physical attacks seems to increase, despite high standards for security of supply in Western Europe. At the same time the importance of electricity for public, economic, and social well-being has increased during the last decade with accumulative dependencies on IT-systems. Proven methods of blackout prevention or mitigation focus on short period of power outages experienced by households and business in the local distribution network. The more unlikely event of a large-scale blackout for a period of days brings traditional methods including emergency diesel generators sets to its limits.

Renewable energy microgrids can improve the resilience of critical infrastructure, assets with greatest importance for the public and national security, and reduce the impact of blackouts. Under certain conditions the additional investment in distributed energy resources, storage and microgrid management systems could contribute to operational improvements.

For a hypothetical military base of the Austrian Armed Forces with critical infrastructure the thesis investigates under which conditions it is feasible to build and operate a renewable energy microgrid to provide sufficient generation for its electrical load and remain islanded in the event of blackout for ten days and to reduce operational cost during standard grid-connected operation.

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1 INTRODUCTION

Austria enjoys an exceptional level of security of supply of all types of energy. In 2017 network customers in Austria experienced less than 38 minutes of interruptions of which about 25 min were unplanned interruptions.[1] Despite the very high standards for security of supply the risk of longer outages of electricity on a European scale are increasing. The vulnerability of our complex energy system to natural disasters, cyberattacks, and physical attacks is of growing concern to decision makers in governments as well as business. United States (U.S.) government departments have increased awareness and their assessment concerning the source of the threat: "*The cyber threat to critical infrastructure continues to grow and represents one of the most serious national security challenges*".[2]

At the same time the importance of electricity for public, economic, and social well-being has augmented during the last decade with accumulative dependencies on IT-systems. The importance of production and distribution of electricity will upsurge further with the process of electrifying large shares of the mobility and heat sector as part of the next phase of the energy transition.

Proven methods of blackout prevention or mitigation focus on short period of power outages experienced by households and business in the local distribution network, uninterruptible power supply (UPS), flywheels, small battery systems, or generators sets are commercially available and are widely used by key customers in the Vienna area.

However, the more unlikely event of a large-scale blackout for a period of days represents a new challenge. Chief Security Officers of large Austrian corporations

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[1] Energie-Control Austria (2017): Ausfalls- und Störungsstatistik für Österreich – Ergebnisbericht 2016. e-control, Wien

[2] Department of Homeland Security (2013): Fact Sheet: Executive Order (EO) 13636 Improving Critical Infrastructure Cybersecurity and Presidential Policy Directive (PPD) 21 Critical Infrastructure Security and Resilience. https://www.dhs.gov/sites/default/files/publications/eo-13636-ppd-21-fact-sheet-508.pdf visited on 8th August 2017.

and governmental organisations stated during a workshop on blackout mitigation, that traditional methods cannot be easily scaled from covered outage periods of two hours to blackout scenario of more than three days. Cost concerns, technical and operational restrictions, such as storage of fuels, and availability of personnel, are the hurdles these entities face.[3]

Renewable distributed resources on regional scale, also referred to as renewable energy microgrids, present a viable alternative due to progress in technology and attractive cost curves.

Microgrids supplied with wind, water or solar power, “Renewable Energy Microgrids” can improve the resilience of critical infrastructure, assets with greatest importance for the public and national security, and reduce the impact of power outages or blackouts. Under certain conditions the additional investment could contribute to operational improvements.

This thesis supports the idea of the microgrid based on renewables for the military sector as an instrument to increase resilience of an element of the armed forces.

The main hypothesis states that this model of a specific renewable microgrid can prove its economic viability by reducing operational cost during standard grid-connected operation and financing the investment over a 20 year period.

For the development of the model, the basic theoretical concepts are reviewed: resilience, critical infrastructure, crisis management, and renewable energy systems.

Causes and probabilities of power outages are explained in Chapter 3 followed by conclusions that can be derived from their characteristics for microgrids. The technology and elements of microgrids are described in Chapter 4 followed by lessons learned in the U.S. from the SPIDERS program, Smart Power Infrastructure Demonstration for Energy Reliability and Security, that can be seen as state of the art microgrids in combination with renewable energy systems and storage used for critical infrastructure sites.

From a technical point it is imaginable already today to build and operate a renewable energy microgrid for a hypothetic base of the Austrian Armed Forces. The technical elements and the associated costs provide sufficient generation for its minimum electrical load and remain islanded in the event of blackout for a certain period are described. Based on the hypothetic site of the armed forces the last

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[3] Resilienz Network Austria: Plötzlich Blackout! Kick Off Workshop und Synergiekonferenz, Mai 2014.

chapter aims to enlighten whether renewably energy microgrids enable operators of critical infrastructure to optimize normal operation and regain the additional investment for appropriate precautions for blackout scenarios.

A model microgrid is developed with photovoltaic (PV) energy, storage, and load management as a method of approach to answer the research question. Based on the cost outcomes of the model, the share of the initial investment that can be recovered from new revenue streams will be assessed.

1.1 Resilience

Resilience is a term which has its origin in medicine and psychology and is used in everyday language according to the Merriam-Webster dictionary. Resilience is defined as

“1 : *the capability of a strained body to recover its size and shape after deformation caused especially by compressive stress*

2 : an ability to recover from or adjust easily to misfortune or change.”[4]

The concept has found its way into crisis management since it has become more and more clear that modern society cannot protected against all types of threats, given its growing complexity, cumulative interdependencies and unpredictability of risks. Hence resilience is defined by Charlie Edwards as the “…*capacity of an individual, community or system to adapt in order to sustain an acceptable level of function, structure, and identity*.”[5]

In the case of renewable microgrids the electricity system suffers a severe negative external effect and has the ability to stay stable or to recover to normal state after a severe blow to a given system. This ability to “bounce back” makes the difference between survival or communities and complimenting systems falling apart as described by Zolli and Healy.[6]

Resilience has become integral part of all crisis strategy and depends on four principles called “”R4-Framework“:[7]

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[4] Merriam-Webster (2017): Resilience https://www.merriam-webster.com/dictionary/resilience visited on 14th August 2017.

[5] Charlie Edwards (2009): Resilient Nation. Demos. London. p. 20.

[6] Zolli A., Healy, A. (2012): Resilience: Why Things Bounce Back. Free Press. New York.

[7] Trachsler D. (2009): Resilienz: Konzept zur Krisen- und Katastrophenbewältigung. CSS Analysen zur Sicherheitspolitik Nr. 60. Center for Securities Studies. ETH Zürich.

- Robustness: the ability of a system to withstand extraordinary strain for a longer period.
- Redundancy: the existence of alternative means to fulfil critical functions of a system.
- Resourcefulness: the capacity of system to find creative and appropriate reaction to an event of disaster.
- Rapidity: the time needed for a first reaction.

These “principles for protection” form the basis for strategies for governments, communities, and businesses and will guide this thesis to find a model for the resilience of assets of critical infrastructure.

1.2 Critical Infrastructure

Infrastructure in common language is defined as “*the basic structural foundations of a society or enterprise*” or “*roads, bridges, sewers, etc. regarded as a country’s economic foundation*”.[8]

These basic facilities and services are fundamental for a community or a society as whole, a section is of superior priority for a nations public and economic activity and is called critical infrastructure. The specific definition is formulated in legally binding acts and are compared between the EU and our reference U.S..

1.2.1 U.S. National Strategy for Homeland Security

The national strategy for the security of the U.S. demands the “*protection of the American people, our critical infrastructures, and key resources and outlines three specific goals for critical infrastructures protection: deter the terrorist threat; mitigate the vulnerabilities; and minimize the consequences*.”[9]

The definition of critical infrastructure (CI) in the U.S. is based on the Patriot Act passed by the U.S. Congress in the aftermath of the terrorist attack on 11th September 2001 in New York. CI is described as “*those assets, systems, and*

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[8] Hughes. J.M. ed. (1993):The Australian Concise Oxford Dictionary. Government Appoved as a standard Australian Dictionary. Melbourne. p. 579.

[9] Homeland Security Council (2007): National Strategy for Homeland Security, p. 1.

networks that, if incapacitated, would have a substantial negative impact on national security, national economic security, or national public health and safety."[10]

CI provides the backbone of the nation's economy, security, and health; the Presidential Policy Directive PPD-21 defines 16 sectors, at its centre Communications, Transport, Water with multiple dependences to the energy industry as shown in the figure below.

For most of the sectors the Department of Homeland Security is viewed as the primary responsible agency.[11] For the energy sector the Department of Energy coordinates all efforts including those energy issues of the military branches, which is of importance for the activities around microgrids, an explicit measure to improve resilience.

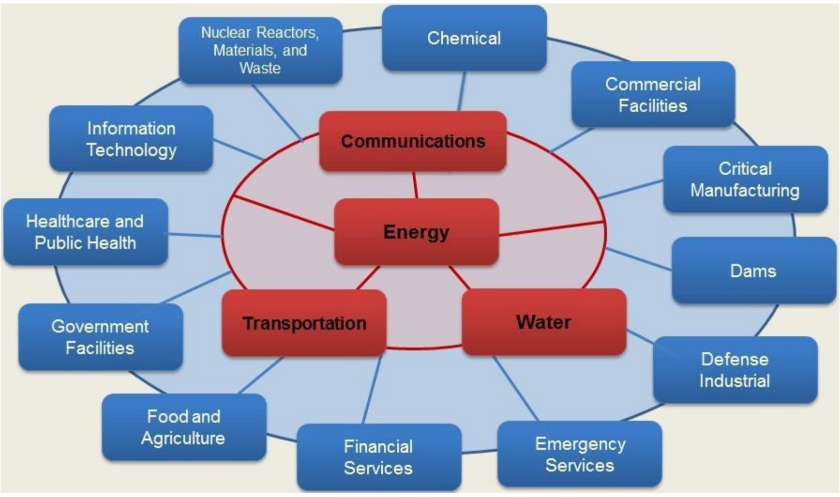

Figure 1-1 Critical Infrastructure Sectors and its Dependencies with Energy Sector[12]

The DOD has the responsibility for its share of public works such as water and energy, where the U.S. Corps of Engineers (the Corp) coordinates construction,

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[10] U.S. Congress (2001): Patriot Act of 2001, Section 1016 (e). https://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=107_cong_public_laws&docid=f:publ056.107.pdf visited on 21st August 2017.

[11] Homeland Security Council (2007): National Strategy for Homeland Security, p. 27.

[12] U.S. Department of Home Land Security Council (2015): Energy Sector-Specific Plan. Washington. p. 19.

operations and maintenance. The Corps oversees 75 hydropower facilities with annual production of 100 TWh or more than 25% of the national hydropower.[13]

The focus of critical infrastructure protection (CIP) is to prevent terrorist attacks, the physical attacks or cyber-attacks. The national threat assessment is reflected in the programs and measures taken by the DOD and Department of Energy (DOE) to secure the energy sector.

1.2.2 Programme for European Critical Infrastructure

The European Union (EU) started a program to protect critical infrastructure in 2004 and created the legal basis with "The European Critical Infrastructures Directive". Directive 2008/114/EC9. §2 defines critical infrastructure as:

> "*an asset or system which is essential for the maintenance of vital societal functions. The damage to a critical infrastructure, its destruction or disruption by natural disasters, terrorism, criminal activity or malicious behaviour, may have a significant negative impact for the security of the EU and the well-being of its citizens*."[14]

The legal framework differentiates between "European Critical Infrastructures"[15] that are of "highest importance for the Community and which if disrupted or destroyed would affect two or more member states" and "National Critical Infrastructures". Based on the principle of subsidiary each Member State must develop its own national CIP programme. [16]

One of four focus areas of European Programme for European Critical Infrastructure Protection (EPCIP) represents energy including the high-voltage electricity grid, the interconnected national high-voltage electricity grids, and production facilities. Due

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[13] U.S. Coprs of Engineers (2017): Going Green: Corps hydropower is clean, reliable, efficient, flexible, renewable and sustainable. http://www.usace.army.mil/Media/News-Archive/Story-Article-View/Article/478053/going-green-corps-hydropower-is-clean-reliable-efficient-flexible-renewable-and/ visited on 10th December 2017.

[14] European Commission (2008): Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection. Official Journal of the European Union, L345/75. Brussels.

[15] European Commission (2004): Communication of the European Commission on a European Programme for Critical Infrastructure Protection

[16] European Commission, Migration and Home Affairs: Critical Infrastructure, https://ec.europa.eu/home-affairs/what-we-do/policies/crisis-and-terrorism/critical-infrastructure_en visited on 27th August 2017.

to these interdependencies, the energy sector must ensure a high degree of protection enhancing the resilience of the whole critical infrastructure system.

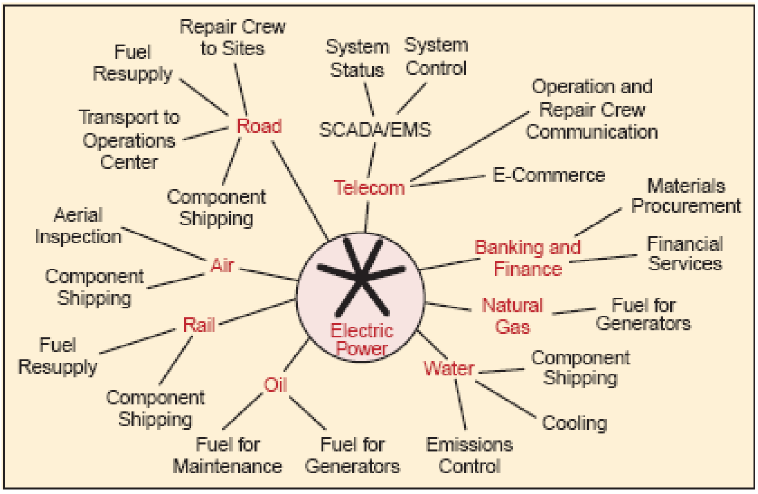

Figure 1-2 Electric Power Interdependencies[17]

1.2.3 Critical Infrastructure Protection in Austria and Electricity

Critical infrastructure protection is part of the national crisis and disaster protection management strategy as defined in the guidelines “Staatliches Krisen- und Katastrophenmanagement (SKKM) Strategie 2020” developed by the Ministry of Interior. Large power outages are assessed as relevant risk with all is secondary effects and the energy systems with energy production and distribution is defined as part of the national critical infrastructure.[18]

The task of engaging or mitigating the effects of disasters is within the area of responsibility of the federal provinces in Austria. The respective provincial laws define the main responsibilities for relief operations within municipalities, districts and federal provinces.[19] The coordination function in case of disasters is organised within the Federal Alarm Center (FAC) and its Operations and Coordination Center (EKC) or “Bundeswarnzentrale”.

In case of European blackouts, the EKC communicates to international organisations such as the ERCC (Emergency Response Coordination Centre of the European Commission) and the EADRCC (Euro-Atlantic Disaster Response

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[17] European Commission (2013): Commission Staff Working Document on a new approach to the European Programme for Critical Infrastructure Protection Making European Critical Infrastructures more secure. Brussels. p. 3.

[18] Bundesministerium für Inneres (2009): Staatliches Kirsen- und Katastrophenschutzmanagement. Republik Österreich, Wien. p. 7f.

[19] Bundesministerium für Inneres (2013): Staatliches Krisen- und Katastrophenschutz-Management - Rechtliche Und Organisatorische Grundlagen. 2nd edition. Abteilung II/4, Wien. p. 22.

Coordination Centre) as part of NATO’s Partnership for Peace and information of authorities in Austria. A wider or national warning by the EKC using the warning and alarm signals of 8000 fire brigade signals has been discussed for years in case of a blackout. The alarm could enable organisations and citizens to take advantage the first hour after a blackout, the “golden hour”, for their own protection measures.

While the “SKKM” focus on disaster prevention and relief by authorities, the Austrian Program for Protection of Critical Infrastructure is more specific on risk management and security management of defined critical infrastructure. Protection and resilience are the objectives of the APCIP, which is defined as responsibility of those governmental or business organisation that build and management elements of critical infrastructure (“Operator based approach”).[20] According to the principle of proportionality the cost for achieving a certain level of protection must be in a levelled relation to the risk and likelihood of prevention.

In relevant public strategy documents electricity is mainly mentioned as “leitungsgebundene Energie” or grid-based energy. Consequently, measures focus on preventive or management instrument of energy crisis of operators or physical protection of energy assets such as grid lines, power plants or transformers.[21] The “Energielenkungsgesetz”, the legal basis for intervention in energy markets, offers a variety of competences including governmental orders to market participants on their production or consumption behaviour including disconnection of certain areas or energy consumers.[22]

Also, the concept of national grid restoration focuses on the role of the transmission system operator (TSO) and the distribution system operator (DSO) while end users of electricity play only limited role in a case of blackout and have to rely vastly on the efforts of grid operators. The concept of microgrids for resilience for users of electricity or even its assistance to restore networks could not be found in these documents.

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[20] Bundeskanzleramt Österreich (2015): Österreichisches Programm zum Schutz kritischer Infrastrukturen (APCIP), Masterplan 2014, Sektion IV – Koordination, Wien. p. 8f.

[21] Bundesministerium für Wissenschaft, Forschung und Wirtschaft (2017): Krisenvorsorgemanagement. Gut vorbereitet: Bestandsaufnahme und Bewältigung möglicher Krisenszenarien im Bereich Energie und Bergbau, Wien.

[22] Friedl, W. (2010): Krisenvorsorge in der Elektrizitätswirtschaft. 11. Symposium Energieinnovation, Wien. p. 15f.

1.2.4 Military Strategy in Austria and Role of Energy

As stated in the Federal Constitutional Law of Austria, the main purpose of the Austrian Armed Forces is the military defence of Austria in the form of a militia system.

In addition to military defence, the Armed Forces must

> *"…protect the constitutionally established institutions and the population's democratic freedoms… maintain order and security inside the country…[and] render assistance in the case of natural catastrophes and disasters of exceptional magnitude."*[23]

The "Military Strategic Concept 2017" emphasises that the military can be called upon especially for disaster relief operations under the frame of the national crisis and disaster protection, as in the case of blackout. The armed forces are labelled as strategic reserve for suppling the population and secure command and control for the political echelons. [24]

In respect to critical infrastructure "electricity" the armed forces improve their own capabilities and resources to:

- protect and restore critical infrastructure such power lines, transformator stations, control centre;
- support civil organisation in case of disasters such as blackouts; and
- to provide its facilities for command and control.

Practical experience with a localized blackout in the aftermath of an ice storm in Slovenia demonstrated the need for, but also the the limited capabilities of a civil and military organisation in central Europe.[25]

A detailed list of requests for assistance from civilian organisations and the army's capabilities is discussed in a series of articles by experts for blackout and cybersecurity.[26] Consequently, the armed services must be operational even if the

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[23] BGBl. I Nr. 146/2001 Wehrgesetz 2001, § 2

[24] Österreichisches Bundesheer (2017): Militärstrategisches Konzept. GZ. S92000/183-GStb/2017. Generalstab ÖBH. Wien.

25 Gutmann, G.: Blackout in Slowenien 2. TRUPPENDIENST - Folge 340, Ausgabe 4/2014. http://www.bundesheer.at/truppendienst/ausgaben/artikel.php?id=1733 visited on 6th August 2018.

26 Saurugg, H., Ladining, U. (2014): Blackout Selbsthilfefähigkeit. TRUPPENDIENST - Folge 328, Ausgabe 4/2012 http://www.bundesheer.at/truppendienst/ausgaben/artikel.php?id=1418 visited on 7th August 2018.

critical infrastructure, such as electricity, is interrupted and the strategic concept requires personnel and material readiness with autarch structures.[27]

According to the structure defined in the concept “Landesverteidigung 21.1” the forces can rely on 14,000 soldiers, almost 10,000 civil employees, and 25,000 militia soldiers in about 80 garrisons.[28] Some of these garrisons must be prepared not only for the military operational requirements including force protection but also as an “island of security” (“Sicherheitsinsel”) for civil organisation. The responsible branch for energy management is situated within the military facility management centre, “Militärisches Immobilienmanagementzentrum,“ and has started activities for energy efficiency and autarchy. However, budgets and project support were limited due to general austerity programs for the armed forces and some basic capabilities (transport, storage capacities, mobility, provision of rations) were reduced in the last 5 to 10 years within the Military Command.

1.3 Renewable Energy Systems

Traditional energy systems for electricity are built on central generation in large scale power plants, transmission via high voltage (HV) power lines and distribution from substations of the distribution system operation to the consumers. Majority of production capacity is mainly based on fossil fuels and large-scale hydro plants. Despite the liberalisation of market for electricity in Austria the players consisted mainly of state-owned incumbent producers and sellers of electricity until about 2010. With increasing numbers of smaller producers of REN also the market concentration has decreased with more than 140 suppliers.[29]

The renewable energy system is built on:

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27 Österreichisches Bundesheer (2017): Militärstrategisches Konzept. GZ. S92000/183-GStb/2017. Generalstab ÖBH. Wien. p. 11.

[28] Bundesministerium für Landesverteidigung (2018): Die Standorte des Österreichischen Bundesheeres: http://www.bundesheer.at/organisation/standorte/index.shtml visited on 4th August 2018.

[29] E-Control (2018): Lieferanten im Vergleich. https://www.e-control.at/konsumenten/strom/lieferanten-uebersicht visited on 6th October 2018.

- a variety of renewable production plants from small scale such as photovoltaics at private homes to large off-shore power plants and hydro power plants;
- distribution on all levels of the network and not centrally controlled;
- a mechanism to integrate variable production of renewables into the market maintain the quality of energy systems.

The EU's Directive on the promotion of the use of energy from renewable sources defines renewable energy as "*energy from renewable non-fossil sources, namely wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases.*"[30]

In most countries of the EU introduction of renewable energy (REN) is encouraged with support schemes, but some technologies have made great progress on the learning curve. According to the Fraunhofer Institut für Solare Energiesysteme (ISE) renewables achieved a remarkable share in the first half of 2018 in the German electricity market: PV and wind produced more than 77 TWh electricity in Germany and exceeded power production of lignite with 66 TWh. The used capacity is even more impressive at certain point of times of the load curve: PV achieved a maximum load of 31 gigawatts (GW) on 6th May 2018 at 13.00 hrs, maximum feed-in of wind was measured on 3rd January 2018 at 21.30 hrs with 43,3 GW while total load in Germany was below 73 GW.[31]

REN is on the edge of being cost competative with fossil production plants and near grid parity for certain situations on network level 7. On large scale the indicators for cost competitiveness are the tendering results in Germany published by the German regulator BNetzA. The last tendering process for onshore wind in August 2018 resulted in average feed-in prices of 6,16 ct/kWh, while average results for PV in June 2018 were at 4,59 ct/kWh.[32] Both values are higher than the previous round and the industry has still to prove that plants can be built and operated at that cost point.

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[30] European Union (2009): Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources, Brussels, p. 11.

[31] Montel (2018): Wind, PV überholen im H1 beim Strom erstmals Braunkohle. Montel News https://www.montelnews.com/News/Default.aspx?497 visited on 6th October 2018.

[32] Bundesnetzagentur (2018): Ausschreibungen für EE- und KWK-Anlagen, https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/Ausschreibungen/Ausschreibungen_node.html visited on 6th October 2018.

The progress of renewables opens opportunities, not only for the energy system on national level, but also for individual buildings or small areas to build up their own energy supply. The system is connected to the DSO to exchange surplus and supply electricity in case of higher load than production. Cost points for roof top installations of PV for business are certainly above large-scale installations, according to own projects contracting prices below 10ct/kWh are possible, which represents grid parity at EEX price levels in mid-2018.

