German Insurance Association (GDV)

Renewable energies

Overall survey of Engineering Insurers
within the German Insurance Association (GDV)
on the level of technological development
and the technical hazard potential

9th edition 2017

GDV
DIE DEUTSCHEN VERSICHERER

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CONTENTS

I Preface 13

II Wind Power 17

III Photovoltaic Power Stations 61

IV Biomass 83

V Biogas 95

VI Fuel Cells 117

VII Geothermal Energy 135

VIII Smart Grids 153

IX Risks of Operation Interruption in the Area of Renewable Energies 169

X List of Abbreviations 189

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Contents

I Preface

II Onshore Wind Power

1 Introduction **19**

2 Fundamental Differences among Power Station Models **19**
2.1 Wind Turbines with Gearbox and High-speed Output Shaft 19
2.2 Wind Turbines with Gearbox and Low-speed Output Shaft 20
2.3 Wind Turbines without Gearbox 20

3 Construction Elements **21**
3.1 Foundation 21
3.2 Tower 22
3.3 Chassis/Gondola 23
3.4 Gondola – Tracking (Azimuth Drive) 23
3.5 Rotor Hub 23
3.6 Rotor 24
3.7 Main Bearing 24
3.8 Main Shaft (Rotor Shaft) 25
3.9 Main Transmission 25
    3.9.1 Gearbox Model for Constant Output Speed without Inverter 26
3.10 Hydraulic System 27
3.11 Brakes 27
3.12 Generator 27
3.13 Electrical Systems 27
3.14 Cabling (Internal Cabling and External Connection) 29
3.15 Transmission Station 30
3.16 Value Distribution in a Wind Power Station 30

4 Operational Safety **31**
4.1 Maintenance 31
4.2 Lightning Protection of the Wind Energy Installation 31
4.3 Fire Protection Systems 32
4.4 Braking Systems 33
4.5 Condition Monitoring 33
4.6 Oil Particle Counter 33

5 State of the Art **35**
5.1 Land-based Wind Turbines 35

6 Damage Risks **37**

7 Damage Scenarios 39
7.1 Rotor Blades 39
7.2 Gearbox and Rotor Main Bearings 40
7.3 Generator 42
7.4 Electrical Equipment 42
7.5 Theft 44
7.6 Foundations 45
7.7 Total Loss 46

8 List of Sources 47

II Offshore Wind Power

9 Support Provided by the Insurance Industry 49

10 State-of-the-art Technologies 49
10.1 Turbines 49
10.2 Foundation Structures 49
  10.2.1 Monopiles 50
  10.2.2 Gravity Foundations 50
  10.2.3 Tripiles 50
  10.2.4 Tripods 51
  10.2.5 Suction Buckets 51
  10.2.6 Jackets 52
  10.2.7 Floating Foundations 52
10.3 Sea Cables and Land Connection 52
  10.3.1 Substation and Converter Station 53

11 Construction 54
11.1 Procedures during Construction 54
  11.1.1 Installation of Foundations 54
  11.1.2 Offshore Substation 55
  11.1.3 Laying of Sea Cables 55
  11.1.4 Installation of Towers and Turbines 55
11.2 Hazards and Damages during the Construction Phase 55
11.3 Risk Management 56

12 Operations 57
12.1 Contracts for Service and Maintenance 57
12.2 CBI Losses 57
12.3 Cumulative Considerations 59

III Photovoltaic Power Stations

1 Introduction 63

2 Solar Cells and Modules 63
2.1 Common Cell Materials, Efficiencies and Market Shares 64
2.2 Organic Solar Cells 65
2.3 Photovoltaic-Thermal (PVT) Collectors 65
2.4 Transparent Modules 65
2.5 Other Special Designs 65
2.6 Building-Integrated Modules 65
2.7 Performance Losses (Degradation) 66
2.8 Measurement of Irradiation 66
2.9 Edge and Back Sealings 66
2.10 Foil Quality 66
2.11 Browning/Yellowing 67
2.12 Hotspots 67
2.13 Snail Trails (Discolouration of PV Encapsulants) 68
2.14 Microcracks 68
2.15 Delamination 68
2.16 Ammonia 69
2.17 Module Frames 69
2.18 Module Connection Socket and Cable Outlet 69
2.19 Connectors 70
2.20 Terminal Box 70
2.21 Medium Voltage Directive of the BDEW 70
2.22 The Impact of Wind 71
2.23 Snow Load according to DIN EN 1991-1-3:2010-12 72

3 Inverters 73
3.1 Inverters with Transformer 73
3.2 Inverters without Tranformer 73
3.3 Additional Functions 73
3.4 Installation Instructions 74
3.5 IP Protection Ratings according to DIN EN 60529/IEC 529 74
3.6 Inverter Reliability 75
3.7 Data Loggers 75

4 Mounting Systems 76
4.1 Load Effects and Mounting Systems 76
4.2 Tracking Systems 76
  4.2.1 Single-Axis Tracking 76
  4.2.2 Dual-Axis Tracking 77
4.3 Storm Safety 77
4.4 Facade Systems 77

5 Standard Safety Certification (Statics) 78

6 Cable Requirements 78
6.1 Aluminium Cables 78

7 Lightning Currents and Surges 79
7.1 External Lightning Protection 79
7.2 Internal Lightning Protection 80
7.3 Earthing Systems 81
7.4 Standards for Lightning Protection Systems 81

8 Causes of Damage and Claims Expenditure for PV Systems 81

IV Biomass

1 Basics 85

2 Energetic Use 86
2.1 Combustion Technology 87
2.2 Heat and Electricity 88
2.3 Biogenic Solid Fuels 90

3 Loss Potential 91

4 Claims Experience 92

5 Conclusion 93

6 List of Sources 93

V Biogas

1 Introduction 97

2 Equipment Technology 99
2.1 Agricultural Biogas Power Stations 99
2.2 Biogas Treatment and Feed-in 101

3 Claims Experience 102
3.1 Gas Production 102
3.2 Gas Utilisation 106

3.3 Fire Damage 109
3.4 Environmental Damage 110
3.5 Events with Major Damage 111

4 Prevention 111
4.1 Maintenance Contracts 111
4.2 Tank Inspections 111
4.3 Thermography 112
4.4 Analysis of Engine Lubrication Oil 112
4.5 Lightning and Surge Protection 112
4.6 Flexible Electricity Production (Discontinuous Engine Operation) 113
4.7 Operator Obligations 113

5 GDV Publications 114

6 Outlook 114

7 Conclusion 115

8 List of Sources 115

VI Fuel Cells

1 Fuel Cells 119

2 How Fuel Cells Work 120

3 Overview 121
3.1 Polymer Electrolyte Membrane Fuel Cell (PEMFC) 121
3.2 High-Temperature PEM Fuel Cell (HT-PEMFC) 124
3.3 Direct Methanol Fuel Cell (DMFC) 124
3.4 Alkaline Fuel Cell (AFC) 125
3.5 Phosphoric Acid Fuel Cell (PAFC) 125
3.6 Molten Carbonate Fuel Cell (MCFC) 125
3.7 Solid Oxide Fuel Cell (SOFC) 126

4 Small Cogeneration Units for Domestic Energy Supply 127

5 Market Overview and Prospects 127

6 Refuelling Infrastructure 128
6.1 Passenger Cars 128
6.1.1 Market Development 128
6.1.2 Safety Aspects 129
6.2 Buses 129

6.3 Forklift Trucks 130
6.4 Railway Engines with Fuel Cell Drive 130
6.5 Stationary Installations 130
6.6 Emergency Power Supply and Mobile Equipment 131
6.7 Large-Scale Electrolysers 131

7 Outlook 132

VII Geothermal Energy

1 Energy Potential 137

2 Types of Usage 138
2.1 Near-Surface Geothermal Energy 138
  2.1.1 Operating Principles of Heat Pumps 139
  2.1.2 Groundwater Heat Pumps 139
  2.1.3 Geothermal Heat Collector 140
  2.1.4 Geothermal Heaters 140
  2.1.5 Carbon Dioxide Ground Probe 140
  2.1.6 GRD Procedures 141
  2.1.7 Grounded Concrete Components, Energy Piles 141
2.2 Principles of Hydrothermal Energy 142
2.3 Hot Dry Rock Method (HDR) 142

3 Design of a Hydrothermal Power Station 143
3.1 Drilling 144
3.2 Rotary Drilling 144
3.3 Flushing Agents 145
3.4 Pipes 145
3.5 Drill Hole Measurements 146
3.6 Stimulation Measures 147
3.7 Multilateral Drilling 147

4 Risks of Drilling Technology 147
4.1 Technological Risk 147
4.2 Geological Risks 148
4.3 Deformation 148
4.4 Salvage Operations 148
4.5 Exploration Risk 148

5 Thermal Water Circulation 149

6 Geothermal Power Stations 150
6.1 Organic Rankine Cycle (ORC) 150
6.2 The Kalina Cycle 151

VIII Smart Grids

Introduction 155

1 Current Situation 155

2 The Electricity Market: Future Conditions and Framework 155
2.1 Energy Production 156
    2.1.1 Battery Storage 156
    2.1.2 Carbon Capture and Storage 158
    2.1.3 Conversion of Energy into Gas (Power to Gas) 159
2.2 Electricity Grid and Infrastructure 161
2.3 Power Consumers 163

3 Impact on the Insurance Sector 164

4 Conclusion 167

5 List of Sources 168

IX Risks of Operation Interuption in the Area of Renewable Energies

Introduction 171

1 Wind Power Stations 172
1.1 Onshore Wind Energy 172
    1.1.1 Technical Risks 172
    1.1.2 Natural Hazards 173
    1.1.3 Official Requirements 173
    1.1.4 Maintenance Contracts 173
    1.1.5 Damage Assessment from the Machinery Loss of Profits Insurance Perspective 174
1.2 Offshore 174
    1.2.1 Special Features of Offshore Sites 174
    1.2.3 Assessment from the Machinery Loss of Profits Insurance Perspective 176

2 Photovoltaic Power Stations 178
2.1 Roof Systems 178
    2.1.1 Technical Risks 178
    2.1.2 Natural Hazards 178
    2.1.3 Theft 179
    2.1.4 Buildings 179
    2.1.5 Damage Assessment from the Electronics Loss of Profit Insurance Perspective 179

2.2 Ground Systems 180
2.2.1 Natural Hazards 180
2.2.2 Theft 180
2.2.3 Damage Assessment from the Electronics Loss of Profits Insurance Perspective 180

3 Biomass 181
3.1 Biogas Power Stations 181
3.1.1 Technical Risks 181
3.1.2 Natural Hazards 181
3.1.3 Damage Assessment from the Machinery Loss of Profits Insurance Perspective 181
3.2 Biomass Power Stations 182
3.2.1 Technical Risks 182
3.2.2 Natural Hazards 182
3.2.3 Damage Assessment from the Electronics Loss of Profits Insurance Perspective 182

4 Geothermal Energy 183
4.1 Prospecting Risk 183
4.2 Failure of a Geothermal Power Station 184
4.2.1 Technical Risks 184
4.2.2 Natural Hazards 184
4.2.3 Damage Assessment from the Machinery Loss of Profits Insurance Perspective 184

5 Hydropower 185
5.1 Technical Risks 185
5.2 Natural Hazards 185
5.3 Damage Assessment from the Machinery Loss of Profits Insurance Perspective 185

6 Outlook 185

7 Conclusion 186

8 List of Sources 186

X List of abbreviations 189

I Preface

I Preface

The negotiations at the Paris climate summit COP21 in December 2015 resulted in a breakthrough. For the first time, all 195 signatory states at the United Nations Framework Convention on Climate Change (UNFCCC) committed themselves to common goals for the protection of and adaptation to the world's changing climate and the number of ratifications required to make the agreement effective was reached just under a year later. The so-called Paris Accord came into effect on November 4, 2016. In this treaty, which is now binding under international law, the signatories commit to keeping the average rise in global temperatures significantly below 2 °C and, if possible even below 1.5 °C.

These targets, as it became clear during the Paris negotiations, could only be achieved if the world's economy were to forego CO_2 emissions altogether by the second half of the century.

During the treaty's implementation, it became evident that the voluntary contributions (Intended Nationally Determined Contributions, INDCs) would not be sufficient to reach the envisioned climate targets. In response, the accord was amended with an agreement to audit the targets for CO_2 reduction every five years and to adjust them as required. New technological developments and reductions in cost for renewable energies were considered as the main pathways to reach the set targets.

The world's economy can only be decarbonised if fossil fuels such as coal, crude oil and gas are no longer burned. Carbon capture and storage (CCS) in underground repositories is an unrealistic option due to the high costs involved and the reservations among communities in many countries. CCS will remain a niche technology, if it is used at all. The use of nuclear energy is not likely to be the solution either, even though nuclear energy is one of the most climate-friendly technologies available. While the number of operational nuclear facilities has remained constant over the last two decades, the proportion of nuclear energy used has been constantly decreasing under the ever-increasing demand for energy. At the same time, the construction of new nuclear power stations has become more expensive due to increased security regulations. The contribution of nuclear energy to decarbonisation will most likely remain severely limited. Consequently, successful decarbonisation will depend on increasing energy efficiency and the complete transition to renewable energy sources.

On November 14, 2016, the German federal government passed the Climate Protection Plan 2050. One day later, the scheme was presented at the COP22 climate summit in Marrakesh. So far, no other country has produced a roadmap as detailed and ambitious as this plan. It contains specific goals for relevant business sectors and provides a tangible basis for decisions that will have to be reached during the years ahead. In addition, the plan specifies intermediary goals for the year 2030: CO_2-equivalent emissions are supposed to decrease by 55% to below those of 1990 (relative to 2014 levels, this is a reduction by 40%). In the energy sector, emissions are to decrease by an additional 50% by 2030 and in the transportation sector by 40%. These goals can only be reached via drastic changes in energy supply and the heating and cooling of buildings and in transportation.

Several developments during recent years have raised hopes that the revolution in the global energy supply could actually succeed. For instance, in February 2016, near Quarzazate in Morocco, the first part of the solar thermal power station Noor, with an energy yield of 160 MW, began operations. The construction of this power plant had been proposed by the industry initiative Desertec a few years earlier. Another reason for the increasing importance of renewable energy sources is the rising number of electric vehicles. Apart from their contribution to climate protection, electric vehicles have the advantage of drastically reducing air pollution. In 2015, worldwide investment into renewable energies had reached

a new all-time high of USD 300 billion, four times the amount in 2005. These developments are expected to galvanise investments in renewable energies in the years to come.

In 2003, the GDV (Association of German Insurers) published the dossier “Renewable Energies” for the first time. Changes in technology and a rapid expansion of renewable energies are accompanied by an increasing demand for renewables-specific insurance policies. In addition to classic coverage against damages during construction and operation, there is a new demand among investors for delivery guarantee coverage, i.e. insurance against interannual fluctuations in solar radiation and wind speed. Consequently, in recent years the insurance industry has been developing novel products including coverage for premature ageing of photovoltaic cells. Based on products like these, the insurance industry takes on part of the producers’ and/or investors’ risks, rendering investments in these technologies more attractive and thereby indirectly promoting climate protection.

Covering such risks in an economical and competitive way calls for appropriate prices and conditions. Therefore the assessment of the individual risk situations, based on extensive engineering expertise, is indispensable. To document the knowledge available today and provided access to it, the project group “renewable energies”, initiated by GDV engineering insurers, has produced this ninth edition of the publication. It offers an overview of the state-of-the-art technologies and discusses the technical risk potential for plants converting sun, wind, water, geothermal heat and biomass into usable energy.

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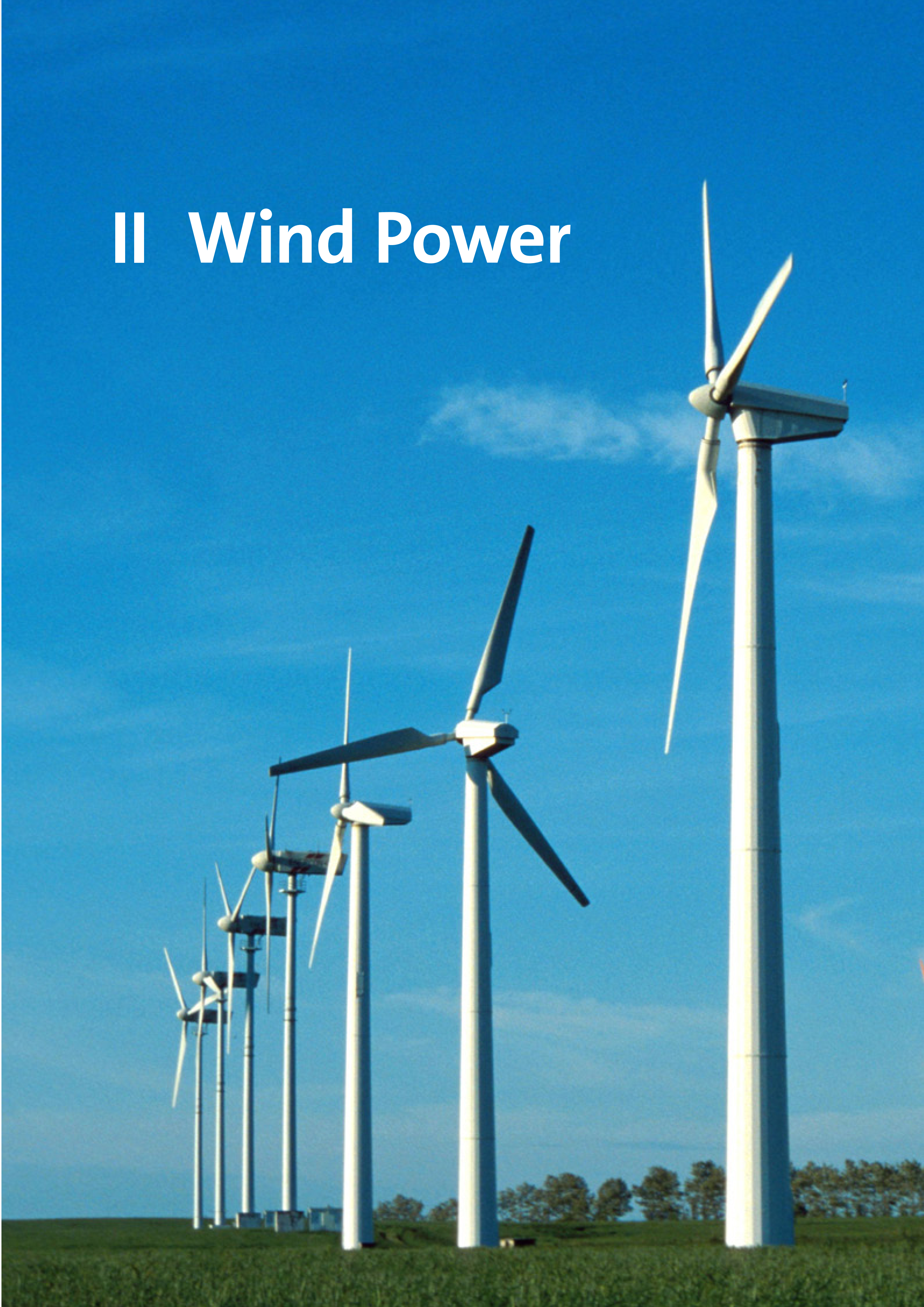
II Wind Power



II Onshore Wind Power

1 Introduction

The technical equipment for the conversion of mechanical to electrical energy already existed long before wind energy plants entered the scene. Hydropower plants, for example, have been generating electricity from the movement of water for decades. Major damage reports or serial damage reports are practically nonexistent in this area. The past few years have shown that electromechanical energy conversion in conventional plants is not comparable to the use of the same technology in wind energy. Changing wind velocities and directions create dynamic loads and load cycle reactions which put an extreme strain on the material used. This chapter provides an overview of the structure of wind energy plants and describes the losses experienced by the insurance industry.

2 Fundamental Differences among Power Station Models

In order to generate electrical energy, the force of the wind must be transferred to the generator as rotational movement via the rotor of the wind power stations. The necessary components form the drive train. The following sections present three different models of drive trains. Other designs available on the market have not been implemented in large numbers in Germany, nor are they used in large multi-megawatt power stations. Therefore, they are not described here in detail.

2.1 Wind Turbines with Gearbox and High-speed Output Shaft

Conventional wind turbine generators using a commercially available generator with 1,500 r/min need an intermediate gearbox to increase rotor speed (about 6 to 30 r/min) to generator speed. Today’s power stations usually feature a combined spur-planetary gearbox.

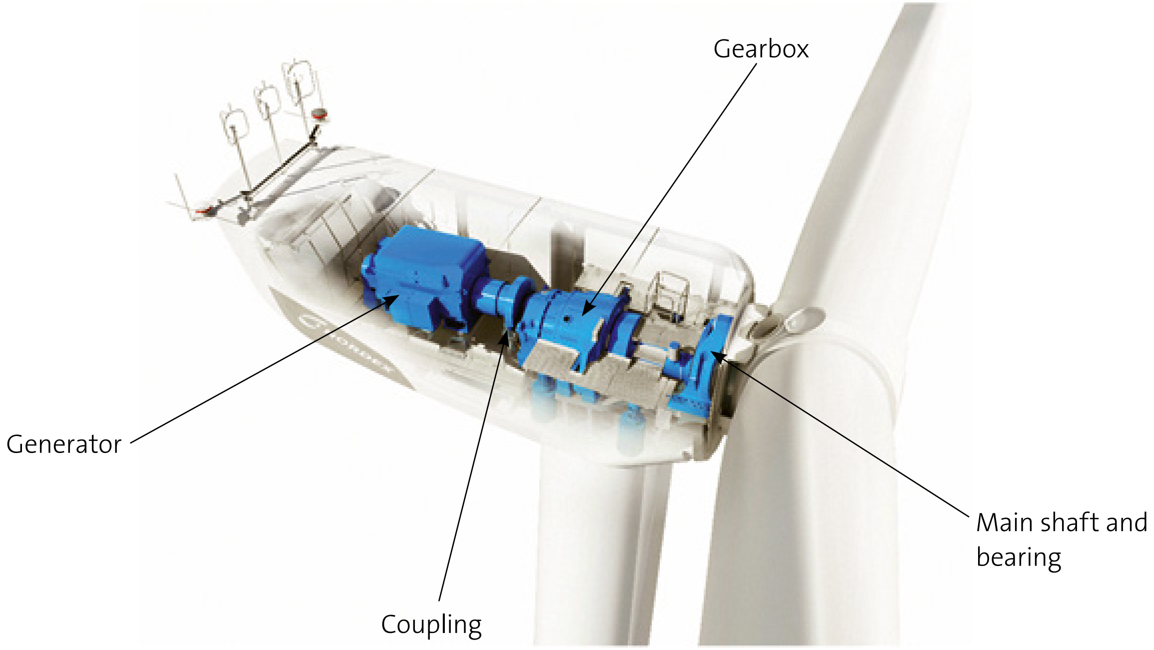


Figure 1: Drive train, model series Gamma; source: Nordex SE

2.2 Wind Turbines with Gearbox and Low-speed Output Shaft

The company Adwen (formerly Multibrid) has a different transmission model in its multi- megawatt turbines because of their slow-running output shaft. Compared to the usual transmission ratios between 1:60 and 1:120, the AD 5-116 has a transmission ratio of approximately 1:10. The lower speeds in the gearbox are meant to reduce dynamic loads.

At the same time, the improved lubrication of the planetary gears has been achieved since, in the case of Adwen's systems, the drive is effected via the ring gear, in contrast to conventional planetary gears, and the planetary gears are fixed in position. The rotor of the generator is directly mounted onto the output shaft and does not have its own bearing.

2.3 Wind Turbines without Gearbox

Here, the rotation of the blades is directly transferred into the generator without an intermediate transmission gear. This means that the rotor and generator speeds (6 to 30 r/min) are the same. In order to reach the required voltage of 690 V and the mains frequency of 50 Hz, the generator's diameter must be correspondingly large. The difficulty lies in finding a suitable generator at all. Manufacturers of this type of turbine therefore use specially designed generators – Enercon's 7.6-megawatt machine, for example, has a generator of about twelve meters in diameter.

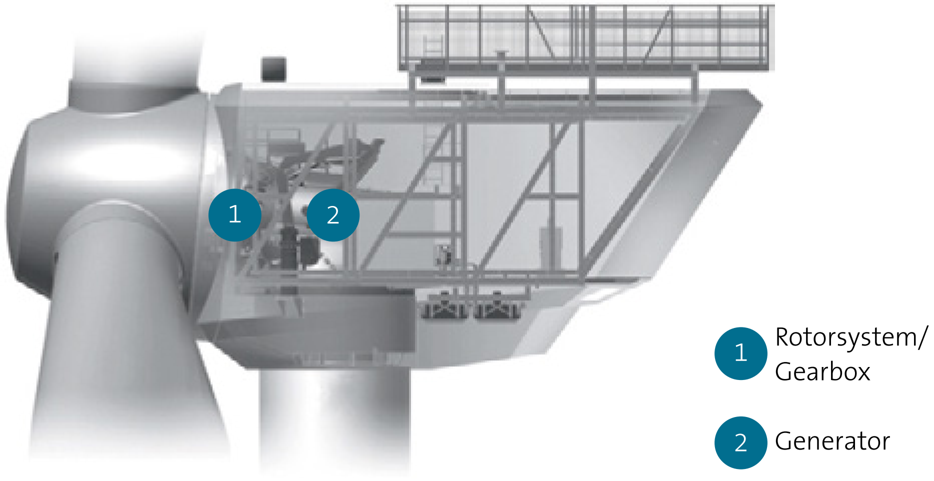


Figure 2: Drive train M 5000; source: Adwen GmbH

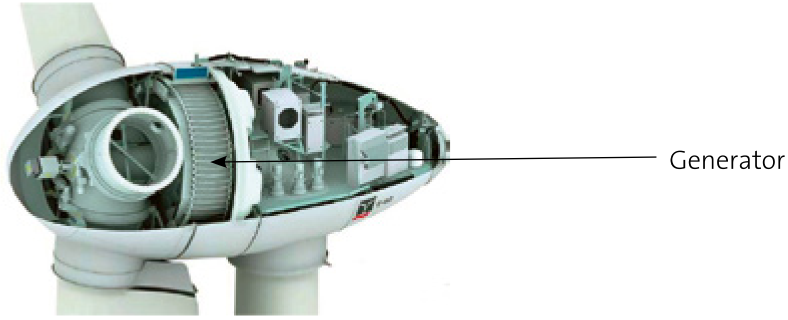


Figure 3: Drive train E 82; source: Enercon GmbH

3 Construction Elements

3.1 Foundation

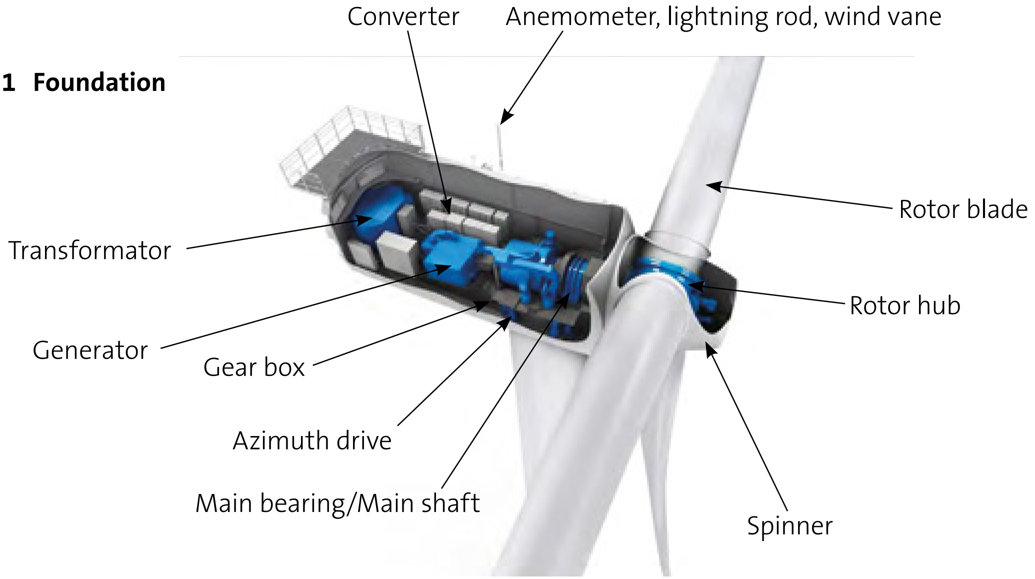


Figure 4: Model series 6.XM; source: Senvion GmbH

The foundation carries the entire weight of the wind power installation and must be able to absorb dynamic movements from tower vibrations and wind loads that result from normal operation.

Figure 5: Construction of a foundation; source: Enercon GmbH

Flat foundations made of steel-reinforced concrete are widely used. Circular, polygonal and cross-shaped versions are also available. In areas where the ground does not meet the requirements (e.g. bog, sand), a pile foundation may be necessary. The construction of a foundation is not within the scope of services provided by all wind turbine manufacturers and is often delegated to a local construction company. Since concrete can only absorb compressive loads and not tensile forces, the design of the reinforcement determines whether the base can provide support for the calculated plant lifespan or becomes a case for restoration after just a few years. If available, the manufacturer's reinforcement plan provides information on the quantity and arrangement of the steel reinforcement.

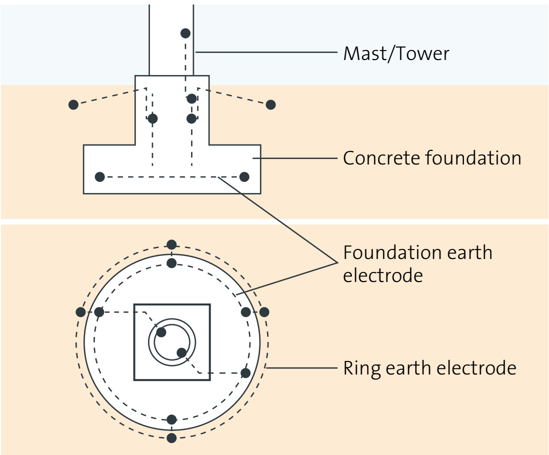


Figure 6: Illustration of an Earthing System;
source: DEHN + SÖHNE GmbH

There are two variants for fixing the tower to the foundation: integration by means of a prestressed anchor basket and flanging the steel tower onto a steel foundation component (FET) that is cast into the concrete.

3.2 Tower

Usually, gondolas of wind energy plants are placed on top of steel towers that either consist of several cylindrical segments or are designed as a framework construction (lattice masts).

However, some manufacturers also offer concrete towers that can be erected on-site (slip formwork).

In order to be able to exploit wind energy economically, even in low-wind regions, plant manufacturers are striving to make ever higher towers. Up until now, heights of 140 to 160 m were reserved for lattice masts alone. Around 2006, the new concept of hybrid towers was introduced to the market. Hybrid towers consist of in-situ concrete or prefabricated concrete in the lower part and of conventional steel elements in the upper part. This model offers several advantages:

- For multi-megawatt turbines with high hub heights, hybrid solutions are cheaper than steel pipe, concrete or lattice towers.
- In logistical terms, this tower variant has additional advantages since height restrictions on transport routes play no role. At tower heights of more than 100 m, the diameter of the lowest pipe section increases significantly over 4 m for steel towers, thus exceeding the total permissible height on a low loader.

Since June 2016, Nordex has been providing the world’s highest wind turbine with its power station at Hausbay in the Rhineland-Palatinate, with a total height of 230 m. The hybrid tower of the N131/3300 consists of a 100 m high concrete tower and two steel tube segments – in total, the tower stands 164 m tall.

In general, the safety evaluations for the foundations and the towers for onshore wind turbines are conducted by the German Institute for Construction Engineering (DIBt) in accordance with the “Directive for Wind Turbines”. In addition to decisive factors such as wind loads, earthquakes and load combinations, various operating conditions and materials as well as the dimensions of the system components must be taken into account. At the present time, wind energy plants can already have rotor diameters of up to approximately 130 m in addition to the aforementioned hub height, sometimes meeting the load limit of the material used due to dead weight, for example.

Figures 7–9 (left to right): Lattice mast, Steel tubular tower, Concrete tower; source: R+V

HIGHEST HUB HEIGHTS (2016)

Plant	Hub height	Tower type
Siemens SWT-3.3-130	up to 135 m	Concrete hybrid tower
Senvion 3.4M114, 3,4 MW	up to 143 m	Steel und concrete hybrid
Enercon E-141 EP4, 4,2 MW	up to 159 m	Concrete tower (conical)
Vestas V136, 3,45 MW	up to 160 m	Steel tower
Nordex N131/3300	ca. 164 m	Concrete-steel-hybridtower
FWT 3000, 3,0 MW	up to 170 m	Concrete-steel-hybridtower

3.3 Chassis/Gondola

Figure 10: Mounting of a rotor; source: Senvion GmbH

The entire technology of a wind power installation is housed in the so-called gondola (machine house), which is mounted on the tower. The base frame is either a welded construction or a cast frame. The components of the wind power installation are bolted to it.

The shell of the gondola is made of plastic, glass fiber-reinforced plastic or steel sheeting.

The weight of the fully equipped gondola has a significant influence on the choice of the crane required for its assembly. The heavier the gondola, the fewer suitable cranes are available. A further complication is the fact that the requirements for roadways to the wind power station increase with increasing crane size.

SIZES OF LOADS FOR LIFTING

Rated capacity	Gondola weight	Rotor weight (inkl. hub)
1,5 MW	42–56 t	28–42 t
2 MW	61–72 t	26–49 t
2,5 MW	85–94 t	50–52 t
5 MW	200–329 t	77–176 t

3.4 Gondola – Tracking (Azimuth Drive)

Since wind can come from all directions, the machine house must be rotatable by 360 degrees. For this purpose, a bearing is mounted on the top of the tower head upon which the entire machine house can rotate. The drive is effected by the so-called azimuth drive, which generally consists of one or more transmission motors. Its control is triggered by a wind direction sensor. The connection between the tower and the machine house is ensured by large rotating rims fitted with roller bearings.

3.5 Rotor Hub

The rotor hub carries the rotor blades and, in the case of pitch-controlled systems, the drives for blade adjustment (motor, inverter). In the case of megawatt power stations, it is usually accessible

in order to allow for maintenance and inspection of the aggregates for blade adjustment and of the safety devices.

3.6 Rotor

The rotor consists of the rotor blades and the rotor hub. Nowadays, a rotor is almost always equipped with three blades and turns clockwise. The blades are usually made from glass fibre-reinforced polyester and more rarely from carbon fibre-reinforced plastic, metal or wood composites.

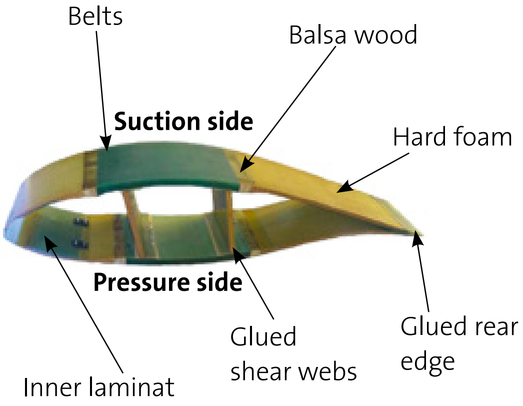


Figure 11: Cross section of a rotor blade; source: R+V

Figure 12: Rotor blade transport with a blade transport vehicle, Goldhofer AG; source: Goldhofer AG

Figure 13: Large rolling bearing; source: SKF GmbH

In modern wind turbines, the rotor blades can be rotated in order to control the power by pitch adjustment. Large rolling bearings are used for this purpose.

3.7 Main Bearing

The rotor mounted on the machine house must be rotatable in order to transfer the wind’s force to the generator. The bearing (on the windward side, a self-adjusting double pendulum roller bearing or similar) must absorb impacts from the rotor caused by wind loads and reaction forces from gravity and moments of bending.

The table on the following page lists a few examples of the various bearing models that are currently in use:

Bearing	Advantages	Disadvantages
Rotor shaft with separate fixed-displacement bearing (four-point bearing). Rotor and gearbox are separately stored (examples: Vestas V90, Nordex N80, Senvion 6.XM series).	Rotor forces transfer to the tower over the base frame. Enables easy gearbox disassembly. For the most part, the transmission takes the torque only.	Higher mass and longer overall length.
Rotor shaft with a three-point bearing. Rotor and transmission share the transmission bearing on the drive side (examples: Nordex N117, Senvion 5M).	Reduced overall length and less mass.	Besides the torques the gearbox also assumes parts of the rotor loads. Rotor must be supported to disassemble the gearbox.
Integration of the rotor bearing into the gearbox (examples: FL1000, Vestas V82, Adwen).	Shortened overall length compared to a three-point bearing.	Transmission takes the rotor loads completely. No dismantling of the gearbox independent of the rotor is possible.

3.8 Main Shaft (Rotor Shaft)

The main shaft is usually forged and hollow to allow the supply of the rotor with electricity and hydraulics.

3.9 Main Transmission

A gearbox has to convert the comparatively low rotational speed of the rotor (approx. 6 to 30 r/min) to a speed of up to 1,500 r/min which is suitable for the generator in conventional wind turbines. Therefore, high transmission ratios are necessary, which can only be implemented with multi-stage transmissions.

In some smaller power stations of up to 600 kW, spur gear units were installed. The combination of a planetary stage and two spur gear stages for wind energy systems up to 2.5 MW is currently available as well as two planetary stages and, if applicable, a spur gear stage for systems with a rated output of 2.5 MW.

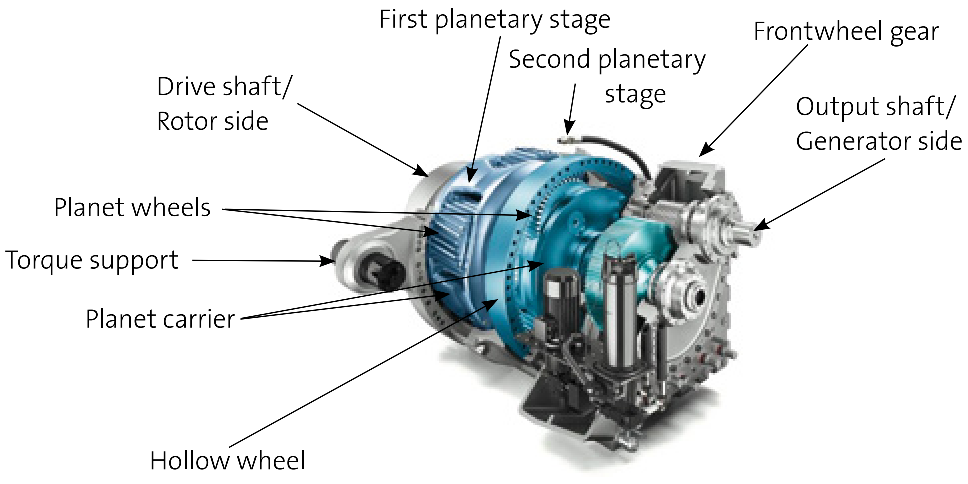
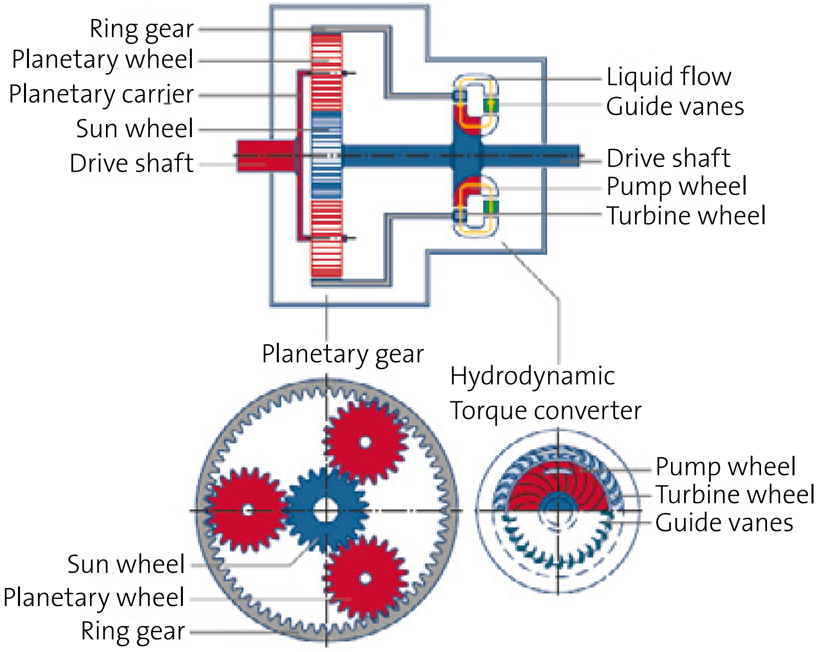


Figure 14: Three-stage Eickhoff EICOGEAR 2,4-transmission of a Nordex N117; source: Eickhoff Antriebstechnik GmbH

3.9.1 Gearbox Model for Constant Output Speed without Inverter

For operation on the grid, the variable rotor speed of the wind turbine must be converted into an electric rotating field with a constant frequency. This is usually created by frequency converters in the stator or rotor circuit of the generators. Voith Turbo GmbH has now introduced the WinDrive gearbox, which can support up to 20 MW_{el} according to the manufacturer. Between the main transmission and a synchronous generator is the aggregate, consisting of a superposition transmission on the drive side and a hydrodynamic torque converter on the output side. This aggregate converts the variable input speeds from the main transmission into constant output speeds for the synchronous generator. Different translation ratios are possible.

At the same time, the unit operates to support the control over the torque limitation by with a speed increase when operating at nominal power.



- WinDrive in the drive train oft the wind turbine between main gearbox and generator.
- The planetary gear unit consists of the sun gear, the rotating planetary gears and the ring gear. The planetary gears are mounted on the planet carrier.
- The torque converter consists of three main components: impeller, turbine wheel and evenly adjustable guide vanes. A sealed housing encloses these components and is filled with liquid.
- The impeller is connected to the output shaft of WinDrive and the turbine is connected to the ring gear of the planetary gear.

Figure 15: Principal design of the WinDrive; source: Voith Turbo GmbH

3.10 Hydraulic System

A compact hydraulic unit in the machine house is used for rotor blade adjustment.

3.11 Brakes

Wind turbine power stations must be able to be braked quickly in an emergency (e.g. excessive speed or external hazards). Depending on the design, a mechanical or aerodynamic brake is necessary.

Older systems, which are partly stall regulated and do not have their own blade adjustment, are equipped with an aerodynamic blade tip brake. (Caution: In case of over-speed, the tip blades, which are approximately 2 m long, are twisted by centrifugal activation by 90°.) Together with a mechanical disk brake, the blade tip brake can stop the system in the shortest possible time. Pitch-controlled wind turbines, on the other hand, brake aerodynamically to zero by twisting the whole blade. The mechanical brake can still be employed for safety and emergency shutdowns, but is mainly used to block the rotor during servicing.

3.12 Generator

The generator converts the mechanically transmitted energy of the wind into electrical energy. It is, together with an inverter if necessary, the connecting element between the variable wind energy and the largely constant properties of the electricity grid (voltage and frequency). The selection of the type of generator has a decisive influence on downstream electrical systems, especially the dimensioning of the inverter (see table on the next page). Today, in wind power stations with capacities of more than 100 kW, various asynchronous and synchronous generators are used.

Figure 16: Double-fed asynchronous generators for on-site installation; source: Allianz

3.13 Electrical Systems

The distribution of the electrical power to the grid requires a large amount of electronic and switching gear, all housed in control cabinets on and in the tower foot and at the top in the machine house. These include: transformer, medium and low voltage circuit breaker, inverter, if necessary reactive power compensation, powet station control (process control computer), condition monitoring system (CMS), cable, lightning protection system and potential equalisation.

In the case of wind turbines in the range of up to 1.5 MW, power electronics consisting of a low-voltage circuit breaker, reactive power compensation and a converter are usually located in the tower foot or on a platform in the tower below the gondola. The transformer with a medium voltage circuit breaker is often located in a compact station in front of the tower.

In the case of higher megawatt outputs, the manufacturers are increasingly placing all these components, including the transformer, in the gondola. This development leads to an increased fire risk.

Generator types	Advantages	Disadvantages
Synchronous generator Synchronous generators can only be connected via rectifier and inverter, since the output voltage and frequency of these generators vary with rotor speed.	high efficiency, high speed range, freely adjustable active and reactive power output, cheap, easy maintenance, moderation of the mechanical load of the drive train due to wind squalls, no load on the drive train due to mains disturbances	expensive inverter, since it must transfer the entire power. Water cooling of the generator
Multi-pole synchronous ring generators Wind turbine power stations without gearboxes require a slow-running ring generator with a correspondingly high number of poles, which reaches its nominal operating point at rotor speed. This can only be achieved with comparatively large diameters (at least six metres).	high efficiency, large speed range, no gearbox, freely adjustable active and reactive power output, low wear, low maintenance requirements, absorption of mechanical loads on the drive train from wind gusts, no load on the drive train from mains failures	more expensive inverter, since it must transfer the entire power, and more expensive generator. Unfavourable weight distribution leads to a concentration of mass in the front of the gondola
Asynchronous generator With short-circuit drives, this generator is favoured by only one manufacturer in currently available wind turbine systems with outputs over one megawatt.	simple and inexpensive, produced as a standard drive motor in large quantities, simple synchronisation. With a pole-changing design, it is possible to adapt the operating point to changing wind conditions	strains the grid with reactive currents, additional costs for partial compensation of the reactive current, lower efficiency than synchronous generators, grid has a direct effect on the drive train, fixed speeds and thus less effective utilisation of the wind energy
Double-fed asynchronous generator The most frequently used generator model in wind turbines, they are widely applied in all performance classes.	high speed range, high efficiency, active and reactive power output freely adjustable, lower inverter power (only slipping power from the generators rotor) and therefore cost-effective inverter, dampening of the mechanical load on the drive train due to gusts	expensive generator (slip ring rotor), higher maintenance requirements, grid has a direct effect on the drive train

Figure 17: Converter cabinets, low-voltage power switches and control cabinet in a gondola; source: Allianz

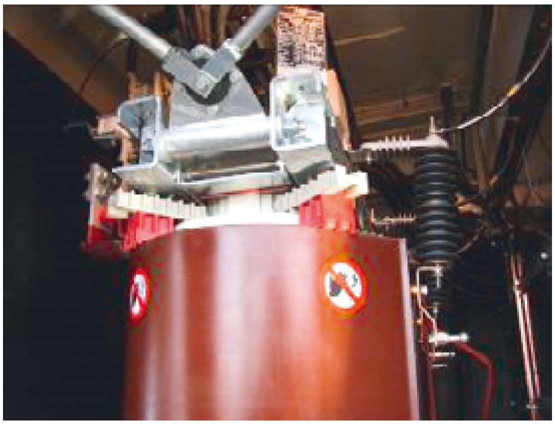


Figure 18: Side view of one of the three coils of a cast resin transformer in the gondola. In the upper middle part of the picture the attachment of the frame in the gondola is visible; source: Allianz

Transformers used in the gondola are mostly cast resin transformers. In the case of liquid-filled transformers, the transformer oil ensures electrical insulation and dissipation of heat. In a cast resin transformer, the overvoltage winding is cast in epoxy resin while other solid insulating materials, such as Pre-preg (pre-impregnated fibers), are used in the undervoltage winding. The insulation of the coils from each other and from the core is ensured by sufficiently large air gaps. A vertical airflow along the coil surfaces and in the cooling channels within the coils ensures the dissipation of heat. Due to convection, the airflow occurs either by itself (cooling type AN – Air Natural), or is additionally reinforced with fans (cooling type AF – Air Forced). This type of transformer is characterised by a low maintenance requirement and a high fire safety level, since the materials used are flame resistant and self-extinguishing.

3.14 Cabling (Internal Cabling and External Connection)

We differentiate between internal and external cabling. The cable leading to the transfer station is operated either by the network operator or the utility company. On the other hand, the cable originating from the transfer station is part of the wind farm itself.

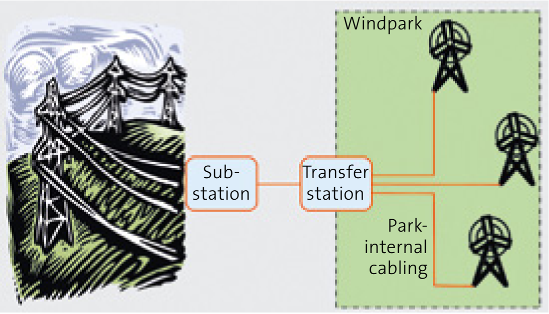
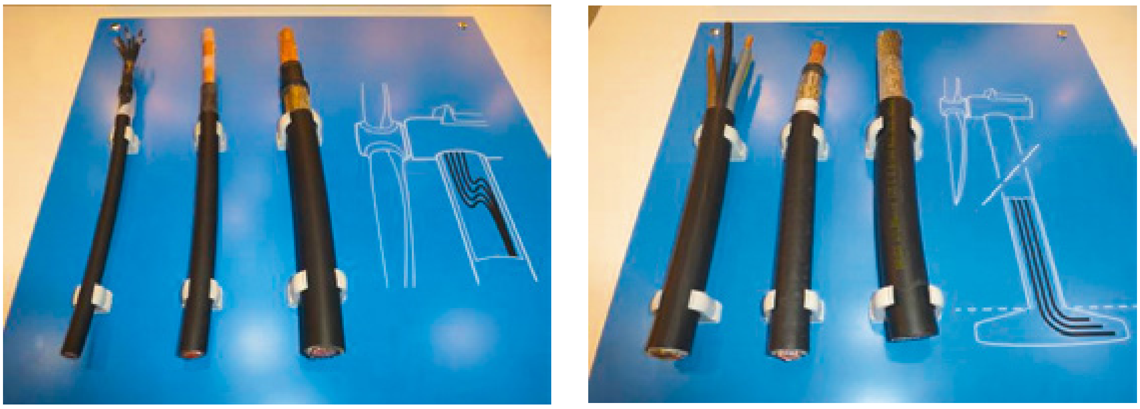


Figure 19: Interfaces for energy transport; source: R+V

In wind parks and wind power stations, various types of cables are used due to the large diversity of loads. Cables in a so-called loop (the part of the cable requiring rotation) must be torsion-proof. Earth cables should be water-resistant. The following applications are available.



Figures 20–21: Tyical cables of a WEA; source: R+V

3.15 Transmission Station

In the transmission station, the electricity from the wind power station is fed into a high-voltage cable leading to the substation. Individual wind turbines and also small wind farms feed the energy produced into the medium-voltage network (20 to 30 kV). Large wind farms are connected directly to the high-voltage grid (110 kV) via a central transformer substation and switchyard.

3.16 Value Distribution in a Wind Power Station

The following table shows the share of the most important components of the total cost of a wind turbine of the type Senvion MM82 (100 m-high steel tower and 40 m-long rotor blades).

Component	Share	Component	Share
Steel tower (100 m)	33%	Rotor hub	2%
Rotor blades (40 m length)	18%	Rotor shaft	2%
Transmission	14%	Azimuth system	2%
Converter	6%	Gondola casing	2%
Pitch system	5%	Rotor bearing	1%
Generator	4%	Braking system	1%
Transformer	3%	Cabels	1%
Machine carrier (base frame)	3%	Screws	1%

Source: Neue Energie, issue 09/2005

4 Operational Safety

4.1 Maintenance

Maintenance is of fundamental importance for the operational safety of wind power stations. Over the last two to three years, maintenance services have improved fundamentally for operators. Today, most manufacturers offer full maintenance plans for their power stations. They have thus caught up with Enercon, a company which for a long time took a pioneering role with its “Enercon Partner Concept” (EPC). In terms of coverage, however, full maintenance contracts differ in many respects among the various manufacturers. The Federal Association WindEnergie e. V. estimates the costs for maintenance and service at 16% of the annual turnover. In November 2004, the association provided its members with a handbook for maintenance contracts.

Maintenance contracts for new plants are usually concluded with plant manufacturers or suppliers. Third-party providers of maintenance services have found it rather difficult to open enter the market of new wind power stations as manufacturers are very restrictive in their willingness to provide maintenance documents and access to spare parts. This problem also affects operators, who would like to eliminate minor malfunctions themselves. In the case of older systems and those for which the warranty has ran out, it is easier for third parties to provide maintenance.

4.2 Lightning Protection of the Wind Energy Installation

Today, plenty of suitable lightning protection systems are available that effectively protect gondolas, rotor blades and electrical devices from the consequences of lightning strikes. In the past, when lightning struck, rotor blades without such protection were often completely destroyed. The functioning of the lightning protection system must be checked at regular intervals. For this purpose, there are relevant directives such as, for example, the working guidelines of the German Advisory Board of Experts of WindEnergie e. V. “Überprüfung des Zustandes des Blitzschutzsystems von Windenergieanlagen” for external lightning protection systems. Special attention must be given to the measurements of the earthing and the throughput resistance between the blade tip and the grounding lug.

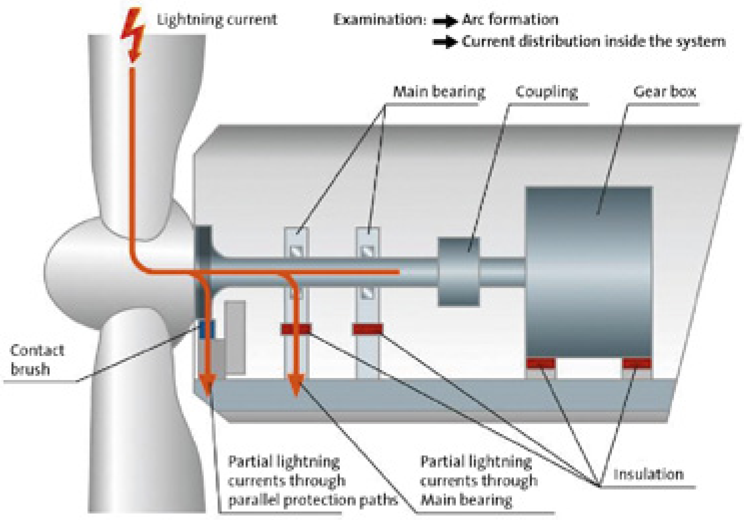


Figure 22: Conduction of a lightning current; source: DEHN + SÖHNE GmbH

The following protective devices are currently state-of-the-art.

Functionality of a modern lightning protection system:

Ideally, lightning strikes the so-called receptor, a metal piece in the blade's tip. The current of the lightning is then discharged to the ground via a steel cable inside the rotor blade, which connects the receptor to the steel structure (rotor blade flange–gondola chassis–tower). The prerequisite for proper functioning is an intact potential equalisation (grounding system) in the foundation or in the soil (see Fig. 22 on 31).

ADVANTAGES AND DISADVANTAGES OF DIFFERENT ROTOR BLADE PROTECTION SYSTEMS

Blade protection system	Advantages	Disadvantages
mesh of copper wires around the entire blade tip	laminating is relatively easy; no discharge through the blade structure into the blade interior; Protection of the entire blade	vulnerable to the destruction of the mesh structure at the point of impact; difficult to repair and replace
replaceable metal tip or cap	little damage from melting at the point of impact; Replacement is possible	construction and fastening to fiberglass structures are complex
replaceable metal receptors	little damages from melting at the point of impact	small capture area; no protection of edges at blade tip; complex construction; conductive connection to the ground must be provided
metal profiles (on blade edges)	little damage from melting at the point of impact; no discharge through the blade structure into the blade interior; additional protection from impacts from the side	attachment to the fiberglass structure is difficult; Replacement is difficult; operational strength is a design requirement

Source: BINE Projektinfo, issue 12/2000

A current innovative approach is the use of conductor strips as a rotor blade protection system. These thin strips of metal are glued to the surface of the rotor blades. They create a channel of ionised air through which the flash is directed to the grounding cable. The advantage of these arrester strips is their increased durability. Conductor strips have a supposed service life of up to 20 years, whereas classical receptors must be exchanged at an earlier stage.

4.3 Fire Protection Systems

To this day, the average power output of wind turbines has been continuously increasing. Acquisition costs, however, have also increased. The placement of transformers, converters and switchgear in the gondola has led to a concentration of value at the top of the windmill, which is inaccessible to the fire brigade. Due to the increasing frequency of fire damage occurring in

recent years, an acute need for fire protection systems has emerged. While large multi-megawatt plants with automatic fire protection systems are already available, for 1 and 2 MW class plants these systems are only available as an extra option.

In 2005, the GDV set up a project group dealing with fire protection in wind turbines. The project group prepared the publication VdS 3523: Windenergieanlagen (WEA), Leitfaden für Brandschutz based on the claims experiences of participating insurance companies.

4.4 Braking Systems

All modern wind turbine systems have redundant brakes which can be operated in emergency situations without generating major strains. They also serve as standstill brakes. This redundancy is necessary because uncontrolled overspeed is the most dangerous operating condition for wind turbines. Due to the enormous centrifugal forces, the blades can tear off and the resulting imbalance can lead to the failure of the whole tower and thus to a complete loss of the system. For this reason, a battery backup for the pitch drives, installed in the rotor hub, ensures that the blades can be adjusted at all times and therefore aerodynamic braking is possible even in the event of a power failure. The charging status of the batteries must be monitored by the control system. For each rotor blade, the pitches are designed as self-sustaining and independent systems. Since a single blade is already sufficient to brake the whole rotor through the blade adjustment alone, three independent primary braking systems are available in the standard three-blade wind turbine configuration.

4.5 Condition Monitoring

With a revision clause (preventive replacement of wear components after a defined service life), insurers have attempted to return the responsibility for the safe operation of the wind power stations to manufacturers and operators over a longer period. Encouraged by this move, various special companies have developed and certified condition-oriented monitoring systems.

MONITORING MUST COVER THE FOLLOWING AREAS

Rotor blades	number of revolutions, vibration
Main bearing	vibration
Transmission	input shaft, vibration
	output shaft, vibration
Generator	A- and B-sides, vibration
Chassis	vibration
Tower	vibration
Oil	temperature, pressure, quality

A part of the data required for integration into CM systems is already being provided by the control and monitoring technology. If the operation management adequately qualified, an effective assessment of the bearing and tooth engagement frequencies with regard to machine kinematics can be expected. In the long run, this should lead to the identification and repair of weak points. Repairs with a sufficient lead time for the delivery of the required components can be planned for windless periods. Ultimately, this will increase the availability and the service life of the entire wind energy installation.

4.6 Oil Particle Counter

Wear or damage to bearings and gear produce a metal powder months before failure. For components of the drive train which have a circulating oil lubrication system, oil particle counters can detect and evaluate the contamination by this powder. The detection is not restricted to metallic particles. However, particle counting cannot

Figure 23: Sensors on the gearbox at the
first planetary stage

second planetary stage

spur gear stage

Figure 24: Sensor on the main bearing. It is designed to detect damage caused by the slowly rotating shaft. Bearing vibrations can arise in the low-frequency range below 10 Hz.

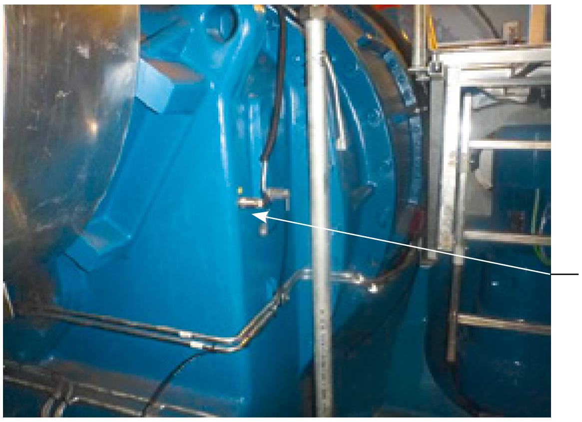


Figure 25: Sensor on the front wheel drive, generator side

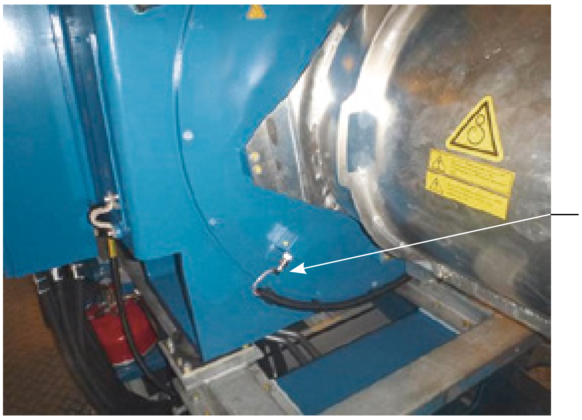


Figure 26: Sensor for the monitoring of a generator bearing (A-side)

Source of all figures on this page: 8.2 Group e. V., Daniel Tönnissen

detect changes in the state of grease-lubricated bearings, such as generator and main bearings, or in the running or vibration behaviour without accompanying material input into the monitored oil circuit.

Oil particle counting used to be economically feasible only as part of an (offline) oil analysis in the laboratory. Only for the last three years, various manufacturers have been offering specific systems for continuous monitoring of gearboxes in wind power stations. Their main component is an inductively or optically operating sensor, sampling the oil returning from the transmission in before it reaches the particle filter. This sensor detects metallic particles above a certain size (e. g. > 200 µm). Thus, the number of wear particles can be assessed in the form of a simple trend. However, no conclusions be drawn from this trend about the operability of the affected component. The origin of the particles must first be determined by means of a visual inspection (e. g. video endoscopy) or a vibration diagnosis.