Austria benefits from installed capacity of hydro power and boasts more than 70% renewable energy of total energy supply on a yearly balance. At a closer look the coverage of the Austria load depends on imports and thermal energy production during the winter months as shown in the figure below.

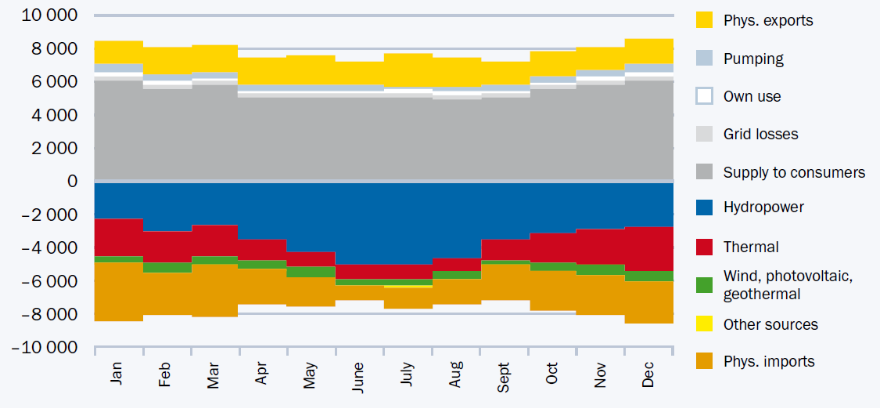

Figure 1-3 12month Electricity Balance in Austria in 2016 in Gigawatt hours (GWh)[33]

PV systems with 1.2 GW installed capacity and wind power plants with 2.9 GW installed capacity contribute less than 9% of gross generation in year 2016. [34] In the years 2009 until 2016 (except 2012) the additional demand of Austrian consumers for electricity was higher than the capacity of renewables added.[35]

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[33] Energie-Control (2018): A Better Deal. Because Knowing Is Better Than Guessing. Key Statistics 2017. Wien. p. 25.

[34] Energie-Control (2018): A Better Deal. Because Knowing Is Better Than Guessing. Key Statistics 2017. Wien. p. 28.

[35] Molnar, P.; Mayer, E. (2017): Ökostrom in Österreich. Dachverband Energie Österreich, Wien. p. 18.

The same is true on a regional perspective for the province of Lower Austria, despite its vast capacity of hydro power along the Danube and large-scale wind farms only on very view days e.g. in mid-February or early September renewables can cover total demand on the region as shown in the example week of the table below. On the 2nd of September 2018 renewables produced 148% of total load.

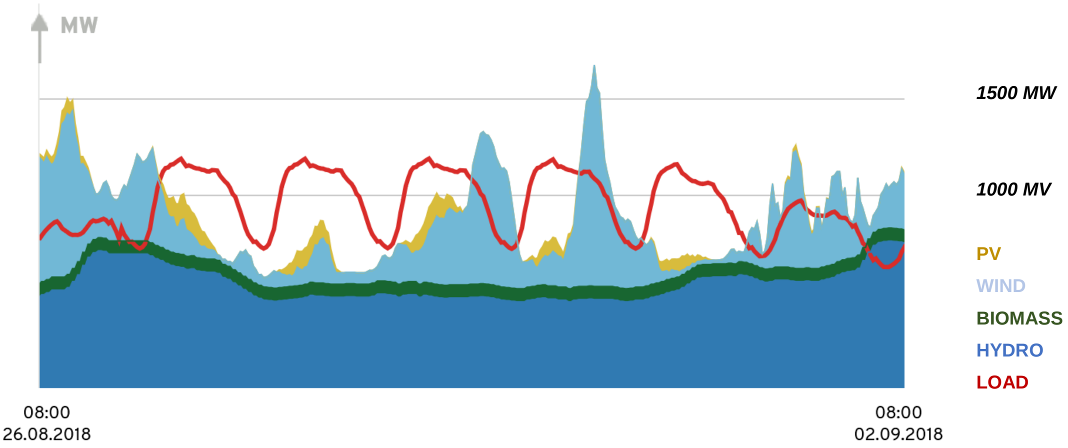

Figure 1-4 Load Curve and Production from Renewables in Lower Austria[36]

The balance of supply and demand is of great importance for microgrids when considering renewable energy sources. They represent a special form of electricity distribution systems with controllable loads and distributed energy resources such as PV or storage. The microgrid is controlled in a decentral mode while connected to the main power network. Their electricity balance will look similar to the graph above under normal operation - most likely with a higher share of renewables due to its own distributed energy resources. In case of emergency operation, the renewable microgrid must rely solely on its own capabilities that will be described in Chapter 5, Renewable Microgrids.

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[36] NÖ Energie- und Umweltagentur GmbH (2018): Energiebewegung – Tagesbilanz. https://www.energiebewegung.at/ visited on 2nd September 2018.

2 DESCRIPTION OF METHODICAL APPROACH

The main hypothesis of this work states that it is feasible to build and operate a renewable energy microgrid for a hypothetical base of the Austrian Armed Forces with critical infrastructure functions to provide sufficient generation for its electrical load and remain islanded in the event of a blackout for two weeks. At the same time the investment in the microgrid elements will reduce operational cost during standard grid-connected operation.

2.1 Method of Approach

After setting the scene for critical infrastructure and resilience the character of power outages or extreme blackout situations that renewably energy microgrids must face will be examined. This part relies on reports from regulators, academic research on the effects of outages, and expert interviews.

Secondly, the state of the art of microgrids is described with focus on the combination of renewable energy systems and storage used for critical infrastructure sites or military installations. This part relies on results from research programs mainly in the U.S. and practical implementations done by the DOE globally. Conclusions on starting conditions, technology, and process will be developed for the scenario investigated in more detail.

Thirdly, the fundamentals of renewable microgrids will be described, while associated costs, and financial benefits will compared to normal operation and assessed for the scenario. The evaluation of load is followed by investigation into elements needed for the microgrid covering the load and their economic implications. This part relies on qualitative research and quantitative business model for a specific case developed from a hypothetical scenario.

The Ministry of Defence has no authority to pass on confidential data on demand and supply of electricity for military installations, therefore the method chosen is the scenario analysis for the research question. The key figures for the business case are based on the author’s pre-existing knowledge with business customers, military sites and their electricity consumption and the microgrid of WEB Windenergie AG, where elements of a microgrid are operational in the same district of this scenario.

Finally, the results are summarized and lessons learned for planning and implementing of a microgrid are presented. Focus in on improving the ROI from other revenue sources.

2.2 Scenario CIP Northwind

The scenario presented below is called Critical Infrastructure Protection Northwind. The scenario's goal is to predict the investment period of renewable energy resources within the timeframe of 15 years.

CIP Northwind is a hypothetical base with the location in Lower Austria, district of Waidhofen/Thaya, Allensteig, 48°41'46" North, 15°19'31" East, with elevation of 525 m a.s.l.

Figure 2-1 CIP Northwind in Allensteig (Google Earth)

The base is designated as command headquarters and, in the case of an emergency, as "island of security" for CIMIC operations. The facility location hosts an equivalent of a staff battalion and carries out the following functions:

- command and Headquarters company;
- C3I staff unit with telecommunication and IT-facilities;
- supply and transport unit with storage facilities for critical supplies, workshops, charging and tanking infrastructure for hybrid transport fleet;

- National Operations Centre for energy assets;
- command post for CIMIC, especially alternate post for national government authorities; and
- total staff under normal operation: 300 military and civil personnel.

For CIP Northwind grid connection to the DSO will be limited at 200kW at network level 6 to cover an average load of 300kW under normal operation.

The major stakeholder is the planner of military infrastructure for this installation with the task to increase the resilience of the base. Based on learnings from the SPIDERS program the Microgrid Design Guide P-601 three principles are followed:

> "*1. Reduction of energy costs and reduction of operational costs by integrating renewable energy and smarter operation.*
> *2. Minimize changes to existing infrastructure and maximize use of existing assets.*
> *3. Provide "N+1" generation redundancy for critical operations and resilience."*[37]

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[37] Andersen, B. (2017): SPIDERS - JOINT CAPABILITY TECHNOLOGY DEMONSTRATION (JCTD). NAVFAC, http://resiliencesummit.com/program/pdf_2017/Bill%20Anderson.pdf visited on 8th August 2017.

3 POWER SUPPLY INTERRUPTIONS

Interruption of electricity has been observed in central Europe mainly after extreme weather events such as storms or floods. Not every interruption is necessarily a blackout event, but are relevant for the reference model and its dimensioning. The majority of Austrian energy customers are not used to longer power supply failures, since they experienced less than 1 hour without electricity in 2016, which is one of the lowest values in years. The objectives for and value of microgrids will depend on the scenario of outages and risk of blackouts and their effects that are described in this chapter.

3.1 Quality Indicators of Power Networks

The quality of electricity network and the continuity of supply can be described with indicators such as number of interruptions, duration of interruptions, and energy not supplied to end-users. Power disturbances are reported by the Austrian regulatory authority E-Control on a yearly basis since 2003 and in accordance with IEEE Standard 1366:

- System Average Interruption Duration Index (SAIDI) describes the average duration of electricity interruptions per user of the electricity grid. It includes also extraordinary regional events such as the recent event of flooding along the Danube from Passau to Bratislava in 2013. SAIDI is calculated based on compulsory reports from every network operator on all interruption lasting more than 1 second. Network customers in Austria experienced less than 38 minutes of interruptions of which about 25 min were unplanned interruptions.[38] A value below 170 min is defined as "*good network quality*" according the relevant ordinance on electricity network "Netzdienstleistungsverordnung END-VO 2012". Still, five network operators in Austria could not achieve that threshold value.
- The Average System Interruption Duration (ASIDI), is computed based on installed transformers in kilo Volts Amperes (kVA). For 2016 the value is on the level of SAIDI with 37 minutes of outages.

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[38] Energie-Control Austria (2017): Ausfalls- und Störungsstatistik für Österreich – Ergebnisbericht 2016. e-control, Wien. p. 13.

In European comparison, Austria is one of the top five countries in terms of network quality. In CEER's last report on benchmarking the electricity networks range within Europe is from approximately 1.000 minutes per customer, per year in Slovenia after the ice storm in 2014 and fifteen minutes in Luxembourg.[39]

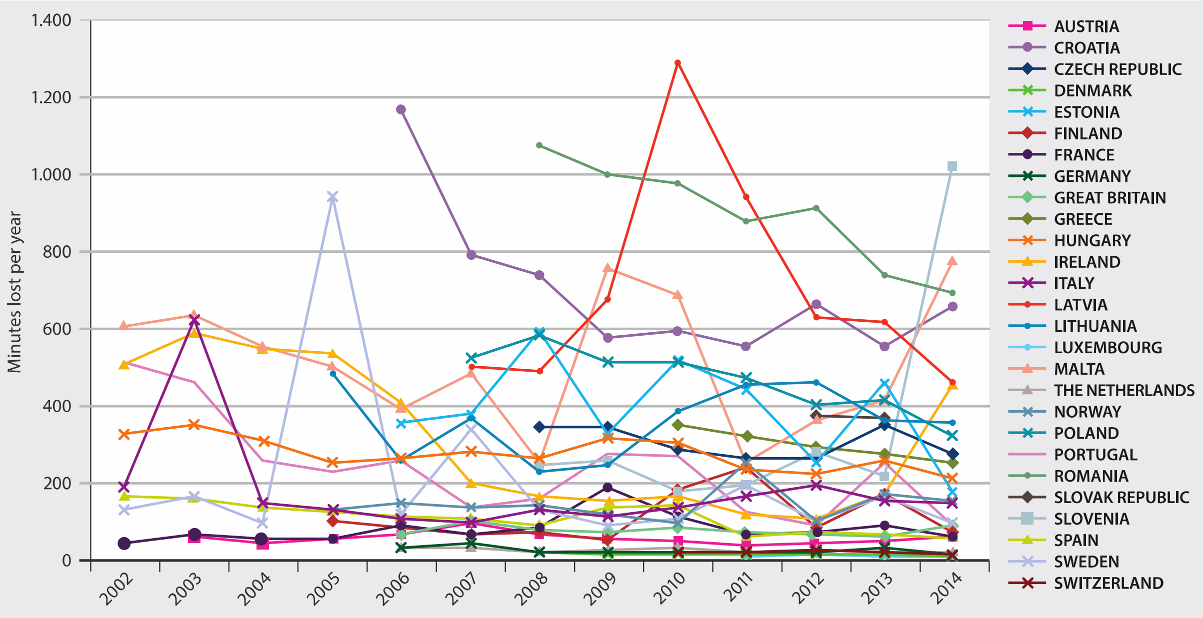

Figure 3-1 Unplanned and Planned Interruptions in Europe[40]

3.2 Causes of Power Interruptions

For the concept of microgrids the causes and the duration of events needs to be considered in greater detail, since outages per customers is not sufficient for risk assessment. Causes of the power interruptions are classified by E-Control as follows:[41]

- Network operators: Outages are reported with less than one hour average duration.
- Third parties: animals, trees, excavations work, dragging activities, planes, fire, or vandalisms. Outages are also reported with less than one hour average duration.

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[39] Council of European Energy Regulators (2016): 6TH CEER Benchmarking Report On The Quality Of Electricity And Gas Supply. CEER, Brussels.

[40] Council of European Energy Regulators (2016): 6TH CEER Benchmarking Report On The Quality Of Electricity And Gas Supply. CEER, Brussels. p. 40.

[41] Energie-Control Austria (2017): Ausfalls- und Störungsstatistik für Österreich – Ergebnisbericht 2016. e-control, Wien. p. 8.

- Atmospheric causes: thunderstorm, storm, ice, snowfall, frozen rain, moisture, low temperature, high temperature, avalanches, landslide and rock fall. Average duration is reported at approximately two hours.
- Retroactive effects from other networks – HV or low voltage (LV) – outage of production or other network operators. Outage endures about one hour.
- Regionally exceptional events: disasters or events not covered by network operators that cannot be avoided with reasonable efforts such as earthquakes, hurricanes, and massive flooding. According to the E-Control benchmarking report these types of extraordinary events have a history of lasting, on average, 12 hours or less. However, the maximum duration of a recorded event was over 50 hours.

Network interruptions in 2016 were half planned and unplanned where the following distribution was reported by network operators:

- 20% atmospheric causes
- 15% network operators
- 10% third parties
- 2% extraordinary regional event
- 1,5% reactive interruptions

Distribution over the year reflects the highest numbers of interruptions during the summer months with more than 1500 events (compared to less than 500 in February), when atmospheric causes, such as thunderstorms, caused about 2/3 of outages. [42] Most of the atmospheric causes take place between 15:00 hrs and the late evening hours of the day.[43]

The European Network of Transmission System Operators for Electricity (ENTSO-E) registers network interruptions in the transmission grid with its nature, area, and duration for transmission networks. The duration of asset unavailability might last for

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[42] Energie-Control Austria (2017): Ausfalls- und Störungsstatistik für Österreich – Ergebnisbericht 2016. e-control, Wien. p. 12.

[43] Energie-Control Austria (2017): Ausfalls- und Störungsstatistik für Österreich – Ergebnisbericht 2016. e-control, Wien. p. 12.

several hours, but not cause any problem if other assets can make up for these disruptions.[44]

From the indicators it can be concluded that a network outage of 50 hours is realistic, even if the event is not categorised as a blackout. Therefore, the minimum period for resilience could be quantified as a range of up to two days.

3.3 Effects of Power Supply Interruptions

The effects of power outages are usually very regional. This can be interpreted as, for example, a confined number of households and businesses whose connection to the grid is disturbed. A more specific example would be that on 1st August 2018 in a quarter in the 7th district in Vienna with about 2.000 households and business without power. Power outages on the LV distribution network of a whole segment of city or a greater regional segment have an impact not only households but also on larger parts of the infrastructure such as traffic, public lights, water systems. These outages can be restored with secondary lines to the affected area.

Power failure in a whole city or town on the medium voltage (MV) distribution network are broader in scale with damages not only to the power lines but also on substations and transformers. Restoration might also require replacement of physical parts.

Power failure on national level are called “Brownout” and classify interruptions of transmission networks in the HV distribution network, e.g. the interruptions during Hurricane Harvey in August 2017. On the third day of the tropical storm more 300.000 households were without electricity, which represents approximately 3% of the customer base. Despite support from non-effected network areas, restoration cannot begin due to strong winds, flood warnings, and customer equipment at homes and business impacted by floods.[45] Utilities reported that it would take up to a week to restore power to all customers. The brown out of a large area in a U.S.

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[44] ENTSO-E Transparency Platform (2017): Planned and Forced Unavailability in Transmission Grid. https://transparency.entsoe.eu/outage-domain/r2/unavailabilityInTransmissionGrid visited on 2nd January 2018.

[45] Department of Energy, Infrastructure Security & Energy Restoration (2017): Situation Report Harvey August 27, 2017. DOE, Washington.

state does not have the characteristics of a blackout, but requires support from the federal organisations. Therefore, it can be conclued that physical destruction of large parts of the network will cause outages or instabilities for weeks, even if repair efforts are supported on national or European network.

A blackout can be defined as failure of the electricity transmission network on ENTSO-E level, i.e. a European region or parts of more than one country, e.g. Southern Germany, Eastern Austria and Czech Republic.

ENTSO-E represents more than 40 national TSOs with more 500 million customers and 500 TWh of exchange between more than 30 countries. One of its main activities is the coordination of synchronous area, which are groups of ENTSO-E countries with connected transmission grids with system frequency of 50 Hz. Loosing that frequency could cause a European blackout situation.

The pooling of generation and reserves allows assistance by other countries to balance differences between supply and demand. On the other hand, imbalances and black outs in one area effect all the other areas, e.g. Austria is dependent of countries in the Continental European Area (CTA) especially Germany, Italy, France as shown in the figure below.

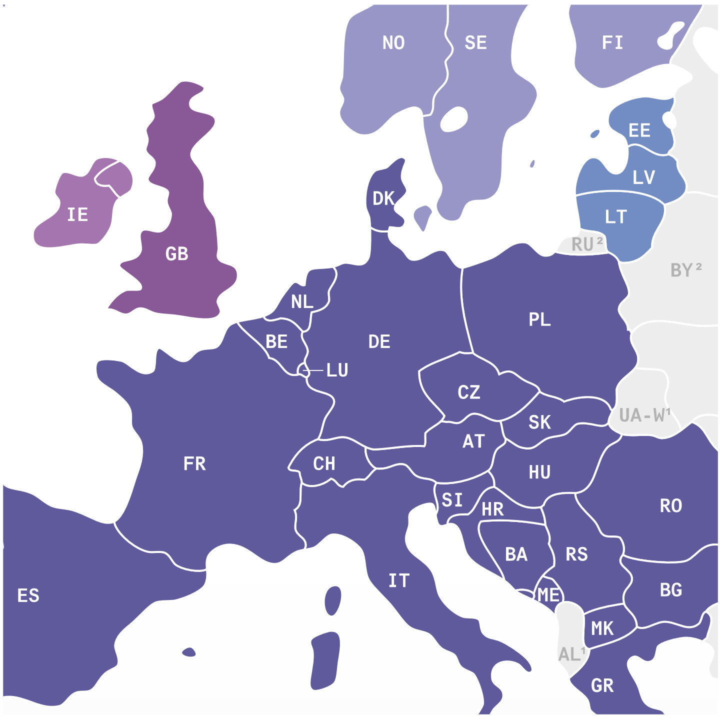

Figure 3-2 ENTSO-E region Continental European synchronous area[46]

The Austrian transmission system operator Austrian Power Grid (APG) operates approximately 7.000 km of HV power lines from 110 kilo Volts (kV) to 380 kV with 12.000 mast and more than 60 transformer stations with connections to the DSOs. As shown in APG's network map, the Austrian transmission grid is interconnected with German transmission grids. These few, but important interconnections to Tennet, Amperion, and Transnet BW ensure physical connection to the important common market area with Germany – despite some restrictions for trade introduced on 1st October 2018.

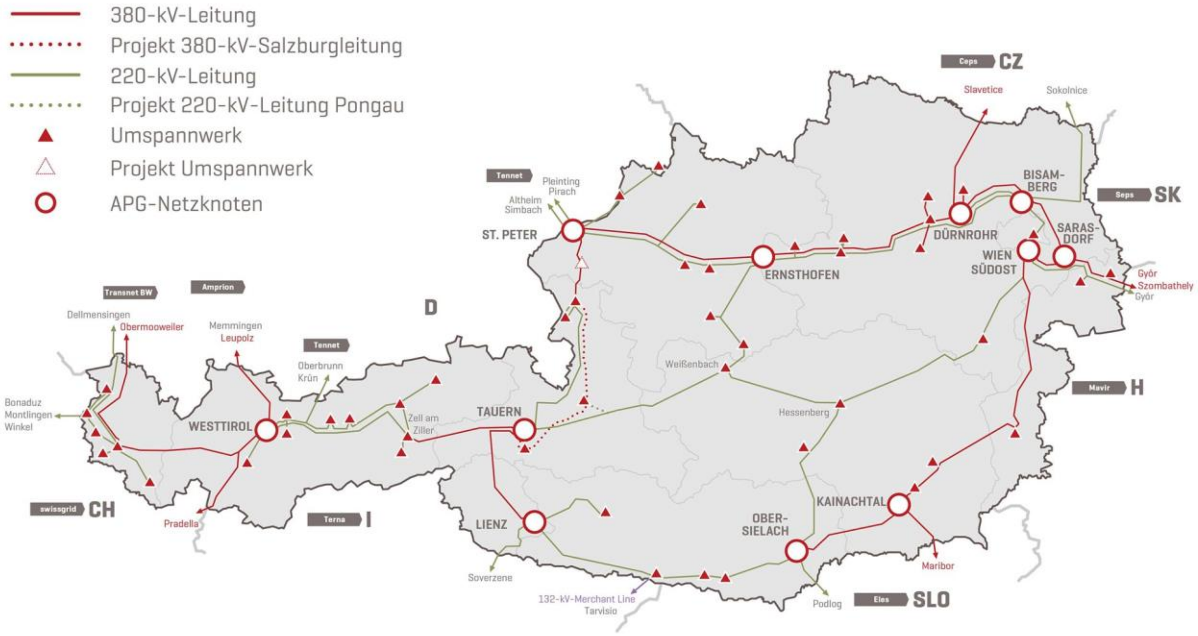

Figure 3-3 Transmission Grid in Austria and International Connections[47]

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[46] European Network of Transmission System Operators for Electricity (2015): ENTSO-E AT A GLANCE. Brussels

[47] Austrian Power Grid (2017): APG-Netz. http://www.apg.at/~/media/FB5E3631B920486682C3804CBD086825.jpg?force=1 visited on 26th August 2017.

3.4 Causes and Duration of Blackouts

Causes of blackouts at the European level vary on a case-by-case basis and are often a result of various unlikely reasons. Below are two examples of pan-European blackouts to illustrate the various nature of these types of incidents on the continent.

In August 2003, a blackout in Italy was triggered by problems on the two HV transmission lines between Switzerland and Italy due to falling trees and overheating. The blackout impacted almost 60 million (Mio) people, while the full reestablishment of the electricity grid took nearly 18 hours.

In November 2006, a planned but erroneous switch-off of an HV transmission line in northern Germany caused a blackout across Europe. 15 million households in Germany, France, Belgium, Italy, Spain and Austria were affected. 50.000 people in Austria were without electricity for about one hour. It's worth noting that this collapse of large parts of the transmission network is not manifested in the memories of Europeans, since it took place during the night hours and lasted for only two hours.[48]

Reviews of blackouts in Europe and the U.S. suggest that the combination of two independent causes at the same time increase the risk of blackout.