5 State of the Art

5.1 Land-based Wind Turbines

In the 1980s and early 1990s, small (50 to 150 kW) to medium (500 to 600 kW) wind turbines appeared on the scene and were built in very large numbers. In 1997/1998, the construction of the first plants of the megawatt class (1 MW) followed. In 2015, the average output of wind turbines installed on land was about 2,727 kW, 144% more than in 2000 (1,115 kW)[1]. Hub heights of 160 m and rotor diameters of far more than 100 m enable the construction of plants with an output of significantly more than 3 MW even in inner country regions with relatively little wind. And the trend already points towards 5 MW onshore.

The types of modern wind turbines can be classified as follows:

- The majority of wind power stations worldwide are built in a conventional manner with the following structure: rotor–main bearing–main shaft–transmission–coupling–generator. Only a few suppliers (including Enercon as the largest and most successful) continue to follow the compact model without a gearbox and with a large, slow-running generator.

- In the case of the plants above the 600 kW class, three-bladed rotors has prevailed, while lower performance classes use all kinds of rotors: two-blade, four-blade and multi-leaf rotors as well as Savonius and Darrieus rotors can be found in smaller power stations.

- While the majority of systems up to 600 kW operate with fixed rotor blades (stall-controlled) and fixed speeds, control by pitch adjustment in combination with variable rotation speed could demonstrate high performance.

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[1] strom-report.de/windenergie/

- In the 1 MW class, mainly air-cooled double-fed asynchronous generators are used. In smaller systems, asynchronous pole-changeable generators are often used. Almost without exception, a ball bearing-supported ring connection is provided with suitable friction devices between the gondola and the tower. The gondolas orientation toward the wind is regulated by two or more gear motors.

- Most towers of modern wind turbines are made of steel pipes. Some manufacturers provide grid masts for specific locations. In-situ concrete is increasingly used, too. For very tall towers of 120 m or more, hybrid constructions have become an alternative, facilitating the transport of tower segments.

Today, all wind turbine systems in the standard classes (600 to 6,000 kW) have the **usual safety features:**

- lightning protection of the blades as well as of the entire system

- redundant braking systems

- monitoring of all operating parameters online

- vibration monitoring of chassis, gearbox, generator

- cooling of generator and transmission oil

- overvoltage protection for the switching and control devices

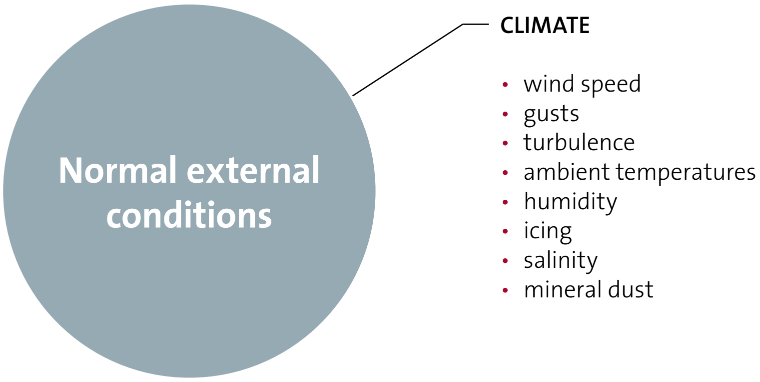
Modern wind turbine systems have installed capacities of up to 7.5 MW. Power stations of the order of 6 MW (Adwen, Senvion) are reserved mainly for offshore use. A further increase in the performance appears to be limited only by the construction of individual components, particularly the rotor blades. For example, the rotor of the N131 3.3-megawatt turbine N131 has a diameter of 131 m, which corresponds to a length of the individual rotor blade of more than 60 m – too long to be shipped via normal transport routes.

6 Damage Risks

Damage to wind turbine systems causes problems similar to those experienced with any other machine, except that the number of load changes over the entire service life of wind turbine systems is much higher compared to other stationary machines. Parts the heaviest dynamic loads, such as the rotor and the drive train, are particularly affected.

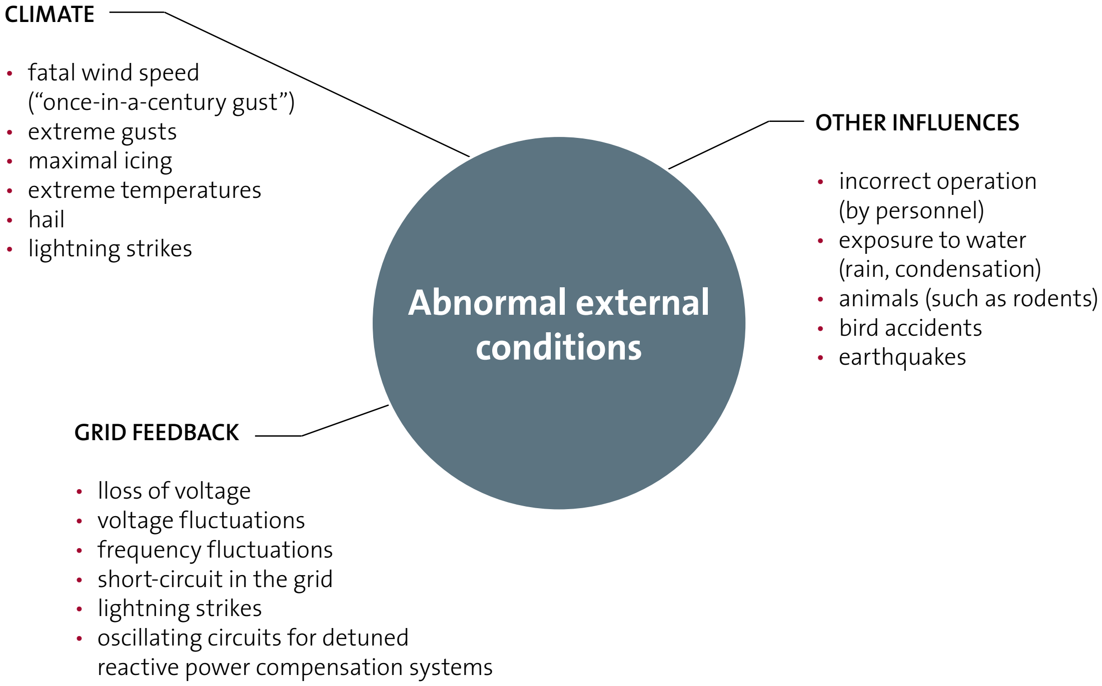
Thus, the risk of serial damage is typical for wind power stations. As in the motor vehicle sector, nearly identical parts are produced in large numbers. For gears of the same design, for example, retrofit measures have had to be applied to a large extent. Generators and rotor blades are also repeatedly affected by serial damage.

The high risk for damage is due to the operating conditions of a wind turbine. In order to examine the origin of an experienced damage more closely, we divide damages into five categories, as illustrated in the following schematic representations:



CLIMATE

- wind speed
- gusts
- turbulence
- ambient temperatures
- humidity
- icing
- salinity
- mineral dust



CLIMATE

- fatal wind speed ("once-in-a-century gust")
- extreme gusts
- maximal icing
- extreme temperatures
- hail
- lightning strikes

OTHER INFLUENCES

- incorrect operation (by personnel)
- exposure to water (rain, condensation)
- animals (such as rodents)
- bird accidents
- earthquakes

GRID FEEDBACK

- lloss of voltage
- voltage fluctuations
- frequency fluctuations
- short-circuit in the grid
- lightning strikes
- oscillating circuits for detuned reactive power compensation systems

Normal internal conditions

OPERATING CONDITIONS

- start and stop
- synchronisation with the mains
- power/speed control
- normal operation
- gondola directional adjustment
- standstill (rotor rotates slowly)
- blocked rotor

FORCES AND BALANCE

- dead weight
- mass acceleration (braking, adjustment)
- centrifugal forces
- rotational forces
- mass unbalance
- aerodynamic imbalance
- torque

WIND-DEPENDENT CONDITIONS

- inclined windflow
- tower-induced build-up or slipstream

Abnormal internal conditions

MALFUNCTIONS

- motor and mechanics of blade adjustment
- drive train
- generator short circuit
- gondola directional adjustment
- mechanical brakes
- aerodynamic brakes
- operation management
- sensors
- power supply/charge status of the batteries (e. g. for pitch drives)

OPERATING CONDITIONS

- overspeed
- excess output
- own vibrations
- enforced vibrations (controls)
- emergency shutdown
- reverse rotation of the rotor

Other conditions

- transport
- assembly
- maintenance and operation

7 Damage Scenarios

7.1 Rotor Blades

- cracks (longitudial- and transverse cracks)
- vibration fractures
- delamination, faulty lamination
- lightning strike/breaking or “explosion” of the blade
- inadequate fixing of earthing cables in the axial and radial direction in the blade (high tensile stress due to centrifugal forces)

Causes:

- overload

Normally, several interlocking, partially redundant safety systems prevent the occurrence of overloads on wind power stations. Nevertheless, damage can occur even under normal weather conditions. Combinations of various small errors are caused, which lead to the failure of the safety system. The following example describes one such case.

After a failure of the medium-voltage grid, a 2.5 MW system attempted to carry out a quick-stop. The control system initiated an emergency maneuver, moving the three blades of the rotor into a 90° position. The energy required for this should be supplied by the accumulators of the emergency power supply of the pitch drives. The accumulators, however, were already discharged. The hydraulic brakes could not stop the rotor either. The brake pads held for only a few seconds before they were worn down completely. The speed continued to rise. Due to the overspeed, one of the blades tore off. Heavy damage to the gondola and foundation was the result. As it turned out, a malfunction of electronics prevented the batteries from recharging. Also, over the course of previous maintenance work, the monitoring of the accumulators had been deactivated so that the low charge state could remain unnoticed.

Frequent causes of control failures in overload situations include:

- deactivated safety-related alarms (see the above example)
- faulty controls and/or signal transmission
- setting of incorrect threshold values for safety-related alarms by commissioning engineers or maintenance personnel
- manufacturing errors
- vibrations
- design errors (load expectations)
- inclined airflow
- aeroelastic vibrations
- frost, ice formation, hail
- thunderstorms

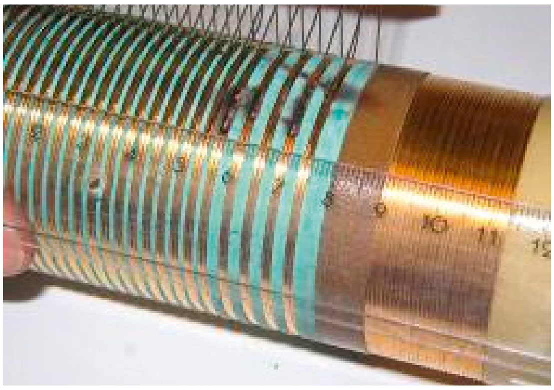


Figure 27: Short circuit tracks on a slip ring transformer. The cause was bent bristles after a bearing damage; source: Allianz

Figure 28: Broken blade tip after lightning strike; source: Allianz

Figure 29: The opening for the receptor of the blades upper shell is clearly recognisable; source: Allianz

Figure 30: Receptor holders with receptors for the blades top and bottom shell. The holder is the connecting piece between grounding cable and receptors; source: Allianz

In the case of rotor blades with an unfavourable arrangement of the receptors or in the case of blades with water inclusions, a lightning strike may penetrate directly into the earthing system through the blade surface. The blade movement makes it difficult for the flash to enter the receptor. The tabular listing of the lightning protection measures in chapter 4.2 (see p. 31) shows various options for protecting the rotor blade. Water in the blade can explosively evaporate during a lightning strike. As a result, the blade tears in this area. This problem can be remedied by providing openings through which water can drain away.

Figure 31: At low outdoor temperatures, repairs must be carried out in a heated tent; source: R+V

7.2 Gearbox and Rotor Main Bearings

- damage to the rotor’s main bearings
- bearing damage at the planetary stage of the main gearbox
- bearing damage at the spur gear stage of the main gearbox
- gear tooth damage at the planetary and spur gear stage

Causes:

- insufficient knowledge about dynamic loads
- construction or design errors
- manufacturing errors
- lubrication
- operating conditions (braking behaviour, gusts, corrosion)
- inadequate maintenance

One of the most challenging aspects of designing a wind turbine is to correctly estimate the various load conditions inside the drive train. It is still very difficult to precisely predict the dynamic loads that actually occur during operation. National and international directives and standards incorporate new knowledge, of course, but they cannot keep pace with the high rate of development in the wind energy sector. A series of damages to drive trains, particularly in the area around the transmission, have shown that the components in wind power stations are subjected to far higher loads than was previously assumed.

Gear and bearing in the gearbox are subject to most of the damage in the drive train. Experience has shown that the actual service life of gearboxes in wind turbines is in some cases significantly below the calculated figures. For example, various types of serial damage have shown that spherical roller bearings used as planetary bearings are problematic in wind power stations. Consequently, cylindrical roller bearings have become the standard.

Frequent types of damage:

- grey stains on the side of the toothing are an early sign of fatigue. They form hairline cracks that can cause failure.
- foreign material compressed on the tooth flanks, originating e. g. from damage to the gearbox (e. g. bearing damage, tooth breakouts)
- residual manufacture impurities

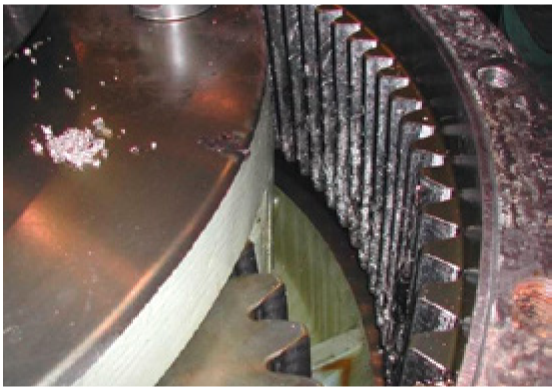


Figure 32: Transmission damage at the planetary stage due to bearing failure after approximately 30,000 operating hours (1.5 MW wind turbine); source: R+V

Figure 34: Grey stains on the sides of gear teeth; source: Allianz

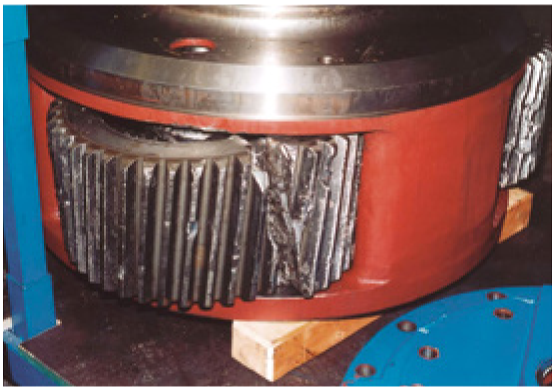


Figure 33: Total damage of the transmission after bearing failure at the planetary carrier after approximately 20,000 operating hours (1 MW wind turbine); source: Allianz

Figure 35: Replacement of the gearbox, without dismantling of the rotor; source: R+V

- rotating bearing seats
- overstrain on the bearing
- oversized fits
- tooth failures caused by overstrain (operational loads, braking torque) or foreign material inclusions
- uneven bearing patterns (tooth flanks, bearing shells) (a sign of local overloads)

Possible consequences:

- cracks or material failure on the tooth flanks
- peeled bearings
- current transfer marks in the bearings after lightning strike
- poor bearing lubrication, for example splash lubrication in the planetary bearings
- absorption of excessive radial/axial loads due to lack of compensation in the gearbox
- loss of lubricity of the lubricant (purity, temperature)
- step formation by frictional corrosion at the coupling between planetary and spur gear units

7.3 Generator

- bearing damage on bearings A and B
- winding damage

Causes:

- manufacturing errors
- overlord
- design errors
- design or service life of the winding
- inadequate cleaning or maintenance
- Incorrect alignment during assembly

Figure 36: Fanned out winding of a slip ring rotor due to a torn rotor bandage; source: Allianz

Double-fed asynchronous generators are used in many wind power stations. They feature a wound rotor whose winding heads and outlets are exposed to high dynamic strains. If the winding head bandage does not withstand these forces, it may fan out. In the worst case, the winding starts rubbing and is destroyed. The support of the outlets that connect rotor winding and slip rings must also have sufficient mechanical strength. An endoscopy makes it possible to inspect the winding head area.

7.4 Electrical Equipment

Faults in the electrical equipment of a wind power station can lead to expensive damage and even to total destruction. Fires have often occurred, most of them caused by overheating due to overload, earth/short circuit or electrical arcs.

Typical errors include:

- technical defects or incorrectly dimensioned components in the power electronics (e.g. switching cabinet, converter cabinet, transformer)

- failure of circuit breakers and/or electric arcs in the switchgear
- failure or overload of cable sockets of the internal or external wind park cabling
- failure of the control electronics
- high transition resistances due to insufficient contacts in electrical connections, e.g. screw connections on contact rails
- an insufficient electrical protection concept with regards to insulation fault detection and selectivity of switch-off devices
- no or no all-pole activation of the generator in case of system failure or shutdown
- missing overvoltage protection on the medium voltage side of the transformer
- resonance in RC resonant circuits (mains filters, reactive power compensations)
- component failure due to wear or limited shelf life
- no/insufficient potential equalisation
- inadequate maintenance

Since wind turbines are not permanently manned, it is only during maintenance and revision that damage from the development phase can be detected and measures to prevent massive damage can be taken. Therefore, the maintenance staff bears a very high responsibility. The condition monitoring systems used today do not improve this situation; they only monitorthe drive train, tower and rotor blade and do not record changes in the operating behaviour of other system components, for example of electrical devices.

Figure 37: Failure of a 110 kV sleeve connection; source: 8.2 Group e.V., Nikolaus Kromm

Figure 38: Internal wind park cabling damaged by dredging; source: Svst.-Büro Vogel, Ullrich Maug

Figure 39: Inverter plug-in unit with defective IGBTs; source: R+V

Figure 40: Generator-stator winding with earthing; source: R+V

Figure 41: Slip ring housing of a generator contaminated with bearing grease; source: Allianz

Figure 42: Transformer damage: Overvoltage from the power supply network with breakdown of the conductor insulation. The overvoltage protection was missing; source: Allianz

Figure 43: Fire damage on a 20 kV transformer due to lack of maintenance; source: R+V

However, maintenance personnel can only carry out their tasks correctly if the conditions permit it. As early as the development stage of a wind power station, care should be taken that all system components requiring regular monitoring are readily accessible.

Every two years, a recurring test of electrical installations (according to VdS) is recommended. While this test is already demanded by the BGV A3 (former VBG 4), the examination cycle here still takes four years. In every case, the test must be carried out by a certified expert.

Since there is always a risk of grid or equipment failure, an optimal electrical protection system should be used to detect grid faults and other abnormal operating conditions in the wind energy installation and associated peripheral systems. Unfortunately, retrofitting is often complicated due to space constraints.

For transformers, the following types of damage have occurred in the past:

- lack of overvoltage protection caused by using contact-safe plug connections on the medium voltage level. (The design with the overvoltage protection is associated with little additional costs if it bought with a new transformer. A retrofit is disproportionally more expensive.)
- lack of temperature monitoring
- incorrectly configured protective devices
- mechanical stress on the outlets
- insufficient maintenance or service of the transformer and the compact station

7.5 Theft

Theft or attempted theft of copper cables can lead to damages to the order of tens of thousands of euros. Without a burglar alarm system, a wind power station is an easy target: the power cables laid in the tower can be easily cut and removed by thieves – for example, with battery-powered hydraulic cable shears.

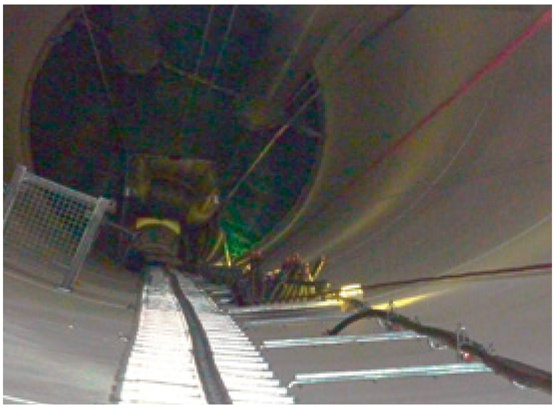


Figure 44: Severed power cables; source: R+V

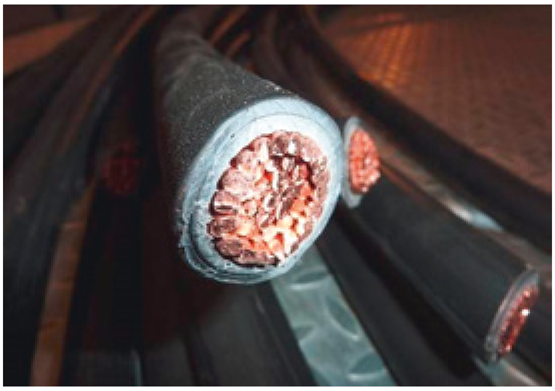


Figure 45: Severed power cables (magnified); source: R+V

7.6 Foundations

Reinforced concrete foundations have received comparably little attention for many years. Yet, they experience high stresses and current research demonstrates that foundations can develop cracks and require regular inspection and maintenance. Therefore, their integration into the maintenance and service plan is urgently recommended. If the operator does not care about the foundation of his wind turbine, damage may occur as a result of normal weather conditions alone:

- Water entering through cracks in the concrete can cause the steel reinforcement to rust. If corrosion advances the steel reinforcement may tear and the stability of the foundation may be jeopardised.
- Water penetrating cracks washes out concrete, cavities are created and ever larger zones of the reinforcement are exposed.
- Water entering the joints between the foundation component (FET) and the foundation itself can lead to a dangerous increase of room for movement between the two components due to leaching and corrosion.

Since 2006, many operators have experienced damage to wind turbine foundations. Several hundred damages to wind power stations from at least two manufacturers have already been reported at home and abroad. Damages were found disproportionately often in foundation components with two surrounding pressure rings. The most frequently occurring and easily recognisable damage patterns are semicircular or annular cracks around the foundation component and cracks inside the tower. Further investigation also revealed cracks above the upper and lower pressure rings and cracks extending radially from the tower shaft to the outside of the foundation.

Cracks are caused by a combination of various factors which influence whether foundations can withstand permanent force input through the tower and the foundation component without damage, for example:

- insufficient reinforcement, e.g. lateral-force reinforcement (thrust reinforcement), suspension reinforcement or rear suspended reinforcement
- missing soft layers above the upper and lower pressure ring
- incomplete concrete underneath the pressure rings

Even after a refurbishment, the foundation must be checked regularly, since long-term data are not yet available for rehabilitation success and some of the problems have not been not remedied by the current rehabilitation plans.

The assessment of damages is complicated by the fact that the legal relationships between operator, the manufacturers of the turbine and of the foundation may vary depending on the contract. The potential for damage and the difficult starting point prompted the Bundesverband Windenergie e. V. to set up the task force “Foundations” in 2008. Its aim is to organise an inventory of observed damages and to exchange information on problems with the foundations of wind power stations.

Figure 46: Restoration of a foundation; source: Gothaer, Edgar Sensen

Figure 47: Cracks inside the tower; source: Gothaer, Edgar Sensen

7.7 Total Loss

- tipping over
- gondola crash
- fire

Causes:

- faulty design or manufacturing
- safety deficiencies
- short circuit/lightning strike (fire, unbalance)
- imbalance due to fractured rotor blades after overload

The total loss of wind power stations is a rather rare occurrence in comparison to overall damage costs. However, they are an extraordinary burden for all parties involved. The cost of restoration for a two-megawatt system can be as high as two million euros. For installations with more than five megawatts, costs of five million euros may well be exceeded.

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II Offshore Wind Power

9 Support Provided by the Insurance Industry

From coverage concepts for steam engines to modern wind energy plants, the German insurance industry has been supporting technological innovation for more than a hundred years. We provide solutions appropriate for various risk scenarios and have become a valued partner for the industry. Our specialist board, dealing with the insurance of wind energy plants, recommends an in-depth analysis of the challenges faced by the relatively young technology of offshore wind energy. In order to support the construction of an offshore test field, insurance companies, in an active alliance with politics, industry, the energy and finance industry and under the patronage of the German federal government, established a charitable Offshore Foundation in 2005. In May 2006 the GDVs application for membership on the board of trustees of the foundation was formally accepted. Thanks to the GDVs collaboration, members of our association can now closely monitor test operations and scientific outcomes at the offshore test field alpha ventus, and they enjoy easy access to decision-makers in business and politics, responsible for financial support of renewable energies.

Another body of the European insurance Industry, the European Wind Turbine Committee (EWTC), was founded in 2009 and consists of about 25 European insurers and reinsurers, exchanging technical expertise on on- and offshore wind development. One of the EWTCs initiatives is an Offshore Code of Practice (OCoP) that is currently being developed in cooperation with the wind industry. Its aim is to promote a profound understanding of the complex risks involved in the construction and operation of offshore wind parks, in order to keep them insurable in the long term. This is a basic prerequisite to further enable the investments required in this area.

10 State-of-the-art Technologies

10.1 Turbines

Turbines for use at sea are not fundamentally different from those used onshore. These are the main differences: offshore turbines are generally equipped with a helipad and with an air treatment system, that sucks in air from the outside, desalinates it, dries it and feeds into the gondola under high pressure to keep the it salt free and dry.

Since transport at sea is barely restricted by the size of the components, offshore systems offer significantly higher capacities than their onshore cousins. In recent years, the offshore standard for turbines performance has been increasing from 3.6 MW to 8 MW and rotors currently have up to 164 meters (as of 2016) in diameter. So the vision of wind energy plants with an output of 10 MW in serial production by the year 2020 appears realistic.

In the past, turbines were always equipped with gearboxes, as these were significantly lighter than directly powered ring generators. The reduced cost for towers and foundations rendered gearboxes more economical. However, the additional cost of ring generators is now made up for by the use of high-performance permanent magnets. Reducing the number of components and moving elements is particularly advantageous in operation, so today directly powered turbines with rated outputs of 6 MW are in operation as well.

10.2 Foundation Structures

Standard foundation structures are monopiles, tripiles and gravity foundations, jacket structures and tripods. While monopiles, tripiles, and gravity foundations are directly connected to the seabed, tripods and jacket structures have to be connected to the ground via smaller piles, grouted with a special concrete or with so-called suction buckets.

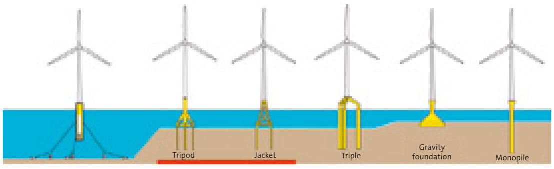


Figure 48: Foundation Structures; source: Foundation Offshore Wind Energy

10.2.1 Monopiles

Monopiles are by far the most frequently used foundation structure for offshore wind power plants. A monopile is a steel pipe with a diameter of 5–8 m, a length of up to 80 m and a weight of up to 1,400 tons, which is rammed into the seabed. This foundation structure has proven to be the best solution, both in economic and technical terms, for water depths between 4 m and 50 m, as is the reality for most operational and approved wind parks today.

Once the monopile is rammed into the sea bed, a transition piece (TP) is attached for docking and safe transfer of people (boatlanding) from a crew transfer vessel (CTV).

Joining transition pieces to monopiles via a grouting link is a proven method in the oil and gas industry, particularly during exploration and production. The positive connection is created via the surface roughness of the corroded steel. In this context is the option to compensate for misalignments of the rammed monopiles up to several degrees of angle is particularly advantageous. However, first experiences during operations show that this connection is not stable in the long term, due to the ongoing oscillatory excitation, typical for wind power plants. As a first countermeasure, monopiles and transition pieces are equipped with shear keys, a type of interlocking connection, and/or the connecting piece was given a conical rather than cylindrical shape. The method was updated when, during several projects, it turned out that a screwed-on flange connection between the monopile and the transition piece did not allow for the required the oblique angles. In addition, flange connections facilitate offshore assembly. They have now replaced grouting connections as a standard.

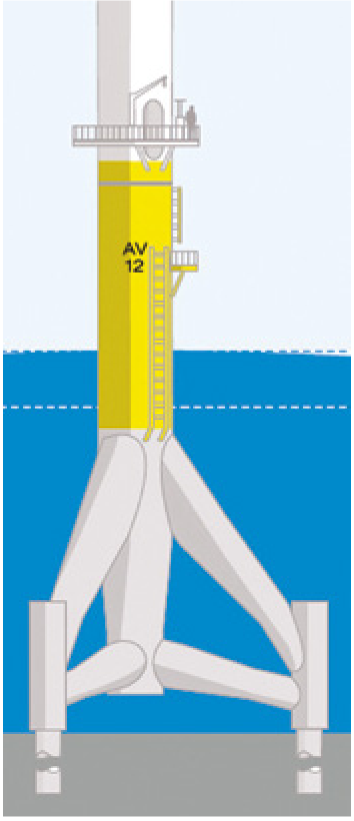
10.2.2 Gravity Foundations

Gravity foundations have thus far been used mostly in shallow water. Onshore they are poured from concrete and are then transported to the offshore construction site. This requires complex logistics both on land and at sea – including ships built specifically for this purpose. At the construction site, the base of the gravity foundation is usually filled with additional ballast, giving it a final weight of several thousand tons.

Gravity foundations have been used in the Baltic Sea. Here, in particular, their upper part of has a conical shape, with the purpose of reducing pressure of sea ice by deflecting it downwards. Another example for the use gravity foundations, can be found at the Thorntonbank wind park in the Belgian North Sea, with a depth of 30 to 35 m.

10.2.3 Tripiles

Tripile foundations were invented by BARD GmbH (Emden, Germany). They are suitable for water depths of 25 to 50 m. They feature a supporting cross piece and struts that are welded from flat steel elements. This type of foundation consists of three piles (hence the name), each up to 90 m long, that are driven into the seabed. A special structure on the stern of the BARD's own construction vessel, the drive template, ensures vertical alignment and precise positioning. When all piles are successfully rammed into the seabed, the supporting cross piece is placed on top of the piles and the connecting seams are closed with a special concrete.



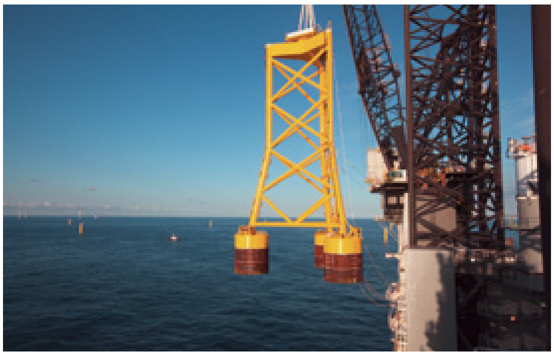
Figures 49–50: Tripod concept and installation at the alpha ventus test field; source: DOTI

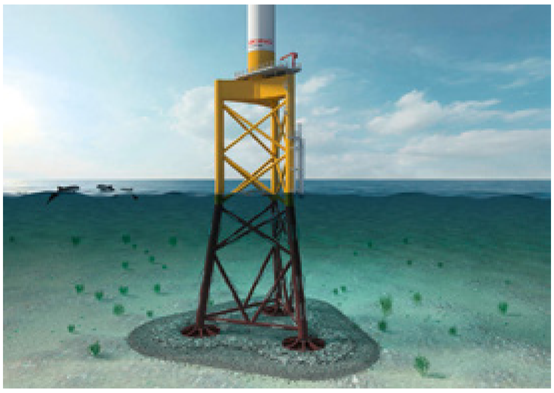
10.2.4 Tripods

Tripods are three-legged constructions required particularly in deeper water. First variants of this type of foundation were realized as early as 2006, for instance the ca. 30 m high steel tripod erected onshore by AREVA Multibrid for their M5000 turbine, making it the world's first offshore wind turbine, whose interaction with a tripod foundation was tested ashore. Including the most recently erected M5000 (as part of the project alpha ventus) a total of six tripods are now in operation in water depths of about 30 m. Each of these tripods weighs about 700 tons and stands 45 m high, with the top 15 m bit sticking out of the sea.

10.2.5 Suction Buckets

A suction bucket resembles an inverted steel cup (open at the base). During installation, this steel cylinder is placed on the sea floor and the water contained therein is pumped out. In this process a kind of quick sand develops along the walls of the bucket, allowing it to sink into the sea floor under its own weight. Once the desired depth is reached, the pump is turned off and, if necessary, the remaining cavity between the sea floor and the cylinder is filled with concrete. DONG Energy successfully erected a 3.6-MW system on the prototype of a three-legged jacket structure with suction buckets as part of the project Borkum Riffgrund 1.

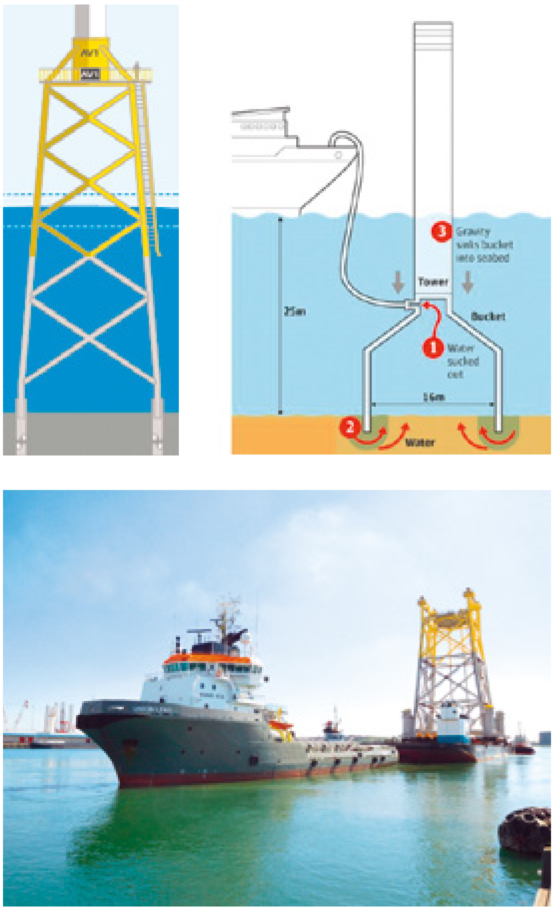




Figures 51–52: Jacket structure on suction buckets; source: DONG Energy

10.2.6 Jackets

“Timber frame”-like jackets are underwater support structures rather than foundations in the usual sense. Jackets can have different shapes and are used as a base for both wind power plants and substations.



Figures 53–55: OSS Sailaway; source: Survey Association

10.2.7 Floating Foundations

Floating foundations allow the construction of offshore wind parks in location, in which other foundations cannot be used at all or are no longer economical. Currently, first research projects are investigating the use of wind energy installations on floating foundations in waters with depths of 100 m or more. One unresolved problem with this approach is the connection to the power grid. Floating foundations are constantly moving due to changing winds, currents and tidal flows, resulting in a corresponding load on the connecting cables. Cables for the transmission of large currents however, have a large cross section and are therefore not very flexible, rendering them unsuitable for constant bending stress.

Figures 56–57: A floating wind energy plant at Project Hywind off the Norwegian coast; source: Statoil

10.3 Sea Cables and Land Connection

Before transmission to the onshore grid, the electricity generated by individual wind farms is bundled in internal transformer stations and is then sent to a substation via individual cable strands or loops. Depending on the power of the turbines, up to six plants can be linked. Wind parks near the coast transmit their power directly via an export cable into a grid operators onshore feed-in station – in the German Bight this is the rule. In contrast, in the German Baltic Sea, the power is transformed to alternating current before being transmitted. The network operator responsible for this is 50Hertz, with headquarters in Berlin. Due to the greater distances in the North Sea, here the power is not only transformed to a different voltage (by the network operator Tennet) but rectified and passed on to a converter station on land by means of high-voltage DC transmission (HVDC). The direct current is then converted back to alternating current an fed into the power grid. The only exceptions in the North Sea are the wind parks Riffgat and Nordergründe; these are connected directly to the mainland due to their proximity to the coast.

In order to protect submarine cables from damage caused by trawlers, anchors or similar hazards, they are embedded into the sea floor sea floor. On sandy grounds, this is usually vone by injecting the cables: first they are placed on the sea floor, then a remote operating vehicle (ROV) lowers jet ploughs into the sea floor on both sides of the cable and travels along the cables length. Nozzles at the front end of the jet plough generate a water stream of high pressure, flushing the sand from underneath, such that the cable sinks into the ground under its own weight. If the desired depth is not reached initially, the procedure can be repeated several times. Even if a cable is freed over time, it can be laid again with this method. The usual laying depths in the North Sea us 3 m in traffic separation schemes (i.e. along the main shipping lines) and 1.5 meters in all other areas (also inside wind parks). In shallower water, rinsing plows are used to guide and lay cables directly into trenches. Depending on the ground, other methods can be used, such as a drawn plough, pre-digging or milling trenches (e.g. in chalk, clay and marl sea beds in the Baltic Sea). When crossing dikes and islands, horizontal drilling or open excavation methods are generally used.

10.3.1 Substation and Converter Station

In addition to switching devices and transformers for bundling and transforming the generated power, other central facilities of the wind park are located on the parks own substation. Data transmission and systems control are performed in that substation, and the emergency power supply is installed here as well. A helicopter landing pad is another standard feature. Some plat-

Figure 58: Transformer platform Riffgat; source: EWE

forms, mostly those at a large distance from the nearest airport, also offer fueling capabilities and a corresponding kerosene storage. Regular accommodation for workers has so far been the exception, as this would require considerably higher safety standards to comply with health and safety regulations.

For parks far off the coast it is more economical to transmit the generated electricity to the mainland as a direct current and at a higher voltage in order to minimize transmission losses. In the German EEZ (exclusive economic zone) the required technology is installed by the responsible grid operator on offshore platforms (offshore outlet). There, the current is transformed to a higher voltage, rectified and fed into the land connection cable. In order to save costs and minimize the number of sea cable connections, clusters of several wind parks are connected via a single land connection (sea cable and + converter station).

The number of networked wind parks is determined by the transmission capacity of the available sea cables (about 1 GW in 2016).

11 Construction

The manufacture of components onshore is the first step in the construction of wind farm. The most important component is the topside of the offshore substation (OSS). For construction various special vessels are required, such as cable carriages and heavy load cranes. Due its weight heavy lift vessels are used for its installation, ships like the Thialf, Hermod, Oleg Strashnov or Stanislav Yudin. For the installation of foundations and turbines, jack-up vessels are typically used. These vessels can fixed their position in the sea with six hydraulically or electrically operated legs (so-called jack-up legs). These legs are lifted during transit and are lowered and placed on the seabed at the intended position. Then, the vessel lifts itself out of the water, stabilized by its own weight, creating in a firmly anchored platform. Alternatively, self-positioning installation vessels (also called dynamic positioning vessels or DP vessels) can be used. However reports of experiences with this type of ship were mixed.

11.1 Procedures during Construction

Offshore installation of the individual components is usually carried out in the following sequence.

11.1.1 Installation of Foundations

Monopiles are rammed into the sea floor. This procedure holds a considerable potential for damage. The main disadvantage of this method, however, lies in the generated underwater noise, which has a significant impact on the submarine fauna. Ramming is not allowed during certain wildlife protection periods, for instance to not disturb the rearing of porpoises. The use of bubble curtains for noise reduction has proven useful and is mostly mandatory, but does allow for ramming during protection periods either.

Instead of ramming, monopiles can be installed by vertical drilling or by means of vibration. Both procedures, however, have not caught on so

far (status in 2016). After the monopiles are inserted, the transition pieces (TP) are installed, usually with bolted flange connections.

In the case of tripiles, the procedure is similar; instead of one big pile, three smaller ones are inserted and a connecting support cross is placed on top. For tripods and jacket structures the insertion of piles is required as well. After assembly, the spaces between the piles and the structures they carry are sealed with a special concrete. Suction bucket and gravity foundations carry preinstalled boat landings and J-tubes (for the connection of cables) and can be installed without generating a lot of noise. While suction bucket foundations are installed by jack-up-vessels, gravity foundations are floated to the operation site, where they are lowered and then ballasted. As a final step, a collapse protection is placed around the foundation to avoid scouring of the sea floor. The protection can consist of a bed of rough stones, concrete mats or sandbags.

11.1.2 Offshore Substation

Ideally, as the next step the offshore substation (OSS) is installed. Usually, the topside of the OSS firmly attached to a jacket, gravity or (in smaller parks) on a monopile foundation. However, self-erecting, floating platforms have also been used, for instance in the wind parks BARD Offshore 1 and Global Tech 1. These platforms feature their own jack-up legs. Once positioned by tugboats, the legs are lowered into the sea with a strand-jack system and driven into the seabed with suction buckets. Subsequently, the platform is raised to a height of about 20 m above sea level.

11.1.3 Laying of Sea Cables

After the foundation and the OSS are installed, the see cables are laid and buried.

11.1.4 Installation of Towers and Turbines

The towers and turbines are installed after the system is linked to the OSS via a cable connection. This external power supply is required to activate the light beacons and their control system, and to ensure that during the rotor blades can be turned out of heavy winds. The air dehumidification system also runs on an external power supply.

The erection of the towers, turbines and their rotors by means of a jack-up vessels is usually carried out in one go. Towers are preassembled on land, loaded onto a jack-up-vessel and made seaworthy in the harbor. For installation of gondolas and rotors there are currently two standard procedures. Either the rotor blades are individually loaded onto a rack and mounted to the rotor hub of a turbine that is already sitting on a tower. Or the whole rotor start (rotor blades and rotor hub) is pre-assembled in a harbour. In this case, the rotor star is transported to and mounted onto the tower in one piece.

One jack-up vessel can carry up to 6 units (6 towers, 6 gondolas and 18 rotor blades) at a time. At the construction site the vessel pushes itself out of the water next to a finished foundation. With an on-board crane a tower is lifted onto the foundation and screwed tight. Subsequently, a turbine is mounted to the tower and rotor blades are attached, either individually or the rotor star is mounted as one piece. Now the system can be put into operation, optionally in idle mode, while the jack-up vessel starts installing the next system.

11.2 Hazards and Damages during the Construction Phase

Due to the long delivery routes for the individual components, damages must be expected already during precarriage. Apart from the usual hazards during loading, an increased risk is to be expected in the case of maritime transport via barge. Since barges are not manned, they are subject to little or no regulations regarding safety and seaworthiness. Barges should therefore be inspected by a specialist and released for the intended use.

Barges are simple floating bodies without propulsion. They are equipped with several separate swimming chambers to allow for trimming. Individual swimming chambers are accessible via manholes, through which they are also filled with ballast water. Since it is not uncommon during passage for the deck of a barge to be washed over by waves, the closure of all manholes (watertight integrity) is of vital importance. Otherwise the barge could capsize. Since barges are not self-propelling, they must be pulled by tugs. The responsibility for the barge and its load during the towing process is neither the owner nor the captain of the tugboat, but solely the owners of barge and cargo – each for their own property. Damage to or loss of the load are therefore bourne by the wind park project and are co-insured in standard policies.

As suppliers are spread far and wide geographically, damage of components during forward transports must be taken into account. Apart from the usual dangers of loading, an increased risk is to be assumed, especially in the case of maritime transport via barge. Since barges are not manned, they are subject to little or no regulations regarding safety and seaworthiness. Before using a barge, it should therefore be inspected by a specialist and released for the intended use.

So far, most damages incurred during the construction phase were related to the sea cables. Damages were usually recorded first during rewinding of cables to the cable-laying vessel and then again during laying and burying. Cables are particularly at risk when they are inserted into the foundations of turbines or the OSS. Even damage to the outer skin of the cables, which at first sight may appear minimal, can lead to a complete breach later on.

11.3 Risk Management

Offshore projects are typically accompanied by a Marine Warranty Surveyor (MWS). The role of the MWS is to examine all offshore activities for feasibility and to approve the planned procedures.

Figure 59: VMOP MP installation; source: Specialist Marine Consultants Ltd

The MWS takes into account both the suitability of the ships, platforms and cranes, as well as the expected currents, wave heights, wind and weather conditions. Another important aspect is sea fastening the cargo, i.e. securing it for sea transport.

The scope of activities performed by the MWS varies greatly from project to project and depends on the attitude of the responsible project managers. Some understand the MWS as an extended their deputy in ensuring quality assurance, in particular with respect to subcontractors. Other project managers consider their MWS a stumbling block, in the way of the project 's speedy implementation, imposed on them by insurers.

The minimum scope of work of an MWS is usually defined in the insurance policy. The respective clause usually contains a whitelist of qualified providers, from which the policyholder can select. The Lead Project Manager should discuss the scope of work in detail with the MWS to ensure that the he can actually perform all tasks. If necessary, individual tasks can be handed over to the risk management of the lead insurer. As a matter of principle, the activity of the MWS should be handled flexibly and it is not necessary to determine beforehand the number of installation procedures the MWS will attend. This is ideally decided after the MWS has had a first impression of the levels of skill of all stakeholders.

In order to support the MWS in her work and to emphasize her recommendations, appropriate legal consequences should be agreed upon in case of disregard or tasks being performed without prior approval as detailed in the policy.

In particular, the lead insurer should carry out a supplementary risk assessment – for example, for the production of cables and for testing of equipment offshore.

12 Operations

12.1 Contracts for Service and Maintenance

A decisive factor in the evaluation of operational risk is the service & maintenance agreement (SMA), which is usually concluded with the supplier of the wind turbine. These contracts are customized for each wind farm individually. The range of different agreements includes pure maintenance services, contracts including the delivery of spare parts and full maintenance contracts with an availability guarantee (analogous to onshore wind) and replacement services. However, all of these contract types consist of numerous levels, which must be included in the evaluation: in addition to absolute or availability-related limits of liability, the replacement of main components must also be considered.

Offshore logistics can incur significant costs: if special vessels are required for the repair of a system or cable, such as jack-up vessels or cable ships, costs will arise from both the actual repair as well as from access, mobilization (equipment on ships for the respective purpose), demobilization and possibly waiting times (e.g. due to bad weather). As charter costs are volatile and availability is uncertain, costs can quickly mount to double-digit million figures.

If these costs are not covered by the SMA, they must be borne by the operator – and hence, in the case of damage, by the insurer. So the insurer should carefully and extensively analyse the SMA prior to the conclusion of a contract.

12.2 CBI Losses

One particular factor that should not be underestimated is damage caused by a failure of the land connection. Grid operators in the German EEZ are legally obliged to reimburse 90 percent of the lost feed-in remuneration. However, in addition to the remaining 10 percent utilization loss, further costs are often incurred: for the emergency power supply and its fuel and for the re-commis-

Figure 60: Wake effect due to turbulent air flow at the wind park Horns Rev 1; source: Vattenfall

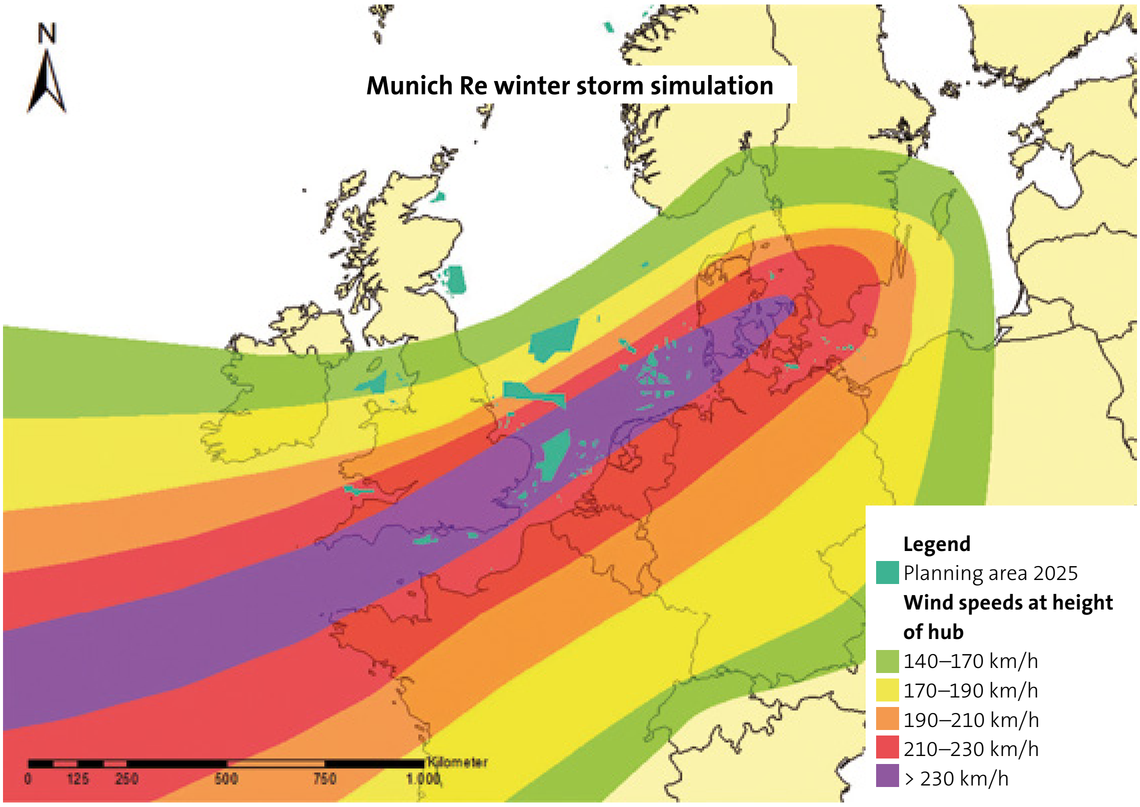


Figure 61: Simulation of a winter storm over Europe; source: Münchener Rückversicherungs-Gesellschaft 2012

sioning of the wind power plant after the land connection is restored. The amount of compensation that must paid by the network operator in the event of actual damage is still disputed, since calculations have to take into account several factors, such as the Wake effect (wind shadows caused by the wind power plant itself) and wind speed.

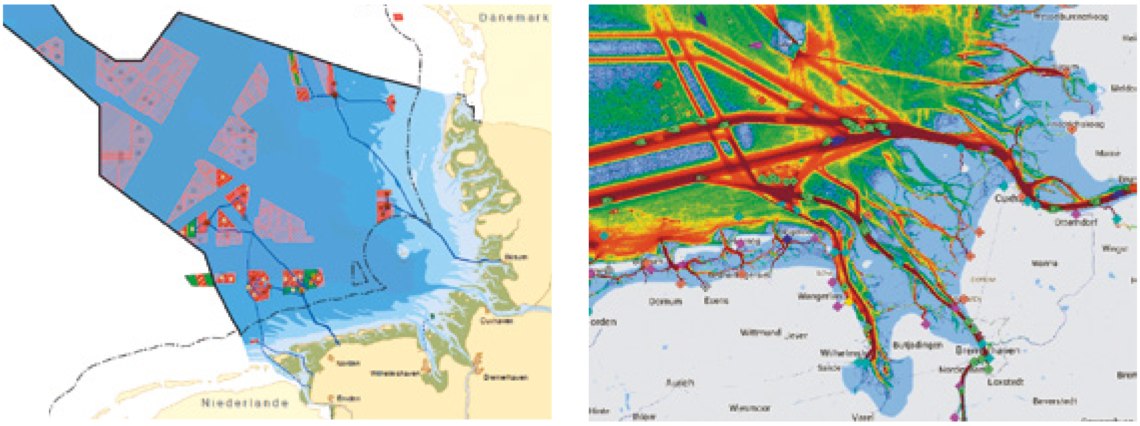
Furthermore, if the emergency power supply fails, e.g. due to lack of refueling during persistently bad weather, wind power plants may suffer mechanical damage; apart from humidity damage due to a lack of air drying, bearings and gearboxes may develop idle marks that can lead to substantial damage in the bearings during subsequent operation.

12.3 Cumulative Considerations

Offshore wind turbines are also threatened by natural hazards, primarily storms. The impact of a storm event on offshore wind parks can only be roughly estimated in the absence of sufficient data. How storm events will change with the global climate is not yet certain. In any case, an increase in extreme weather events can be expected during the coming decades. So insurers, especially reinsurers, must incorporate these hazards into their cumulative considerations.

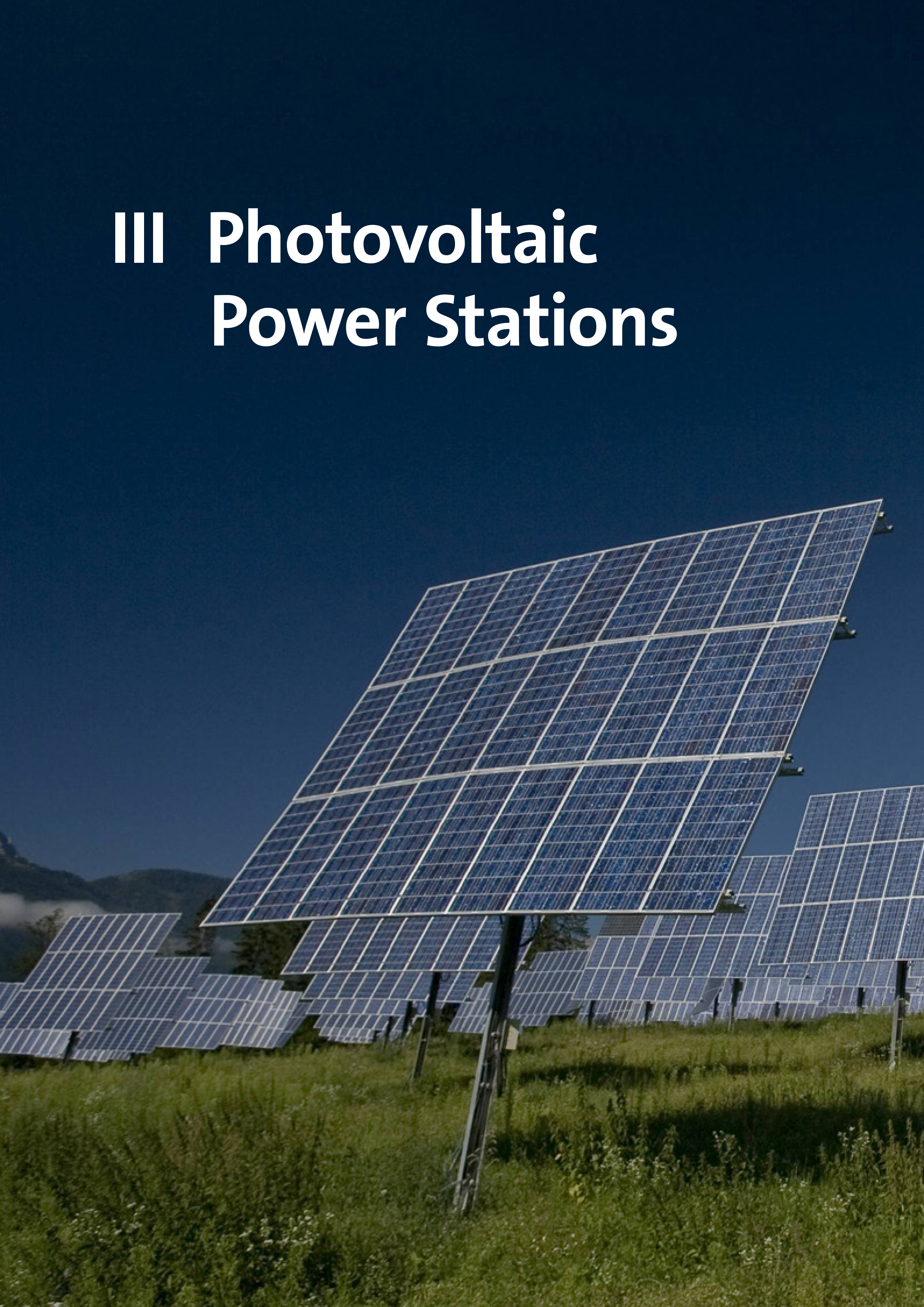
In contrast, earthquakes and tsunamis and so-called “monster waves” (also called “freak waves”) play barely any role in cumulative considerations for the North Sea. Earthquakes and subsequent tsunamis are not typical in this region. So-called monster waves (i.e. freak waves) are the result of additive interference of multiple waves and can reach heights up to 20 m, but only for a short time, as the waves involved quickly separate. As a result, these events are extremely rare and do not pose a considerable risk for wind farms.

In addition to natural hazards, disruptions to the land connections of several parks cannot be ruled out. One possible scenario here is damage to land connection cables as a result of an emergency anchorage maneuver of a fully loaded, large container ship. In order to minimize the effect on the protected mud flats of the German North Sea, HDCV land connection cables are bundled in a few relatively narrow corridors (about 1,000 meters wide). These corridors cross the so-called traffic separation scheme, an area frequented by a large proportion of international shipping, for instance on route to the port of Hamburg. In the event of a failure of control and navigation systems, a captain may be forced to perform an emergency anchorage maneuver, where the ship is stopped exclusively by letting its anchor plough through the sea floor. Large vessels can have breaking distances of several kilometers. If the braking path in such an event intersects a cable corridor, damage to several sea cables cannot be ruled out. Even though cables are buried into the sea floor, their covering layer can be reduced due to ground movements in the North Sea. Even at a laying depth of five meters, damages of sea cables by a large vessel’s anchor are still possible.



Figures 62–63: Cable routes and traffic densities in the traffic separation scheme; source: bsh.de

III Photovoltaic Power Stations



III Photovoltaic Power Stations

1 Introduction

Solar energy power stations include systems for harnessing energy from heat (solar thermal) and for generating electricity from sunlight (photovoltaic). Here, only photovoltaic systems will be discussd.

Photovoltaic cells transform light into electricity. Approximately 50% of the light's energy originates from the visible part of its spectrum ~380–780 nm wavelength, (blue to red) while 49% originates from infrared radiation. The remaining 1% comes from UV radiation.

Germany receives 900–1,000 kWh/m^2 of solar energy per year with an average of 1,300–1,900 hours of direct sunlight per year at a minimum irradiation of 0.2 kW/m^2. The amount of irradiation is about five times higher in summer than in winter.

The total amount of light reaching the earth's surface is called global radiation. It consists of direct and reflected (diffuse) radiation. In Germany, diffuse radiation makes up 60–70% of the global radiation.

2 Solar Cells and Modules

The building block of a photovoltaic (PV) system is the photovoltaic cell, a component with a thickness of 0.18 mm and an edge length of 156 × 156 mm. PV cells convert light into electricity, irrespective of the of the particular mix of wavelengths. Sixty solar cells connected to each other on a foil form a standard PV module. All cells in a module are connected in a series, i.e. the output of one cell is the input of the next. In this chain or string, the cells are usually linked by a soldered silver-plated copper tape or by a conductive paste. Faulty cell connections are a common cause of power loss and premature power system ageing.

Voltage and current: The voltage generated in a PV cell depends on the photon energy (wavelength), the light current density. The power at the MPP (Pmpp) is the product of the MPP voltage (Vmpp) and the MPP current (Impp), with MPP standing for Maximum Power Point.

The most common material used for PV cells is ultra-pure silicon, which responds to a wavelength of up to 1,100 nm. However, silicon only uses a narrow spectrum of light. Therefore, one major strand of photovoltaics research is to try and find materials (or their combinations) that can use a much broader segment of the light spectrum, including UV light.

A module usually consists of a cover glass, an encapsulation material and a backsheet film. Instead of a film, some modules are mounted on a rear glass pane. Connection sockets are located on the back of each module, connecting the modules in series.

PV modules are available in various designs: with and without a frame, as a solar roof tile, as roof sheeting, as an insulating glass pane for window and roof glazing, curved, and so on.

The performance ratio is the ratio of the alternating current (AC) yield to the nominal yield of the generator's direct current (DC).

The scientific community differentiates between:

- the efficiency rate measured in laboratories
- the efficiency rate measured in a single cell
- the efficiency rate measured in a module
- the efficiency rate measured in the power station, influenced i.e. by inverters and cables

In 2017, silicon modules have an efficiency of 15—22% , while the efficiency of three-layer coating technology reaches up to 25%.

Scientists are working hard on novel cell materials and production processes and soon efficiencies could reach over 40%. New developments must be taken into account. Various prototypes can be expected. Insurers should also take into account the fact that economic or technical developments can lead to production adjustments or relocations, making replacements more expensive or in some cases even impossible.

In a series circuit the weakest module determines the power of the entire string. As the degrees of efficiency vary, modules of different types cannot be combined with each other without performance losses. Therefore, a single string must always consist of modules of the same type. In the case of a claim involving modules that are no longer produced, a manufacturer can produce single modules according to individual specifications.

This, however, makes replacements more expensive and more time-consuming under certain conditions, increasing potential out of service periods.

Current research in photovoltaics has the following objectives:

- to increase efficiency, i.e. to increase the amount of electricity generated over the same surface area at the same light intensities
- to reduce silicon consumption,
- to substitute silicon with other materials,
- to structurally modify PV cells/modules to improve their performance (e.g. with pyramidal structures or concentrator cells), and
- to reduce production costs.

2.1 Common Cell Materials, Efficiencies and Market Shares

Cell material	Efficiency	Lifetime	Market share
silicon (amorphous)	5–10%	< 20 years	14%
cadmium telluride	5–12%	> 20 years	none
organic solar cells	12%	low	none
silicon (polycrystalline)	14–20%	25–30 years	47%
silicon (monocrystalline)	16–22%	25–30 years	38%
gallium arsenide (three-layer)	25%	> 20 years	none

2.2 Organic Solar Cells

Organic solar cells consist of hydrocarbons (i.e. plastics), a group of materials studied in organic chemistry. They are also referred to as polymer or plastic solar cells.