Some market participants and analysts assume that the probability for a blackout is below 1%. However, this probability is increasing, possibly reinforced by a novel about Blackout widely known in the energy business.[49] Based on the examples and the final report *Blackouts in Austria [Blackouts in Österreich]*[50] the conclusion can be drawn that the following variables will increase the risks for a blackout:

- changes in the total energy systems with increasing decentralized renewable production;
- increasing load on the HV network due to an increase of demand and distribution of production, including large share of renewables in the north of Europe with cascading loads in case of failures;
- slow increase of capacities in TSO infrastructure with increasing power transits between national grids;
- N+1 security not always guaranteed; and

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[48] Saurugg, H., Ladinig, U. (2012): Blackout. Truppendienst 2/2012 Nr. 325. Bundesheer, Wien. p. 36f

[49] Elsberg, M. (2012): Blackout. Morgen ist es zu spät. Novel: 15th edition. Blanvalet Verlag: Germany.

[50] Reichl, J., Schmidthaler, M, ed. (2011): Blackouts in Österreich - Teil I – Endbericht. KIRAS, Wien.

- increasing cyber threat and direct attacks on European utilities and grid with criminal or political background.[51]

The final report on *Blackouts in Austria* indicates the duration of network outages of 6 to 30 hours in rural and urban network segments. Restoration efforts from the TSOs (coordinated by ENTSO-E) and the DSOs will require time and follow predefined execution plans that are regularly exercised by the network control centres. In Austria, that responsibility lies APG and its counterparts of the Regional Group Continental Europe (RGCE). Restoration is based on the ENTSO-E Network Code on Emergency and Restoration of Frequency. In Austria the pathway for restoration goes from west to east and south or alternatively starting from islands in Salzburg and Kärnten.[52] For Slovenia, in 2014, reenergising the electricity system after severe destructions such as the ice rain took more than 24 hours.[53]

The role of the DSO is limited and only relevant if they have the capacity to operate in island mode and to start a power plant, i.e. black start. This would require the permanent balance of load and supply to keep the frequency at 50 Hz. Formation of “emergency clusters” have been discussed in Austria to equip DSOs with the required capacity. This could contribute to a reduced duration of blackouts. Microgrids could have the same role on a smaller scale, however the Austrian federal government is not factoring this option into their policy decisions. There are however local initiatives of communities, partly supported by federal-level funds, such as energy cell system in the region of Feldbach in Styria. The program intends to provide electricity for the community for 1 to 3 days and to support network stabilisation. [54]

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[51] Saurugg, H.: Blackout – Eine nationale Herausforderung bereits vor der Krise. p. 33f

[52] Weixelbraun, M. (2014): Aktuelle Herausforderungen des österreichischen Übertragungsnetzbetreibers. Synergiekonferenz 2014. Wien.

[53] Reichl, J., Schmidthaler, M, ed. (2011): Blackoutprävention und –intervention – Endbericht. KIRAS, Wien. p. 360f.

[54] Saurugg H. (2017): Das Energiezellensystem - Eine nachhaltige Energieversorgung erfordert einen sicheren Umgang mit Komplexität. http://www.herbert.saurugg.net/energiezellensystem/konzept-energiezellen visited on 9th August 2018

As policies and priorities advance within Austria and other European counties, the baseline duration of blackouts should assumed to be between 3 hours to 3 days. Such considerations should anticipate an extended period of time before economic and daily life is fully re-established after restoration of electricity. The resilience of the microgrid requires establishing the framework for a process to be implemented after restoration of the network for the purposes of resupplying, maintenance, or other logistic processes.

3.5 Damage Assessment of Blackout Events

The effects of a blackout will hurt all sectors without chance to escape completely and will depend strongly on organisational, infrastructural, and individual preparations.[92]

Effects will be immediate in the following sectors of infrastructure:

- Facility management systems such access control, elevators, cooling and heating;
- Public lights and traffic control;
- Communication including mobile networks, fixed networks, data networks and broadcasting;
- Water and sewage system;
- Public transport, road traffic including refuelling;
- Logistics for food supply;
- Public health;
- Payment systems and finance sector; and
- Public administration

Based on the blackout simulator of

Johannes Kepler Universität Linz a blackout of 24 hours on a working day in March 2018 would cause the lack of approximately 40 GWh electricity with damages of EUR 200 million.[55]

Table 3-1 Electricity not supplied caused by Blackout in Lower Austria (calculation with blackout simulator)

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[55] Reichel, J; Schmidthaler, M (2011): Blackouts in Österreich (BlackÖ.1) Teil I. Endbericht. KIRAS Bmfit, Wien. p 89f.

Sector (NACE-code)	Sector description	Electricity not supplied
A	Agriculture, forestry and fishing	1,094.09 MWh
BDE	Mining and quarrying; electricity, gas, steam and air conditioning supply; water supply; sewerage; waste management and remediation activities	4,531.01 MWh
C	Manufacturing	14,508.92 MWh
F	Construction	339.82 MWh
GHI	Wholesale and retail trade; repair of motor vehicles and motorcycles; transporting and storage, accommodation and food service activities	3,409.23 MWh
J	Information and communication	164.59 MWh
K	Financial and insurance activities	52.55 MWh
LMN	Real estate activities; professional, scientific and technical activities; administrative and support service activities	867.95 MWh
OPQRS	Public administration and defense; compulsory social security; education/human health and social work activities; arts, entertainment and recreation; other services activities	3,031.01 MWh
	Households	8,269.65 MWh
	Sum	**36,268.82 MWh**

The damage assessment of a blackout for an individual organisation or companies reveal a broad spectrum of effects from inconvenient to total destruction. Therefore, it is difficult to quantify the financial value for resilience. In case of critical infrastructure as well as public administration it will not only be based on the financial effort for reconstruction or monetary losses for the community, but also on the value of keeping control and public security.

Table 3-2 Damage caused by Blackout in Lower Austria (calculation with blackout simulator)

Sector (NACE-code)	Sector description	Total loss due to power outage
A	Agriculture, forestry and fishing	9,568 T €
BDE	Mining and quarrying; electricity, gas, steam and air conditioning supply; water supply; sewerage; waste management and remediation activities	3,345 T €
C	Manufacturing	81,443 T €
F	Construction	5,866 T €
GHI	Wholesale and retail trade; repair of motor vehicles and motorcycles; transporting and storage, accommodation and food service activities	14,649 T €
J	Information and communication	2,259 T €
K	Financial and insurance activities	2,285 T €
LMN	Real estate activities; professional, scientific and technical activities; administrative and support service activities	12,638 T €
OPQRS	Public administration and defense; compulsory social security; education/human health and social work activities; arts, entertainment and recreation; other services activities	33,793 T €
	Households	23,782 T €
	Sum	**189,628 T €**

3.6 Security of Supply for Critical Infrastructure and Blackout

Critical infrastructure depends on the security of supply of electricity on the network. Uninterruptible power supply (UPS) systems are standard for companies and organisations, especially with information technology (IT)-systems or other critical loads, should be able to cover the loss of the grid for the first 20 milliseconds. This provides a period of coverage until emergency power systems, such as generator sets, takeover to support the system. Information is limited with regard to critical infrastructure in Austria and its ability to operate for days, or even weeks, without external power supply, refuelling of generators, or its connection to special grids for military or governmental installations. Therefore, it is recommended that additional research is invested by the government on this topic.

Renewable microgrids can close the gap in improving the resilience of installations with critical infrastructure, where a power supply base on generator sets are now possible or economically not feasible.

If the renewable microgrid could supply facilities outside the boundaries of CIP Northwind with substantial additional value for the community as shown in the table above. However, it remains challenging to generate investment funds from public institutions for extending the microgrid, e.g. to the local hospital, the additional value would hardly find its way into the business case for “CIP Northwind”.

4 SMART GRIDS AND THE MICROGRIDS CONCEPT

Until the start of the "Energiewende," distribution networks in central Europe were designed as centrally controlled networks. This was done to ensure security of supply under all peak demand conditions with upstream connection to high voltage networks where the connection points for the large generation units was provided.[56] Today the LV distribution network not only handles supply of customers but also has to provide access for a great number of renewable energy generation plants such of biomass, PV and wind, and the medium voltages (MV) networks for wind parks or larger biomass units.

This development requires management and monitoring on the DSO level summarized under the term "Smart Grid" and is part of the much wide transition of the energy system within the EU. The fundamental transformation of Europe's energy system "*will be achieved by moving to smarter, more flexible, more decentralised, more integrated, more sustainable, secure and competitive ways of delivering energy to consumers*."[57]

In 2005 the EU started developing a vision and strategy for Europe's future electricity infrastructure and to provides the strategic legal framework for the market participants. The idea was to integrate central and distributed generation into the network maintaining the hierarchical structure as shown in the figure below.

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[56] Heuck K., Dettmann K., Schulz D. (2007): Elektrische Energieversorgung – Erzeugung, Übertragung und Verteilung elektrischer Energie für Studium und Praxis. Vieweg, Wiesbaden. p. 77f.

[57] European Commission (2015): Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation. Brussels. p. 2.

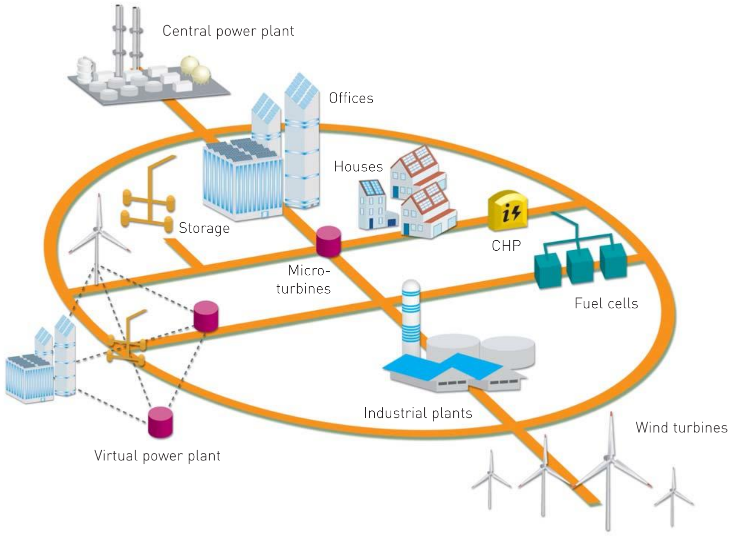

Figure 4-1 Early Concept of Smart Grids by the EU Commission[58]

Smart grids are defined in EU documents as "an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that assume both roles – to efficiently deliver sustainable, economic and secure electricity supplies."[59]

This evolution of distribution networks delivers preconditions for developing microgrids, especially providing data for all market participants. In 2015 EURELECTRIC, the union of the electricity industry, concedes that "*…DSOs and suppliers are no longer the only players serving consumers*" and that consumers are becoming more active. The key for the transition will be data enabling not only smart grids but also microgrids. The term data is applied within the scope of 3 categories:

1. Smart Meter Data refers to the consumption data on energy usage of an individual energy customer, production data from the individual's production units, such as PV, and master data of these customers. This set of data remains under the control of the private or business consumer and can only be used by the DSO or Energy Service Company (ESCO) to fulfil their service obligation, e.g. the network operator must delivery metering data to the ESCO for billing purposes.

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[58] European Commission, Directorate-General for Research, Directorate J – Energy (2006): European Smart Grids Technology Platform - Vision and Strategy for Europe's Electricity Networks of the Future. Luxembourg.

[59] DOLIGÉ, S. ed. (2016): The power sector goes digital - Next generation data management for energy consumers. EUELECTRIC Brussels. p. 7ff.

2. Smart Market Data is derived from commercial bids of suppliers, appliances or external sources such as meteorological data, customer research, and social media. It is used by the ESCO to offer services and make market-based decisions.

3. Smart Grid Data is defined as information that “covers all technical data (e.g. voltage, power quality, frequency etc.) collected by sensors in the network – including smart meters – allowing system operators to plan, operate and manage their networks.”[60]

This type of data is essential for both DSOs and TSOs to manage and monitor network behaviour. It is necessary not only for the smart grid but is also the basis for decentralised energy systems with microgrids and for the flexibility market.

The EU’s strategic plan for the transformation of energy systems focuses on increasing the resilience, security, and smartness of the energy system and includes initiatives in the Strategic Energy Technology (SET) Plan until 2020. The SET Plan is dedicated to “*Connecting the different networks in an integrated energy system* [to]…*increase stability and security of the electric system*.”[61] This represents a top down approach to implementing fundamental changes to the European electricity system from the view of large grid operators.

The microgrid concept starts from the bottom of individual energy customers and local energy production that are assembled under the umbrella of a microgrid. From the TSO’s perspective, microgrids could be a “controlled entity with the power system that can be operated as a single aggregated load or generation”[62]

The microgrid concept has one of its origins in the U.S. with its federal departments playing a leading role in developing and extending the concept. The official definition by the U.S. Department of Energy as follows:

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[60] DOLIGÉ, S. ed. (2016): The power sector goes digital - Next generation data management for energy consumers. EUELECTRIC Brussels. p. 7.

[61] European Commission (2015): Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation. Brussels. p. 11.

[62] Hatziargyriou, N., ed. (2014): Microgrids – Architectures and Control, IEEE Press, Wiley, Chichester. p. 2.

> "*A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in grid-connected or island-mode.*"[63]

According to N. Hatziargyriou, emphasises that energy storage is the missing link between supply and demand, stating that microgrids *"…comprise [of] LV distribution systems with distributed energy resources (DER) (micro-turbines, fuel cells, PV, etc.) together with storage devices (fly wheels, energy capacitors and batteries) and flexible loads*."[64]

The focus in this view is on the LV grid and the integration of demand-side, supply-side, and storage on the local level. The microgrid is often in ”normal” operation and connected to a medium voltage grid that supplies electricity to a certain proportion or in certain times up to 100%. The MV grid serves as "infinite battery" to absorb the overproduction to the DER in the microgrid.

In rare incidents the microgrid is disconnected and switches to emergency operation without delay, when the MV or even HV network in a case of a blackout is not available.

The island mode puts the microgrid in a physical island, which requires a perfect synchronisation of demand, DER production and storage. Hatziargyriou points out the lack of rotating masses that provide stability to conventional electricity grids. This must be compensated by power electronics and storage devices that would prevent frequency to drift from its nominal value.

In contrast to microgrids, virtual power plants (VPPs) represent only a cluster of DERs with some central control, but they are not physically connected on the same LV grid and can influence storage or local loads. In some remote areas, a microgrid might be the only option for infrastructure planning and development. However in a country with well-developed infrastructure, such as the U.S., the microgrid concept has a strategic role in the national network modernisation and maintains local

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[63] Ton, D. (2014): DOE Activities on Microgrids and Grid Resilience. U.S. Department of Energy, Washington (DC). p. 2.

[64] Hatziargyriou, N., ed. (2014): Microgrids – Architectures and Control, IEEE Press, Wiley, Chichester. p. 4.

importance by covering electricity needs with local renewable sources. In a national context a microgrid with e.g. 5 MW might be negligible, for the local community it could improve power quality and system reliability, some argue that small sources of power or storage represent in fact the “democratisation of energy production”.

The various types of microgrid can be grouped into the following categories:

- Remote “Off-grid” microgrids
- Campus microgrids
- Commercial and Industrial (C&I) microgrids
- Military Base microgrid
- Deployable microgrid for operations abroad
- Tactical microgrid with <1 MW for forward bases
- Military Base microgrid >1 MW

The relevant categories for CIP and resilience of CIP Northwind are the tactical and the military base microgrid. They are designed to cover the operational needs of smaller basis or large military installations and the guidelines developed in the US help to assess the case of CIP Northwind.

5 SPIDERS MICROGRIDS - LESSONS LEARNED IN THE U.S.

The U.S. has gained knowledge and experience with military microgrids with support from a great variety of demonstration projects. Initiatives have been driven by two departments the U.S. Department of Defense (DOD) and the U.S. Department of Energy (DOE) since 2011 and research institutes, operators and suppliers have gained knowledge and developed technical solution for all type of applications.

5.1 U.S. Department of Defense

Based on security reviews and analysis of hacker attacks, the U.S. DOD concluded that military installations were mainly dependent on commercial power grids with risks of extended power outages. These outages were typically caused by criminal activities, storms, heavy snowfall and ice, or technical failures. The risk was assessed as severe and increasing due to aging of public grid and local infrastructure, fragility of public networks and the dependence on fossil fuels.

U.S. DOD, primarily supported by operational combatant commands, United States Northern Command NORTHCOM and Pacific Command PACOM, enhanced its mission capabilities with secure, smart microgrids capable of off-grid operation and with mixed generation.

The DOD started the program Smart Power Infrastructure Demonstration for Energy, Reliability and Security called SPIDERS with the objective to "*reduce the unacceptably high risk of mission impact from an extended electric grid outage by developing the capability to maintain energy delivery for mission assurance*." [65] DOD invited all services and all DOD's research institutions to the program as illustrated below.

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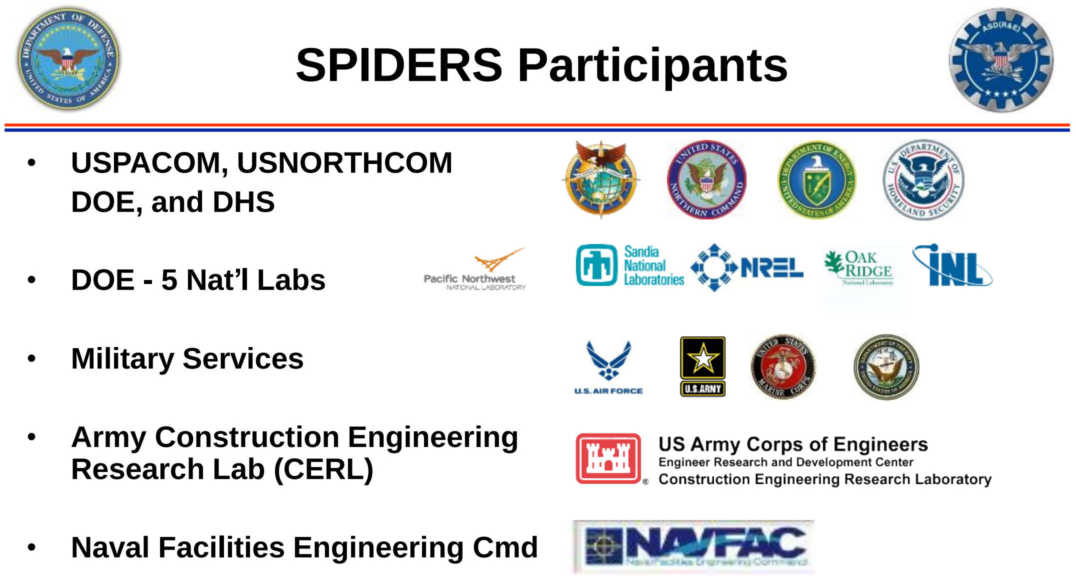
[65] Department of Defence (2011): Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS). p.3. http://www.ct-si.org/events/APCE2011/sld/pdf/89.pdf visited on 7th August 2017.


SPIDERS Participants

- USPACOM, USNORTHCOM DOE, and DHS
- DOE - 5 Nat'l Labs
- Military Services
- Army Construction Engineering Research Lab (CERL)
- Naval Facilities Engineering Cmd

Figure 5-1 Participants in the SPIDERS Program[66]

Necessities were defined based on the analysis of energy system disruptions in year 2012 through 2014 at 18 military assets where almost 75% of outages lasted between 8 to 12 hours.

5.1.1 SPIDERS objectives and functionalities

SPIDERS demonstrates the fulfilment of 4 critical requirements under the assumptions of increasing probability of power failures caused by cyber-attacks:

1. "Protect task-critical assets from loss of power due to cyber-attack
2. Integrate renewable and other distributed generation to power task critical assets in times of emergency
3. Sustain operations during prolonged power outages
4. Manage installation power and consumption efficiently to reduce petroleum demand, carbon "boot print", and cost." [67]

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[66] U.S. Department of Defence (2011): Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS). p.5. http://www.ct-si.org/events/APCE2011/sld/pdf/89.pdf visited on 7th August 2017.

[67] Naval Facilities Engineering Command: Technology Transition Final Public Report. Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS). Joint Capability Technology Demonstration (JCTD). Washington, DC.

The SPIDERS program's avenue to reach the objective is a secure microgrid concept that could strengthen reliability, security, and resiliency of electric power system at a military installation and other critical infrastructure.

The key operational target was set as the SPIDERS microgrid had to be capable to supply 100% of critical load for at least 72 hours in the case of loss of power from the public grid.[68]

SPIDERS developed a model for DOD-wide implementation at military installations and demonstrated the following functionalities at three selected locations in Hawaii and Colorado:

1. Cyber-security of electric grid
2. Smart Grid technologies and applications
3. Secure microgrid generation and distribution
4. Integration of distributed and intermittent renewable sources such as PV, wind, solar, fuel cell and biofuels
5. Demand-side management
6. Redundant back-up power systems such as batteries, vehicle to grid and as fall-back solution diesel generators.

5.1.2 Starting Situation

Individual buildings at facilities with some renewables at the public grid level and diesel generators acted as the starting point of the initiative as shown below. Despite the fact that a large numbers of diesel generators are used in all branches of the U.S. Armed Forces, power outages could not be excluded and were frequent in certain areas. Diesel generators are important assets to cover short-term outages, but reviews showed that operation was limited to a few hours, due to operational reasons, limited availability of diesel and lubricants, and limited storage capability for fuels at the premises. Furthermore, only selected buildings of a camp were supported, while non-mission critical areas staid without energy, but their importance for operational activities increased the longer the outage lasted.

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[68] Sandia National Laboratories (2012): SPIDERS: The Smart Power Infrastructure Demonstration for Energy Reliability and Security. Albuquerque, New Mexico.

In the case of power failure at the public grid and additional failure of diesel generators, critical buildings would not be served as shown below, which could impact other buildings on the site and potentially jeopardise the whole mission.

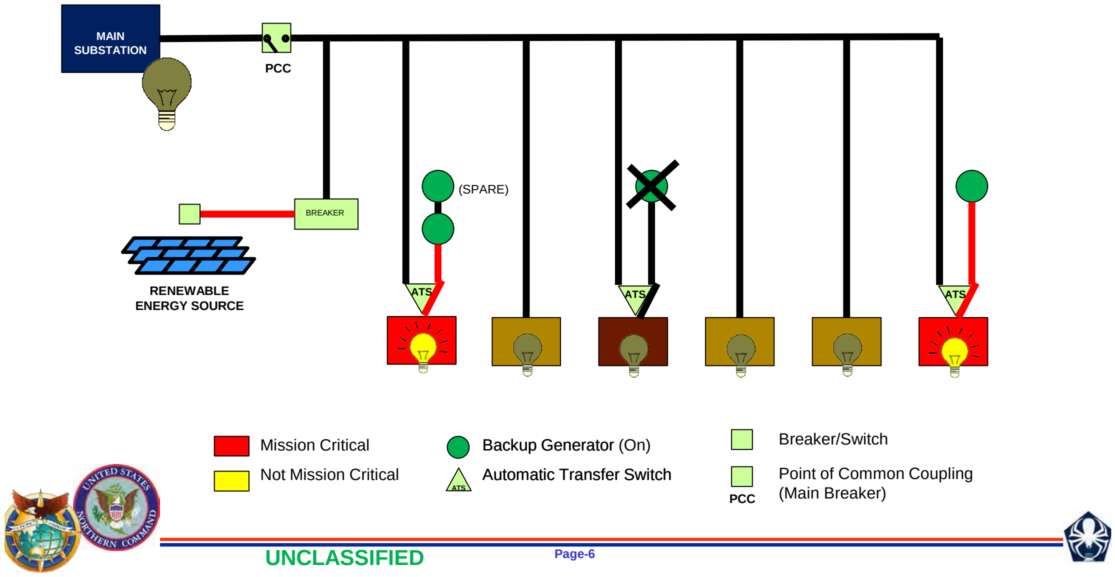

Figure 5-2 Loss of grid power and failure of backup without microgrid[69]

5.1.3 Concept, results and transfer of technology

Combining distributed energy resource (DER) generation, storage, back-up resources, and distribution into the microgrid increases resilience in the Phase 1 project.