Organic solar cells with an area of about 1 cm^2 have an efficiency of 12% under laboratory conditions in 2016. Since many organic molecules can be synthesised and selectively modified, it is now possible to design materials that have both of the desired electrical and optical properties. As a result, organic solar cells have several advantages over silicon cells: they are flexible, transparent and have all the mechanical properties of plastics. Their efficiency remains constant when subjected to heat and they exploit diffusely-scattered light more efficiently than conventional PV cells.

On the downside, organic solar cells exhibit an insufficient long-term stability (5,000 hours). They easily oxidize, altering their electrical properties in the process, and their contact materials and interfaces age rapidly. The aim of current research in this area is to understand the mechanisms causing this kind of degradation.

2.3 Photovoltaic-Thermal (PVT) Collectors

Photovoltaic-Thermal-Collectors or PVT collectors, also referred to as solar hybrid collectors, consist of a photovoltaic module and an internal heat absorber. PVT collectors generate electricity and transfer heat to a transfer medium.

2.4 Transparent Modules

Solar modules can be opaque or semitransparent. When very thin PV cells are mounted on a glass pane, a semitransparent effect is produced. Various semiconductor materials can be used for this purpose. The most important are:

- amorphous silicon (a-Si)
- a tandem of amorphous and microcrystalline silicon (a-Si/µc-Si)
- copper indium diselenide (CIS)
- cadmium telluride (CdTe)

In contrast to crystalline modules, thin-film modules have a reduced efficiency of 6–12%.

A further method of creating semitransparent amorphous solar cells is to remove a part of the coating with a laser, creating stripped or patterned surfaces. In this way, standard silicon modules can be produced that allow approximately 10% of the light to pass through their cells.

A-Si modules on glass substrate feature a front and rear glass pane, a so-called glass-glass laminate. Both framed and frameless amorphous solar modules are available.

2.5 Other Special Designs

- PV roof tiles: These modules with the shape of roof tiles are still a niche product. Several manufacturers have ceased their production.
- Triangular, trapezoidal, curved or round modules are custom-made. Due to their individual production volumes, they come at an additional cost.
- Solar foils
- Coloured PV modules
- Blind or dummy modules have an optical function only and do not generate electricity.

2.6 Building-Integrated Modules

Building-integrated PV modules are used in a multi-purpose manner, i.e. they are part of the building envelope (facade, roof, parapet, etc.) and fulfil additional functions in and around buildings, such as shading or sound insulation.

2.7 Performance Losses (Degradation)

PV modules can sustain performance losses in single incidences as well as over their entire service life. In the course of a monitoring period of 25 years, a cell loses approximately 10–13% of its original output. The causes for this performance loss are very diverse. The community distinguishes between:

- age-induced degradation,
- light-induced degradation and
- potential-induced degradation.

Age-induced degradation

Age-induced degradation is caused by general wear and tear. Stiffening of the semiconductor material as well as different external influences are the underlying causes. Estimates for standard levels of degradation are inconsistent and range between 0.1% and 0.5% per year for mono- and polycrystalline PV modules.

Light-induced degradation

Light-induced degradation only plays a role in amorphous modules (thin-film modules). Crystalline modules are not affected. Researchers assume one cause to be the formation of boron-oxygen complexes inside solar cells during long-term exposure to light, leading to reduced conductivity. The effect is observed particularly in p-type silicon modules. However, the exact cause is scientifically not fully understood.

Potential-induced degradation (PID)

Potential-induced (voltage-induced) degradation (PID) is observed exclusively in systems consisting of crystalline silicon with high voltages and transformerless inverters. PID is triggered by leakage currents. Charges generated inside the PV cells are supposed to flow to the cells outlet and to contribute to the modules overall electricity production. In PID, however, charges find their way through the encapsulation material (EVA) and the front glass pane to the earthed module frame. This effect often arises in unearthed PV systems with a negative voltage with respect to the ground or with respect to earthed aluminium frames. PID is caused by high system voltage, high temperatures and high atmospheric humidity. As a result, power losses of up to 30% have been observed.

Potential-induced degradation can be prevented by earthing the positive or negative pole to an inverter. Also, modified antireflection layers on the cells, reduced oxygen content and different encapsulation materials can reduce the effect.

Several cell and module manufacturers are trying to minimise PID. For more details on PID caused by DC-AC conversion, see section 2.10.

2.8 Measurement of Irradiation

To determine whether a module is operating properly, reference measurements must be performed. For this purpose, pyranometers, or reference cells, calibrated by the module's manufacturer are used. These reference devices should be of the same type as the tested module and should also have the same cover glass in order to record all influencing variables.

2.9 Edge and Back Sealings

Penetrating moisture can corrode cells and connectors, rendering the whole module inoperable. Hence, sealing materials are of crucial importance. For edge sealings, until recently manufacturers have been using EVA encapsulation material. This material, however, turned out not to be very suitable. As a result, polyisobutylene (PIB) is increasingly being used (see fig. 1).

2.10 Foil Quality

The quality of the ethylene vinyl acetate film (EVA film) significantly affects a module's lifetime and long-term performance. Low-grade film, which is regularly used, can cause a whole range of damages. For instance, poor foil quality can cause PID. Inferior foil quality is also associated with delamination and other kinds of corrosion, such as defective cell metallisation or so-called snail traces, which reveal microscopic hairline cracks and cell fractures. The quality of a foil can be assessed by polymer analyses in a specialist laboratory.

2.11 Browning/Yellowing

The so-called browning effect is a brown-yellow discolouration. Browning refers to an ageing process during which the ethylene vinyl acetate (EVA) layer turns brown or yellow. The effect can be caused by inferior EVA quality, incorrect storage, missing additives and heat. As a result of the discolouration, the EVA ages and the embedded PV cells can corrode or form bubbles (see fig. 2).

Figure 1: Corrosion of cell connectors due to humidity at the edges; source: PVGutachten.info

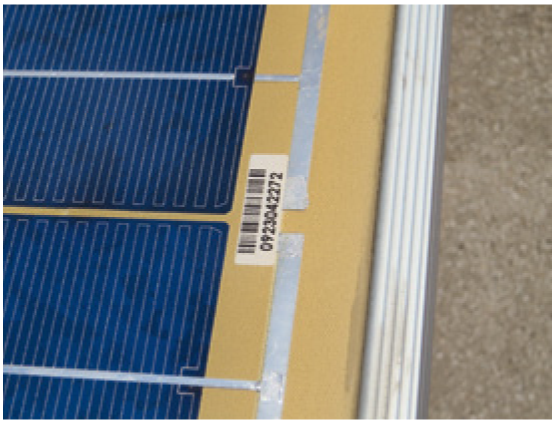


Figure 2: Yellowing of the film on the back of a PV module. In the long term this discolouration leads to a reduction in performance; source: PVGutachten.info

2.12 Hotspots

Faulty solder connections can cause strong resistances that generate heat. These hotspots also emerge as a result of partial shading (small or large) caused by snow, bird droppings or leaves. A partially shaded cell behaves like ohmic resistance – the voltage becomes negative and the cell starts operating as a consumer. It is heated by the current generated by the other cells. As a result, cells can become discoloured and the EVA plastic can blister and corrode. At an irradiation exceeding 900 W/m^2, hotspots can turn into burn holes. Thermal imaging can easily reveal emerging hotspots.

In order to prevent hotspots, each cell's circuit has an integrated bypass diode connected in parallel. These diodes direct backflow currents around a shaded cell. However, if a shadow covers only part of a cell, the bypass diode may not activate and a hotspot can still form.

Hot spots can be detected by infrared imaging

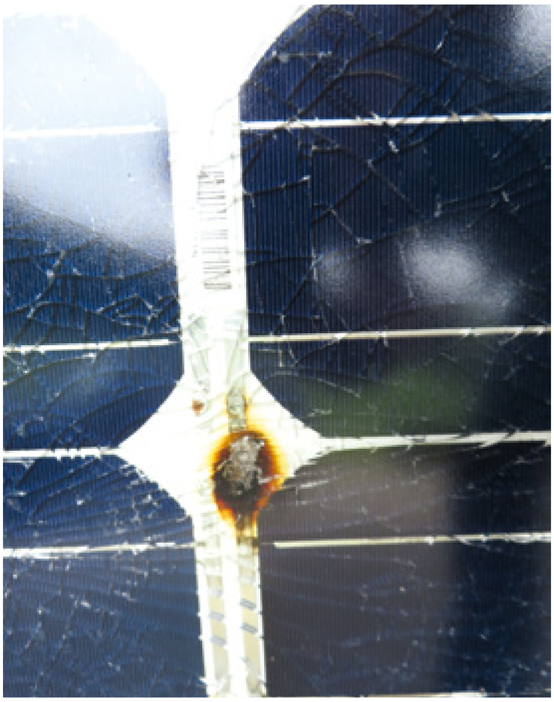


Figure 3: An inadequately soldered connection caused heat hotspot. As a result, the glass pane is damaged as well; source: PVGutachten.info

2.13 Snail Trails (Discolouration of PV Encapsulants)

So called snail trails are discolourations. They show up at cells' edges and/or along internal microcracks. The conditions leading to the formation of snail trails are created by certain material combinations and during the manufacturing process. Experts have identified several critical factors including moisture permeability of the backsheet and a differential chemical composition of EVA foils and silver pastes. Moisture penetrating through the backing film can reach the surface through microcracks or at the cells' edges. Under the influence of electric fields, heat and possibly UV radiation, the interface between the silver contact fingers and the encapsulation film begins to corrode, allowing particles containing silver to migrate into the film.

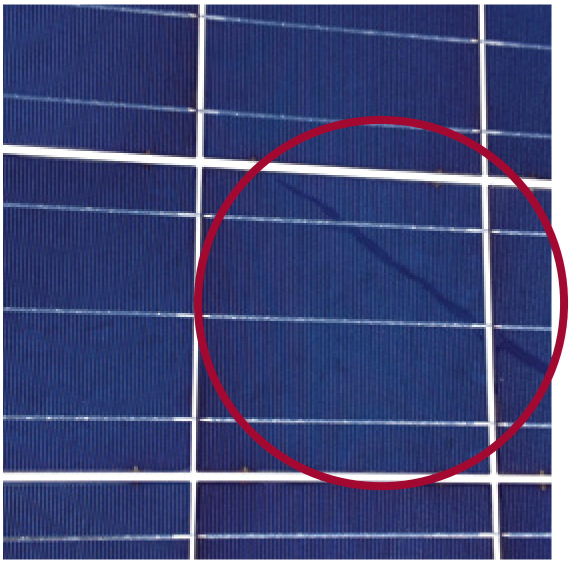


Figure 4: A snail trail; source: PVGutachten.info

2.14 Microcracks

The causes of microcracks are considered to be mechanical stress and different expansion behaviours (expansion coefficients) of composite materials.

PV-Modules are exposed to mechanical and thermal loads during production and shipping. Frameless modules are especially affected.

Different substances such as glass, plastic and metal are combined in PV modules by soldering and lamination. Radiation, heat, wind and snow loads lead to mechanical and thermal stresses that result in microcracks.

2.15 Delamination

Delamination is the separation of the ethylene vinyl acetate (EVA) foil from the PV cells below the cover glass, resulting in bright, gray or milky spots. One explanation for delamination is thermal stress, e. g. due to hotspots. Other causes are considered to be faulty manufacturing processes or incorrect storage of the EVA prior to process-

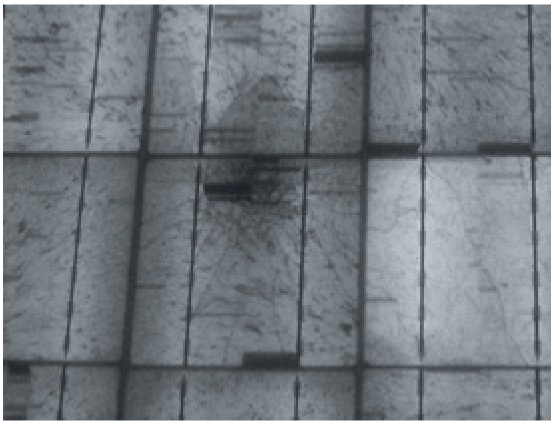


Figure 5: Microcracks. Here, hair-like cell fractures, caused by a hailstorm, are visualised. Microrcracks can only be detected through electroluminescence; source: PVGutachten.info

Figure 6: Delamination; source: PVGutachten.info

ing. Delaminated cells are no longer properly protected from the environment, allowing moisture to reach the cells, which leads to corrosion.

Another possible cause of delamination is physical ageing, particularly effects such as uptake and release of compounds with low molecular weight, post-crystallisation, reorientation of molecular chains and release of processing-related residual stress. Since delamination occurs frequently in older systems, experts consider it another result of ageing.

Chemical damage: PV cells also age chemically. When plastics react with oxygen or aggressive chemicals, their constituting molecular structure can get damaged. Oxidation is the most frequent cause of chemical ageing, including both thermo-oxidative (heat + oxygen) and photo-oxidative (UV radiation + oxygen) processes (Bittmann: Bad Staffelstein, 2007). Chemical ageing is provoked by high operation temperatures or high energy radiation. Since mainly older modules are affected, experts consider this a type of ageing as well.

2.16 Ammonia

PV modules, cables and sockets on the roofs of farm animal stables with ventilation over the roof are frequently affected by ammonia. In conjunction with high humidity in the air, ammonia forms an aggressive condensate, which can lead to the corrosion of the glazing, the connection box or the backing film. Non-metallic materials such as protective coatings and plastics are also attacked. The damage is permanent and results in loss of performance. Ammonia resistance is tested according to the IEC 62716. This standard applies to flat plate modules.

2.17 Module Frames

Modules are available with or without frames. Frames are usually made of aluminium. Stainless steel or plastic frames are also common.

A frame protects the edges of the module’s glass pane, fixes the module to its substructure and reinforces its structure.

A PV module's data sheet or installation manual must specify how to mount the module safely and without tension in accordance with the manufacturer's recommendations. The number and location of fixing points for clamping must be specified. In addition, the permissible static load ratings must be specified with reference to the RAL solar environmental load rating. A particular combination of module and mounting systems from different manufacturers may be specified if that combination has been explicitly approved (see RAL-GZ 966).

For framed modules, the frame’s shape, level and glass inset must be chosen such that even with a shallow installation angle, dirt and water cannot build up and the shadowing of cells is prevented. Rainwater and condensation must be able to drain (see RAL-GZ 966) off of the module. Otherwise water may freeze and burst the frame (“frozen frame” damage).

2.18 Module Connection Socket and Cable Outlet

One special source of faults is the cable outlet on the back of PV modules. The cables are either passed through a hole in the rear glass pane or around the module’s edges. In the first case, a connection socket is glued to the module right over the opening of the cable outlet. Moisture must be prevented from entering the connector box or the module itself. Protection class II and protection level IP 54 are required (see section 3.5).

Module sockets and connectors must be suitable for the module’s expected service life, the ambient conditions at the installation site (temperature, UV stability, etc.) and the expected voltages and currents.

Furthermore, manufacturers must construct connection sockets and cable outlets so that they withstand the electrical (up to 1,500 V), thermal, mechanical, corrosive and weather-related loads that occur during their intended use. Finally, they must not pose a risk to the user or the environment. The technical characteristics of module sockets must meet the specification in DIN EN 50548 VDE 0126-5: 2012-02 (see RAL-GZ 966, January 2008).

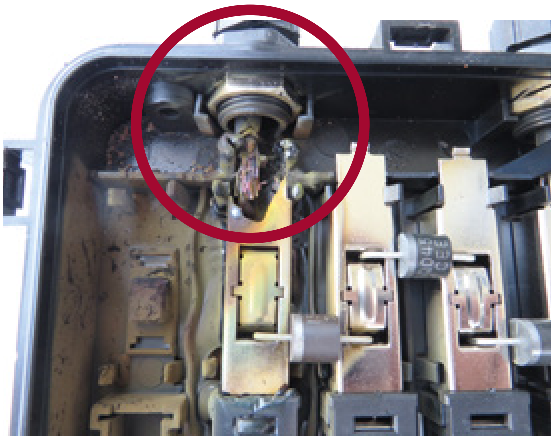


Figure 7: Electric arcs burned a cable and connector; source: PVGutachten.info

2.19 Connectors

In PV cables, currents reach up to 40 A at voltages of up to 1,000 V. So the quality of PV connectors is a prerequisite for smooth and, above all, safe operation of a PV system.

Requirements for connectors:

- high plugging, disengaging and pulling force
- should have a lock
- contact resistance even after repeated insertion
- high insulation resistance
- test finger must not be touchable when the connector is open

The standard for 'connectors for DC voltage applications in photovoltaic systems' (DIN EN 62852 VDE 0126-300: 2015-10 "Safety requirements and tests") applies to plug connectors with rated voltage of up to 1,500 V DC and rated current of up to 125 A per contact, as well as to connectors without switching capacity that can be disconnected and plugged in under voltage. The standard also applies to connectors installed in the housings of devices with an integrated PV system.

2.20 Terminal Box

The module strings in PV power plants converge on a single terminal box, that in turn connects to the inverter. The connection box contains a conductor for potential equalisation or earthing and a surge diverter. Also, monitoring elements can be installed here that respond in case faults are detected.

The terminal box must be suitable for at least the modules' service life and selected according to the ambient conditions. The basis for selection and operation is DIN VDE 100-712 and the standard for switchboards is DIN EN 61439-1 (VDE 0660-600-1 and -2).

2.21 Medium Voltage Directive of the BDEW

The so-called 'Medium Voltage Directive' of the German Association of Energy and Water Industries (BDEW) came into force in 2011. Since then, power stations with a capacity of more than 1 MWp must be certified for short-circuit resistance, continuous-current ratings and for active and reactive power as well as their control. An amendment to the directive has been in force since 1 January 2013.

An additional certificate for production units (EZE) is issued by the manufacturer. It ensures that inverters comply with all relevant regulations. The test basis for this certification is the Technical Guideline of the German Society for Wind Power and Other Decentralised Energy Sources (FGW). According to this guideline, in-

verters must not switch themselves off in the event of faults in the network. In the case of a short circuit in the public network, they must continue to provide a defined short-circuit current. Finally, a certificate is required for earthing cables with a length of more than 2 km.

The aim of these various certifications is to ensure that renewable energy systems operate in a manner comparable to a large power stations.

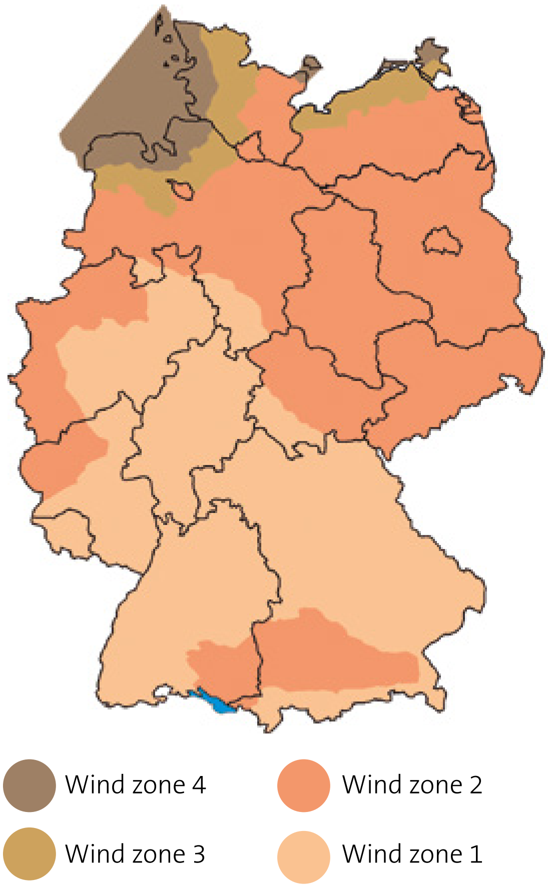


Figure 8: Wind zones according to DIN 1055-4:2005-03; source: Wikipedia, Störfix

2.22 The Impact of Wind

PV systems must withstand local wind speeds and should be constructed and installed accordingly. In Germany, wind speeds are recorded by a large number of measuring stations. For the construction industry, 10-minute-averages at 10 m above ground are provided. The relevant factor here is not wind speed itself but its resulting static pressure, a function of the square of the wind speed: when the wind speed doubles, the resulting static pressure increases fourfold.

WIND ZONES ACCORDING TO DIN 1055-4:2005-03

Wind zone	Wind speed (m/s)	Static pressure (kN/m^2)
1	22,5	0,32
2	25,0	0,39
3	27,5	0,47
4	30,0	0,56

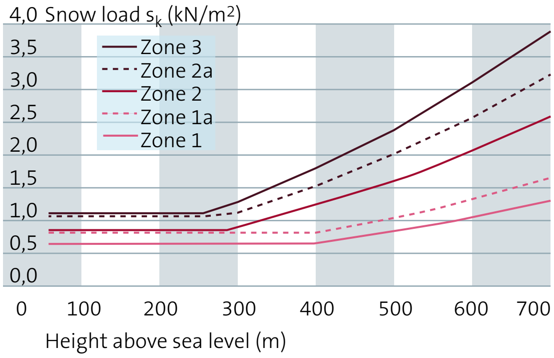
Based on this data, Germany is divided into four wind zones:

- **Terrain Category I:** Smooth and flat land without obstacles
- **Terrain Category II:** Hedges, individual farms, houses or trees, e. g. an agricultural area
- **Terrain Category III:** Suburbs, industrial or commercial areas, forests
- **Terrain Category IV:** Urban areas – at least 15% of the area is occupied by buildings with an average height of more than 15 m

2.23 Snow Load according to DIN EN 1991-1-3:2010-12

Standards in structural engineering also take snow loads into account. The snow load at a particular location is determined by the local climate and topographical altitude. A snow load map summarises snow loads for different geographic regions. These standards apply to an elevation of up to 1,500 m. For higher altitudes, the standards contain national annexes.

Characteristic value s_k for the snow load at different elevations in different snow load zones according to DIN 1055-5



The shape of a roof is an essential parameter for the snow load. The relevant equations incorporate the steepness of roofs as a coefficient, describing how fast snow will slip off. The distribution of snow loads is also influenced by the wind conditions; at high elevations snow drifts occur frequently and must be taken into account.

The coefficient is the ratio between the amount of snow on the roof and a certain amount of snowfall.

Figure 9: Snow load zones according to DIN EN 1991-1-3/NA:2010-12; source: Wikipedia, Störfix

3 Inverters

PV modules generate DC voltage, so before the generated electricity can be fed into the national grid, it must first be converted into grid-compatible alternating voltage (230 V or 400 V at 50 Hz) by a converter/inverter.

There are two types of inverters: central inverters and phase inverters (also called string inverters).

Central inverters are usually used in large plants and require an additional transformer. They feed into the grid at the medium voltage level. In terms of electrical engineering the 'medium voltage level' ranges from 1 kV to 75 kV, whereas 'low-voltage' refers to the range below 1 kV.

String inverters are available with a separate transformer but do not strictly require one. They offer the advantage of allowing modules to be connected in series. As the weakest module determines the performance of the whole string, modules are sorted according to their efficiency and those of similar efficiency are installed in separate strings. Also, all modules in a string should be of the same type and operate under the same conditions, e.g. the same roof angle or east-west orientation. Modules in strings are equipped with bypass diodes, directing current around faulty, shaded or partially shaded modules. However, in the case of a partially shaded module the bypass effect can set in quite late, in which case the shaded module will reduce the efficiency of the entire string.

Inverters, which are equipped with more than one MPP tracker (MPP = Maximum Power Point) can operate different strings. They are referred to as multi-string inverters. With multistring inverters, different module types can be installed as far as all moduls in one string have the same capacity.

Inverters also have the task of protecting the power grid and the photovoltaic plant. They are required to feature a 'device for network monitoring with two independent switching elements' (ENS). An ENS monitors frequency, voltage and impedance of the grid and is required for certification according to VDE 0126.

To ensure grid stability and to prevent the simultaneous shutdown of multiple inverters, which could potentially lead to a blackout, Germany adopted the System Stability Regulation, which was most recently amended in 2016. One of its impacts was the retrofitting of all inverters in PV systems with a capacity of more than 10 kWh, enabling a step-by-step shutdown and a 'gentle' disconnection from the grid.

3.1 Inverters with Transformer

A transformer converts a given alternating voltage to the mains voltage level. Input and output voltages are galvanically separated (electrically isolated).

50 Hz transformers inevitably incur magnetic and ohmic losses. In some inverters, high-frequency transformers are used.

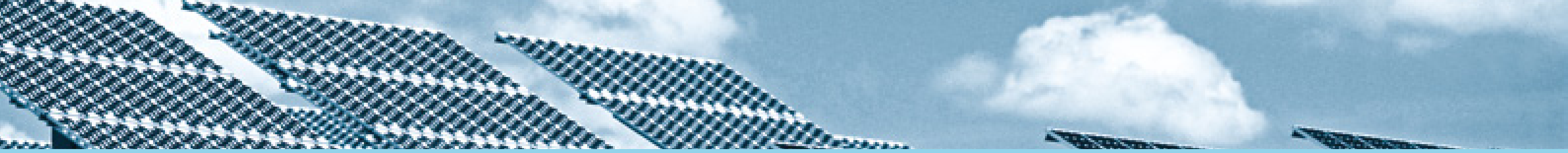
3.2 Inverters without Tranformer

A transformer is not required for systems with PV modules whose voltage is significantly higher than the peak value of the sinusoidal alternating voltage (= 325 V). Input and output voltages of the inverters in these systems are not galvanically isolated. However, these transformerless inverters must feature a DC-sensitive residual current protection circuit that conforms to the specifications of the German Association of the Electricity Industry (VDEW). As has already been pointed out above, the topology of transformerless inverters may be responsible for the accelerated ageing of the transparent layer (TCO layer).

3.3 Additional Functions

Inverters can fulfil a whole range of additional functions:

- Data collection, e.g. the temperature inside the inverter, various voltages at its input and



output, its duration of operation, the amount of electricity generated, the inverter's status and its faults

- System monitoring: error messages can be sent via SMS, fax, PC, Internet or e-mail
- Evaluation software: mostly optional, enables the evaluation of all data on a PC via a modem or computer interface
- ON and OFF switch
- MPP tracking: Solar modules deliver their maximum power at a particular current-voltage relationship. Inverters with MPP tracking search for the voltage U and the current I at which power (their product: $P = U \times I$) reaches its maximum.

3.4 Installation Instructions

Since inverters are manufactured for different environmental conditions, the manufacturer's installation instructions must be observed.

The manufacturer's instructions specify:

- Maximum ambient temperature: Inverters are often installed close to the modules. However, in non-aerated attic rooms without air conditioning, temperatures can climb up to 70 °C on warm summer days. Most inverters only allow ambient temperatures of 25–60 °C. It is not uncommon for inverters to have a minimum operating temperature of 0 °C or a maximum operating temperature of only 40 °C.
- Maximum permissible temperature at rated power. This is not always the same as the maximum ambient temperature. Inverters that exceed the permissible maximum temperature require active cooling.
- Relative humidity. The permissible relative ranges from 0 to 90%, less often to 100%.
- Installation site: Inverters are manufactured either for outdoor or indoor use.
- Behaviour at temperatures below the dew point: Inverters exposed to strong temperature fluctuations can build up condensation. Some manufacturers therefore demand that temperatures inside the inverter do not fall below the dew point. In such cases, an inverter may require heating.

3.5 IP Protection Ratings according to DIN EN 60529/IEC 529

The IP rating indicates the degree of protection of the inverter against touch, contamination and water. IP stands for 'Ingress Protection Code'. The first digit indicates the degree of protection provided by the housing against contact with live parts and against contamination. The second digit describes the level of protection against water. Outdoor inverters should at least have the degree of protection IP 54.

Codes for protection against contact – first digit (excerpt)	
IP 5x	Ingress of dust is not entirely prevented, but it must not enter in sufficient quantity to interfere with the satisfactory operation of the equipment.
IP 6x	No ingress of dust; complete protection against contact (dust tight). A vacuum must be applied. Test duration of up to 8 hours based on air flow

Codes protection against water – second digit (excerpt)	
IP x4	protection against spray water
IP x5	protection against hose water from all directions
IP x6	protection against water penetration during temporary flooding

The IP protection rating does not take ageing into account. Thus, the protection class cannot be guaranteed over the course of the housing's whole service life.

3.6 Inverter Reliability

Long-term experiences with inverters reveal that an average defect-free service time of five to eight years can be expected. On average, a repair or a complete replacement has to be carried out after ten years of operation.

Experts consider high temperatures to be one of the main causes of component failures. Older inverters can reach operating temperatures of over 90 °C. In some instances, the Institute for Solar Energy Supply Technology (ISET) measured component temperatures of more than 135 °C. At 40 °C ambient temperature, cooling elements can become as hot as 90 °C and transformer temperatures can exceed 130 °C.

During one test, temperatures of 121 °C were measured inside the inverter at an ambient temperature of 26 °C. The test report concluded: 'Temperature differences of 95°C and more will definitely reduce the lifetime of the device'.[1]

Lower operating temperatures allow a longer service life. Modern inverters made from silicon carbide semiconductors achieve efficiency rates of at least 98%. In laboratory tests, significantly lower component temperatures were measured for these newer inverters (65 °C with some manufacturers). However, it is still unclear whether their service life will reach 20 years.

Here are some examples of known causes for failures in electronic circuits during normal inverter operation:

- insufficient encapsulation of a component
- circuit-related continuous operation of a device at its load limits
- electrostatic attraction of moving conductive particles in cavities of a component causign permanent or temporary cross currents
- moving ions are attracted, causing current leakage paths
- electrolytic corrosion due to moisture, trapped during production
- condensation in cavities of enclosed components due to temperature fluctuations

Fan motors constitute a point of weakness. They have a limited service life: 100,000 hours at 25 °C are the exception. When a fan fails, the inverter may overheat and turn itself off. In a dusty environment, fan contamination may lead to premature failure. Consequently, maintenance plans should include provisions for cleaning and, where appropriate, for regular replacement of the fan(s).

3.7 Data Loggers

A data logger monitors and stores an inverter's performance data. From the stored data, a yield log can be generated. The data logger can be connected to the inverter via an RS485 interface or a Bluetooth link. Data is usually transmitted online via a PC or a mobile phone. Based on comparisons with reference data, the data logger can generate and send performance notifications by SMS or email.

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[1] Peter Funtan, Thermal Component Loads for Photovoltaic Inverters, 2001

4 Mounting Systems

Since PV modules do not have their own mounting systems, they require a structure that allows them to be mounted securely and reliably at the intended location and for the intended purpose. This mounting system must be stable enough to withstand expected snow and wind loads and it should remain corrosion-free for 20 to 25 years.

4.1 Load Effects and Mounting Systems

The design and proof of stability for a mounting system (with or without a solar generator) must be based on the effects and loads described in DIN EN 1991 (Eurocode 1) part 1–3 and 1–4 and DIN 1055 (effects on structures). For the calculation of the statics according to DIN 1055, extended load combinations $S_k + S_e$ (snow load and snow accumulation) must be considered (cf. RAL GZ 966 2008).