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[69] U.S. Departement of Defense (2013): Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS). p. 6f .http://www.ultracarbon.net/uploads/5/8/1/5/5815108/spiders_declassified_overview.pdf visited on 7th August 2017.

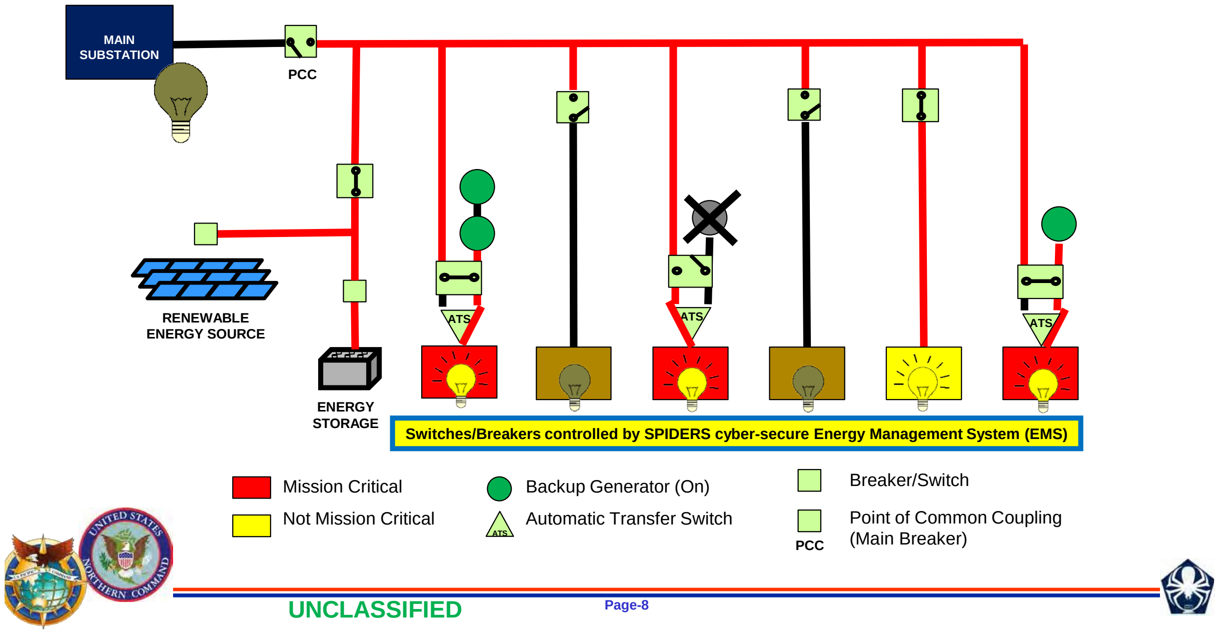

Figure 5-3 Initial concept with microgrid[70]

The initial basic concept of Phase I was designed by Sandia National Laboratory and was implemented at select areas of the Joint Base Pearl Harbor Hickham. Previously isolated generators were integrated, the existing 1 MW and an additional 146kW PV system plus a 50kW small wind system were augmented to the microgrid.

Joint Capability Technology Demonstration (JCTD) Phase I at Fort Pearl Harbor Hickham showed promising results. The main target of increased power reliability measured the percentage of time critical load not served (CLNS.) The CLNS rose almost 40-fold despite some initial problems with the battery system. At the same time the power endurance increased by more than 30% with the same fixed quantity of fuel and the CO_2 emissions were almost halved. Results were achieved with a basic design that left the electric grid almost unchanged but added the elementary control system of the microgrid on top of the installation.

Seamless hand-over between public grid, microgrid, and black start were demonstrated and savings of up to $40,000 per year were achieved from reducing peak demands.[71]

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[70] U.S. Departement of Defense (2013): Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS). p.8f. http://www.ultracarbon.net/uploads/5/8/1/5/5815108/spiders_declassified_overview.pdf visited on 7th August 2017.

In Phase II the entire base of Camp Smith near Colorado Springs with a population of more than 14,000 persons was turned into a microgrid called the “fence-to-fence approach”. Again, the MV distribution system was overlayed with microgrid components. The existing 2 MW PV plant was largely connected to the microgrid without changing the inverters. Motor-operated switches sectionalizing the MV grid on camp replaced manual switches; existing generators were connected to the LV distribution grid.

As a new component, the Camp Smith grid integrated Plug-In Electric Vehicles (PEV) with a storage capacity of 80 to 120 kWh per unit. Burns & McDonnell engineers designed bi-directional fast chargers for a fleet of electric vehicles. The idea is to deliver power back to the microgrid when needed to meet demand or improve overall power quality.[72] Trucks were delivered by Boulder Electric Vehicle (http://www.boulderev.com) and Smith Electric Trucks (liquidated in 2016).

Figure 5-4 Bidirectional Charging Station for Electric [73]

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[71] Casey, T. (2013): In First Test, U.S. Military’s SPIDERS Microgrid Uses 90% Renewable Energy. https://cleantechnica.com/2013/02/12/u-s-militarys-new-spiders-renewable-energy-microgrid/ visited on 7th August 2017.

[72] Burns & McDonnell (2013): SPIDERS Delivers First-of-a-Kind Bidirectional Electric Vehicle Chargers at Fort Carson, Colorado. http://www.burnsmcd.com/insightsnews/news/releases/2013/08/spiders-delivers-firstofakind-bidirectional-elec visited on 8th August 2017.

[73] Burns & McDonnell (2013): SPIDERS Delivers First-of-a-Kind Bidirectional Electric Vehicle Chargers at Fort Carson, Colorado. http://www.burnsmcd.com/insightsnews/news/releases/2013/08/spiders-delivers-firstofakind-bidirectional-elec visited on 8th August 2017.

In Phase III, Camp Smith in Hawaii was transformed into a microgrid with contributions from renewables and focus on cyber security.

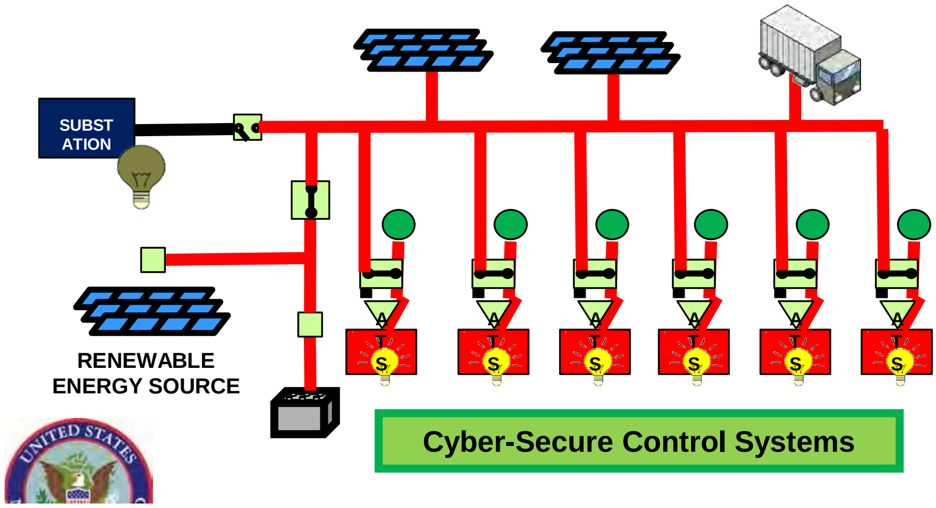

Figure 5-5 Concept for Microgrid at CAMP SMITH (HAWAII) [74]

The facility covers an area of almost 1 km^2 and is home to mission critical commands including the Commander U.S. Pacific Command. With the exception from some residences, the primary loads emanate from critical buildings. Manual disconnection was planned for non-critical loads - except buildings with PV.

Power outages were previously common due to frequent hurricanes, therefore cooperation with local utilities smart grid was intensified to improve grid stability with contributions from ancillary services from the camp's microgrid or reducing peak loads in the grid.

As previously stated, the MV 12kV distribution network remained unchanged, but new utility-grade generators were sourced, while the existing generator sets were used as N+1 redundancy. A new system, the integrated storage and inserter module (ISIM) was introduced to serve demand in case of grid failure from the battery system in less than one electrical cycle and to maintain the electric phase.

The cyber secure microgrid control system was added on top of the existing supervisory control and data acquisition (SCADA) system with programmable logic controllers. SNL defined an important strategy of enclaves in addition to the definition of critical/non-critical units. All actors such as PV systems, generators,

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[74] U.S. Departement of Defense (2013): Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS). p.8f. http://www.ultracarbon.net/uploads/5/8/1/5/5815108/spiders_declassified_overview.pdf visited on 7th August 2017.

switches, and software systems were assigned to enclaves where communication was possible in principle only within the enclave. Outside communication with other enclaves was only allowed within functional domains, with a defined set of characteristics such as source, receiver, speed, data type, and encryptions.

These communication processes and parameters were frequently tested with the U.S. Department of Homeland Security's (DHS's) Cyber Security Evaluation Tool and met cyber security requirements in combination with network architectures.

5.1.4 Transition and new developments

In the final report "*the SPIDERS JCTD Microgrid successfully met the stated objectives of increasing system efficiency and reliability while maintaining adequate power quality.*"[75] The DOD-wide roll out the SPIDERS JCTD Reference Design was introduced at the Resilience Summit in Hawaii in July 2017. The Summit featured a wide public attendance, including representatives from vendors who were informed about guidelines and objectives:

> *"1. Reduction of energy costs and reduction of operational costs by integrating renewable energy and smarter operation.*
> *2. Minimize changes to existing infrastructure and maximize use of existing assets.*
> *3. Provide "N+1" generation redundancy for critical operations.*
> *4. Do No Harm: Built in fail safe modes revert to traditional (facility-dedicated) back up power operations."*[76]

The Microgrid Design Guide P-601 based on the pillars of reliability, efficiency, and cost were published and roll out has been supported by regular trainings based on SNLs course *Fundamentals of Advanced Microgrid Evaluation, Analysis and Conceptual Design*. At the same time the DOD Unified Facilities Criteria (UFC) were reviewed and aligned with lessons learned from SPIDERS. Regular exercises including black starts were conducted and coordination with federal departments and utilities on cyber security substantially increased the expertise of DOD staff.

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[75] Saurugg, H. (2016). Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS), http://www.herbert.saurugg.net/2016/blog/energiezellensystem/spiders

[76] Andersen, B. (2017): SPIDERS - JOINT CAPABILITY TECHNOLOGY DEMONSTRATION (JCTD). NAVFAC, http://resiliencesummit.com/program/pdf_2017/Bill%20Anderson.pdf visited on 8th August 2017.

The transition to commercial sector started in 2014 and SPIDERS projects became part the annual Energy Conservation Investment Program and reach multimillion U.S. dollar levels as shown in the list of below. [77] In 2016 DOD continues to spend more than 100 million USD to increase energy efficiency.

Table 5-1 Examples of SPIDER projects and investments[78]

Project Description	Location	Project cost	Investment per kWp/ Payback/ Savings to investment ratio
2MW Solar Photovoltaic	Dugway Proving Ground (Utah)	9,966,000 $	4,933 $ per kWp
1500 KW Wind Turbine	Dugway Proving Ground (Utah)	5,900,000 $	3,933 $ per kWp
Energy Management Control System	Tooley Army Depot (Utah)	5,500,000 $	
Microgrid	Tooley Army Depot (Utah)	4,300,000 $	
5MW PVs with 3MWHr Battery Storage	Fort Hunter Liggett (CA)	22,000,000 $	11 years 1,5 SIR
4-Wind Turbines 250KW	Ascension Aux Airfield St Helena (Bahamas)	5,500,000 $	9 years 1.8 SIR

The U.S. Air Force has started the next phase of microgrid development: mobile systems for worldwide operations. The concept consists of PV systems on tents, light wind systems, containerized battery systems and microgrid control systems.[79]
As part of the Operational Energy Strategy, DOD will integrate renewable generation, primarily PV and waste-to-energy for military camps as well as to the

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[77] U.S. Department of Defense (2014): Energy Conservation Investment Program, Congressional Notification, http://www.acq.osd.mil/eie/Downloads/IE/FY2016%20ECIP%20Congressional%20Notification.pdf visited on 8th August 2017.

[78] U.S. Department of Defense (2016): Energy Conservation Investment Program 2016 , Congressional Notification, http://www.acq.osd.mil/eie/Downloads/IE/FY2016%20ECIP%20Congressional%20Notification.pdf visited on 8th August 2017.

[79] Lindner, D (2017): Air Force Develops New, Deployable, Energy Systems. https://www.defense.gov/DesktopModules/ArticleCS/Print.aspx?PortalId=1&ModuleId=753&Article=1143863 visited on 7th August 2017.

individual war fighter equipment. [80] This reflects the assessment of the operational environment and the increase of improvised explosive devices (IEDs), irregular combatants, terrorist, or hybrid attacks at the tactical mile of supply of operational energy.

The challenges ahead for microgrids are related to the increasing share of generation within the microgrid from renewable energy sources. According to SPIDERS assessment the failure of PV or wind plants still require fly wheels or diesel generators to cover the load in case of technical issues or extreme weather events.

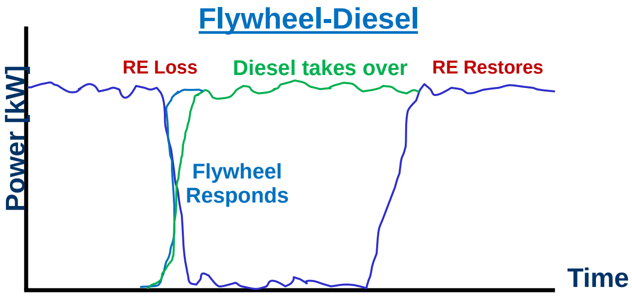

Figure 5-6 Combination of Renewables, Flywheel and Diesel[81]

For short-term back-up the DOD proposes fly wheels and diesel generator until RENs generate power again, the long-term storage will be batteries or H2 cells. Again, the complexity of the microgrid control system will surge.

In addition to microgrids a study conducted at the Michigan University of Technology assessed that 17 GW of PV capacity is needed to cover the DOD’s total demand of more than 80 GWh per day for more than 400 installations. Currently only 27 sites have installed PV systems with total less than 0,5 GW while the DOD has set a target of 3 GW by 2025 which is less than 25% of capacity need. The study recommends to shift budgets from the 18 billion USD energy expenditures to capital expenditures to implement a 100% PV microgrid infrastructure across all U.S.

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[80] Office of the Assistant Secretary of Defense for Energy, Installations and Environment (2016): 2016 Operational Energy Strategy. Department of Defense, Washington.

[81] Andersen, B. (2017): SPIDERS - JOINT CAPABILITY TECHNOLOGY DEMONSTRATION (JCTD). NAVFAC, http://resiliencesummit.com/program/pdf_2017/Bill%20Anderson.pdf visited on 8th August 2017.

military branches.[82] The list of microgrids is growing constantly and tests are performed for 100% renewable microgrids for at least 24 hours off grid operations. [83]

5.2 U.S. Department of Energy

The U.S. Department of Energy (DOE) has been active in microgrid research and development (R&D) for many years. One of their first pilot programs for microgrids was in reaction to grid failures caused by two extreme weather events in 2011 – Hurricane Irene and the 2011 snowstorm). The activities were accelerated after the superstorm Sandy during the hurricane season 2012 caused not only damage to homes but also to critical infrastructure leaving large swaths of the east coast without electricity.[84]

DOE defined a vision of the smart grid of the future as a network of integrated microgrids that is capable of monitoring and healing itself. The definition mentioned earlier is still valid and rest on the pillars of demand management, renewable generation, processors, and storage. Microgrids are part of DOE's network modernisation strategy and contribute to the target system efficiency and reliability of the electric network.

Microgrids' assets will increase the system stability of generation and transmission by shaving peaks and changing intentionally into islanding mode of operation. They are also a way to integrate CHP and renewables on a local base.

DOE has supported R&D activities across the U.S. and set up programs to reach specific cost and performance goals with microgrid systems by 2020:

- "*reducing outage time of required loads by >98%;*
- *cost comparable to non-integrated baseline solutions (UPS + diesel genset);*
- *reduce emissions by >20%;*
- *improve system energy efficiencies by >20%*"[85]

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[82] Prehoda, E., Schelly, C., Perce, J. (2017): U.S. Strategic Solar Photovoltaic-Powered Microgrid Deployment for Enhanced National Security. Preprint Renewable & Sustainable Energy Reviews. Elsevier, Amsterdam (NL). p. 5f.

[83] Microgrid Media (2018): Microgrid Projects. http://microgridprojects.com/military-microgrid-army-navy-air-force-microgrids-drivers/ visited on 2nd September 2018.

[84] Ton, D. (2014): DOE Activities on Microgrids and Grid Resilience. U.S. Department of Energy, Washington (DC)

[85] Ton, D. (2014): DOE Activities on Microgrids and Grid Resilience. U.S. Department of Energy, Washington (DC). p. 6.

The first target can be divided into energy security for critical loads and reduced downtime for other loads, specific standards could not be identified so far.

Major outputs of the program are standards for microgrid such as IEEE 1547 defining the interconnection of distributed resources with electric power systems. A few years after publication it was amended with IEEE 1547.4 the Guide for Design, Operation and Integration of Distributed Resources Island Systems with Electric Power Systems which represents one of the most important guidelines for microgrid operators.

5.3 Consortium for Electric Reliability Technology Solutions (CERTS)

The Consortium for Electric Reliability Technology Solutions (CERTS) has been operating a test bed to improve the seamless disconnection and reconnection to the grid. The technology includes flexible energy management systems for dispatch, storage devices, intelligent load shaving, and are commercially used in microgrids around the U.S.[86]

Optimal DER capacity and schedules are defined to meet cost targets based on inputs received from energy service data of buildings, tariffs for network, electricity and gas plus DER data and weather data the. The core components are the prognosis for loads and the weak-ahead schedule for generation.

The activities of the DOE are complemented by development of DER-CAM software for microgrids. Distributed Energy Resources Customer Adaptation Model is a software development initiative at Lawrence Berkeley National Laboratory to model and control the capacity and operating cost of a microgrid. The load and generation is assessed based on the selected site, operational concept, energy services, and required production.

5.4 Experience in the Europe

In Europe today, no initiative for military microgrids is under consideration and documented experiences remain on civilian applications for quarters in Germany and the Netherlands.

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[86] Hatziargyriou, N., ed. (2014): Microgrids – Architectures and Control, IEEE Press, Wiley, Chichester. p. 235.

In a field test in Mannheim the local supplier, MVV, demonstrated the transition from grid connected operation to island mode described by Kariniotakis.[87] Starting in 2016, this residential application with approximately 600 households has demonstrated in a sub-microgrid level with battery storage as buffer that is able to supplement a supply of 10kW for one hour. An additional battery is used to stabilise the frequency when interactively and automated switching between off grid and on grid mode. Interestingly energy efficiency increased due to proper demand side load management in this small installation.

In the Netherlands Van Overbeeke describes the Bronsbergen Microgrid as a test site for the DSO Liander. There, Liander demonstrates smart storage and islanded operation. The microgrid has to be able to survive on an average summer day for 24 hours on its own capability and reconnect automatically.

5.5 Conclusion for Scenario „CIP Northwind"

The described programs and experiences offer indications for the design of the renewable microgrid of the "CIP Northwind":

- Boundaries: Microgrids have a clear geographic perimeter with clear ownership structure and defined users with their requirements. Projects for "communities" or "quarters" that include the military base might be too complex in terms of objectives and responsibilities.
- Building Classification: The physical location of military functions is linked to a type of building, which are grouped, and have a defined consumption pattern, such as accommodation, workshops and office buildings for easier design.
- Defining critical infrastructure: Not every military installation is part of critical infrastructure and the critical infrastructure element does not need the whole base to be operational at all times. Defining the core functions that are absolutely needed and their emergency level of power is the prerequisite to find solutions for CIP in case of blackouts.

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[87] Hatziargyriou, N., ed. (2014): Microgrids – Architectures and Control, IEEE Press, Wiley, Chichester. p. 221f.

- Define Basic Threats and Vectors: For military planning the scenario with the worst effect for the own operation and highest probability is selected as the basis for planning. For the supply with electricity the physical destruction of large parts of instructor and targeted cyber-attacks on national grids have influenced planning in the U.S. with power outages of 72 hours to 14 days. Consequently, the objective for planning is the supply of 100% of critical load for at least 72 hours in the case of loss of power from the public grid.
- System Modification and Microgrid setup: The implementation of the microgrid requires modification of the military installation and the network infrastructure on MV and LV level that is often grown in steps of decades.
- Operational Concept: The concept for normal and emergency is often reassessed since microgrids offer benefits for daily operation. The operational concept for blackout situations needs to be planned and trained beforehand.

6 RENEWABLE MICROGRIDS FOR CIP NORTHWIND

The microgrid concept is based on of interconnected and controllable loads and energy resources that act as a single entity towards an electricity network. In order to build a microgrid the following technical units are necessary and are described for the selected scenario:

1. Loads and demand side management
2. Distributed Energy Resources (DER) and Renewables (REN)
3. Storage System
4. Microgrid controls and management system with Common Point of Coupling
5. Operation strategies and forecasting

6.1 Loads and Demand Side Management

Within a microgrid the electrical load is a machine or device that utilizes electrical energy and transforms it into other forms like light, work or heat. Electronic loads differ in their voltage, current, power, and frequency. Loads that have to be considered for microgrids for business facilities typically include:
- lightning of offices
- IT and telecom appliances
- cooling fans
- heating systems
- electrical appliances used in canteens or restaurants
- pumps
- charging infrastructure for emobility
- induction motor for workshops, repair and assembling shop and production facilities, which are mainly composite load as a function of frequency and voltage.

The specific combination of load types mentioned above is summarized for different building categories that can be labelled mission critical or non-critical.

For the dimensioning of the microgrid two questions need to be addressed:

- What is the total system load and how is it distributed over time in the form of a load curve?

- What parts of the load is critical and must be covered at all times and what can be moved to a later point of time?

Company or government sites with a maximum load of less than 100kW are typically supplied on network level 7 in Austrian distribution networks. For the scenario “CIP Nothwind” the maximum load is assumed in the range of 500kW supplied on network level 6. The load curve has its seasonal peak during winter and in some cases during the summer when cooling of buildings and electric car is the main driver for electricity demand.

Controllable loads are not critical or can be shifted to a later point of time, when the total system load is below the maximum load at a specific quarter of an hour or production capacity of REN can be increased. Typical controllable loads are heating or climatization, except for IT systems, or charging infrastructure for e-mobility or certain production activities.[88] The load-shedding can also be used as a mean against frequency deviations which must be avoided in the microgrid. The manageable load is regulated either by Programmable Logic Controller (PLC), a personal computer (PC) card, or manually. Converters for battery storage systems may also offer this function. The controller unit must react fast to stabilize the microgrid and restore frequency to normal value since deviations of 0,25 Hz already requires load shedding of up to 30%.[89]

For the scenario “CIP Northwind” the installation requires the permanent coverage of a minimum load of 31 kW with renewables or batteries, which equals a CLNS factor of 0%. In a business impact analysis, according to the Business Continuity Management, ISO 22301 the critical processes are defined and measures are taken to continue these processes with minimum load or discontinue them in a controlled manner in order to restored after resuming full power supply.
The maximum load is about 500 kW, if all appliances are operational and all charging points are used during the same period of time mirroring the SPIDERS’ “fence to fence approach” as shown below.