Mounting systems can be divided into fixed systems and tracking systems. Rigid modules are fixed to the ground or to a building structure. They can be integrated into the facade or a roof.

Typically, PV modules are mounted on roofs. Fixed systems share an orientation to the south at an angle with the horizon of circa 30°.

For flat roofs, two fixing methods are used: modules are either fixed to the roof's substructure or they are 'floated'. Floating systems are not fixed to the roof but placed into carriers such as plastic trays filled with gravel or concrete brackets. However, this method often lacks the required wind-related safety standards.

Glued laminates

Another way of mounting PV modules is laminate bonding: mounting brackets are glued to the roof's surface with a laminate composite glue without the need for drilling through the roof. When this method is used, a proof of stability (statics) should be requested. In terms of insurance, glued modules are considered a part the building itself.

4.2 Tracking Systems

The highest yield is achieved when the sunlight hits the module's surface at a 90° angle. So modules that follow the sun over the course of the day, have increased yields by up to 30% compared to fixed systems. However, production and repair of these sun-tracking systems are more costly. Furthermore, tracking systems have moving parts that are subject to wear and tear and require regular maintenance. The increased energy consumption is an additional disadvantage.

4.2.1 Single-Axis Tracking

Tracking systems are divided into single-axis and dual-axis systems. In the case of single-axis tracking, a distinction is made between vertical tracking and horizontal tracking.

In vertical tracking, the angle to the horizon is fixed as in the case of a rigid system. These systems track the sun on a vertical axis from east to west.

In horizontal tracking, the modules follow the sun's position by rotating them on an axis that is horizontal or nearly horizontal. Tracking systems

with an axis tilted by up to 20° with respect to the horizon are also offered. The advantage of horizontal tracking lies in the flat design with correspondingly reduced wind loads. This type of system is also available for smaller roof installations.

4.2.2 Dual-Axis Tracking

In the case of dual-axis tracking systems, a mechanism continuously orients the PV modules so that the sunlight always falls on the modules' surface at a 90° angle. This type of system yields the highest power output. In the case of concentrator technology, dual-axis tracking is a prerequisite. An angular accuracy of 0.1° is required.

4.3 Storm Safety

The 2007 storm Kyrill demonstrated that many PV systems are not safe from storm damage. In particular, 'floating' systems secured only by ballast, flat roof systems and tracking systems were affected. The latter systems are meant to move their modules into a horizontal position if wind speeds exceed a particular threshold (defined by the manufacturer). However, many systems did not feature this option. Other systems had already been so badly damaged by wind gusts that they could no longer be moved into the intended position. Apparently, single-axis systems are significantly less affected than dual-axis systems.

It became evident that securing PV modules with ballast alone, as is the case with floating systems, is sub-optimal. These mounting systems are not sufficiently stable. A large support surface, created, for instance, when rows of module are rigidly coupled, is a great advantage.

Severe storms such as Anatol, Lothar (both December 1999) and Kyrill with wind speeds of over 200 km/h are no longer an exception. This fact must be considered in stability calculations. The highest wind speed ever measured in Germany is 335 km/h (93 m/s), measured on 12 June 1985 on the mountain Zugspitze. This example shows that calculations for solar power plants must take local exposure into account.

4.4 Facade Systems

There are no defined standards for PV panels installed on building facades. These solar facades follow the general guidelines for glass construction. The responsible installation technician must observe all standards and approval requirements for the building sector. Diligence is of particular importance for public buildings with publicly accessible spaces in front of the facade.

There are two types of solar facades:

- vertical glazing: photovoltaic modules are mounted parallel to the wall, either directly or at a certain distance

- overhead glazing: the modules are installed at an angle as a 'canopy' and the area underneath the modules can be accessed.

With facade systems, there is a fundamental risk of glass pieces from damaged modules falling on pedestrians. In this case, the exact cause of the damage to the module is irrelevant.

5 Standard Safety Certification (Statics)

The standard safety certification is a calculation required for the fastening elements and the modules for the specific installation site. Under no circumstances should this be understood as equivalent to a building's statics.

When a PV system is installed on a building, the load-bearing capacity of the building must be recalculated. Without a special qualification, neither the installation technician nor the supplier of the system can perform this calculation. Information about the statics and the general condition of a building are required. These can either be extracted from the original statics report or determined by an architect or structural engineer, which may necessitate an on-site survey.

Issues can also arise with newer buildings as well. Under a snow load, a building whose structure was calculated according to the old DIN 1055 (valid until 2007) can quickly reach its load-bearing limits. The new DIN 1055 assumes much higher snow loads in certain parts of Germany. They range from approximately 65 kg per m^2 (0.65 kN/m^2) in snow load zone 1 to 700 kg per m^2 (7 kN/m^2) in snow load zone 3 and in locations higher than 1,000 m above sea level.

6 Cable Requirements

Cables must meet the following specifications:

mechanical strength	resistance to compression, tensile, bending and shear stress
weather resistance	UV, ozone, temperature e.g. −55 °C to +125 °C
short-circuit-proof laying	single cable with double insulation

Cables do not resist UV-A (400–320 nm) and UV-B radiation (320–280 nm) very well. As shown during a laboratory study (see project SIDENA, ISET Kassel, 2005), cables of the type H07RN-F are not resistant to ozone either. They exhibited significant damage after 24 hours of exposure. These rubber hose insulations were used in about two thirds of all PV systems until 2001.

6.1 Aluminium Cables

During the installation of aluminium cables, extra diligence is essential. Failure to comply with the specific installation instructions has been known to cause fires.

Compared to copper, aluminium has a number of disadvantages. Aluminium reacts intensely with oxygen, forming an insulating oxide layer. An exposed conductor end must be freed carefully from this oxide layer, for example by scraping with a knife (attention: files, abrasive paper or brushes must not be used!). Immediately after removal of the oxide layer, the conductor must be covered with acid and alkaline-free grease, such as technical Vaseline. This prevents a new oxide layer from forming. An ohmic resistance caused by the oxide layer can cause the cables to heat up, in the worst case resulting in fire damage.

The above procedure should be repeated when a cable is reconnected. Under a load, aluminium tends to ‘creep’: a time- and temperature-dependent deformation. Due to the retardation of aluminium, terminals must be tightened before commissioning and after the first 200 operating hours.

The terminal must have a sufficiently large surface area of contact with the cable end in order to break the fat layer and oxide layer, which may be present despite proper conductor treatment. The terminal must be approved by the manufacturer for use with aluminium cables. Unsuitable terminals have caused failures and even fires due to loose contacts.

7 Lightning Currents and Surges

Currents during a lightning discharge can be coupled into photovoltaic power stations in different ways:

- by galvanic coupling,
- by magnetic field coupling and
- by electric field coupling.

These events include:

- surges caused by atmospheric electricity (inductive, galvanic and capacitive coupling)
- switching operations of inductive and capacitive consumers (e. g. electric motors and compensating systems)
- reactions of the power grid, e. g. due to switching of power supplies or frequency converters

Galvanic coupling requires the direct injection of the lightning current into the system. When a building is hit by lightning, the current flowing into the earth usually produces a galvanic voltage.

Magnetic field coupling, also called magnetic induction, is a process by which the magnetic field of a lightning passes through a conductor loop, generating a current. Magnetic couplings can be considerably reduced by increasing the distance between the components of the PV system and the interception units and discharge lines, respectively.

Electric field coupling requires an ‘electrically effective antenna’, for example the frame of a PV module.

7.1 External Lightning Protection

External lightning protection systems generally include an interception device, a conducting ca-

ble (at least 16 mm^2 copper cable) and an earthing system (see DIN EN 62305-3 supplement 5).

The tasks of external lightning protection systems include:

- the interception of direct lighting strikes
- discharging the lightning current into ground via a grounding conductor
- distributing the lightning current via an earthing system

PV systems on buildings do not increase the likelihood of a direct lightning strike as long as they do not tower above the building by more than 1.5 m. However, if an external lightning protection is not installed, it is recommended that the PV system's metal mounting system be earthed. It is sufficient to connect the module frames and racks to the main earthing bar of the building and to connect all racks to each other. The cross section of the lightning conductor (in the case of copper wire) measures at least 6 mm^2 (see the leaflet "Lightning and surge protection" ZVEH).

If an external lightning protection system is already in place or is to be installed, the PV system must be integrated into the protection concept. The goal is to prevent lighting bolts from hitting the PV modules directly. This does not mean, however, that the photovoltaic PV system may be connected to the lightning conductor. In contrast, direct connections must be avoided under all circumstances. It is recommended that appropriate separation distances of 0.5–1 m are met. If these separation distances cannot be realised, the PV system itself must be considered a part of the external lightning protection system.

For metal roofs, metal facades, and, if applicable, metal roofing covers, separation distances are irrelevant. In this case, it is necessary to ensure suitable connections between the lightning protection system and the components of the PV system. Cables and wires should be installed with a conductive cover.

A lightning protection system is not without maintenance. Contacts may loosen or corrode. An inspection should be carried out at intervals of three to five years. As a matter of principle, a lightning protection specialist (DIN VDE 0185-305) must always be consulted. Tracking and concentrating PV plants are discussed in detail in Annex 5 of Annex B to DIN EN 62305-3.

7.2 Internal Lightning Protection

Internal lightning and surge protection encompass a set of indoor measures and devices. Lightning strikes within a radius of 1 km from a PV system have an indirect effect. Conseqently, the likelihood of indirect lightning effects is significantly higher than of direct lightning strikes. A prerequisite for the correct operation of an internal lightning protection is complete potential equalisation in accordance with VDE 0100, part 540 or IEC 364-5-54.

Inductive coupling can occur in PV modules, cables and the DC main line. In order to protect the PV system from coupling and surges in the mains line, surge arresters are installed in the terminal box. An external protection against atmospheric overvoltage can be forgone if the PV components are equipped with an appropriate surge protection (usually varistors) by the manufacturer.

Whether and how a PV plant is earthed must be decided on a case-by-case basis. Due to different requirements, no general decisions can be made. However, these examples may provide more insight:

- An earthing model is not needed for systems up to 5 kW with modules of protection class II in the case of a model for safe extra-low voltage and when the system is mounted on the ground or close to a building.
- For systems with transformerless inverters and total area of more than 10 m^2, earthing of the module frames is recommended (see DGS).

The German building regulations (LBO) differ from state to state and do not regulate the design, testing and maintenance of lightning protection systems. Instead, lightning protection is separately regulated in each German federal state. Generally, it is required for specific buildings to ensure public safety, e.g. for hospitals, meeting spaces and schools.

7.3 Earthing Systems

In accordance with Annex 5 of Annex D to DIN EN 62305-3, ground systems require a earthing system. This standard distinguishes between screw foundations on the one hand and plate, strip or circular foundations on the other. Foundations must be equipped with a foundation earthing rod with a minimum length of 2.5 m and must be connected to the concrete reinforcement at multiple points.

7.4 Standards for Lightning Protection Systems

DIN EN 62305 Teil 1–4 (Neue Blitzschutznorm) (DIN VDE 0185-305 1–4)

DIN EN 62305 Teil 3 Beiblatt 5: Blitz- und Überspannungsschutz für Photovoltaik-Stromversorgungssysteme

DIN VDE 0100 Teil 712 (Photovoltaik-Versorgungssysteme)

DIN VDE 0100 Teil 540

DIN VDE 0185 Blitzschutz

Recommended reading: Association of German Insurers (GDV):

- VdS 2010: Risikoorientierter Blitz- und Überspannungsschutz.

8 Causes of Damage and Claims Expenditure for PV Systems

EXEMPLARY STATISTICS PROVIDED BY A GDV MEMBER

Cause	Claims expenditure	Loss
Snow load	6%	6%
Surges	5%	9%
Storm events	23%	6%
Theft	9%	2%
Hail	4%	3%
Marten bites	3%	8%
Fire	18%	2%
Lightning	17%	21%
Miscellaneous causes	15%	43%
	100%	100%

IV Biomass

IV Biomass

1 Basics

Biomass

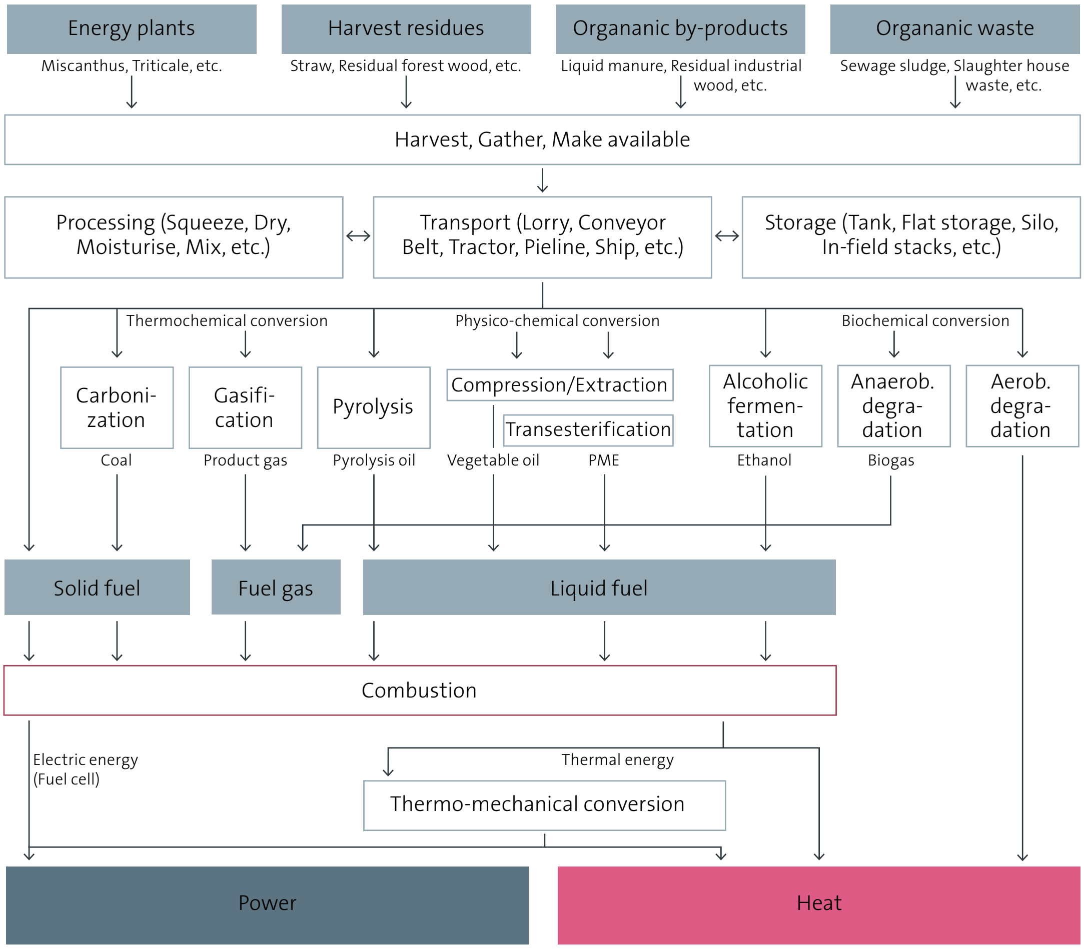
The term "biomass" refers to all substances of organic origin (i. e. carbonaceous matter). Biomass therefore includes:

- living or dead (but not yet fossil) plant and animal mass (e. g. wood, straw and flotation fats),
- the resulting residues (including animal excrements such as manure) and
- all other organic substances which have been produced by a technical conversion or which are caused by material or food use (including vegetable oil, alcohol, paper, slaughterhouse waste).

The boundary between biomass and fossil fuels runs along peat, the fossil secondary product of rotting. Peat is no longer biomass in the strict sense. This is contrary definition used in some countries (including Sweden and Finland). Here, peat is also considered biomass due to its high reproduction rate.

The processing chain for biomass is as follows:

Typical consumer supply chains for biomass energy



Source: Handbuch Bioenergie-Kleinanlagen, Fachagentur Nachwachsende Rohstoffe e. V.

Use of Vegetable Oils as Fuel

Biofuels such as rapeseed and rape oil methyl ester (RME, also known as rapeseed biodiesel) can be used as fuels in mobile and stationary engines. However, all engines must be “adapted” for biofuel usage and certified by the manufacturer.

2 Energetic Use

The heat energy released during combustion can be used for heating or for generating electricity.

Heat from Solid Biomass

Historically, culturally and economically, the production of heat from wood is of special significance. Today, most techniques for burning wood in small plants are mature and well tested. For large combustion plants however this applies only to a limited extent. While methods for the thermal utilization of other solid biomasses are available, yet extensive experience with these biomass fuels is rare.

BURNING PROCESS	
Phase 1 (drying)	The moisture moisture of freshly felled and sawn wood varies considerably. Conseqently, all wood must be actively dried sufficiently before burning. In this process water (H_2O) trapped inside he wood is released to the atmosphere.
Phase 2 (pyrolysis)	Combustible pyrolysis gas, a mixture of hydrocarbons, carbon monoxide (CO) and molecular hydrogen (H_2), is released from biomass that is heated in the absence of oxygen.
Phase 3 (oxidation)	Adding secondary air to the pyrolysis gas makes a combustible gas. During combustion heat is generated as well as water (H_2O), carbon dioxide (CO_2), nitrogen gas (N_2) and unwanted products, such as dust and nitrous oxides (NO_X). After complete combustion, ash is the only solid residual.
The 3-T rule	“Time”: Fuel particles or gases must remain in a high temperature zone (circa 750–850 °C) until they are burned. This takes 2–2.5 seconds.
	“Temperature”: Hydrocarbons (CH) and carbon monoxide (CO) have a high ignition temperature (about 650 °C). Temperatures of around 850 °C are required.
	“Turbulence”: Fuel gases do not mix in the absence of external forces. So the gas must be maintained in a swirling motion, by an adequate secondary air source with a high nozzle exit velocity.

2.1 Combustion Technology

Small-scale Systems

In Germany, the term “small-scale firing system” covers all installations from 15 kW to 1 MW, as defined in the Federal Emission Control Act. The term covers both manually loaded stoves and fully automated systems.

Small-scale firing systems can divided into installations that burn either logs, woodchips or pellets. For small-piece fuels, such as wood shavings, an injection furnace is used, which can reach a thermal output of 200 kW to 50 MW.

Generally, small-scale firing systems are distinguished based on their combustion management type:

- upper combustion
- burn-through combustion
- lower combustion

At temperatures over 1,000 °C ash turns into slag. So when firing straw or wood pellets, it is of crucial importance that the burner is water-cooled.

Installations with a movable grate are more reliable, but also more expensive. Larger biomass firing systems are fitted with inclined push grates.

Large-scale Systems

Large-scale firing systems include all installations with thermal output of 1–50 MW ($\mathrm{MW_{th}}$) and plants fired with stalk material with a thermal output of at least 100 kW ($\mathrm{kW_{th}}$). They are subject to emission regulations under the “Technical Instructions for the Protection of Air” (“TA-Luft”) and must be approved in accordance with the Federal Emission Control Act.

Biomass plants are designed to ensure a low-emission combustion, so their technology must be fine-tuned to the fuel type and to the required amount of heat.

Figure 1: Biomass power station with adjoined raw material storage; source: VGH

Fuels: Waste wood of categories A I (natural) to A IV (contaminated), driftwood, renewable raw materials and other raw materials as defined in the Regulation on Biomass (part of the Renewable Energy Sources Act). The total volume amounts to about 150,000 tons per year.

Performance data: The power plant generates 20 MW of electrical energy ($\mathrm{MW_{el}}$) all year round and has a heat output of 70 MW. The steam has a temperature of 500 °C at a pressure of 85 bar.

Figure 2: Associated delivery and processing area; source: VGH

OVERVIEW FIRING TECHNOLOGIES

Firing mode	Feed-in	Suitable biomass	Performance
preheating	mechanical	wood chips	35 kW–3 MW
underfeed firing	mechanical	wood chips + shavings	20 kW–2 MW
grate firing of wood	mechanical	wood, bark, damp fuels + high ash content	ab 1 MW
grate firing of stalk biomass	mechanical	bales of stalk material	2,5–20 MW
fluidized-bedfiring	mechanical	wood, bark, fuels + high water content	ab 10 MW
injection furnace	pneumatic	dust, wood chips + stalk material	ab 200 kW

Source: Philipp Michaels

Further information on combustion technologies can be found at: www.carmen-ev.de/biogene-festbrennstoffe/biomasseheizkraftwerke/dampfkraftprozesse/637-feuerungstechnologien

2.2 Heat and Electricity

So-called coupled generation, i. e. the conversion of energy into the various forms (electricity, heat, etc.), is one of the most important means of rational energy conversion.

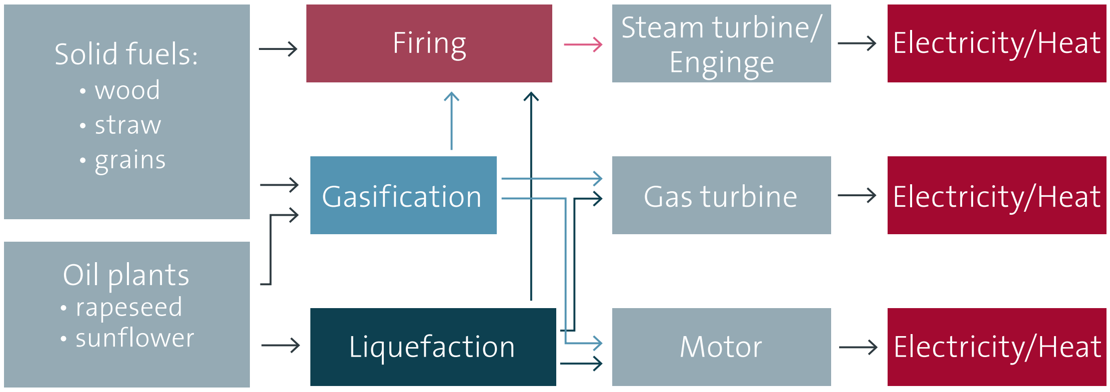
Cogeneration

(Definition according to the guideline of the Association of German Engineers, VDI 4661, www.vdi.de/uploads/tx_vdirili/pdf/2090463.pdf)

Combined heat and power (CHP) is the simultaneous conversion of energies into several target energies, i. e. mechanical or electrical energy, heat or cold, etc. These target energies are then delivered to the final consumers (see also chapter VII on biogas).

Not all combustion concepts are equally suitable for biomass and of fossil resources. Today, burning solid biomass is only a viable option in conjunction with a steam turbine or steam motors.

Applications of biomass in cogeneration



Source: Philipp Michaels

Other power and heat generation technologies (Some of these are prototypes):

Stirling processes

Stirling engines are combustion engines with an external heat supply. Gas enclosed in the engine is repeatedly heated by an external source and cooled, releasing mechanical energy to a flywheel. Both waste heat and mechanical energy can be used in various ways.

Organic Rankine Cycle Method (ORC)

The Organic Rankine Cycle process is based on a turbo generator, operating like a conventional steam turbine. Heat energy is converted into mechanical energy in the turbine. A generator then converts the turbines rotational into electrical energy. In ORC systems an instead of water, an organic liquid with a higher molecular mass is evaporated, resulting in slower turbine speeds, lower pressure, and thus in less wear on metal components and blades. On the downside, all materials, especially the seals, must be resistant to the gas phase of the organic liquid.

In a biomass combined heat and power (CHP) plant, the conversion of energy is based on the following thermodynamic cycle:

1. A heat source heats thermal oil inside a closed circuit to a high temperature, usually to about 300 °C.

2. The hot thermal oil is pumped through the ORC module. Inside the module, a heat exchanger system, consisting of a preheater and an evaporator, turns biomass material into steam.

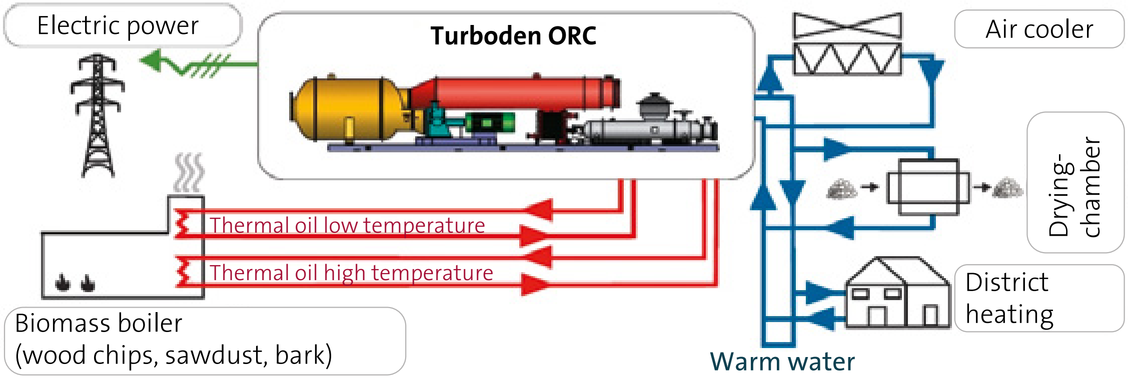
3. The organic steam expands into the turbine, turning the turbines drive shift, which in turn powers a generator.

4. The steam is then cooled by a cooling liquid in a closed circuit. The cooling liquid heats up water to 80–90 °C, which is then used for various heat-consuming applications.

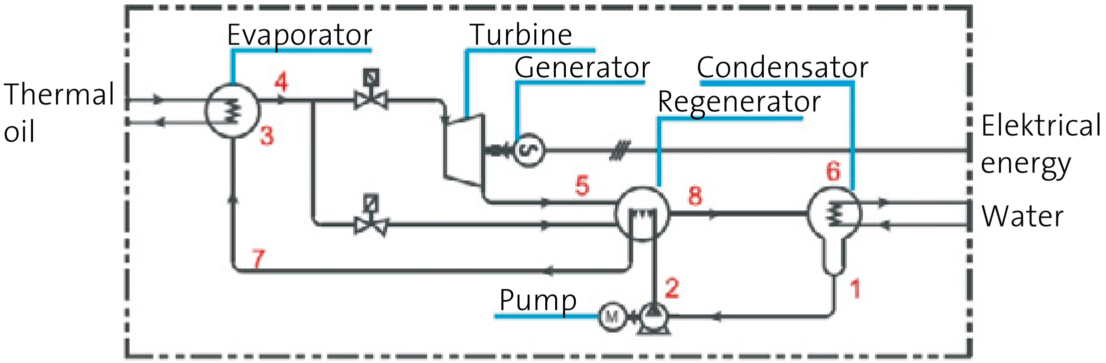
5. The condensed organic liquid is pumped back into a regenerator, closing the circuit and starting a new cycle.

Efficiency

The ORC process has good overall energy efficiency. Approximately 98% of the thermal oils incoming thermal energy is converted into electrical (20%) and heat (78%). Thanks to heat insulation, eat loss is minimal (2%).



Source: www.turboden.eu



Source: www.turboden.eu

2.3 Biogenic Solid Fuels

The availability and of biogenic raw materials and their origin are very variable. There is a large selection of fuel types, forms of preparation and material quality:

- Forest wood (thinning and harvesting)
- Wood industry (processing waste)
- Landscape conservation (residual materials from the nursing)
- Agriculture (straw and energy crops)
- Waste disposal (old and used wood)

Depending on the particular combustion technology (including filters and smoke gas cleaning), only the type of fuel approved by the manufacturer and the legislator may be used. In case of non-compliance, the combustion system (including the feeding system) and its immediate environment may suffer damage.

3 Loss Potential

The firing of wood (except old wood) in small-scale firing systems is largely a mature technology. Most today's experience with biomass as a fuel source is based on this type of type of installation.

For large-scale firing systems, a number of points must be considered:

- The firing type must match the fuel.
- The fuel composition must be known.
- Ideally, each fuel type has its own firing system.

If an inappropriate type of biomass is used, tar and sintered ash (i. e. mineral deposits) may form. Both can lead to problems with the firing system.

For the production of heat and electricity, only the classical approach of steam generation and subsequent expansion via in steam turbine or a steam engine are sufficiently developed.

Installations for gasification and liquefaction (pyrolysis) have not yet reached market maturity. In terms of insurance, they must be classified as prototypes.

In motors and turbines running on biomass fuels, complex gas purification stages must be installed in order to avoid serious machine damage. Minimum fuel requirements for the respective engines must be monitored and ensured at all times. The fuel used in a particular firing system should be approved by the original manufacturer.

Maintenance concepts and related maintenance contracts are indispensable for power plants. It is reasonable to assume that, over time, operators will move from preventive maintenance to condition-oriented maintenance. This may mean that maintenance is carried out at the last minute and that insurance is taken out for the residual risk. Suitable revision clauses, defined in advance, can provide clarity and thus make the risk more manageable for all parties involved.

In general, a detailed risk analysis is recommended, including an inspection of the facility as well as conversations with the operator, the maintenance companies and, where appropriate, with the planners and manufacturers. The contractor should be asked for certification of his experience.

Non-turnkey installations usually involve a higher cost potential due to lack of clarity with respect to liability in the event of a claim.

In light of the available damage experience, careful risk assessment is highly recommended.

These are a couple of important starting points for risk assessment:

- Project description with timeline
- Delivery contract
- Detailed description of the biomass material
- Flow diagrams for all workflows
- Operating times and full load hours
- Technical specifications of the system and all its components
- Measures planned to prevent premature wear and tear
- Safety systems

In addition, the following questions should be asked:

- To what extent is this a prototype construction?
- When will trial operations commence and how long will they take?

- Is the performance delivered as ordered?
- Has the installation been approved by an independent expert?
- Did the planner and installer provide any meaningful references?

4 Claims Experience

"Fires have already occurred in biomass power plants. However, due to the careful behaviour on the part of the operating teams, most of these fires could be detected and extinguished during an early phase. As a result, neither the plants themselves nor their environment suffered major damage or sustained disturbance. Due to the accumulation of dust with specific properties during processing and transport of biomass, the risk of creating an explosive atmosphere is increased."[1]

Examples of damage:

- Fireclay bricks may become detached or emaciated due to slag deposits.
- Slag may impede combustion and evacuation.
- Chlorine and sulfur contained in the fuel gas can lead to damage in components of the boiler system (e.g. the superheater or boiler pipes) caused by high-temperature corrosion.
- Damage to the feeding system can cause processing faults.
- Defects of the burn back protection may lead to expensive fire damage.
- Dust explosions are rare, but they can cause considerable damage.
- Stored biomass can combust spontaneously.

(For further information, see "Fire and explosion safety in biomass power plants", herausgegebenen vom VGB PowerTech e. V., www.vgb.org/vgbmultimedia/VGB_S+018+Content-p-7676.pdf)

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[1] Source: "Fire and explosion safety in biomass power plants", published by the International Association for the Generation and Storage of Electricity and Heat, VGB PowerTech e. V.