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[88] Kollmann, A., Moser, S., & Schmidthaler, M. (2014). Endbericht: Lastverschiebung in Haushalten, Industrie, Gewerbe und kommunaler Infrastruktur. Linz.

[89] Lopez, J. ed. (2004): Large Scale Integration of Microgeneration to Low Voltage Grids. Deliverable DD1 Emergency Strategies and Algorithms. Project MICROGRIDS. p. 23.

Table 6-1 Load Types and Load Shifting for "CIP Northwind" (own estimation)

Load Type	Minimum Load	Maximum Load	Load shifting
IT, security and access system	10 kW	20 kW	Limited for IT system, reduction of users in case of emergency
Cooling with heat pump	5 kW	20 kW	Reduction of cooling depending on outside temperature, no cooling in case of emergency except for ambulance area
Heating with heat pump	5 kW	20 kW	Reduction of temperature to 15° C, 10° C in case of emergency for only one section, except ambulance area
Canteen and ambulance facilities	10kW	10kW	No reduction, full load at all times
Motors and tools in repair workshop	0 kW	100 kW	Reduction of repairs works, no activities in case of emergency
Lights for offices	1 kW	5 kW	Reduction of areas used in case of emergency
Charging Infrastructure	0 kW	325 kW	Load management for each charging point, no charging in case of emergency, only if PV production covers load
TOTAL	**31 kW**	**500 kW**	

Maximum load is avoided under normal operational conditions and the charging infrastructure is controlled with load management in order not to exceed the capacity of network connection of 100 kW. The process is operational at the reference microgrid of W.E.B around CIP Northwind as shown below.

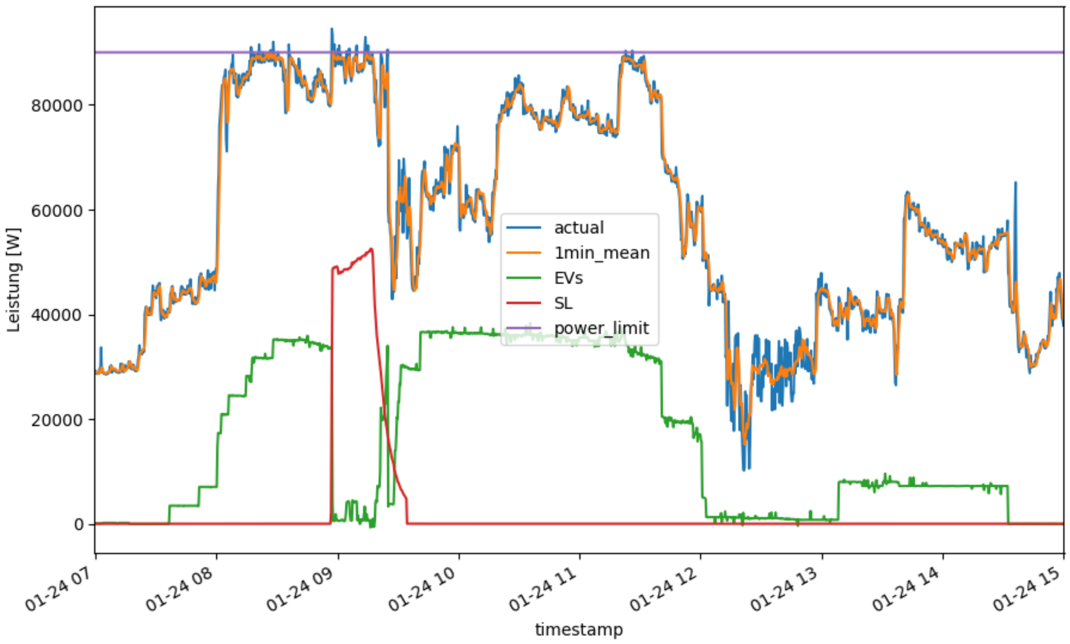

Figure 6-1 Load Shifting under standard operational conditions[90]

6.2 Distributed Energy Resources and Renewables

Almost all microgrids and emergency power systems use generator packs operated on fossil fuels. Renewable energy microgrids typically use two main energy resources without demand for supply of fuels and have been selected for review within the scope of this thesis, photovoltaics and wind energy plants.

6.2.1 Photovoltaics

Photovoltaic systems are based on the long known photoelectric effect and convert radiation of the sun directly into electricity. With an installed capacity of 300 GW worldwide in 2017 the learning curve has been reduced and made PV to a competitive technology.[91] With less than 1,000, - € per installed kWp systems cost W.E.B projects have reached grid parity allowing business customers to cover their electricity demand at the same cost level as supply from the electricity grid – at least for certain proportion of their total load.

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[90] Mader, F. (2018): Lastverlauf eines Tages am Standort WEB Windenergie AG. Präsentation Energiewendepartnerschaft, Pfaffenschlag. p. 19f.

[91] Schmela M. (2017): Global Market Outlook 2017-2021: Solar Boom Continues. SolarPower Europe. p.12.

For the quality of the business case the system design is targeted at maximizing the share of consumption at the respective premises of our scenario to 30% of PV production. The plant is connected to the distribution system operator's network at the lowest network layer (NE7 or NE6 in Austria). Under grid operation the remainder is delivered into the battery or to the grid. In the case of off-grid operation, the PV converter controlled by the load controller adjusts production to the system load.

The PV system uses standard polycrystalline modules and converters and is separated in PV 1 on the roof top (100kWp) and PV 2 on the parking area (100kWp) which is also favourable according the stipulations for feed in tariffs.

Based on the PVGIS Tool the PV production is assessed for the location 48°41'46" North, 15°19'31" East, with elevation of 525 m a.s.l. and the following key performance indicators: [92]

- Solar radiation database used: PVGIS-CMSAF
- Nominal power of the PV system: 200.0 kW (crystalline silicon)
- Estimated losses due to temperature and low irradiance: 7.4% (using local ambient temperature)
- Estimated loss due to angular reflectance effects: 3.0%
- Other losses (cables, inverter etc.): 14.0%
- Combined PV system losses: 22.7%

The total yearly yield is calculated with 204,000 kWh with maximum production of 24,900 kWh in July as shown in the table below. The biggest concern is the average daily sum of global irradiation per square meter received by the modules of less than 1.5 hours per day in November, December and January with about 6.000kWh of production.

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[92] Šúri M., Huld T.A., Dunlop E.D. Ossenbrink H.A., 2007. Potential of solar electricity generation in the European Union member states and candidate countries. Solar Energy, 81, 1295–1305, http://re.jrc.ec.europa.eu/pvgis/ visited on 10th August 2018.

Table 6-2 Monthly Production of 200kWp PV (calculation based on PVGIS)[93]

Month	E_d	E_m	H_d	H_m
Jan	214.00	6630	1.27	39.3
Feb	390.00	10900	2.33	65.1
Mar	610.00	18900	3.80	118
Apr	820.00	24600	5.29	159
May	799.00	24800	5.26	163
Jun	801.00	24000	5.38	161
Jul	802.00	24900	5.46	169
Aug	764.00	23700	5.15	160
Sep	631.00	18900	4.12	124
Oct	449.00	13900	2.82	87.5
Nov	237.00	7110	1.45	43.5
Dec	184.00	5720	1.10	34.2
Yearly average	559	17000	3.63	110
Total for year	**204 000**		**1 320**	

E_d: Average daily electricity production from the given system (kWh)
E_m: Average monthly electricity production from the given system (kWh)
H_d: Average daily sum of global irradiation per square meter received by the modules of the given system (kWh/m^2)
H_m: Average sum of global irradiation per square meter received by the modules of the given system (kWh/m^2)

Based on a standard polycrystalline module the PV system for the REN microgrid would require 1200 m^2 for construction on rooftop or parking areas with an expected investment of 730 € per kWp total planning and installation cost minus subsidies for investments.

From a resilience perspective, the PV shall cover a minimum of 30% of the monthly electricity demand in the summer period from April to September. The PV is not capable to cover the maximum load of 500kW every quarter of an hour during that

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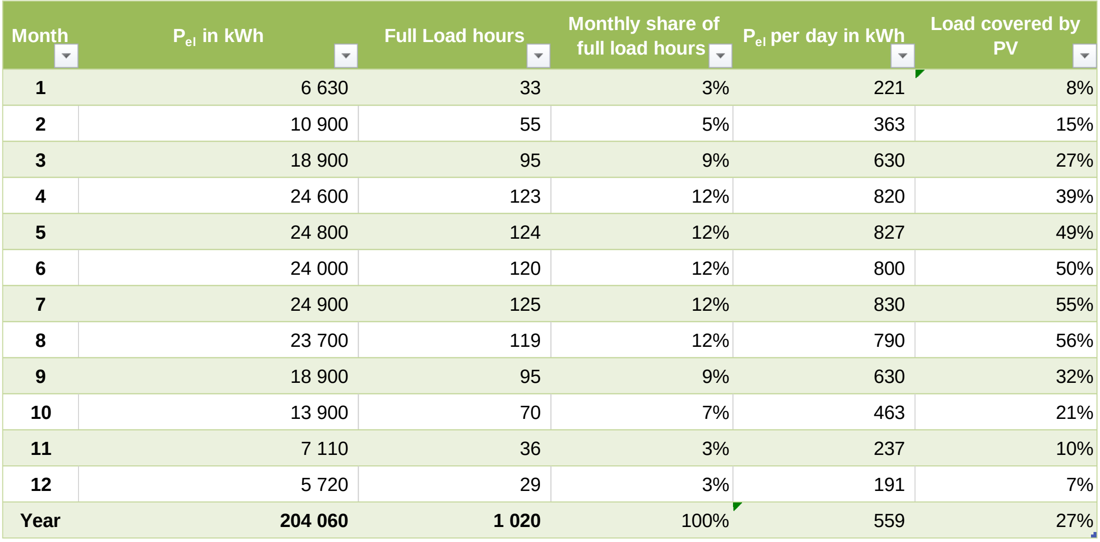
[93] Šúri M., Huld T.A., Dunlop E.D. Ossenbrink H.A., 2007. Potential of solar electricity generation in the European Union member states and candidate countries. Solar Energy, 81, 1295–1305, http://re.jrc.ec.europa.eu/pvgis/ visited on 10th August 2018.

period. Its coverage rate during winter on a monthly base remains on the very moderate level of 7% in December or 8% in January as shown in the table below.

Table 6-3 Production of PV and Load Covered (own calculation)



Month	P_{el} in kWh	Full Load hours	Monthly share of full load hours	P_{el} per day in kWh	Load covered by PV
1	6 630	33	3%	221	8%
2	10 900	55	5%	363	15%
3	18 900	95	9%	630	27%
4	24 600	123	12%	820	39%
5	24 800	124	12%	827	49%
6	24 000	120	12%	800	50%
7	24 900	125	12%	830	55%
8	23 700	119	12%	790	56%
9	18 900	95	9%	630	32%
10	13 900	70	7%	463	21%
11	7 110	36	3%	237	10%
12	5 720	29	3%	191	7%
Year	**204 060**	**1 020**	100%	559	27%

In summary, PV is a valuable energy source on balance base for half of the year with cost at grid parity. However, during the winter months it only may support emergency operations with very limited loads. A PV location near “CIP Northwind” the 15 minute intervals without any PV production are more than 60% of total 15 minute intervals in January.[94] Subsequently the PV systems must be combined with battery systems and with other sources of renewable energy.

From an economic perspective, PV achieves a positive net present value (NPV), a long run generation cost of electricity of 78,25 € per MWh and with current feed in tariffs of less than 77 €/MWh. Under the assumption of 40% self-consumption rate and network cost of about 40 €/MWh and electricity prices of almost 60 €/MWh for comparable customers the PV system generates a benefit of about 94 €/MWh as shown in the table below.

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[94] Expert Interview on PV Production Data and Storage with Markus Höllrigl, PV and Storage Expert, WEB Windenergie AG on 4th September 2018.

Table 6-4 Key Financial Indicators of PV System (own calculation)

Financial parameters	Value	Unit
Discount Rate / cost of capital	3%	[year]
Rated capacity PV System	0,20	[MWp]
Investment Costs Installed Syster	730 000	[€/MW peak]
Repair Works (in year 6)	40 000	[€/MW]
O&M (incl. all variable costs)	15,00	[€/MWh] in t=0
Real escalation of O&M Costs	0,5	[%/year]
Degradation	0,4	[%/year]
Investment horizon T1	15	[years]
Performance Ratio PV System	78%	
Global Radiation in North NOE	559	[kWh/m^2]
Size of Power-Module	1,65	[m^2]
P_{MPP} Mono	0,280	[kWp]
Area per kWp	5,9	[m^2]
Total area of PV	1 180,5	[m^2]
Self consumption rate	40%	
Feed-In-Tariff for 13 years (flat)	76,7	[€/MWh]
Variable Cost Electricity	96,4	[€/MWh]
Calculations		
Full Load Hours PV System	1 020	[hours/year]
Generation P_{el}	204	[MWh/year]
Sale of energy/replacement of supply from grid	84,58	[€/MWh]
Electricity Sale (nominal)	17 259	[€]
Capital Recovery Factor T=15	0,0838	
Area per kWp	6,00	[m^2]
Size of System	1 200	[m^2]
Long Run Electricity Cost inlcuding cost escalation	-€ 78,25	[€/MWh]

The system operates at grid parity, profitability will improve with the development of electricity prices, since reference prices for the power future Phelix Year Call Base and Peak currently increases strongly at the European Electricity Exchange, and investments in achieving higher self-consumption rates are also economically beneficial if the cost is less than 30 €/MWh.

From an ecological perspective, the energy produced by the small PV system reduces CO_2 emission by about 13 tons per annum compared to electricity from the grid with Austrian average of 64 g CO2/kWh[95]

6.2.2 Wind converting engine

Wind is the result of differences in temperature and pressure of air mass. The kinetic energy of the mass depends on the flow and velocity of the wind. Blades capture this flow of wind and transfer it into mechanical energy by the shaft to the generator. The kinetic energy is the product of velocity v to the second power and the mass flow of air m.[96]

$$E = \frac{1}{2} \times \dot{m} \times v^2$$

The mass flow is the product of density ρ and the area covered by the rotor A:

$$\dot{m} = \rho \dot{x} A \times v$$

The theoretical power is then calculated as:

$$p_{th} = \frac{\rho}{2} \times A \times v^3$$

The theoretical power in Watt enclosed in the wind is p_{th}, ρ is the air density in kg/m^3, A is the vertical surface or rotor swept area in m^2 and v is the flow speed of the wind in m/s.[97]

The amount of energy produced depends mainly on the specific climate and wind conditions of a region at the height of the tower and the type of wind turbine used for harvesting the kinetic energy of wind, since the wind speed influences the result to the third power. Therefore, the design for the wind energy engine seeks a balance of cost for height of the turbine and production in the laminar wind sectors at 100m or

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[95] Energie-Control Austria (2018): Stromkennzeichnungsbericht 2018. Wien. p. 11.

[96] Heuck K., Dettmann K., Schulz D. (2007): Elektrische Energieversorgung – Erzeugung, Übertragung und Verteilung elektrischer Energie für Studium und Praxis. Vieweg, Wiesbaden.

[97] Krenn A. (2015): Wind power – Technical Systems. Energiewerkstatt. Friedburg.

above. In contrast to urban environment of many military installations the location of "CIP Northwind" offers good wind conditions as well as available areas.[98]

The site for wind parks must be in line with environmental laws concerning distances to areas inhabited by endangered species (NÖ Naturschutzgesetz 2000), building regulations (Bauordnung) for wind plants with N_p of more than 50kW and airspace restrictions of the exercise ground. In addition, the regional government of Lower Austria issued an ordinance for territorial planning (based on the NÖ Raumordnungsgesetz 1976) of areas reserved for wind plants, which enables wind plants in three areas in the distance of less than 10km. The closest possibility of a direct cable would be in the community of Göpfritz an der Wild in a distance of 5km to the base of "CIP Northwind" as shown in the map of the ordinance below. Assuming a good chance for positive environmental impact assessment and agreements with land owners a developed project can be built within a year, a development from start would take at least three years.

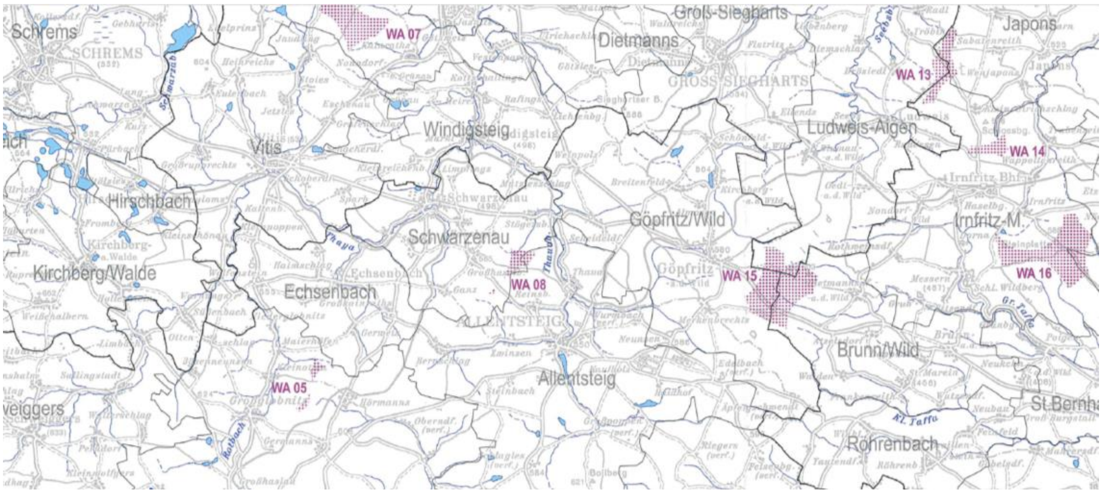

Figure 6-2 Reserved areas for wind plants in near "CIP Nortwhind"[99]

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[98] Stifter R., Farghadan M. (2013): Standorte für Windkraftanlagen in Wien unter bestimmten Rahmenbedingungen – UPDATE. ENERGON, Wien.

[99] Niederösterreichische Landesregierung (2014): Verordnung über ein Sektorales Raumordnungsprogramm über die Windkraftnutzung in NÖ. Anlage 4 Karte NW. LGBl. 8001/1-0.

Wind speeds in the area of the proposed scenario are satisfactory in the range of 5.5 to 6.5 at 100m height, but not sufficient for an efficient turbine with 50m height as shown in the Austrian Wind Atlas below:

Green 4.5. – 5.5m/s

Blue 5.5. – 6.5m/s

Orange 6.5. – 7.5m/s

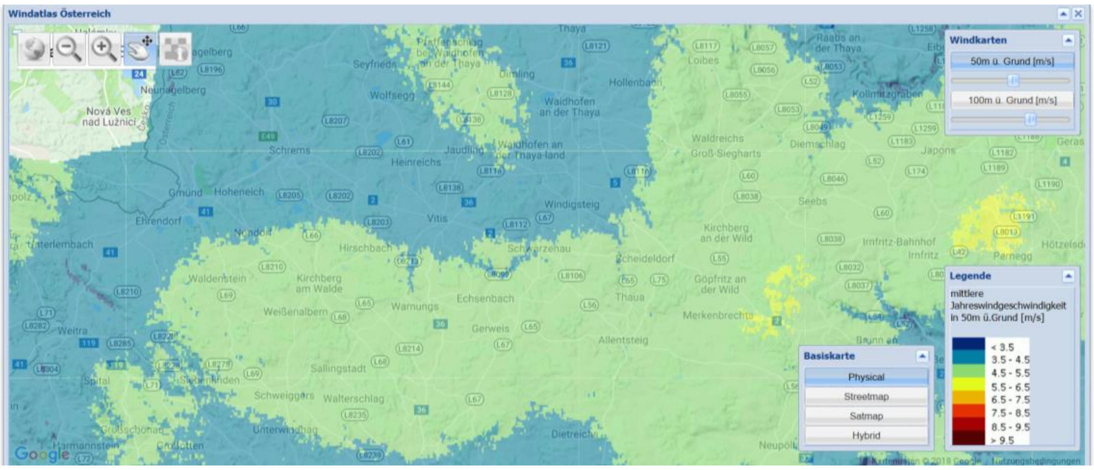

Figure 6-3 Windatlas of Austria: Average Wind Speeds in Allensteig at 50m [100]

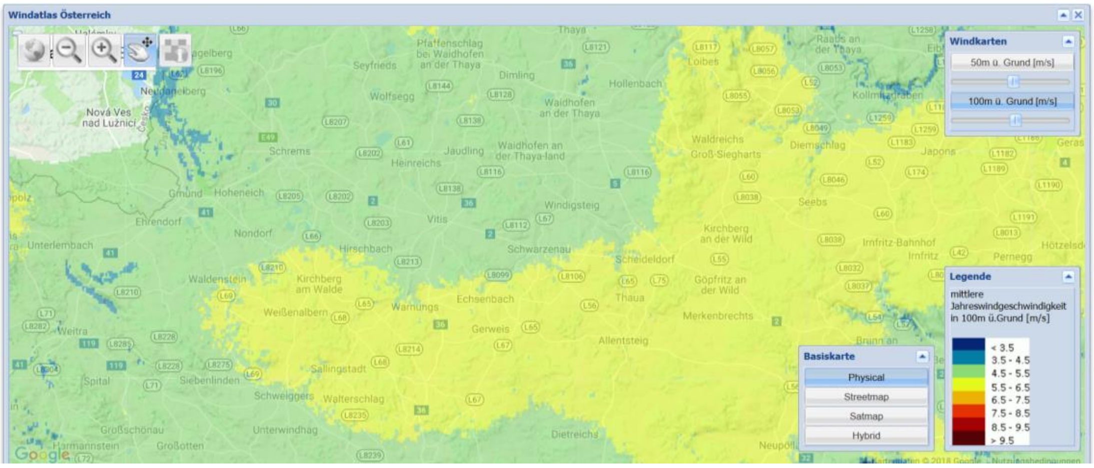

Figure 6-4 Windatlas of Austria: Average Wind Speeds in Allensteig at 100m [101]

To cover the energy demand of our scenario installation a small systems with rated power of about 800kW or less would be sufficient, which were common around 2000

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[100] Krenn A., Biberbacher M. (2012): Austrian wind potential analysis. www.windatlas.at visited on 15th August 2018.

[101] Krenn A., Biberbacher M. (2012): Austrian wind potential analysis. www.windatlas.at visited on 15th August 2018.

and built in large numbers (also for military microgrids in the U.S.). Small wind turbines with less than 100kW have not yet achieved technical maturity and comparable efficiency and are mainly used for isolated applications or hybrid systems with gen-sets for farms or water pumping.[102] For the scenario commercial turbines in the 1MW class or higher will be compared.

Today, there are very few systems available from the top vendors with less than 800 kW, but a sizeable secondary market for used system has been established. Consequently, historic data for the small system is used, as proxy the Vestas V44 is selected which could cover the load demand and offers hub heights of up to 63m with 44m rotor diameter to benefit from the windspeeds at our scenario.