5 Conclusion

Apart from the classical use of solid fuels, their gasification could play a role in the energetic use of biomass and residual materials in the future. This technology offers an option of producing fuels from renewable energy sources. Another possible application for gasification technology is the development of CO_2-free coal-fired power plants. Almost all processes for CO_2 separation require prior gasification, allowing carbon dioxide to be separated from the fuel gas with far less effort than from solid coal.

None of the current methods of thermochemical gasification of biomass have reached market maturity. Evidence of a low-impact, durable and economic operation is not in sight. A launch date for this technology cannot be predicted, due to diverse market developments and political requirements regarding the reduction of carbon dioxide as well as for the use of biofuels (e. g. “biomass to liquid” or BTL). It remains to be seen, whether large-scale or small and medium-sized decentralized systems will be able to penetrate the market.

In addition to the technical challenges of producing clean and engine-matched fuel gas, logistical challenges (provision, preparation, storage and transport) must be considered.

6 List of Sources

Energie aus Biomasse/Grundlagen, Techniken und Verfahren (Springer-Verlag)

Handbuch Bioenergie-Kleinanlagen
www.fnr.de

Pelletheizungen
www.fnr.de

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit
www.bmu.de

Leitfaden Bioenergieanlagen – Planung und Installation, Deutschen Gesellschaft für Sonnenenergie e. V. (DGS)

Leitfaden Bioenergie
www.nachwachsende-rohstoffe.de

Rechtliche Anforderungen an Anbau und Gewinnung von Biomasse, Stiftung Umweltenergierecht, Christian Witschel

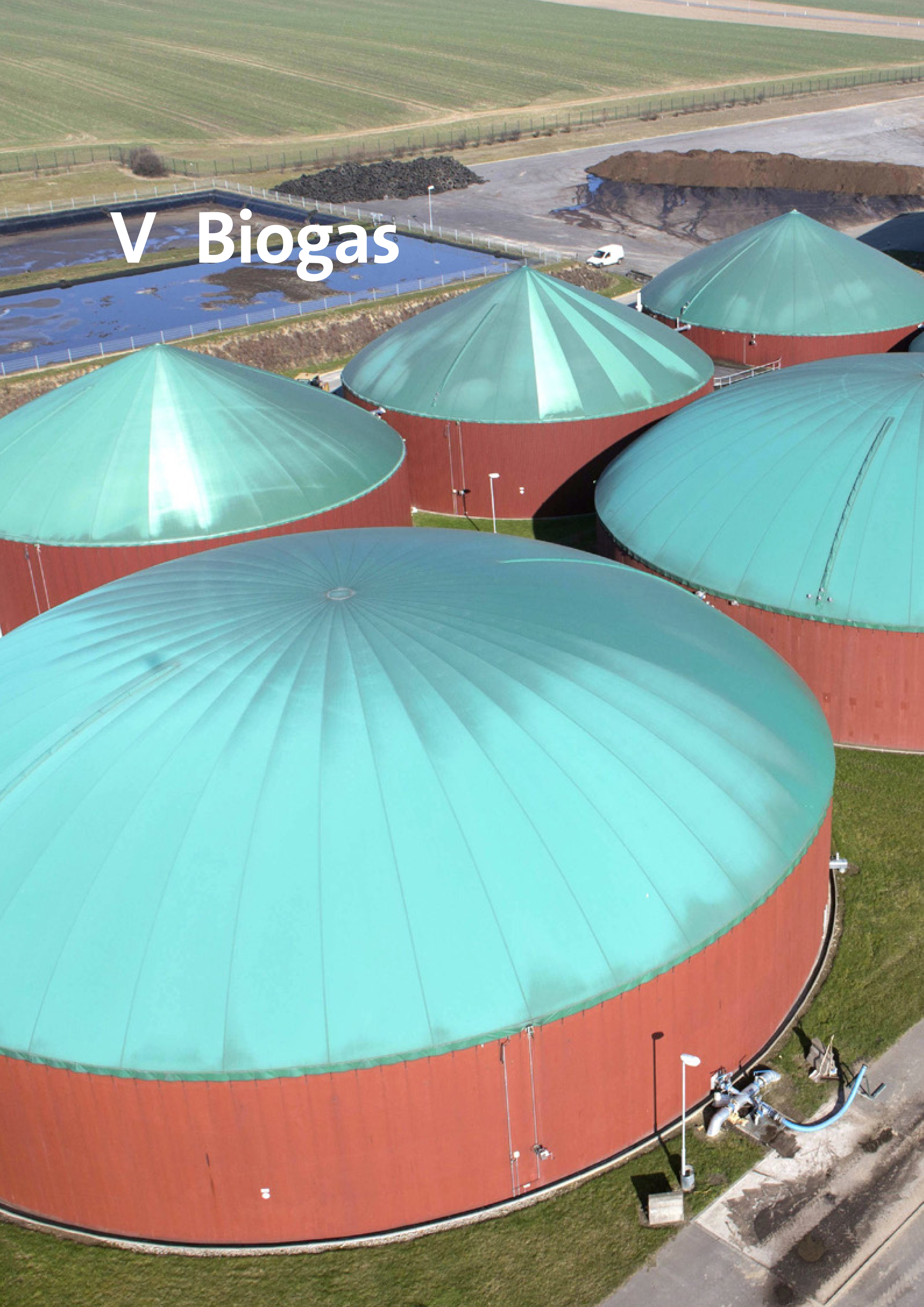
Die deutsche Biomasseverordnung
www.erneuerbare-energien.de/EE/Redaktion/DE/Gesetze-Verordnungen/biomasseverordnung_biomassev_2011.html

Altholzverordnung
www.gesetze-im-internet.de/bundesrecht/altholzv/gesamt.pdf

Europäische Normung für Biomasse-Festbrennstoffe
www.tfz.bayern.de/festbrennstoffe/brennstoffe/034721/index.php

Biogene Festbrennstoffe
www.carmen-ev.de/biogene-festbrennstoffe

V Biogas



V Biogas

1 Introduction

Figure 1: Agricultural biogas plant; source: VGH Insurance Lower Saxony

Biogas is a combustible gas produced in biogas power stations by the anaerobic fermentation (in the absence of oxygen) of biomass. In agricultural biogas power stations, waste such as dung, liquid manure or a renewable raw material is fermented.

Raw materials are biogenic substances, including:

- fermentable biomass-containing residues (sewage sludge, organic waste, food leftovers)
- farm manure (dung, liquid manure)
- plants and plant parts (catch crops, plant residues, etc.) – not used thus far
- crops planted specifically as renewable raw materials (abbreviated NawaRo in German)

The produced gas can be used for generating electrical energy to power vehicles or it can be fed into the gas supply grid. Its methane content is of central importance for the utilisation of biogas; the combustion of methane achieves the highest energy yield. Biogas is an umbrella term for energetic gases produced by microorganisms from biomaterial under anaerobic conditions:

- Sewer gas: generated during the purification of sewage
- Digester gas: produced during the digestion of sewage sludge
- Landfill gas: leaks from landfills

Fermentation Process

Biogas is produced during the natural process of microbial anaerobic (without oxygen) degradation of organic substances. Bacteria convert the constituents of biomass, i.e. carbohydrates, proteins and fats, into their main metabolic products: methane and carbon dioxide.

Further information can be found in the “Guide to Biogas – From Production to Use” (FNR) under “2. Basics of Anaerobic Fermentation”.

Composition

The composition of biogas varies considerably. It depends on the composition of its substrates and on the operational mode of the biogas power station.

Typical values in power stations using renewable raw materials.

AVERAGE COMPOSITION OF BIOGAS

Component	Concentration	NawaRo-plant: Typical values
Methane (CH_4)	50–75 vol%	53–56 vol%
Carbon dioxide (CO_2)	25–45 vol%	
Water (H_2O)	2–7 vol% (20–40 °C)	
Hydrogen sulphide (H_2S)	20–20.000 ppm	5–100 ppm for activated carbon
Nitrogen (N_2)	< 2 vol%	
Oxygen (O_2)	< 2 vol%	
Hydrogen (H_2)	< 1 vol%	

Source: Guide to Biogas (FNR)

The main component gases in biogas are methane (CH_4) and carbon dioxide (CO_2). Other components are nitrogen (N_2), oxygen (O_2), hydrogen sulphide (H_2S), water (H_2O), hydrogen (H_2) and ammonia (NH_3).

The main component in water-saturated biogas is methane with 53–56% (NawaRo). The higher the proportion of methane in biogas, the higher its energy content.

Before raw biogas can be used, water vapour content must be removed. Two other major contaminants in raw biogas are hydrogen sulphide and ammonia. They must be removed in large enough quantities in order to prevent damage to gas pipes, gas control valves, gas solenoid valves, motors and other downstream components (silencers, exhaust heat exchangers). These measures minimise hazards to humans as well as odor problems.

Combined Heat and Power Plants (CHP) with Catalytic Converters

When using catalytic converters for exhaust gas purification, the hydrogen sulphur content must be kept close to 0 ppm in order prevent damage to the catalyst. Depending on the mode of operation of the oxidation catalyst, sulphur residues may be oxidized to highly corrosive sulphur compounds that can damage the exhaust gas system (exhaust gas heat exchanger, silencer, etc.) after very short exposure. Today, catalysts are available that are fairly insensitive to sulphur.

2 Equipment Technology

2.1 Agricultural Biogas Power Stations

Figure 2: Aerial Photo NawaRo plant; source: R. Evers

Power station engineering for biogas production and utilisation is very individualised. The range of components and aggregates is nearly limitless. We recommend that an experienced planning office with references in the field of biogas plant construction conducts a case-specific examination of the suitability of the unit and system. Turnkey biogas stations designed and constructed by a single supplier (general contractor, also GU) have proven most reliable.

Clients of general contractors enjoy several advantages. The built-in components are generally highly compatible. The warranty for individual components and the system as a whole is given by the contractor. Also, successful biogas production is covered by that warranty. Liability for the completed station is usually only transferred when the power station has reached its nominal load after an inspection and approval of the station's performance. Since the risk of starting up the power station is borne by the contractor, delays in production, for instance due to a missed handover date, will not result in a financial risk for the operator. Moreover, the risk of faults with interfaces between the plant's various technical components is minimised, since general contractors usually use configurations that they already had the chance to test extensively.

There are also a number of disadvantages for the client: many full-service providers offer standardised system modules. The client has relatively little influence on the choice of the technology, which implies reduced flexibility and in some cases less than optimal quality. Reduced flexibility can make it difficult to adapt to specific operating conditions (for example, the selection of raw materials or the integration with existing buildings).

In contrast to turnkey power stations, in the case of component stations the client buys only the planning service (engineering contract). He then offers contracts for each individual building to a specialist contractor. While this approach means greater influence for the client, the client must be sufficiently experienced with biogas installations. If problems occur during start-up that lead to a decrease in performance or if an interface turns out to be faulty, the client is left to his own devices. Recourse claims must be coordinated with each respective specialist contractor individually, which proves to be problematic in the case of damage.

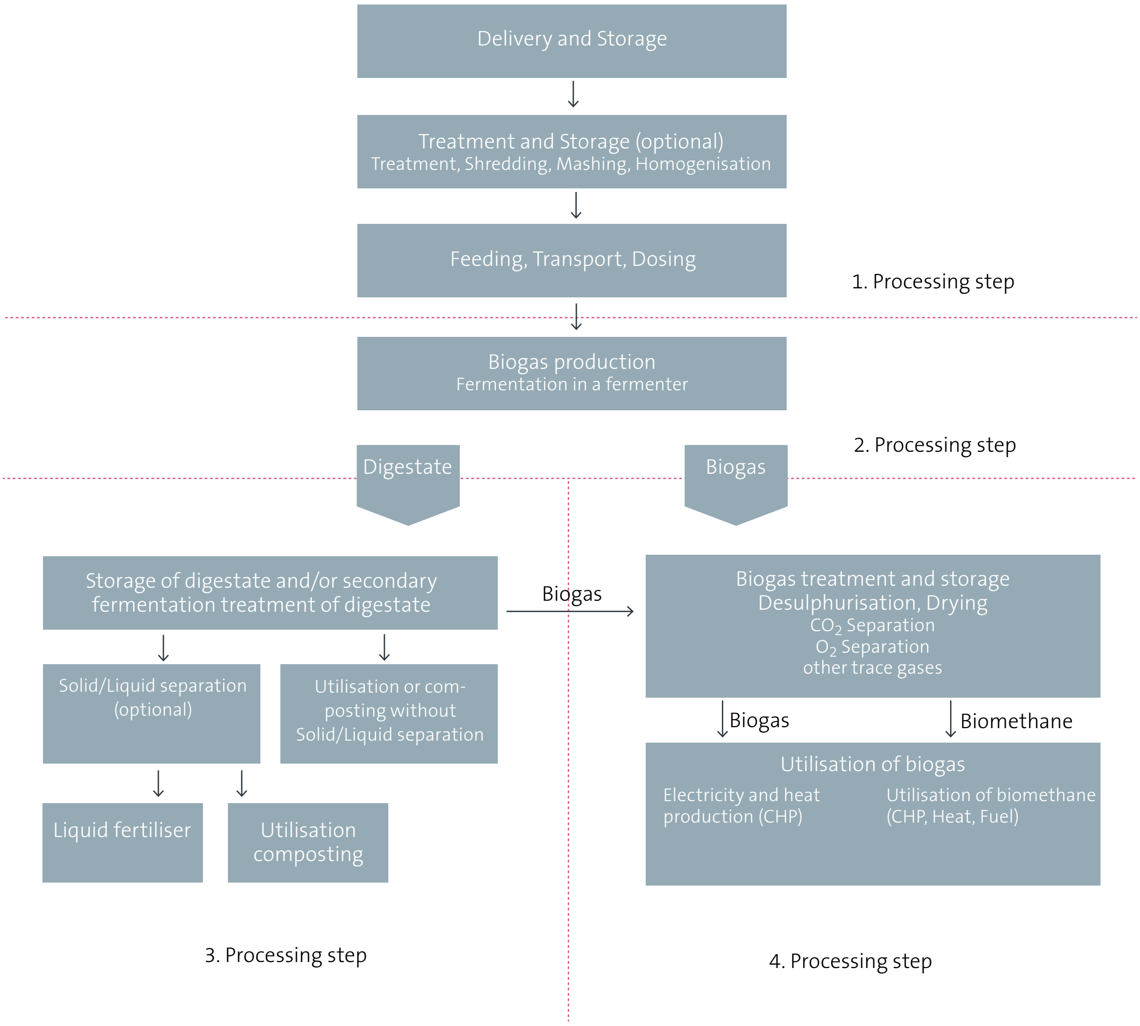
OPERATING VARIANTS

Criterion	Distinctive properties
Dry Mass Content of The Substrate	wet/solid matter fermentation
Feeding Type	discontinuous/quasi-continuous/continuous
Number of Processing Phases	one/two phases
Processing Temperature	psychrophilic/mesophilic/thermophilic

Source: Guide to Biogas (FNR)

The most common operating variant for agricultural biogas stations in Germany is wet fermentation (continuous, mesophilic) in classic circular tanks. Apart from good process characteristics, this variant ensures convenient access to all technical facilities, a very helpful feature during repairs.

General processing sequence in biogas production:



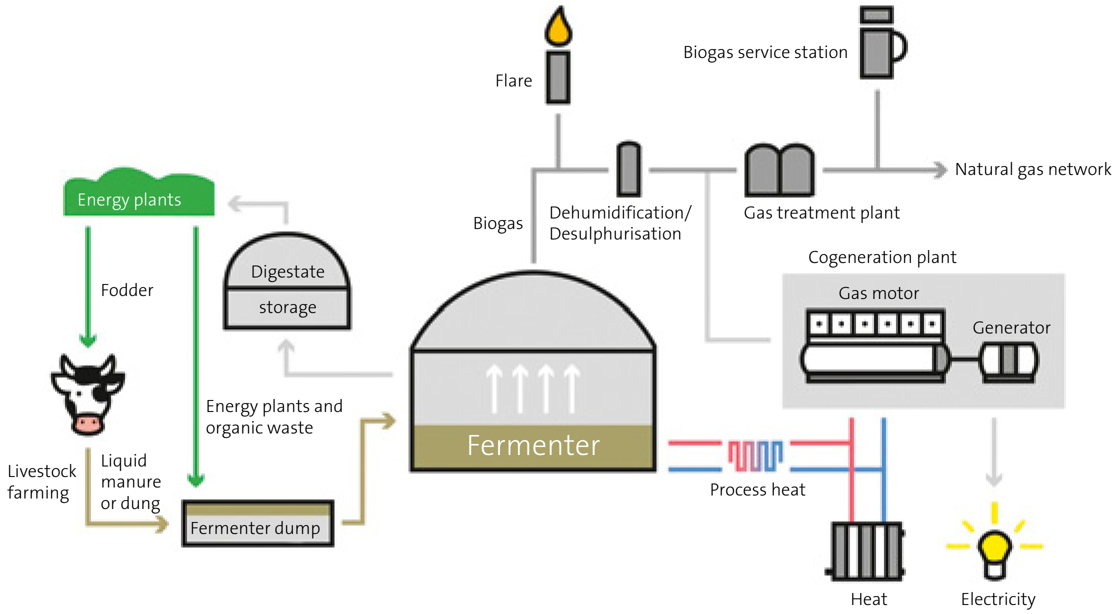
Source: Guide to Biogas (FNR)

Further information can be found in the “Guide to Biogas – From Production to Use” (FNR) under “3. Plant engineering for biogas production”, a publication of German insurers for damage prevention in VdS 3470: Biogasanlagen.

Relevant Technical and Occupational Safety Regulations

A number of power station and work safety regulations as well as legal provisions must be observed. A list of examples can be found in the “Guide to Biogas” (FNR) in Section 3.4.

Agricultural biogas power station



Source: Philipp Michaels

2.2 Biogas Treatment and Feed-in

Biogas can only be fed into the natural gas network if it achieves the quality standards described in the DVGW worksheet 260 (2-1). As part of the biogas treatment processes, the methane content is raised from 50–55% up to 98%. At the same time, carbon dioxide and other contaminants are removed. Prior to this, the raw biogas must be desulphurised and dried. As a general rule, biological desulphurisation takes place inside the fermentation tank, when appropriate by the addition of iron hydroxide/iron salts. The gas is subsequently dried and cleaned with activated carbon. This procedure is mandatory and important in order to avoid corrosive damage.

In practice, five different treatment methods are used in Germany. These include amine scrubbing, pressurised water scrubbing (DWW), physical and chemical scrubbing, pressure swing adsorption (PSA), and a membrane process. Cryogenic treatments for biogas have not yet reached the industrial level. Today, the most commonly used treatment methods are amine scrubbing and the pressurised water scrubbing.

Further information can be found in the "Leitfaden Biogasaufbereitung und Einspeisung" (FNR) (Guideline for Biogas Treatment and Feed-In).

Figure 3: Amine scrubbing for methane treatment (left); source: VGH

Figure 4: Pressure boosting station; source: VGH

3 Claims Experience

Due to the wide range of technical facilities, only the most typical types of damage will be discussed here. The following list is based on damage claims experience gained over the past 16 years. We do not guarantee its completeness.

The claims situation has so far been characterised by the following areas:

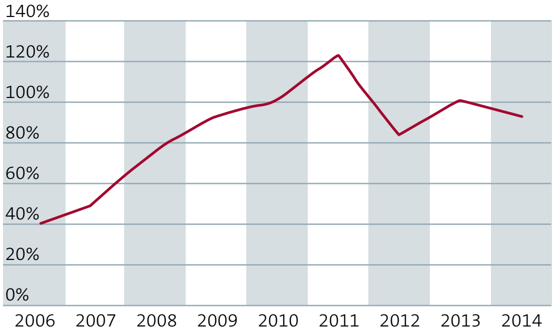
- combined heat and power units (motors and generators)
- damage to stirrers, the feed system and the roof construction

One third of losses are caused during gas production and two thirds by the combined heat and power units. Claim amounts for breakage and downtime (business interruption) range from 20,000 to 150,000 euros. Depending on the scenario, losses can reach seven-digit figures.

Rarely occurring damages include:

- Fire damage
- Explosions/bursts
- Storm damage
- Environmental damage

Claims Quotas between 2006 to 2014



Source: GDV

3.1 Gas Production

Feed System/Pumps

Depending on its origin and composition, the substrate may contain stones, tires, wood, broken tines and other foreign bodies. All of these contaminants can cause damage to any part of the feed system, e. g. the scraper floor, conveyors, gearboxes, electric motors and pumps. Repair costs also include search operations, for example, when foreign bodies are stuck in pipelines.

Damage can also occur due to inadequate maintenance. For example, when moisture or a substrate penetrates a seal, it can cause damage the gears and bearings. If the ventilation is not properly cleaned, the coils of an electric motor can blow out. If spare parts are not immediately available, the fermentation reaction can slow down the point where gas production stops altogether.

Agitator Technology

By far the highest proportion of the claims expenses in the field of gas production originates from damage to agitators. Depending on the design and type of application, this often results in downtime. Therefore, regular inspections are recommended, making the unavoidable downtimes at least more predictable. Agitators with an external motor and without a ground bearing are a sensible technical solution, as they can be completely removed and overhauled without opening the roof. If a replacement agitator is available, the process can be swiftly completed.

Submersible agitators are frequently used. These mixers are submerged in the warm substrate (~40 °C), suspended from a mount with steel or plastic cables. Usually, submersible mixers are not easy to access. Their failure is most commonly caused by wear on the propeller or on the seal of the motor, which is in turn caused by cracks in the cables or fractures on the mount.

During a major malfunction, it may become necessary for the fermenter tank to be completely emptied. Emptying, storage or disposal of the substrate involves costs and the resulting downtime will further increase these costs. The total cost can easily amount to 20,000–100,000 euros or more, in the case of a feed-in operation.

Large-blade agitators are sometimes used in biogas power stations. When these agitators need to be accessed, their tank is usually emptied to ensure personal safety in the event of a failure.

When an agitator fails, floating layers of substrate will start to form. In extreme cases, these layers can grow up to several metres thick. The floating substrate must either be mixed in again, which is time-consuming, or it must be separated and removed, sometimes even with an excavator. An agitator failure can also lead to increased concentrations of hydrogen sulphide gas in the biogas. Often, hydrogen sulphide remains undetected. However, it can cause considerable damage later on, for instance inside combined heat and power stations (over-acidification of the engine lubrication oil with subsequent damage to engines, attack on non-ferrous metals, corrosion of exhaust gas heat exchanger, etc.).


Figure 5: Defective mount; source: VGH


Figure 6: Torn propeller; source: VGH


Figure 7: Breakage; source: VGH


Figure 8: A fractured agitator; source: VGH


Figure 9: View into a tank with a surface-mounted heating system and high sediment layer. Near the upper image border, the remaining part of a large-blade agitator is visible. This tank had been in operation for seven years; source: VGH


Figure 10: Agitation of a floating layer; source: VGH

Fermenters and Tanks with Wooden Beams as a Roof Structure

Damage to roof structures due to a collapse of wooden beams is, unfortunately, no longer a rare scenario. In older power stations (older than 10 years) broken beams have been found. In all reported cases, the replacement of beams was handled within the framework of minor losses and was therefore not investigated in detail. Unfortunately, along with the frequency of such events, repair costs and downtime have substantially increased.

Even though fires and natural hazards (e.g. storms, hail, snow pressure, frost and thunderstorms) are rare phenomena, they usually involve six to seven-digit losses. Apart from these events, damage analyses have revealed the following causes of damage:

<u>Wooden beams falling into the fermenter</u>:

Often, roof beams are not supported on their substructure with a large enough area. Under these conditions, beyond a certain level of deflection, the beam will slip off the substructure, and may fall into the substrate, causing damage to the agitators and potentially the tank's heating system. Often, these events call for a complete inspection of the tank, involving long downtimes. If the substrate has to be discarded, losses are set to increase further.

Collapse of a roof structure. The joist hangers turned out to be too short.

Figure 11: Beams deflection; source: VGH

A particularly insidious type of failure is the sudden collapse of the wooden roof structure due to wood corrosion or maceration (Krause 2015). High humidity and an acidic atmosphere slowly dissolve the wooden structure. The structure becomes weaker and finally collapses (see fig. 14).

<u>Damage caused by negative pressure</u>:

Atmospheric pressure in the tank can fall below safe levels, for instance if a connected combined heat and power station pumps more biogas from the tank than the tank can produce. A negative pressure inside the tank may lead to overloading of its wooden beam structure, particularly if the

Figure 12: Short joist hanger; source: VGH

Figure 13: Sulfide deposits; source: VGH

safety equipment is not sufficient, does not respond in time, is badly designed or fails due to maintenance errors. If a part of the roof structure fails and damages the roof, oxygen will enter the tank, increasing the formation of sulphuric acid and slowing the fermentation process.

Depending on the type of power station and its size, recovery costs for this type of damage range in the higher five to six-digit figures. It is therefore recommended that wooden beam structures are examined during all regular tank inspections.

Specialists seriously question the suitability of wood as a material for the roof substructure. Hence, belt systems are being retrofitted after major crashes with increasing frequency. The used belts, especially their fittings, must be acid-resistant. Belt systems exhibit their own particular risks: belts have been caught by agitators, causing the entire roof construction to collapse.

Tarpaulin Roof/Roof Membrane

Depending on the design of the gas storage tank, the roof is either a tarpaulin or a floating dome, in which case the tarpaulin is spanned underneath the dome. Storm and hail damage are the most common causes of damage to tarpaulin roofs. Also, too much pressure inside the tank may tear the tarpaulin membrane (see fig. 15).

Corrosion of the Tank

Biomass substrates and biogas (due to its composition) can cause significant corrosion in both concrete and steel biogas tanks.

Stainless Steel Tanks

According to a recent study (see Dr. Redeker/ Dr. Kuever 2016) damage to stainless steel in the gas space of fermenters is specifically caused by sulphur-oxidising bacteria. These bacteria produce sulphuric acid in areas with sulphur deposits. If the gas space in the fermenter holds sufficient amounts of hydrogen sulphide and oxygen (O_2 approx. $> 0.5\%$ by volume), the hydrogen sulphide is oxidized to sulphur, which in turn is oxidized by the bacteria to sulphate and sulphuric acid. The relevant chemical reaction can be represented as follows:

$S + O_2$ (air dosing) + H_2O (100% relative humid biogas) $\rightarrow$ H_2S (as gas) $\rightarrow$ H_2SO_4.

This process also takes place on the walls of fermenter tanks, where the sulphuric acid dissolves the steel. A visible indication of this corrosion are yellow deposits of elemental sulphur in the gas space and the formation of black to black-brown iron sulphides as corrosion products on the steel surface. Damage analyses show that this process is most pronounced at the boundary of the gas space and the fermentation substrate.

If sulphuric acid corrosion is not avoided, the tank may start leaking gas and lose its structural integrity. This can be avoided by monitor-

Figure 14: Corrosion; source: VGH

Figure 15: Storm damage ~100,000 euros; source: R. Evers

ing the composition of the biogas and by controlling air dosing in a way that sulphur does not form and sulphur-oxidizing bacteria cannot develop or multiply. Hydrogen sulphide would then only cause slight corrosion and could be removed by biological or chemical desulphurisation treatments (source: DAS – IB GmbH, Kiel). Analysers used to monitor the composition of the biogas must be properly calibrated (see. fig. 16–17).

Concrete Tanks

In biogas power stations, concrete is subject to various stresses, two of which are essential:

- relatively weak chemical attack on the area of contact with the liquid substrate
- strong chemical attack in the gas space by biogenic sulphuric acid

The concrete used must be able to resist these chemical attacks. Therefore, concrete sections of biogas fermenters – in newer manure plants often the entire fermenter – are coated. It is recommended that only high-quality concrete is used, as the coating can be expected to have a shorter service life than the concrete itself. But even if the coating is aged or becomes damaged at some point, the unprotected concrete must then, at least for a certain period of time, be able to resist the stress from the acid and the sulphate.

It is indispensable for the durability the tank that its concrete coating is regularly inspected and repaired in a timely manner. If the concrete breaks, its reinforcement will quickly be attacked, endangering the stability of the whole structure. If a tank becomes damaged due to biogenic sulfuric acid corrosion, silage effluents can leak uncontrollably, leading to environmental damage (source: Heidelberger Beton) (see fig. 18–19).

Further information on corrosion can be found in the “Leitfaden Korrosion metallischer Werkstoffe in Biogasanlagen” (FNR) (Guidelines on Corrosion of Metallic Materials in Biogas Plants).

This container collapsed for unknown reasons. The only remaining suspected cause is a water pocket that formed on the roof. Other weather-related causes were excluded. No internal damage (vacuum, etc.) was detected.

3.2 Gas Utilisation

The bulk of the biogas produced is burned in internal combustion engines. The most common systems are gas engines with a spark ignition and diesel gas engines with auto ignition (pilot injection gas engines). Currently, these engines cause most of the expenditures for operating dam-

Figure 16: Concrete tanks; source: VGH

Figure 17: Corroded stainless steel wall after five years of operation. Damage costs: ~120,000 euros; source: DAS – IB GmbH

age in biogas power stations. We assume that some of engine types have not been adequately tested or are not robust enough for use in a biogas power station.

The following are typical causes of failure.

Defects in High-performance Engines

- broken crankshafts
- damaged valves and camshafts
- detached connecting, sometimes with partial block penetration

The least amount of damage is reported from power stations equipped with a technical drying system and a multi-stage activated carbon filter, where control maintenance intervals (according to the specifications of the manufacturer) are strictly observed. Unfortunately, this is not always the case.

Container damage caused by external forces

Figures 18–19: Dented container, damage costs: 200,000 euros; source: VGH

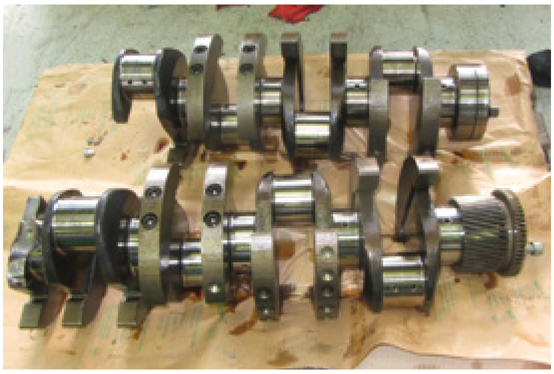


Figure 20: This crankshaft broke after 5,000 operating hours; source: VGH

Figure 21: Consequential damage to the engine block; source: VGH

Figure 22: Defective plunger; source: VGH

Figure 23: Due to a defective plunger, the camshaft had to be replaced, source: VGH

Maintenance Errors/Engine Lubrication Oil

Oils for lubrication must be approved by the engine manufacturer. In addition, operators must follow the respective manufacturer's recommendations for lubrication. In practice, many operators carry out oil analyses only sporadically. In such cases, analysis values (impurities, aging, alkaline reserve, acid number, buffer acid capacity, etc.) cannot be adequately monitored or evaluated, which can cause total failures (piston seizures, torn connecting rods) and complex overhauls early on. A large proportion of the incurred damage can be attributed to a failure to observe the engine manufacturer's recommendations for lubrication oil. In addition, damage analyses are not always optimally supported by maintenance companies (see fig. 24–26).