Figure 6-5 Vestas V44 with steel tube[103]

Rotor diameter	44,0 m	Swept area:	1.521m²
Cut in speed:	4 m/s	Cut out speed:	15 m/s

Based on the technical data and assumed 1700 full load hours, the small plant produces maximum 1 GWh per year. With the chosen system V44, the long run costs of energy amount to about 95,-€/MWh as shown in the table below. The turbine height is less than 70m and does not reach laminar wind speeds. The large system with two turbines is by far more efficient with more than 2500 full load hours and nominal LRCE of less than 60,- €/MWh.

Table 6-5 Comparison of two Wind Energy Engines - Production and Investment Cost ("Windparkertrags-Analyse")[104]

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[102] European Wind Energy Association (2015): Wind Energy – The Facts. A guide to the technology, economics and future of the wind power. earthscan. p. 127f.

[103] WEB Windenergie AG (2018): Kraftwerke – Vösendorf I. https://www.windenergie.at/page.asp/-/97.htm?kw=52 on 10th August 2018.

Location	Small System	Large System
wind turbine	Vestas V44-600 kW	Enercon E126 4,2 MW
rated power	600 kW	4200 kW
rotor diameter	44 m	127 m
swept area	1520.5 m²	12667.7 m²
maximum capture	0.432	0.451
Number of turbine	1,0	2,0
Total rated power	0.6 MW	8.4 MW
average wind speed	6,34 m/s	6.5 m/s
average wind power	246.3 W/m²	321.3 W/m²
average power wind park	0.12 MW	2.45 MW
yearly production	1.016 GWh/a	21.464 GWh/a
Full Load hours	**1693 h/a**	**2555 h/a**
Investment	**0.72 Mio. €**	**10.08 Mio. €**
O & M cost	0.0216 Mio. €/a	0.3024 Mio. €/a
Long run electricity cost (nominell)	9.43 €ct/kWh	5.81 €ct/kWh

Typically, the average wind speeds are distributed around 6 m/s where the power coefficient cp of the systems reaches its maximum of 0,5, which is substantially higher than for small wind energy systems as shown below.

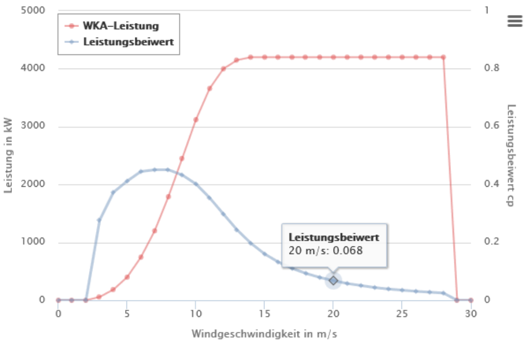

Figure 6-6 Large System - calculated power curve in kW and power coefficient cp

The large wind systems guarantee production over a large bandwidth of wind speeds with cut in speed of 3 m/s (compared to 4 m/s of the small V44), still the relative probability of wind speeds below cut in speed is 1%.[105] So theoretically there will be hours and even days where no electricity production from wind is achieved, which was typical during long stable weather situations in spring and summer 2018. The PV system will not cover every quarter of an hour of the load, which again requires battery storage facilities even if during stable weather conditions PV is likely to produce power.

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[104] Quaschning V. 2017. Windparkertrags-Analyse. http://www.volker-quaschning.de/software/windertrag/index2.php visited on 12th May 2017.

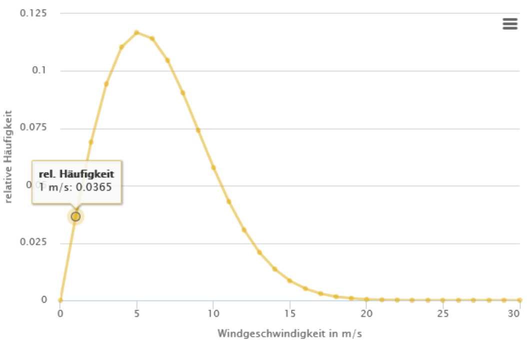

Figure 6-7 Large System - Distribution of production in relation to wind speed[106]

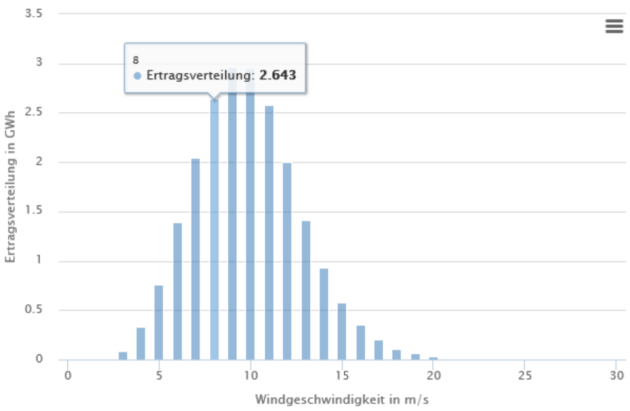

Figure 6-8 Large System - Distribution of production in relation to wind speed

From a resilience point of view the total production of the small V44 could easily cover the demand in the scenario on a monthly basis. The more efficient large systems would cover a multitude of demand needed, in case of emergency operation the production must be drastically reduced to keep the frequency in off-grid operation of the microgrid, which is feasible and used regularly to curb wind park production in network congestion situations.

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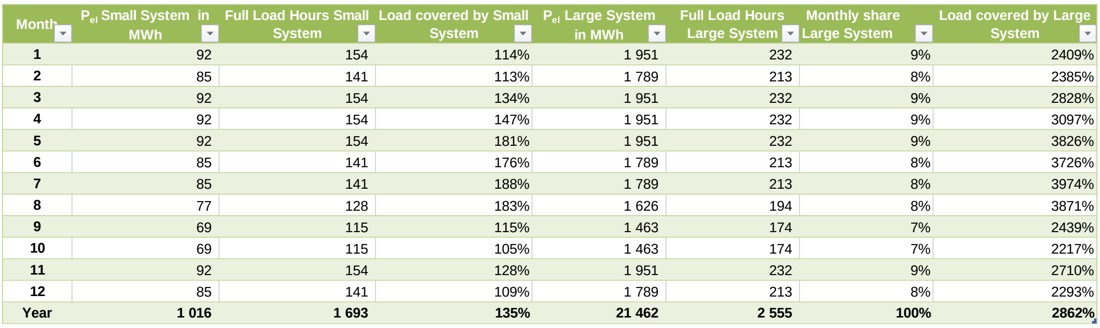
[106] Quaschning V. 2017. Windparkertrags-Analyse. http://www.volker-quaschning.de/software/windertrag/index2.php visited on 15th August 2018.

Table 6-6 Comparison of Small and Large Wind Turbine System (0wn Calculation)



Month	P_{el} Small System in MWh	Full Load Hours Small System	Load covered by Small System	P_{el} Large System in MWh	Full Load Hours Large System	Monthly share Large System	Load covered by Large System
1	92	154	114%	1 951	232	9%	2409%
2	85	141	113%	1 789	213	8%	2385%
3	92	154	134%	1 951	232	9%	2828%
4	92	154	147%	1 951	232	9%	3097%
5	92	154	181%	1 951	232	9%	3826%
6	85	141	176%	1 789	213	8%	3726%
7	85	141	188%	1 789	213	8%	3974%
8	77	128	183%	1 626	194	8%	3871%
9	69	115	115%	1 463	174	7%	2439%
10	69	115	105%	1 463	174	7%	2217%
11	92	154	128%	1 951	232	9%	2710%
12	85	141	109%	1 789	213	8%	2293%
Year	**1 016**	**1 693**	**135%**	**21 462**	**2 555**	**100%**	**2862%**

From an economic point of view the large wind energy turbine has a very attractive level of LREC (discounted) of less than 55,- €/MWh, if service as maintenance cost are as planned, which is sometimes a challenge with ENERCON turbines.

The business model is based on 100% production for the feed-in-tariff in the first 13 years, therefore total production has to be fed into the public grid and the green power balance group managed by OeMAG and probably at network level 5. Therefore, under normal operation, no electricity is used for the installation of “CIP Northwind”. In the case of a blackout, the installations can only be supplied if the wind power plant is connected with direct cable to the microgrid and transformed into the corresponding network level. The additional cost for the network connection, production management, and critical battery systems for start under off grid situation adds up to the investment cost depending on the distance network connection point to the base.

Still, there is a positive business case with an NPV of approximately 6,7 Million € under the assumption shown below, details of the business case are shown in the appendix. The financial risk of the large system corresponds with the possibility to sell the power after the feed in period at cost plus margin.

Table 6-7 Key Indicators of Wind Turbines (own calculation)

Financial parameters	Value	Unit
Assumptions		
Discount Rate / cost of capital	3%	[year]
Rated capacity Small System	0,60	[MW]
Rated capacity Large System	8,40	[MW]
Full Load Hours Small System	1 693	[hours/year]
Full Load Hours Large System	2 555	[hours/year]
Investment Costs Small Sys	1 200 000	[€/MW]
Investment Costs Large Sys	1 200 000	[€/MW]
Repair Works (in year 6)	12 000	[€/MW]
O&M (incl. all variable costs) Small System	22,00	[€/MWh] in t=0
O&M (incl. all variable costs) Large System	14,00	[€/MWh] in t=0
Feed-In-Tariff for 15 years (flat) Small System	81,20	[€/MWh]
Feed-In-Tariff for 15 years (flat) Large System	81,20	[€/MWh]
Real escalation of O&M Costs	1	[%/year]
Investment horizon T1	15	[years]
Calculations		
Generation P_{el} Small System	1 016	[MWh/year]
Generation P_{el} Large System	21 462	[MWh/year]
Electricity Sale Small System (nominal)	82 483	[€]
Electricity Sale Large System(nominal)	1 742 714	[€]
Capital Recovery Factor T=15	0,0838	
Long Run Electricity Cost inlcuding cost escalation Small System (discounted)	-70,49	[€/MWh]
Long Run Electricity Cost inlcuding cost escalation Larbe System (discounted)	-54,76	[€/MWh]

After year 13, the total production is available for supply for all installations and other locations of the organisation of the organisation or public administration. In the case of no feed-in-tariff, an agreement can be achieved with OeMAG due to a long waiting list, the alternative could be a private power purchasing agreement e.g. with the Ministry of Defence to supply a great portion of the demand for electricity.

If the technical setup of one or both turbines is prepared for off-grid operation in the microgrid it could also take part in the market for balancing energy. The TSO can contract power plants to deliver positive or negative balancing energy in a tendering system. On a small scale the microgrid has to be able to maintain frequency according the same principle, on large scale assets with response times from seconds to minutes according the figure below.

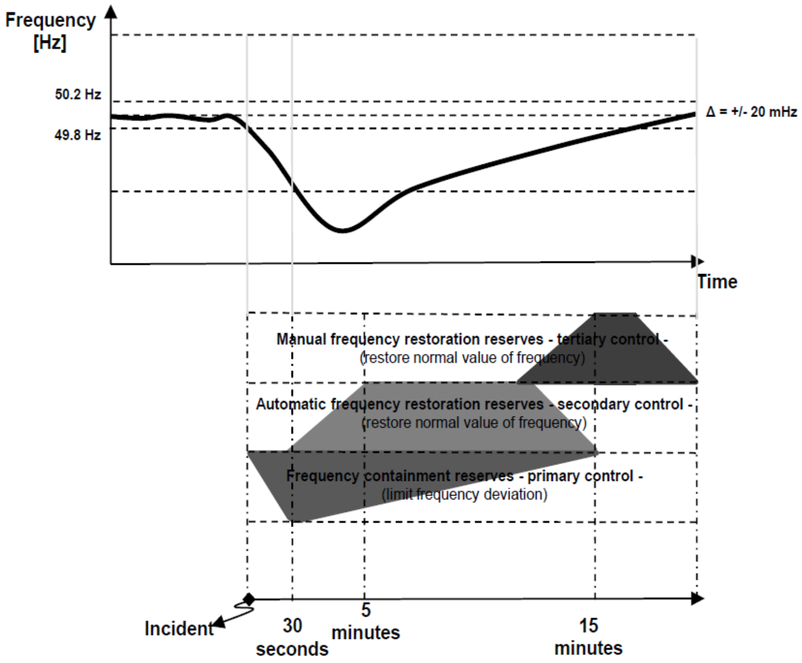


Figure 6-9 Frequency Control Reserves for Electricity Networks[107]

Wind turbines are prequalified according technical specification for the secondary reserve (i.e. automatic Frequency Restoration Reserve) and are procured in weekly and daily tenders by the control area manager.[108] Minimum bid is set at 5MW and in case of successful tender the plant has the obligation to supply. Consequently, both turbines should tender as a plant and can only offer negative control energy if wind prognosis offer enough production for the tender period.

The positive contribution of the revenue stream control energy is difficult to assess, market participants expect increasing demand with growing share of renewables but also falling prices with more offers from independent plant operators in the renewable sector. The amount of revenue can be based on weekly results and the prices for offering the control energy and energy price for the actual supply. For our systems, a bid with 5 MW for negative control energy would be possible. The wind turbines could generate the capacity price of 5€/MW/h fee for an assumed 4000

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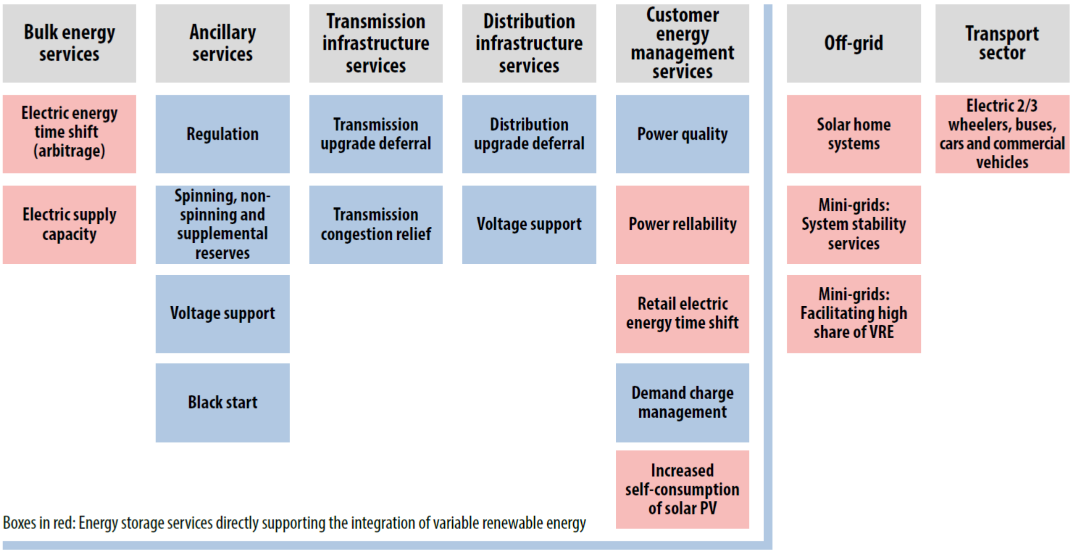
[107] Rezania, R. (2017): Chemical storages and energy efficient mobility. Script Module 5 Renewable Energy Systems, Technische Universität, Wien. p. 19f.

[108] Austrian Power Grid (2018): Tenders for aFRR in the APG Control Area. https://www.apg.at/en/markt/netzregelung/sekundaerregelung/ausschreibungen visited on 24th August 2018.

calls per annum in time resolutions of 15 min and 90,- €/MWh energy resulting in a yearly revenue of 90,000,- € p.a. in best case. The additional revenue is reduced by the loss of revenue for electricity not produced. At EXAA price levels of 60,- €/MWh during off peak the additional revenue melts down to 35.000,- € p.a.

6.3 Storage Units

Storage units are a significant part of the energy transition to renewables on grid and customer levels and importance will increase with increasing share of renewables in the electricity network.[109] The review of PV and wind power systems has demonstrated the demand for storage systems for the on grid as well as for the off-grid operation mode of the microgrid in the selected scenario in different functions. As shown in the figure below the integration of renewables storage systems is needed for customer energy management services to increase self-consumption of renewable production. In off-grid operation the storage facilities of the microgrid are required to take over the function of the TSO in a national power grid, the maintenance of network frequency, and the role of the DSO, the stabilisation of power quality and voltage.



Boxes in red: Energy storage services directly supporting the integration of variable renewable energy

Figure 6-10 Services from electricity storage units[110]

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[109] Lettner, G. (2016): Systemanwendungen vom Klein- bis zum Großbatteriespeicher - Aktuelle Forschungskonzepte. p. 10.

[110] IRENA (2017): Electricity Storage and Renewables: Cost and Markets to 2030. International Renewable Energy Agency, Abu Dhabi. p. 11.

The application of storage devices in the microgrid can be derived with focus on hourly storage and ancillary services as shown in the figure below.

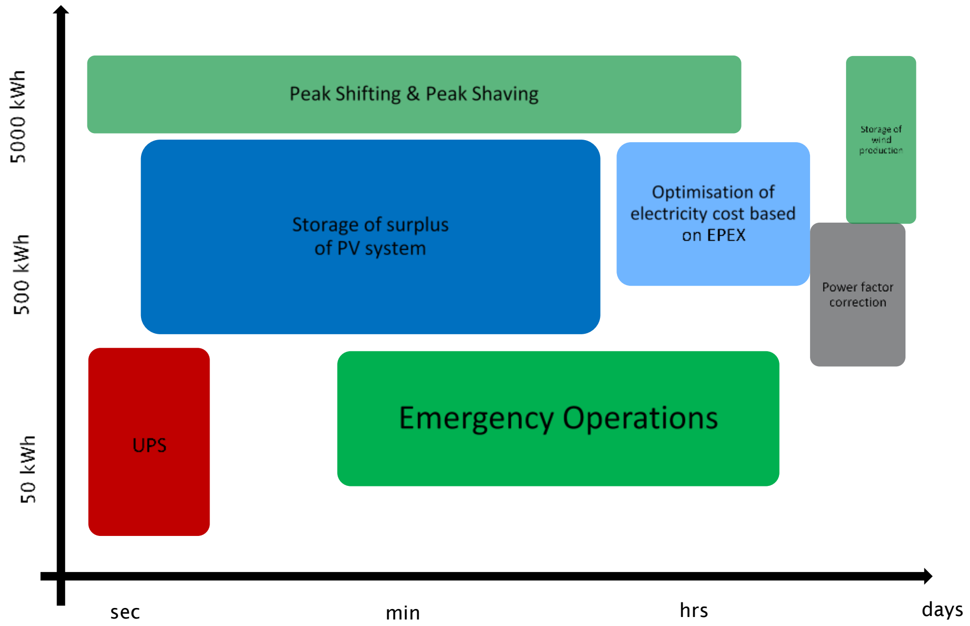

Figure 6-11 Application of storage device in microgrid

For selection of technology and dimensioning for cost assessment the requirements mainly in terms of capacity are summarized in the table below:

Table 6-8 Capacity Requirements for Storage Device for Scenario "CIP North"

Function	Minimum Capacity	Maximum Capacity	Comments
UPS < 20ms	5 kWh	10kWh	High requirements on converter of battery and off grid capability
Power Reliability for 30min	0,02 MWh	0,15 MWh	Emergency supply with off grid capability
Daily Storage of surplus from PV production	0,055 MWh	0,728 MWh	Especially for summer with high production and lower consumption, high capacity
10-day Storage of average demand for emergency operation	13,5 MWh	26 MWh	Without production from sun or wind
10-day Storage of	0,420 MWh	0,830 MWh	Without production from sun or

reduced demand for emergency operation			wind
10-day Storage of reduced demand for emergency operation with PV	0,200 MWh	6,5 MWh	Based on daily production of PV, storage of surplus during summer month
Daily Storage of power from wind for emergency operation	47 MWh	62 MWh	after FiT period or in case of offgrid operation and full production, very high capacity
Frequency control	0,015 MWh	0,150 MWh	30% of load
Black start	0,3 MWh	0,5 MWh	Same as daily storage

In terms of discharge time and capacity the conventional and flow batteries can cover most applications required for the microgrid. To keep costs balanced, two small battery storage systems for applications in the second and minutes segments plus two high capacity redux flow systems for storage for 10 days is selected for the scenario, which are illustrated below.

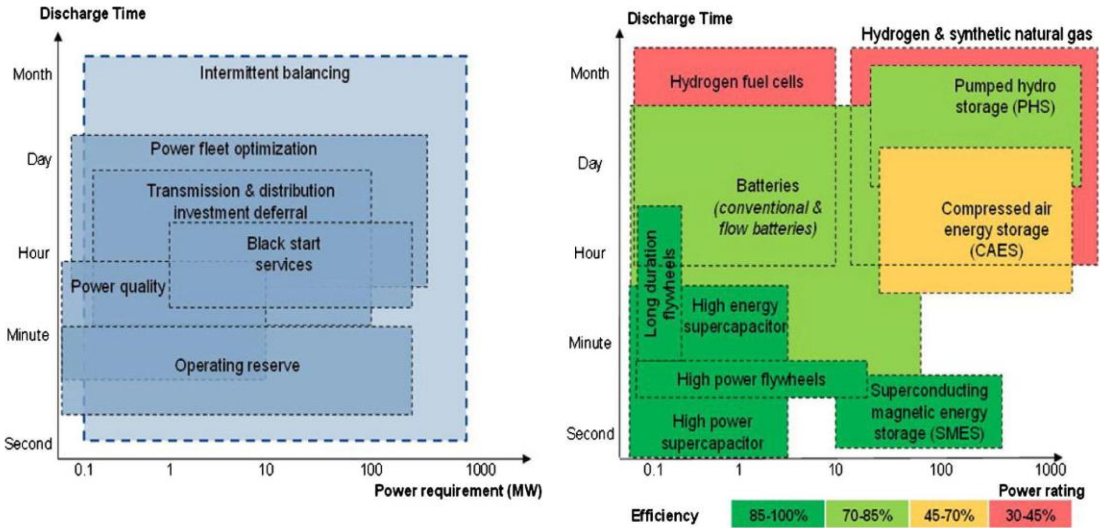

Figure 6-12 Capacities and efficiencies of Electricity Storage System[111]

The storage of surplus production from wind systems is not feasible and economical at a first glance with necessary capacities of minimum 47 MWh, since reducing production from one or both turbines would be the more viable option during off grid operation.

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[111] Harasek, M. (2018): Biomass-free renewable fuels for the mobility sector (windgas). Script Module 9 Perspectives on the use of REN. TU Wien. p. 19

The total capacity of the redux flow system should be at 1MWh to store the surplus of PV and to cover 10 days off grid operation without any production and average demand.

The capacity of the small system should be at 180 kWh. The small systems role is UPS, ancillary services for the microgrid especially if load is larger than generation and coverage of reduced load for a short period of days. In this situation, the system frequency will start to decrease, generation must then be increased to restore frequency to its nominal value. Since REN systems will operate normally without reserves, the PV or wind system will not able to secure the required power. Then the small batteries can help by providing the remaining power without delay.

The price point for Li-Ion ESS for end users is expected to fall by 9-16% p.a., where 11% are caused by the battery storage part and about 10% to the converters until 2020 and 3% thereafter as shown in the graph below.

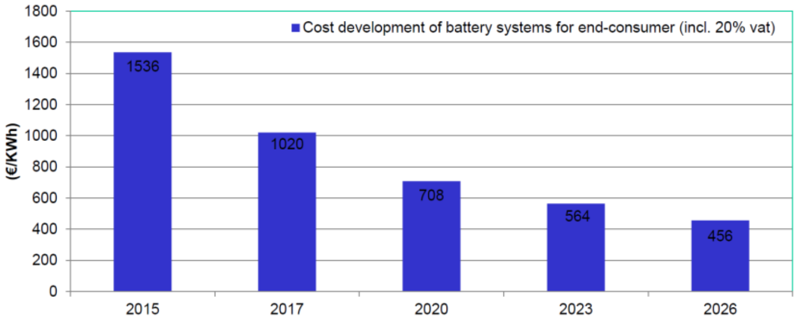

Figure 6-13 Cost Development of Battery Systems[112]

The small battery system could increase the self-consumption rate of the PV under normal operation. The technical solution is robust Lithium Iron Phosphate ($LiFePO_4$) batteries with two systems in compliance with the n+1 where each module has a capacity of 100kWh and power of 90kW as shown below. The battery systems are stored inside the building with IT infrastructure and the building with the command post with some additional requirements for HVAC. The operational mode is focused

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[112] R. Rezania (2017): Chemical storages and energy efficient mobility. Lecture Msc Renewable Energy System. TU Wien.

on UPS plus increasing PV self-consumption. 10kWh are always kept in reserve for UPS which might also increase life time of the battery.

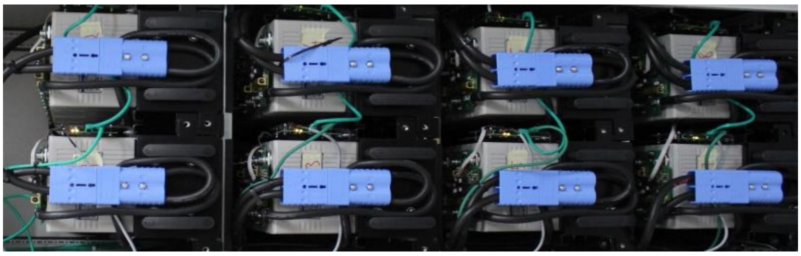

Figure 6-14 LiFePO$_4$ Battery Packs of the ESS at the WEB Microgrid (own picture)

The kWh produced by the PV has then a higher economic value than the feed-in-tariff, the delta is increasing with growing network fee even with constant electricity prices as shown in the figure below. Consequently, the additional benefit of the small battery valued at the cost of electricity from the grid is positive, the resulting NPV is 18.000 € is positive due to an increase of self-consumption rate from 40% to 90%.

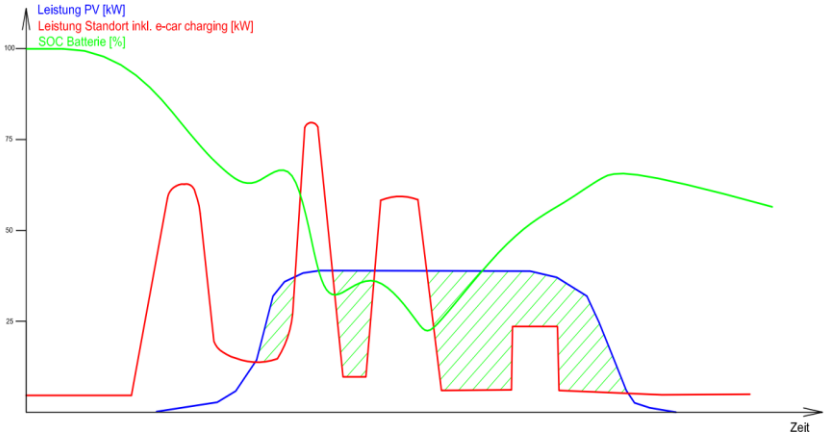

Figure 6-15 SOC of ESS LiFePO$_4$ with PV and Load Management[113]

For the large battery system, the redux flow battery with salt water is selected, that is in use with military microgrids.[114] The capacity of 1 MWh is built with flexible

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[113] Mader, F. (2018): Lastverlauf eines Tages am Standort WEB Windenergie AG. Präsentation Energiewendepartnerschaft, Pfaffenschlag.

[114] Elisa Wood (2017): The Life and Death Value of Energy Storage in Military Microgrids. https://www.essinc.com/wp-content/uploads/2017/01/The-Life-and-Death-Value-of-Energy-Storage-in-Military-Microgrids.pdf visited on 14th August 2018

modular system of 4 containers stored outside the workshop building within "CIP Northwind" as shown below from a product developed in Austria.

Figure 6-16 Concept of Redox Flow Batteries in Microgrid Scale[115]

Redux flow batteries with vanadium (VRFB) are far above 500,- €/kWh CAPEX with high cost reduction potential as in IRENA's assessment shown below. Nevertheless systems based on salt water are available for 1 MWh capacity with CAPEX at 600,- €/kWh today and expected to sell below 300,- €/kWh in two years' time according suppliers.

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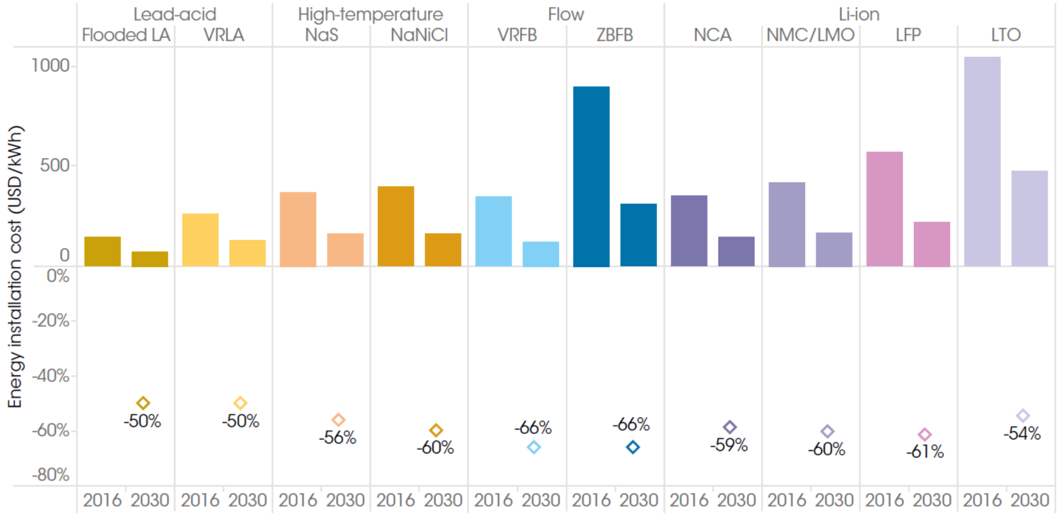
[115] GILDEMEISTER energy solutions GmbH (2017): Flow battery applications for the utility world. Reliable storage systems based on vanadium redox flow technology. Wiener Neudorf.



Note: LA = lead-acid; VRLA = valve-regulated lead-acid; NaS = sodium sulphur; NaNiCl = sodium nickel chloride; VRFB = vanadium redox flow battery; ZBFB = zinc bromine flow battery; NCA = nickel cobalt aluminium; NMC/LMO = nickel manganese cobalt oxide/lithium manganese oxide; LFP = lithium iron phosphate; LTO = lithium titanate.

Figure 6-17 Battery Electricity Storage Systems – Cost and Cost Reduction Potential[116]

The large battery system causes investments of more than 700,000,- € to store 1 MWh. The size is not relevant for daily storage of the wind production, at best case it can avoid to balancing energy for minutes. However, the flow battery can cover the reduced load for 10 days without any DER production in case of blackout even during the winter months.

The additional benefit is derived from avoiding additional network fees from exceeding the network connection limit of 300 kW with up to 200 kW. This might occur almost monthly with associated cost of 40,- €/kW and produces an NPV of about 5000,- € as shown in the table below and in the appendix.

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[116] IRENA (2017), Electricity Storage and Renewables: Costs and Markets to 2030, International Renewable Energy Agency, Abu Dhabi, p. 18.

Table 6-9 Key Financial Indicators of Electricity Storage System (own calculation)

Financial parameters	Value	Unit
Assumptions		
Discount Rate / cost of capital	3%	[year]
Rated capacity Small System LiFePh	0,16	[MWh]
Rated capacity Large System Redux Flow	1,00	[MWh]
Full Load Hours Small System	638	[hours/year]
Full Load Hours Large System	2 555	[hours/year]
Investment Costs Small Sys	525 000	[€/MWh]
Investment Costs Large Sys	720 000	[€/MWh]
Repair Works (in year 6)	100 000	[€/MWh]
O&M (incl. all variable costs) Small System	2,00	[€/MWh] in t=0
O&M (incl. all variable costs) Large System	2,00	[€/MWh] in t=0
Variable Cost Electricity	96,4	[€/MWh]
DSO fee per kW (nominal, Leistungspreis)	40,0	[€/kW]
Real escalation of O&M Costs	2	[%/year]
Investment horizon T1	15	[years]
Calculations		
Amount of electricity Discharged Small System	102	[MWh/year]
Additional power for maximum load avoided (>300kW network limited from grid)	1 800	[kw/year]
Electricity Sale Small System (nominal)	9 836	[€]
Avoided DSO fee p.a.(nominal, Leistungspreis)	72 000	[€]
Capital Recovery Factor T=15	0,0838	
Long Run Electricity Cost inlcuding cost escalation Small System (discounted)	-81,34	[€/MWh]
Long Run Power Cost inlcuding cost escalation Larbe System (discounted)	-39,73	[€/kW]

The LREC can be interpreted as “Levelized Cost of Storage”, where capital cost is the most prominent factor followed by battery replacement due to performance decrease of the period of use and storage cycles. Both values are below the bench mark of supply from the grid with a small margin, the business case is therefore on the edge but improving with increased costs of electricity or costs of network usage.

6.4 Microgrid Controls and Management System

The capability to control load, storage, and production represents the main difference between microgrids to a system of distributed energy resources. Energy management within the microgrid is vital to achieve the operational objectives described below and to form a unit to the upstream network as well as to the energy service provider company.

The microgrid control is the link between the upstream network interface to the DSO and the local control and protection to the distributed energy resources and loads within the microgrid.[117]

Core functions of the DSO pertain to off-grid or on-grid mode and on import or export of electricity. Internal microgrid control functions encompass the following:

1. secondary voltage/frequency control;
2. secondary active/reactive power;
3. load and RES forecast;
4. load shedding or management;
5. unit control and dispatch;
6. security monitoring; and
7. black start.

Local control includes protection functions, primary voltage/frequency control, primary active/reactive power control, and battery management.

The management of assets will only be able with information and communication technology and a control architecture connecting all nodes with the microgrid central controller as shown in the figure below.

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[117] Hatziargyriou, N., ed. (2014): Microgrids – Architectures and Control, IEEE Press, Wiley, Chichester. p. 26f.

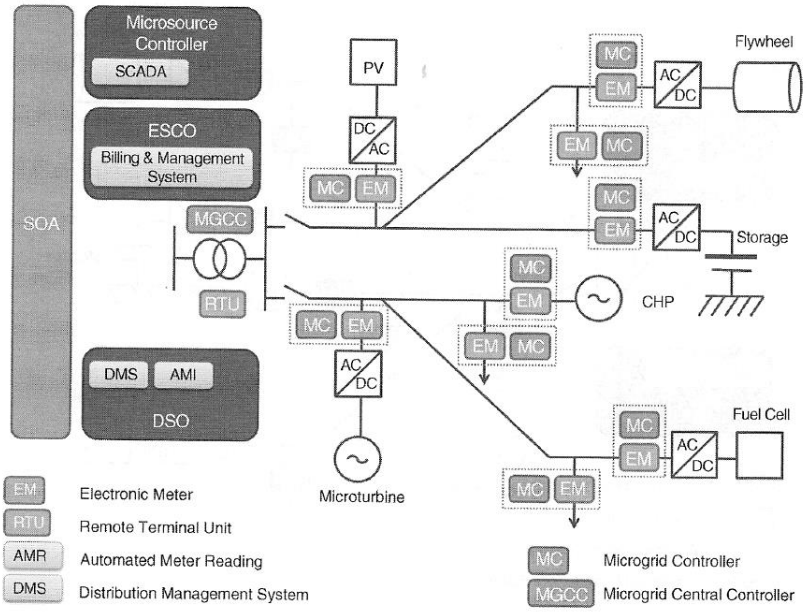

Figure 6-18 Management Architecture Required for Control of Microgrids[118]

Electronic metering (EM) provides real time or 15 minute data from generation units, storage facilities, and consumers. Microsource controller (MC) consists of software modules in the element or a separate device with power electronic interface that monitor and manage the microgrid elements.

The microgrid central controller (MGCC) represents the main interface to the upstream network of the DSO as well as to the ESCO's billing and management systems if needed. Under a liberalized market model, the DSO does not intervene in to operation of the microgrid as long as the network parameters are observed. The DSO however might act as a flexibility facilitator to the microgrid operator providing information on network status.

If DER have a single owner, professional experience, and personnel is available, centralized control by one microgrid control is preferred, which allows implementation of more complicated algorithms. The opposite would be a completely decentralised control by each individual asset in the microgrid that might follow competitive objectives such as technical stability versus maximising profit from renewable production.

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[118] Hatziargyriou, N., ed. (2014): Microgrids – Architectures and Control, IEEE Press, Wiley, Chichester. p. 30.

The MGCC controls the common point of coupling, which is the defined boarder between the DSO and the microgrid and secures the complete disconnection from the network in case of blackout with an automatic switch. This is necessary for safety reasons to avoid supply of electricity into the grid in case of outages or planned revisions. Under emergency operation it enables the microgrid to maintain frequency in its own grid.

Standard products consisting of a CPU and controllers for functional blocks are offered by all vendors in the electricity market, e.g. Siemens, Schneiders, and GE as used for U.S. military microgrids shown below.

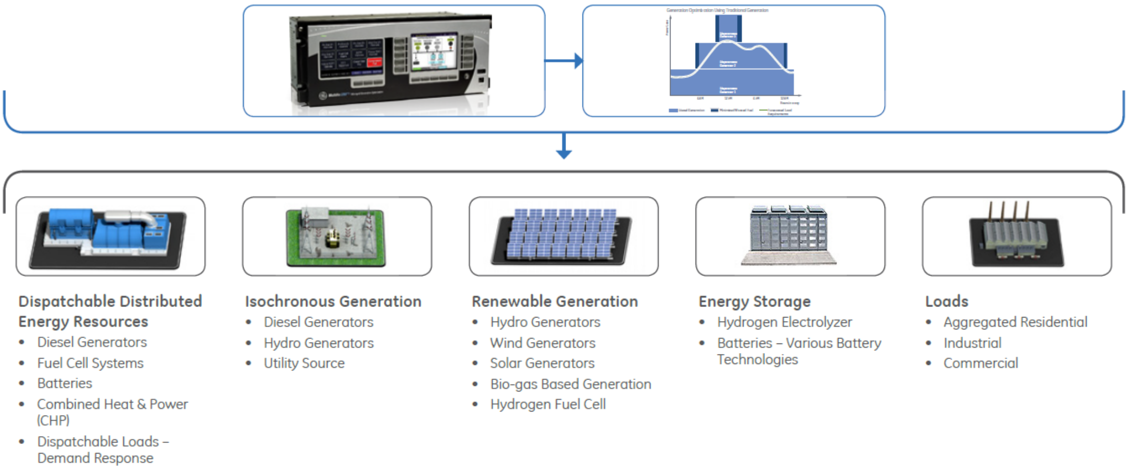

Figure 6-19 Example of Microgrid Control Systems with Applications[119]

The investment cost for the MGCC consists of the hardware including rack systems with CPUs, local controllers, automated switches, and breakers plus the software with the user interfaces. For “CIP Northwind” the total costs are estimated at 250.000 € based on the investments for larger installations of SPIDERS projects and cost for WEB’s microgrids.

6.5 Operation Strategies

As for a national network or the strategic options for operation must be balanced between economic, technical, and environmental objectives.

Economic targets include:

- a reduction of cost of energy as average €/kWh per annum;
- a reduction of cost of short outages or blackout;

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[119] GE Digital Energy (2012): Grid IQ™ Microgrid Control System. Markham (ON)

- optimisation of cost of operation; and
- increase of benefits from markets for control energy.

Technical goals include energy balance, stable grid voltage, network capacity limits of DSO. Environmental focus on the reduction of GHG emissions and a reduced need for additional network infrastructure on DSO level.

In case of CIP Northwind the primary target is to reduce damage from blackouts that have to be balanced with investments. Reducing CO2 emissions or cost of operations represents a secondary objective in most projects.

Operational concept for CIP tries to secure a seamless switch from on grid status to off grid supply of critical assets and follows defined standard operating procedures in the event of failure at the moment of time “t” as follows: [120]

t + 1 second: MGCC shows same behaviour as without microgrid: DER (e.g. PV) is shut down according safety requirement (to reduce risk of accidents from back-feeding into the DSO’s grid as described above). After 2 to 5 minutes the supply from PV or other renewables is restored.

For the defined load of critical assts at “CIP Northwind” the battery UPS starts seamless until the microgrid prime system with DER and large batteries is up and running.

t + 1 minute: Non-critical assets at “CIP Northwind” are without power and expect the public grid to return. In contrast to the SPIDERS installation, where standby emergency diesel generators are used with less than 30sec start up time, the renewable microgrid must survive with battery systems and production from the DER.

t + 10 minutes: The microgrid is built up gradually for the total base, which site is disconnected from the DSO’s grid with breaker controls. The automated distribution switches are open and loads are removed from high-voltage distribution network, segmenting switches are opened step by step and power is re-established to all buildings. This “black-start” ability could contribute also to the reliability and resilience of the public grid if there is large amount of dispersed generation.

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[120] Lopez, J. ed. (2004): Large Scale Integration of Microgeneration to Low Voltage Grids. Deliverable DD1 Emergency Strategies and Algorithms. Project MICROGRIDS. p.2ff.

t + >15 minutes: The microgrid is automatically optimised for longer outages where predefined loads are shut down manually by the operator.
t + x minutes: If the public grid returns, the microgrid prime power is synchronised with the DSO’s frequency, prime power with batteries or DER is reduced, but REN generation remains.

6.5.1 Success factor Forecasting

Prediction of demand and supply is of great importance for any microgrid and decisive in off grid operation mode. During the on-grid operation the upstream network could be seen as infinite storage facility buffering the residual load or problems in the operation of the DER. Still the business case for the microgrid depends on decision based on price signals and the exact forecast.

While participants in the electricity market have excellent tools for mid and long-term prognosis for weather, demand and production, there is an absence of near term forecasting for smaller units of microgrids. The resolution required is not only on day or hourly basis but a resolution of 1 to 5 minutes to be capable of controlling the limited number of assets. According to the literature forecasting of demand based on electronic metering data is inappropriate due to high variations. A weather forecast is required to determine the load and the PV and wind production, which would be generated locally in the case of a blackout. Therefore, the MGCC needs to run at least a simplified model for forecasting demand and supply.

6.6 Cyber Security

The microgrid must function especially in emergency situation caused by disaster or attacks on the public grid by a capable adversary. Hence the cyber security has a vital role and shall prohibit access points to the vector of cyber warfare as used e.g. to attack the Ukraine power grid (3 DSO and 1 TSO) in 2015 and 2016.

Sandia National Laboratories has developed a cyber security reference architecture to reduce vulnerability. The main idea of the IT architecture is to form enclaves that operate under a single authority and security policy in a trusted environment. The communication between enclaves is very much restricted and defined by functional domains such as domain renewables and domain distribution with their own security policy. The microgrid energy management system (EMS) has a network connection and an intelligent electronic device (IED) such as the microgrid central controller. This is critical since storage facilities might not have a direct connection to the VLAN. At the boundaries of enclaves attacks or attempts of intrusion are repelled. As a transport layer TCP/IP is used, on the internet layer IPv6 is recommended, on the application layer SCADA. The reference architecture with renewable DER, automatic transfer switch, breakers, IEDs, transformers, the EMS and the human-machine interface (HMI) client is shown in the graph below.

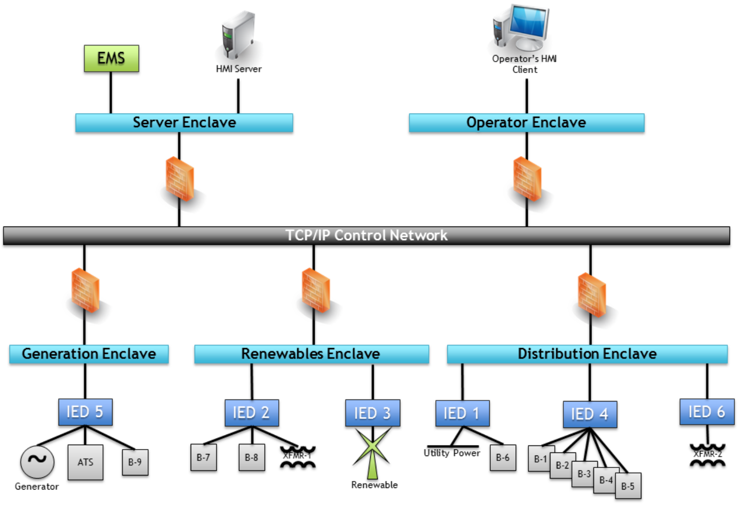

Figure 6-20 Sandia's reference architecture for Microgrid Control[121]

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[121] Veitch, C. et al. (2013): Microgrid Cyber Security Reference Architecture Version 1.0. Sandia National Laboratories, Albuquerque (NM). p. 69. http://prod.sandia.gov/techlib/access-control.cgi/2013/135472.pdf

7 RESULTS FOR SELECTED TECHNOLOGIES AND CIP NORTHWIND

7.1 Feasibility of Technical Solution

The renewable microgrid for “CIP Northwind” is capable of controlling the load, generate electricity under normal conditions and in emergency mode, and connect and disconnect from the public grid.

The renewable microgrid consists of a:
- PV system with 200 kWp;
- small battery system with 180 kWh capacity;
- wind energy system 8, 4MW;
- large battery system with 1 MWh; and
- supporting system with load management, microgrid controller and IT system.

These elements are technologically mature and are commercially available.

Covering ten days without supply from the public grid and limited production from the renewable resources of the microgrid seems feasible, “CIP Northwind” could survive with drastically reduced load covered by the battery system as shown in the table below. MGCC would be able to disconnect the microgrid and restore step by step the average supply as soon as PV or wind generation starts again and is available at least for few hours of the day.

Wind production could cover even normal plus peak load within the microgrid with substantial investment. The availability of wind resources and direct access is an exception for the locations of military bases in Austria, only a view location in Lower Austria (Allensteig, St. Pölten, Horn, Korneuburg, Grossmittel, Bruckneudorf) have a theoretical change of a direct link to wind power plants. Most garrisons are located in Western Austria where wind power is not supported or in the urban areas of Vienna, Graz and Linz where no assets are in reach for direct links as shown below.

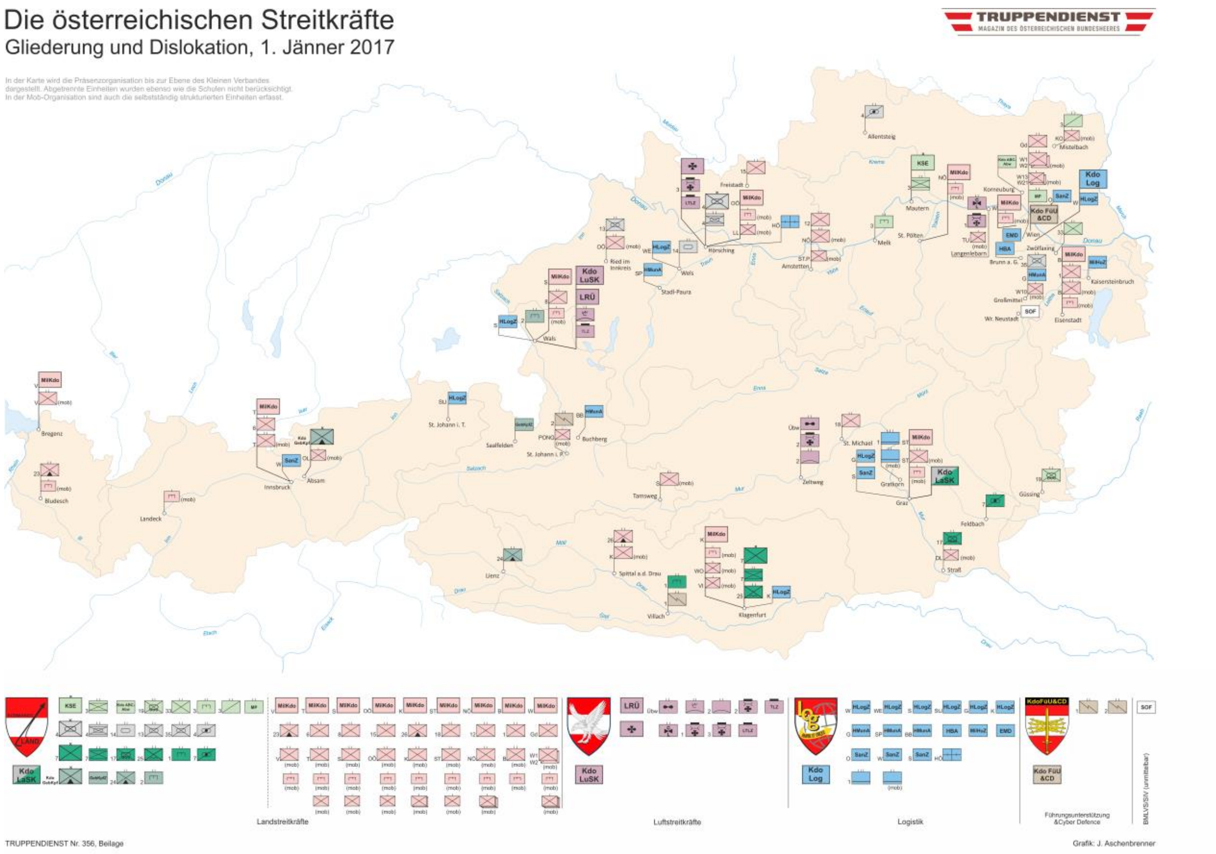

Figure 7-1 Military Bases of the Austrian Armed Forces

For the hypothetical scenario of “CIP Northwind” the effort of 2 turbines might be deemed as over dimensioned, but could be applied to a wider concept of smart grid configuration where segments of the public grid could be supplied in case of an emergency.

Operating and maintaining all elements of the microgrid requires substantial expertise and 24/7 service from a network operation centre, which might be a challenge for only one location.

7.2 Economic appraisal

Under normal operation the PV system has a clearly positive NPV independent of its function for emergency operation, since it reduced demand from the network. Self-consumption of power produced by the PV modules could be increase with a small battery system. Both elements have a small contribution to improve the load profile by reducing peak demand, the effect is small but positive in the calculation of electricity prices of the supplier.

The wind power has a positive NPV from its sale to the grid with feed-in-tariffs and is a viable project of its own, additional revenues from participation in the tendering for aFCR might be positive, but market conditions are changing quickly so it is a neglectable contribution with low probability.

The large battery system has its main role for the case of emergencies. Under normal operation it could be reduced in combination with load management network fees, if the load from the network connection can be limited to 200 kW.

To summarize, the investment in renewable DER has a positive financial effect even without of microgrid functionality. The additional investment for off-grid functionality for a blackout situation could be financed from this positive NPV even if the wind project is not realised for "CIP Northwind".

Table 7-1 Financial Performance of Renewable Microgrid (own calculation)

	Invest		Net Present Value		Improvement to Base Case	Additional Revenue p.a	
PV	-€	146 000	€	352 348	5% Higher Share of Base for Calculation	€	1 000
Wind	-€	10 080 000	€	6 773 475	Tender revenue for automatic Frequency Control	€	35 000
Small Battery System	-€	84 000	€	18 344	Increase of PV self consumption to 90%	€	-
Large Battery System	-€	720 000	€	5 793	Avoided network fees for additional power	€	-
Ancillary Systems, VLAN and Cyber Security	-€	250 000	-€	250 000		€	-
MGC	-€	150 000	-€	150 000		€	-
TOTAL	**-€**	**11 430 000**	**€**	**6 749 960**		**€**	**36 000**

Additional revenue from ancillary services that are "*required by the transmission or distribution system operator to enable them to maintain the integrity and stability of transmission or distribution system as well as the power quality*"[122] are not relevant since the microgrid elements are too small to justify the extra effort.

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[122] Hatziargyriou, N., ed. (2014): Microgrids – Architectures and Control, IEEE Press, Wiley, Chichester. p. 15.

8 CONCLUSIONS

Existing projects and programs in the U.S. and investigations into the scenario “CIP Northwind” the conclusion can be drawn that a renewable microgrid for normal operation and under blackout scenarios is feasible under the condition of reduced load. The investment in the microgrid elements could reduce operational costs during standard grid-connected operation but has not necessarily a positive total NPV if the large contribution from the sale of wind power is excluded.

Detailed technical and electrical planning is required, especially the cost for IT and microgrid software. The method requires the analysis of 15 minute or 1 minute time intervals of production and supply and proper tools to simulate and plan the elements of microgrids.

As for the energy transition in general, the main challenge remains in the winter half year. This time period reflects the highest demand, but minimal production from PV or wind, and runs the risk of no production at the moment of a blackout. Dimensioning of storage facilities to cover normal or even peak load is out of reach, only CIP Northwind ESS would require the capacity of 25 MWh to cover normal demand with no production from DER.

The lesson learned from “CIP Northwind” is similar to efficiency projects and could be viable for industrial or campus microgrids as well as for military microgrids. First, detailed analysis and reduction of demand is required, the critical assets that need to be supplied at all times should be quantified and optimised. Secondly, the boundaries for CIP projects are decisive for availability of renewable resources, since wind may be relegated, to a role in very view special situations. Thirdly the investment for protection of critical infrastructure can only partly be justified with savings for normal operation. The substantial argument is still the benefit of avoiding damage to the critical infrastructure.

Preparing critical infrastructure for blackouts might require a process with many steps from planning, changing facilities, installing renewable resources, extending storage, and optimising operations over years. Every step towards a renewable microgrid increases the resilience of the base with critical infrastructure and might have a major contribution to the state in case of a blackout.

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10 APPENDIX

Table 10-1 Calculation of Net Present Value of PV System

Year	Dicsounted CF	Nominal CF	O & M	Investement/ Replacement/	Electricity Sale/Own Consumption (discounted)	Devistement (discounted)	Costs (discounted)	Discount factor
0	-€ 146 000	-€ 146 000		-€ 146 000			-€ 146 000	1,00
1	€ 13 837	€ 13 748	-€ 3 076	€ -	€ 16 824		-€ 2 987	0,97
2	€ 13 485	€ 13 307	-€ 3 092	€ -	€ 16 399		-€ 2 914	0,94
3	€ 13 142	€ 12 878	-€ 3 107	€ -	€ 15 985		-€ 2 843	0,92
4	€ 12 807	€ 12 459	-€ 3 123	€ -	€ 15 582		-€ 2 774	0,89
5	€ 12 481	€ 12 050	-€ 3 138	€ -	€ 15 188		-€ 2 707	0,86
6	€ 5 464	€ 3 651	-€ 3 154	-€ 8 000	€ 14 805		-€ 9 341	0,84
7	€ 11 854	€ 11 261	-€ 3 170	€ -	€ 14 431		-€ 2 577	0,81
8	€ 11 552	€ 10 881	-€ 3 186	€ -	€ 14 067		-€ 2 515	0,79
9	€ 11 258	€ 10 510	-€ 3 201	€ -	€ 13 712		-€ 2 454	0,77
10	€ 10 972	€ 10 148	-€ 3 217	€ -	€ 13 366		-€ 2 394	0,74
11	€ 10 692	€ 9 795	-€ 3 234	€ -	€ 13 028		-€ 2 336	0,72
12	€ 10 420	€ 9 450	-€ 3 250	€ -	€ 12 699		-€ 2 279	0,70
13	€ 10 155	€ 9 113	-€ 3 266	€ -	€ 12 379		-€ 2 224	0,68
14	€ 166 240	€ 165 128	-€ 3 282	€ -	€ 168 410		-€ 2 170	0,66
15	€ 162 041	€ 160 860	-€ 3 299	€ -	€ 164 159		-€ 2 117	0,64
NPV:	**€ 330 400**			**Total Revenues**	**€ 521 033**	NPV of Costs:	**-€ 190 633**	
Annuity:	**€ 27 677**					Annuity of Costs:	**-€ 15 969**	
Long Run Electricity Cost inlcuding cost escalation			**-€ 78**					

Table 10-2 Calculation of Net Present Value for Wind Turbine Systems

Year	Dicsounted CF	Nominal CF	O & M	Investement/ Replacement/	Electricity Sale (discounted)	Devistement (discounted)	Costs (discounted)	Discount factor
0	-€ 720 000	-€ 720 000		-€ 720 000			-€ 720 000	1,00
1	€ 70 266	€ 72 374	-€ 10 109	€ -	€ 80 081		-€ 9 815	0,97
2	€ 68 124	€ 72 272	-€ 10 210	€ -	€ 77 748		-€ 9 624	0,94
3	€ 66 046	€ 72 170	-€ 10 313	€ -	€ 75 484		-€ 9 437	0,92
4	€ 64 031	€ 72 067	-€ 10 416	€ -	€ 73 285		-€ 9 254	0,89
5	€ 62 076	€ 71 963	-€ 10 520	€ -	€ 71 151		-€ 9 075	0,86
6	€ 54 150	€ 64 658	-€ 10 625	-€ 7 200	€ 69 078		-€ 14 928	0,84
7	€ 58 341	€ 71 752	-€ 10 731	€ -	€ 67 066		-€ 8 726	0,81
8	€ 56 557	€ 71 644	-€ 10 839	€ -	€ 65 113		-€ 8 556	0,79
9	€ 54 826	€ 71 536	-€ 10 947	€ -	€ 63 216		-€ 8 390	0,77
10	€ 53 148	€ 71 426	-€ 11 056	€ -	€ 61 375		-€ 8 227	0,74
11	€ 51 520	€ 71 316	-€ 11 167	€ -	€ 59 587		-€ 8 067	0,72
12	€ 49 941	€ 71 204	-€ 11 279	€ -	€ 57 852		-€ 7 911	0,70
13	€ 48 410	€ 71 091	-€ 11 392	€ -	€ 56 167		-€ 7 757	0,68
14	€ 46 925	€ 70 978	-€ 11 505	€ -	€ 54 531		-€ 7 606	0,66
15	€ 45 484	€ 70 862	-€ 11 620	€ -	€ 52 943		-€ 7 459	0,64
NPV:	**€ 129 844**	**€ 45 484**		**Total Revenues**	**€ 984 676**	**NPV of Costs:**	**-€ 854 833**	
Annuity:	**€ 10 877**					**Annuity of Costs:**	**-€ 71 606**	

LARGE SYSTEM

Year	Dicsounted CF	Nominal CF	O & M	Investement/ Replacement/	Electricity Sale (discounted)	Devistement (discounted)	Costs (discounted)	Discount factor
0	-€ 10 080 000	-€ 10 080 000		-€ 10 080 000			-€ 10 080 000	1,00
1	€ 1 397 322	€ 1 439 242	-€ 303 473	€ -	€ 1 691 956		-€ 294 634	0,97
2	€ 1 353 763	€ 1 436 207	-€ 306 507	€ -	€ 1 642 675		-€ 288 913	0,94
3	€ 1 311 528	€ 1 433 142	-€ 309 572	€ -	€ 1 594 831		-€ 283 303	0,92
4	€ 1 270 578	€ 1 430 046	-€ 312 668	€ -	€ 1 548 379		-€ 277 802	0,89
5	€ 1 230 873	€ 1 426 920	-€ 315 795	€ -	€ 1 503 281		-€ 272 407	0,86
6	€ 1 107 959	€ 1 322 962	-€ 318 953	-€ 100 800	€ 1 459 496		-€ 351 536	0,84
7	€ 1 155 055	€ 1 420 572	-€ 322 142	€ -	€ 1 416 986		-€ 261 931	0,81
8	€ 1 118 870	€ 1 417 351	-€ 325 364	€ -	€ 1 375 715		-€ 256 845	0,79
9	€ 1 083 788	€ 1 414 097	-€ 328 617	€ -	€ 1 335 645		-€ 251 858	0,77
10	€ 1 049 776	€ 1 410 811	-€ 331 904	€ -	€ 1 296 743		-€ 246 967	0,74
11	€ 1 016 802	€ 1 407 492	-€ 335 223	€ -	€ 1 258 974		-€ 242 172	0,72
12	€ 984 835	€ 1 404 140	-€ 338 575	€ -	€ 1 222 305		-€ 237 470	0,70
13	€ 953 845	€ 1 400 754	-€ 341 961	€ -	€ 1 186 704		-€ 232 859	0,68
14	€ 923 803	€ 1 397 334	-€ 345 380	€ -	€ 1 152 140		-€ 228 337	0,66
15	€ 894 679	€ 1 393 880	-€ 348 834	€ -	€ 1 118 582		-€ 223 903	0,64
NPV:	**€ 6 773 475**	**€ 894 679**		**Total Revenues**	**€ 20 804 411**	**NPV of Costs:**	**-€ 14 030 937**	

Table 10-3 Financial Performance Indicator Battery System (own calculation)

LARGE SYSTEM

Year	Dicsounted CF	Nominal CF	O & M	Investement/ Replacement/	Network fee avoided (discounted)	Devistement (discounted)	Costs (discounted)	Discount factor
0	-€ 720 000	-€ 720 000		-€ 720 000			-€ 720 000	1,00
1	€ 66 338	€ 68 328	-€ 3 672	€ -	€ 69 903		-€ 3 565	0,97
2	€ 64 336	€ 68 255	-€ 3 745	€ -	€ 67 867		-€ 3 530	0,94
3	€ 62 394	€ 68 180	-€ 3 820	€ -	€ 65 890		-€ 3 496	0,92
4	€ 60 509	€ 68 103	-€ 3 897	€ -	€ 63 971		-€ 3 462	0,89
5	€ 58 679	€ 68 025	-€ 3 975	€ -	€ 62 108		-€ 3 429	0,86
6	-€ 26 845	-€ 32 054	-€ 4 054	-€ 100 000	€ 60 299		-€ 87 144	0,84
7	€ 55 180	€ 67 865	-€ 4 135	€ -	€ 58 543		-€ 3 362	0,81
8	€ 53 508	€ 67 782	-€ 4 218	€ -	€ 56 837		-€ 3 330	0,79
9	€ 51 885	€ 67 698	-€ 4 302	€ -	€ 55 182		-€ 3 297	0,77
10	€ 50 309	€ 67 612	-€ 4 388	€ -	€ 53 575		-€ 3 265	0,74
11	€ 48 781	€ 67 524	-€ 4 476	€ -	€ 52 014		-€ 3 234	0,72
12	€ 47 297	€ 67 434	-€ 4 566	€ -	€ 50 499		-€ 3 202	0,70
13	€ 45 857	€ 67 343	-€ 4 657	€ -	€ 49 028		-€ 3 171	0,68
14	€ 44 460	€ 67 250	-€ 4 750	€ -	€ 47 600		-€ 3 140	0,66
15	€ 43 104	€ 67 155	-€ 4 845	€ -	€ 46 214		-€ 3 110	0,64
NPV:	**€ 5 793**	**€ 43 104**		**Total Revenues**	**€ 859 531**	**NPV of Costs:**	**-€ 853 738**	
Annuity:	**€ 485**					**Annuity of Costs:**	**-€ 71 515**	

Financial Performance Indicators

`	Performance Indicator	Large System	Small System	Unit	Comment
Net Present Value		**€ 5 792,91**	**€ 18 343,79**		
Annuity		**€ 485,25**	**€ 1 536,60**	=NPV * CRF	
Long Run Power Cost inlcuding cost escalation					
	[€/kW]	**-€ 39,73**	**-€ 81,34**	[€/MWh]	=annutiy of cost/yearly Pel

SMALL SYSTEM

Year	Dicsounted CF	Nominal CF	O & M	Investement/ Replacement/	Electricity Discharged (discounted)	Devistement (discounted)	Costs (discounted)	Discount factor
0	-€ 84 000	-€ 84 000		-€ 84 000			-€ 84 000	1,00
1	€ 9 430	€ 9 713	-€ 123	€ -	€ 9 549		-€ 119	0,97
2	€ 9 153	€ 9 710	-€ 125	€ -	€ 9 271		-€ 118	0,94
3	€ 8 884	€ 9 708	-€ 128	€ -	€ 9 001		-€ 117	0,92
4	€ 8 623	€ 9 705	-€ 131	€ -	€ 8 739		-€ 116	0,89
5	€ 8 370	€ 9 703	-€ 133	€ -	€ 8 484		-€ 115	0,86
6	-€ 5 276	-€ 6 300	-€ 136	-€ 16 000	€ 8 237		-€ 13 513	0,84
7	€ 7 885	€ 9 697	-€ 139	€ -	€ 7 997		-€ 113	0,81
8	€ 7 653	€ 9 694	-€ 141	€ -	€ 7 764		-€ 112	0,79
9	€ 7 428	€ 9 692	-€ 144	€ -	€ 7 538		-€ 110	0,77
10	€ 7 209	€ 9 689	-€ 147	€ -	€ 7 319		-€ 109	0,74
11	€ 6 997	€ 9 686	-€ 150	€ -	€ 7 106		-€ 108	0,72
12	€ 6 791	€ 9 683	-€ 153	€ -	€ 6 899		-€ 107	0,70
13	€ 6 591	€ 9 680	-€ 156	€ -	€ 6 698		-€ 106	0,68
14	€ 6 397	€ 9 677	-€ 159	€ -	€ 6 503		-€ 105	0,66
15	€ 6 209	€ 9 673	-€ 162	€ -	€ 6 313		-€ 104	0,64
NPV:	**€ 18 344**	**€ 6 209**		**Total Revenues**	**€ 117 418**	**NPV of Costs:**	**-€ 99 074**	
Annuity:	**€ 1 537**					**Annuity of Costs:**	**-€ 8 299**	

Table 10-4 Estimation of Daily Load and Capacity (own calculation)

Month	Full Load Hours	Energy Demand p.m. in kWh	Energy demand p.d. in kWh	Energy Supply PV in kWh p.d.	Battery Capacity for 10 days Average Daily Load without PV kWh	Battery Capacity for 10 days Offgrid with PV	Energy Supply Wind	Surplus demand minus DER for 1 day
Average Load	300		-	-				
1	270	81 000	2 613	214	26 129	23 990	1 951 091	- 62 557
2	250	75 000	2 679	389	26 786	22 893	1 788 500	- 57 480
3	230	69 000	2 226	610	22 258	16 161	1 951 091	- 63 366
4	210	63 000	2 100	820	21 000	12 800	1 951 091	- 63 756
5	170	51 000	1 645	800	16 452	8 452	1 951 091	- 64 163
6	160	48 000	1 600	800	16 000	8 000	1 788 500	- 58 817
7	150	45 000	1 452	803	14 516	6 484	1 788 500	- 58 947
8	140	42 000	1 355	765	13 548	5 903	1 625 909	- 53 587
9	200	60 000	2 000	630	20 000	13 700	1 463 318	- 47 407
10	220	66 000	2 129	448	21 290	16 806	1 463 318	- 47 041
11	240	72 000	2 400	237	24 000	21 630	1 951 091	- 62 873
12	260	78 000	2 516	185	25 161	23 316	1 788 500	- 57 207
Year	**2 500**	**750 000**	**24 194**	**6 583**	**20 595**	**15 011**	**21 462 000**	
			-	-				
Emergency Load	31		-	-				
1	270	8 370	270	214	2 700	561	1 951 091	- 64 978
2	250	7 750	277	352	2 768	- 748	1 788 500	- 59 722
3	230	7 130	230	610	2 300	- 3 797	1 951 091	- 65 429
4	210	6 510	217	794	2 170	- 5 765	1 951 091	- 65 639
5	170	5 270	170	800	1 700	- 6 300	1 951 091	- 65 687
6	160	4 960	165	774	1 653	- 6 089	1 788 500	- 60 251
7	150	4 650	150	803	1 500	- 6 532	1 788 500	- 60 292
8	140	4 340	140	765	1 400	- 6 245	1 625 909	- 54 842
9	200	6 200	207	610	2 067	- 4 030	1 463 318	- 49 201
10	220	6 820	220	448	2 200	- 2 284	1 463 318	- 49 013
11	240	7 440	248	229	2 480	186	1 951 091	- 65 025
12	260	8 060	260	185	2 600	755	1 788 500	- 59 539
Year	**2 500**	**77 500**	**2 500**	**6 583**	**2 128**	- **3 357**	**21 462 000**	

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List of Abbreviations and Symbols

AC	Alternating Current
APG	Austrian Power Grid
ATM	Automatic Transfer Switch
BNetzA	Bundesnetzagentur
CHP	Combined Heat and Power
CI	Critical Infrastructure
CIP	Critical Infrastructure Protection
CIMIC	Civil-Military Co-operation
C3I	Command, Control, Communications and Intelligence
CLNS	Critical Load Not Served
CO_2	Carbon dioxide
CPC	Common Point of Coupling
CTA	Continental European Area of ENTSO-E
DC	Direct Current
DER	Distributed Energy Resources
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DHS	U.S. Department of Homeland Security
DSO	Distribution System Operator
EHV	Extra High Voltage with U_n 380 or 220kV
EM	Electronic Metering
ENTSO-E	European Network of Transmission System Operators for Electricity
ESCO	Energy Service Provider Company
ESS	Electricity Storage System
FiT	Feed-in Tariff (for electricity from renewables)
GUI	Graphical User Interface
GWh	Giga Watt hour
HV	High Voltage with U_n >36kV and <220kV (e.g.110kV)
J4	Joint Chief of Staff Directorate 4 – Logistics (Operational and Strategic)
kWh	kilo Watt hour
HVAC	Heating, Ventilation and Air Conditioning
ISIM	Integrated Storage and Inverter Module
LV	Low Voltage with U_n <1kV (e.g. 230 or 400V)
MV	Medium Voltage with U_n >1kV and <36kV (e.g. 10 or 20kV)
MC	Microgrid Controller
MGCC	Microgrid Central Controller
mph	miles per hour (equals 1,609 km/h)
MW	Mega Watt
NAVAC	Naval Facilities Engineering Command
N_p	Nameplate capacity in MW or GW
NORTHCOM	Unified Combatant Command Northern America
NPV	Net Present Value
OeMAG	OeMAG Abwicklungsstelle für Ökostrom AG (Clearing and Settlement Agency for Electricity from Renewables)
PACOM	Unified Combatant Command Pacific
PCC	Point of Common Coupling
PLC	Programmable Logic Controller
PEV	Plug-In Electric Vehicles

PV	Photovoltaic
SAIDI	System Average Interruption Duration Index
SCADA	Supervisory Control and Data Acquisition
SPIDERS	Smart Power Infrastructure Demonstration for Energy Reliability and Security
SOC	State of Charge (ESS)
SOP	Standard Operating Procedures
TCA	Task Critical Asset
TSO	Transmission System Operator
U_n	Nominal System Voltage
UPS	Uninterruptable Power Supply
V2G	Vehicle to Grid