Maintenance Errors/Cooling Agents

Coolants too, have to be examined and replaced regularly. If a coolant is cracked, particles will form and may clog the cooling circuit. Strictures in the tubing turn into hotspots of increasing temperature that can cause serious engine damage. If combustion gases make it into the cooling circuit, coolants can become oily, resulting in damage to the seals (O-rings) of the cylinder liner. Coolants must be approved by the manufacturer. In addition, only high-quality, temperature-resistant O-rings should be used (see fig. 27–28).

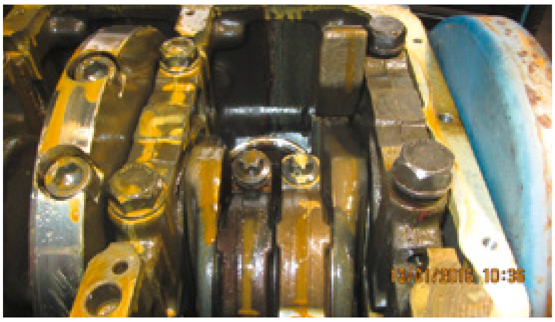
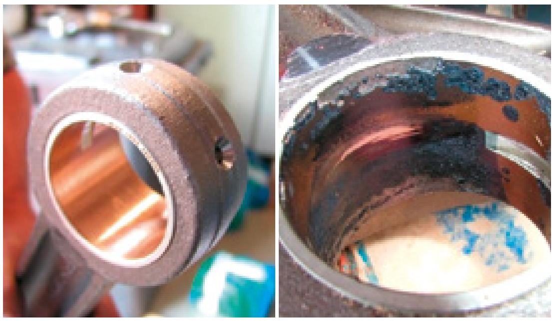


Figure 27: Coolant in lubricant oil, caused by damaged seals due to usage of the wrong coolant; source: VGH



Figures 24–25: New connection rod (left); Corroded connection rod (right); source: Image: VGH

Figure 28: Excessive rusting all over the insides of the cooling circuit due to insufficient coolant treatment; source: VGH

Figure 26: Water contamination of the lubrication oil caused cavitation damage on a crankshaft bearing; source: VGH

Figure 29: Despite warning messages the engine was restarted; source: VGH

Operating Errors

Modern power station control systems have various safety and signaling devices to ensure optimal monitoring of the engine. However, if messages are disregarded or misinterpreted, serious engine failures can easily occur (see fig. 29).

Surge Damage

Biogas power stations generally feature internal overvoltage protection systems and are well-earthed. As a result, surge damage is not a relevant issue.

3.3 Fire Damage

Fire damage as a secondary event usually occurs due to technical failure. Causes can include a (rare) container breakage, a leaking gas accumulator (rare), an engine fire (more frequent) or an electrical defect that triggers a fire (more frequent). Biogas explosions are very rare events. This is presumably due to consistent compliance with explosion protection plans.

Causes of Electric Fires

Rubbing cables and loose cable lugs can cause fires, particularly in older systems. Under-dimensioned or badly laid power cabling is another fire hazard. When a power station's performance is upgraded, under-dimensioned switchboards represent a fire risk. When biogas power stations are improperly designed and regular inspections are neglected, fire damage can range in the millions of euros.

Mechanical Causes of Fire

Leaking or rubbing fuel or lubrication oil lines can also lead to fires; the red-hot turbocharger in their immediate vicinity is as a perfect ignition source. If an oil centrifuge is located near a turbocharger, an oil leak can easily cause a fire. If, during an uncontained failure, parts get ejected from an engine, oil can ignite on the hot parts of the engine itself. Yet another fire risk is the post-combustion of unburned fuel gases in the catalytic converter. This risk can be avoided by monitoring the temperature.

Figures 30–31: Turbocharger, ~600 °C; source: VGH

Figure 32: The fire brigade at the site of an engine fire; source: Volunteer Fire Brigade of Gartow

3.4 Environmental Damage

Environmental damage caused by silage effluents or substrate from tanks does occur. Operating staff must attend regular training on relevant topics, such as the "Technische Regeln für Gefahrstoffe" (Technical Rule for Hazardous Substances, TRGS 529).

Silage effluent (more frequent)

So far, silage effluent has entered the environment exclusively from leaky storage areas (plate and side mounting/driving silos). To avoid this, safe seals and functioning restraint systems must be in place and all relevant regulations must be observed.

Figure 33: Leaked biomass/substrate; source: VGH

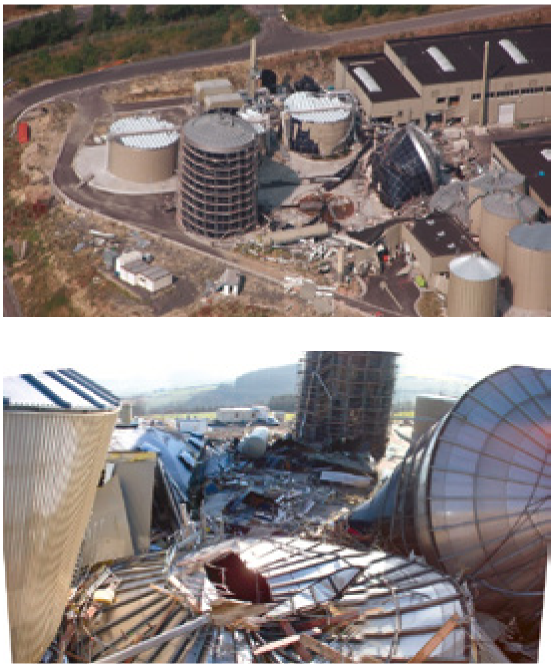
Container breakage (rare)

In most biogas power stations, tanks are circular and are made of concrete. Experience thus far shows that this type of construction is particularly robust – very few tank breakages have been reported. It remains to be seen, however, whether concrete tanks are resistant to corrosion.

Occasionally, metal tanks break (a major event). If breakage occurs during or shortly after commissioning, a fault in the material, construction or design is usually responsible. Corrosion can, in the worst case, jeopardise the impermeability and stability of the whole tank.

Shut-off valves/Extraction points (more frequent)

Leakage damage has happened after unauthorised persons meddled with unsecured shut-off valves (see fig. 33).



Figures 34–35: Tank rupture after refilling; source: www.as-nds.de

Figures 36–37: Tank rupture after commisioning; source: Thomas Warnack

3.5 Events with Major Damage

January 2006

Two fermentation tanks burst at a biogas power station for the treatment of household waste near Göttingen, Germany. About seven million litres of fermentation sludge and rainwater spread across and down the slopes of a landfill. Every third 20 m-high tank was at immediate risk of collapse. Not only the terrain but also the Schneenbach and Leine rivers were contaminated. Fortunately, there was no danger to the area's population. The bursting fermenters damaged an adjacent building and a fuel oil tank, causing about 1,000 litres of fuel oil to leak out. The damages amounted to about ten million euros. To date, the cause of this major damage event has not been identified (see fig. 34–35).

December 2007

Due to mechanical failure, a fermenter tank (20 m high and 17 m wide) broke at a biogas power station in Daugendorf near Riedlingen, Germany, creating a scene of devastation. The fermenter's biomass covered an area of up to 200 m around the power station. Some construction equipment was heavily damaged and some nearby buildings were destroyed. Hundreds of litres of fuel oil leaked from a damaged tank. This event occurred just shortly after commissioning.

The immediate damage amounted to about one and a half million euros, while the damage caused by the operations interruption was approximately one million euros (see fig. 36–37).

4 Prevention

To ensure smooth operation, we recommend that power station operators conclude a full maintenance contract with their manufacturer. Engines in particular have to meet higher maintenance requirements due to their mode of operation and the fluctuating quality of biogas. Shorter maintenance intervals and heavier wear is to be expected due to the requirements of control energy (discontinuous engine operation, partial engine runs, engine idle periods and more frequent starts).

There are several types of maintenance contracts.

4.1 Maintenance Contracts

Contracts according to VDI guideline 4688:

- inspection contract
- service contract
- repair contract
- full maintenance contract
- full service contract

In principle, service contracts for a combined heat and power station should follow VDI guideline 4680. In addition, for all technical facilities the manufacturers' and suppliers' maintenance plans must be adhered to. We recommend that the maintenance requirements in the insurance contract be made obligatory by means of a revision clause.

4.2 Tank Inspections

We recommend that containers and their technical equipment are inspected in at least five year intervals. For this purpose, the fermenter tank must be shut down, emptied and cleaned. The walls and all components of the tank can then be inspected for cracks and complete operabil-

ity can be verified. In this manner, unscheduled standstills due to technical faults, which may extend to the whole power station, can be avoided.

Inspection intervals depend on the technology used. Each regular inspection or event of damage is an opportunity for a general overhaul of the combined heat and power unit.

4.3 Thermography

Electrical switchboards

Thermography is now the standard method for examining the condition of electrical systems (feed, transformer, medium voltage system, low voltage distribution and control cabinet). Defects can already be detected and easily eliminated (e. g. loose generator terminals) during the approval phase of the plant. Thermography quickly reveals unusual transition resistances and defective components that are visible as hotspots (see fig. 38–39).

Seal test with a methane camera

Gas leaks can be visually detected with a methane camera. Further information is available from DAS – IB GmbH Kiel.

4.4 Analysis of Engine Lubrication Oil

As described in 3.2, the engine manufacturer's recommendations for lubrication oil must be observed at all times. Over-acidified and expired lubrication oil is still one of the most common causes of engine failure. In the interest of a long-life engine service life, lubrication oil should be regularly analysed and evaluated. A trend evaluation provides valuable information about the wear condition of cylinders (Fe) and bearings (Cu, Pb), the general degradation levels (oxidation and nitrification), the oil's alkaline reserve (also TBN) and its acid level (also TAN) including its PH.

If these recommendations are diligently followed, heavy engine damage can be avoided. However, practical experience has shown that this strategy has often been incorrectly applied, if at all.

See also: 3.2 Gas Utilisation – Maintenance Errors/ Engine Lubrication Oil

4.5 Lightning and Surge Protection

If prescribed by law, an external lightning protection system must be installed. An internal surge protection plan (Type 1, 2, 3) is also applicable. Protection systems require proper earthing, in-

Figure 38: Load-break switch; source: VGH

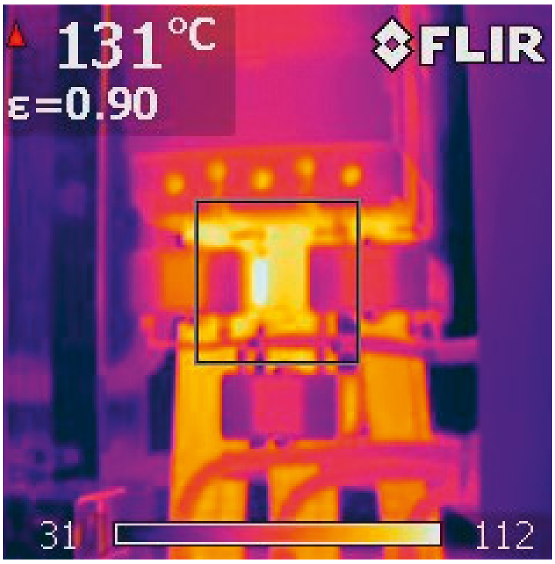


Figure 39: Infrared image of the load-break switch with regions of excessive temperature; source: VGH

cluding a TN-S network (5-wire) and a central grounding point, preferably on the transformer. Further information can be found in the documents on lightning and overvoltage protection in the current GDV/VdS publications.

4.6 Flexible Electricity Production (Discontinuous Engine Operation)

Combined heat and power stations are designed for full load operation. However, as the renewable energy sector expands, economic aspects and the technical adjustments of all other production power stations have been re-evaluated, including those for biogas power stations. Today, biogas technology must be geared towards the flexibility of electricity and heat consumption. Similar to larger gas and heat accumulators, it should be designed for safe operation with minimal wear. To allow for such a design, the recommendations of the engine manufacturer must be taken into account. For instance, at standstill all engine parts must be kept warm to avoid corrosion from condensation. Depending on the engine size, pre-lubrication and re-lubrication systems are useful. Also, any existing activated carbon gas purification system has to be adapted in such a way as to allow for the sufficient separation of contaminants during each operation period. Maintenance plans should always be adapted to the changing modes of operation.

Further information can be found in the publication VdS 3470: Biogasanlagen.

4.7 Operator Obligations

The operators' obligations are derived from:

- legal requirements
- the specific authorisation
- other official decrees

The operator's basic duty is to run his or her biogas power station properly and safely at all times. He or she must ensure that his or her plant is built in accordance with the relevant standards and technical regulations and in accordance with the rules of the EU common market (CE conformity).

For continuous operation, regular tests must be carried out in accordance with:

- water legislation (VAwS/AwSV, JGSF VO)
- §14 of the act Industrial Safety Regulation (BetrSichV)
- energy legislation
- the recommendations of the special insurers (VdS)
- the Emission Control Act (§29a BImSchG: Störfallvorsorge)

5 GDV Publications

Sources of useful information are the relevant legal and official provisions for biogas power stations, the safety regulations of the agricultural trade associations and the following GDV publications:

VdS 2000: Leitfaden für den Brandschutz im Betrieb

VdS 2010: Risikoorientierter Blitz- und Überspannungsschutz

VdS 2017: Überspannungsschutz für landwirtschaftliche Betriebe

VdS 2025: Elektrische Leitungsanlagen

VdS 2033: Elektrische Anlagen in feuergefährdeten Betriebsstätten und diesen gleichzustellende Risiken

VdS 2046: Sicherheitsvorschriften für elektrische Anlagen bis 1000 Volt

VdS 2057: Sicherheitsvorschriften für elektrische Anlagen in landwirtschaftlichen Betrieben

VdS 3470: Biogasanlagen

6 Outlook

Over the past 16 years, considerable efforts have been made toward making biogas an integral part of renewable energy production. After numerous innovations (optimisation of the biological process, improved materials, engines with higher efficiency, connection to local heating networks for a more sensible use of the engine heat, etc.), the number of newly built power stations has started to decrease. At present, the only new installations are small-scale liquid manure plants with a 75 kW output. To allow for the demand-driven feed-in of electricity, some older systems have been equipped with larger storage tanks and larger engines (500–1,000 kW). As a result of these adjustments, some suppliers have already disappeared from the market, affecting the service of existing power stations.

Today, operators of power stations face ever stricter environmental regulations (including water protection) and recurring changes to the law. It remains to be seen how biogas power stations can continue to operate economically after the Renewable Energy Sources Act (EEG) has expired – for some stations, this will occur after some 20 years of operation.

Competing forms of renewable energy, such as wind and solar, get their raw materials (wind and sunlight) for free. In contrast, sustainable biomass must be cultivated, harvested, transported and processed. Declining remuneration has an impact on maintenance and repair. At current market electricity prices, an economic operation of biogas plants appears almost impossible after EEG subsidies have ceased. Thus, presumably, many of the existing power stations will be decommissioned.

7 Conclusion

The operation of a biogas power station is subject to heavier wear than originally expected. Abrasion and corrosion make high-quality wear-resistant materials indispensable. Unfortunately, this reality is not always taken seriously enough, resulting in expensive damages. In many cases, the ideal of a largely automated, trouble-free biogas operation cannot be realised.

Combustion engines must be operated with clean and dry fuel gas and only approved lubricants. Practical experience shows that even these basic requirements are not always met. In many cases, high-efficiency engines are not inspected at the intervals specified in maintenance plans, leading to otherwise unnecessary complete overhauls at an early stage.

But even if all maintenance requirements are met, engines that are not robust enough will still suffer technical failures, such as crankshaft breaks, torn connecting rods or damaged camshafts. The selection of individual components and the experience of the installer/maintenance contractors are other important factors for trouble-free and safe power station operation. The operator of a biogas power station, however, remains the most important factor. Operating a power station requires a considerable amount of technical expertise (e. g. when observing technical rules and regulations) and thus a high degree of specialisation that cannot be acquired overnight.

8 List of Sources

Energie aus Biomasse. Grundlagen, Techniken und Verfahren, Kaltschmitt/Hartmann/Hofbauer (Ed.), Springer Verlag

Tagungsband: Biogasanlagen & Prüfungen und neueste Regelwerke/Entwicklungen am 20.09.2012 in Weimar, DAS – IB (Ed.) und weitere Tagungsbände

Tagungsband: 2. VDI-Fachkonferenz, Bedarfsorientierte Stromerzeugung aus Biogas und Biomethan am 18./19.09.2012 in Mannheim

Fachagentur Nachwachsende Rohstoffe e. V. (FNR)

Leitfaden Biogas/Von der Gewinnung zur Nutzung

Leitfaden Biogasaufbereitung und -Einspeisung

Leitfaden Korrosion metallischer Werkstoffe in Biogasanlagen

Biogashandbuch Bayern – Materialienband

Beton für das landwirtschaftliche Bauen, Heidelberger Beton

VI Fuel Cells

VI Fuel Cells

1 Fuel Cells

A fuel cell is a galvanic cell that converts the energy released from a chemical reaction of a continuously supplied fuel and an oxidizing agent into electrical energy. In other words, in a fuel cell, the opposite of the process of electrolysis takes place. In electrolysis, water is separated into its constituent parts – oxygen and hydrogen – by means of an electric current between two electrodes. As its name suggests, no combustion takes place in a fuel cell. At the most, we can speak of cold combustion. In contrast to combustion engines, a fuel cell converts chemical energy directly into electrical energy and is thus not subject to the Carnot factor, which plays a central role in conventional power generation in thermal power stations:

chemical energy ⇒ thermal energy ⇒ kinetic energy ⇒ electrical energy

Fuel cells have had an eventful history. Around 1838, electricity was generated directly from hydrogen and oxygen for the first time. The discovery initially had no practical application. In the 1960s, fuel cells were explored more intensively for applications in space exploration. In subsequent years, the technology was used on satellites and in the Apollo lunar missions. Since 2016, passenger cars, buses, etc. as well as cogeneration power stations for homes and large power stations are available in serial production. A major market launch is expected for the period after 2020.

The development goals for fuel cell remain the same:

- reducing size
- reducing costs
- increasing efficiency
- extending service life and reach
- reducing degradation (ageing)

The spectrum of potential applications for fuel cells is very diverse. Micro-fuel cells in the 1–500 W range can generate power for portable computers, telecommunication devices or mobile telephones. Most of today's fuel cells are combined heat and power (CHP) units in the range of 200–300 kW. These systems supply local heating networks or groups of buildings, hotels or hospitals. Another major type of fuel cells are mini-CHPs for individual buildings and small-scale systems with a capacity of 1–5 kW.

Numerous proposals exist for the use of fuel cells as power stations in the range of 10–100 MW. In combination with steam or gas turbines, a high overall efficiency rate is possible. In Asia, for instance, fuel cell power stations with an output of several MW are currently in operation and several more are in the planning stage.

A new practical application is hydrogen generation in electrolysers based on Proton Exchange Membranes (PEMs). As of 2016, their output reached a total of 1.25 MW. Advancements in this technology can be expected.

2 How Fuel Cells Work

All fuel cells operate based on the same basic principle: the total reaction of hydrogen and oxygen to water is separated into two catalysed individual reactions.

In a fuel cell, two electrodes are separated gastight by a semipermeable membrane or an electrolyte. Hydrogen or a hydrogen-rich gas is fed to only one of these electrodes, the anode. A catalyst layer on the anode strips hydrogen atoms of their electrons, leaving positively charged hydrogen ions behind.

This results in an electrical potential between the anode side (positive) and the cathode side (negative) of the fuel cell. In trying to cancel out this potential difference, electrons flow from the anode through an external circuit to the cathode, powering consumers in their path. At the same time, the positively charged ions migrate through the membrane or the electrolyte to the cathode side. Depending on the fuel, these will be either hydroxide ions, protons, carbonate ions or oxygen ions.

The electrode plates or bipolar plates usually consist of metal or carbon nanotubes or plates. As electrolytes dissolve, alkalis, acids, alkali metal carbonate melts, ceramics or membrane films are used.

With proton exchange membranes (PEMs), a catalyst is required on both sides of the membrane to trigger the chemical reaction. Currently, platinum is mainly used for this purpose, making the production of fuel cells quite expensive. Researchers are trying hard to find cheaper catalyst materials. The first promising results with palladium-tungsten mixtures have been reported from Sweden.

The current generating reaction with oxygen can be performed with fuels other than hydrogen, such as methane, methanol and other organic compounds.

Theoretically and under standard conditions (STC), the gross reaction can achieve a cell voltage of 1.23 V at 25 °C. However, in real cells, losses must be considered and cell voltages typically range between 0.6 and 0.9 V. An operation at about 0.7 V has proven to be a good compromise between increasing the current and decreasing voltage.

To achieve higher voltages and currents, several cells can be connected in series, in parallel, or both. Because of its shape, these circuits are called stacks.

Like any galvanic element, fuel cells produce a direct current.

3 Overview

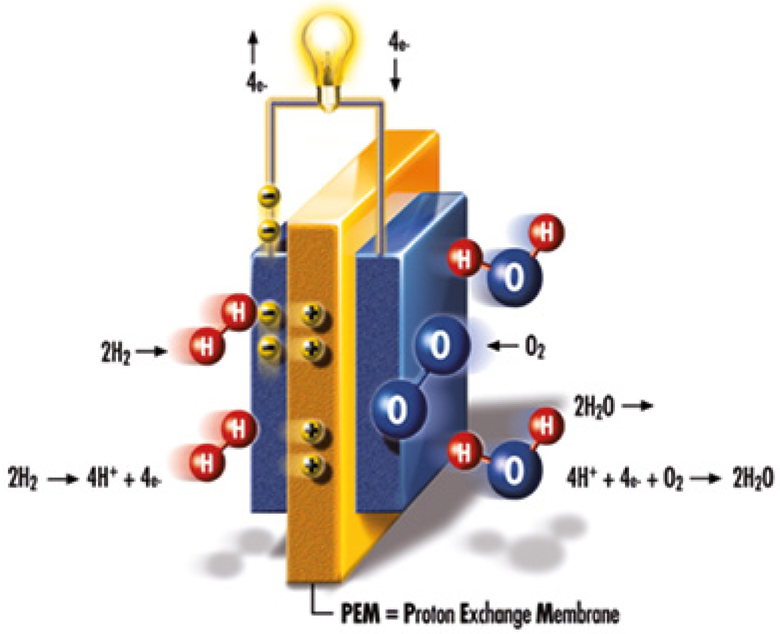
Term	Short form	Electrical efficiency (%)	Operating temperature (°C)	Electrolyte	Fuel
Polymer electrolyte membrane FC	PEMFC	35–60%	10–90 °C	polymer membrane	hydrogen
High temperature PEMFC	HT-PEMFC		HT-PEMFC 130–180 °C	polymer membrane	hydrogen
Direct methanol FC	DMFC	< 60%	60–130 °C	polymer membrane	hydrogen
Direct ethanol FC	DEFC				
Phosphoric acid FC	PAFC	38–40%	11–220 °C	concentrated liquid phosphoric acid (H_3PO_4)	hydrogen
Molten carbonate FC	MCFC	48–70%	550–700 °C	molten alkali carbonates	natural gas, methane, coal gas, hydrogen
Alkaline FC	AFC	40–60%	150–220 °C	40–60% potassium hydroxide solution (KOH)	hydrogen and oxygen
Solid oxide FC	SOFC	47–70%	440–1.000 °C	oxide ceramic electrolyte	natural gas, biogas, H_2; coal gas

FC = Fuel Cell

3.1 Polymer Electrolyte Membrane Fuel Cell (PEMFC)

In PEM fuel cells, the core of the membrane electrode assembly (MEA) is a polymer electrolyte membrane. Some MEAs consist of Nafion, a sulphonic acid tetrafluoroethylene polymer (PTFE). The PEM is coated with carbon on both sides. A catalyst made of platinum particles, palladium or a platinum-ruthenium alloy is embedded into that coating (see fig. 1 on the next page).

In PEM fuel cells, hydrogen gas reacts to the catalyst. Each hydrogen molecule is separated into a positively charged hydrogen ion (i.e. a proton) and two electrons. The excess of protons on the hydrogen side drives the hydrogen ions across the membrane into the oxygen part of the fuel cell. In contrast, the negatively charged electrons cannot pass through the membrane. This leads to a separation of charges, i.e. an electrical voltage difference between the anode and the cathode. As a result, negatively charged electrons by-



MEA: Membrane Electrode Assembly
Carbon Carrier with Catalyser

Figure 1: Electricity-producing reaction of hydrogen with oxygen; source: H-TEC EDUCATION GmbH

pass the membrane and perform electrical work on their way. At the cathode, protons, electrons and oxygen meet and combine to form water molecules, again aided by a catalyst. To remain conductive, the membrane must be kept moist.

Research publications from 2015 report a manufacturing process in which the catalyst layers are produced first. An inkjet printer prints a liquid polymer electrolyte dispersion onto the catalyst layers. Due to its initial liquid state, the printed membrane layer can better connect with the catalyst layers, allowing for the creation of a very thin membrane layer with reduced protonic resistance and higher conductivity values of 4 W/cm^2 or more.

PEM fuel cells can only run on hydrogen and oxygen/ambient air.

The properties of the three membrane layers play a decisive role for the performance of a fuel cell. The catalyst layers should have good electrical and protonic conductivity and contain as little platinum as possible due to its high cost. Membranes have strong potential for further improvement. The research focuses on the development of new polymers with high chemical and mechanical stability and high proton conductivity. At varying humidity levels, the membrane can change its spatial expansion. However, the membrane must be mechanically fixed or sealed inside a frame to prevent hydrogen leakage to the oxygen side.

The air supply, too, has a strong influence on the performance and the overall efficiency of a fuel cell. A fuel cell's specific output depends on the pressure of the supplied air. Another performance factor is air stoichiometry: the mass flow ratio of injected oxygen and consumed oxygen. The performance of the fuel cell can be significantly increased by increasing the air stoichiometry.

Wear and Tear (Degradation) on PEM Fuel Cells

Laboratories have revealed that sulphur-containing gases (SO_2, H_2S) will irreversibly damage PEM fuel cells, even at concentrations of one part per

million. Exposure to nitric oxide (NO_x) also leads to (in this case reversible) drops in voltage, but exposure to air can remedy the problem. Tests have shown that in the vehicle sector, air filters must be used to keep harmful gases and nitric oxides away from the membrane.

Many of the materials used in PEM fuel cells are exposed to extremely aggressive atmospheres. Analyses have shown that their product water contains nitric acid (HNO_3), hydrogen peroxide (H_2O_2), hydrogen fluoride (HF) and sulphuric acid (H_2SO_4). PH values well below four were detected. Impurities like these can permanently damage fuel cells.

Chemical decomposition of the membrane is another damage mechanism. PTFE membranes (PTFE = polytetrafluoroethylene, trade name: Teflon) can decompose in the presence of metal ions in hydrogen peroxide. Furthermore, at low temperatures carbon monoxide (CO) reacts with the platinum catalyst, usually resulting in its destruction.

When hydrogen is produced in a steam reformer, the resulting CO content must be reduced to below 10 ppm. The resulting ammonia (NH_3) also damages the fuel cell. Therefore, if natural gas or liquid hydrocarbons are used as fuels, a considerable technical effort in reforming these gases is paramount. Carbon monoxide can be removed from the membrane by rinsing the fuel cell with pure hydrogen.

While hydrogen diffuses through the membrane to the cathode side, nitrogen may diffuse in the opposite direction, a process termed crossover. Crossover will destroy a fuel cell. A new concept for the control of anode gas has led to a longer service life and higher efficiency (as of 2016).

Humidification

Dry membranes are not conductive. To prevent membranes from drying out, the PEM fuel cell should be sealed and gas-tight on both sides while the cell is not operating. At ambient temperatures below the freezing point, ice formation can hinder the starting ability of the fuel cell. In a nutshell, the diffusion of combustion gases must remain unimpeded. For instance, using suitable electrodes and heat sources can prevent the formation of ice.

Apart from air humidity, its purity also affects the long-term stability and efficiency of PEM fuel cells. Intense research and development efforts have gone into optimising humidification and developing filters to prevent salt mist, which can form when a car being driven.

The intended life expectancy of PEM fuel cells in combined heat and power stations is 40,000–80,000 operating hours (= approximately 10 years) and 5,000 hours in passenger cars, corresponding to a running performance of about 250,000 km.

Stationary Use of PEM Fuel Cells

There are two concepts for the stationary use of fuel cells: in combined heat and power stations with an output of 200–250 kW (analogous to a PA fuel cell), and in homes with an output of 1–5 kW (see 4. Small Cogeneration Units for Domestic Energy Supply).

High expectations are placed on the use of PEM fuel cells for small consumers, such as laptops or mobile phones. Several laboratories reported the development of PEM fuel cells the size of a credit card (1.2 V) that do not emit water vapour. This technology is based on substrate layers of fullerenes (“soccer molecules” or spherical carbon structures of C_{60} or higher), which carry the fuel gas instead of water. This greatly simplifies the design and allows for operation at low temperatures.

Summary

Degradation is an ageing process ranging from normal to premature wear due to certain operation conditions to corrosive attacks and abrasion. The literature distinguishes between mechanical, thermal and chemical degradation (see also Vogel: “Zersetzungsmechanismen von Polymerelektrolytmembranen für Brennstoffzellen-

anwendungen" [Degradation mechanisms of polymer electrolyt membranes for fuel cell applications]).

The mechanisms of degradation include:

- dissolution of platinum in water,
- water management inside the PEM fuel cell,
- corrosion of the carbon-containing catalyst carriers due to high operating voltages,
- contamination of the catalyst with impurities in the hydrogen or in the air,
- chemical degradation of ionomer materials (membrane and ionomer networks in the catalyst layer),
- membrane obstruction by foreign ions, reducing H^+ conductivity,
- mechanical stress on the membrane from clamping as well as swelling and shrinkage,
- embrittled seals and
- coalescence of platinum nanoparticles, reducing their active surface area.

3.2 High-Temperature PEM Fuel Cell (HT-PEMFC)

In high-temperature PEM fuel cells, a high-temperature resistant plastic membrane (e.g. polybenzimidazole, PBI) is used. As an electrolyte, phosphoric acid (H_3PO_4) is incorporated into the membrane. HT-PEM fuel cells operate at temperatures between 130 and 200 °C. They are more cost-effective, more efficient and also more reliable than conventional low-temperature cells.

HT-PEM fuel cells do not require water management and their gas treatment is simplified. Due to their high operating temperatures, these cells tolerate carbon monoxide very well. At an operating temperature of 160 °C, they can be operated without significant power loss in the presence of carbon monoxide. Stable operating conditions at carbon monoxide concentrations of up to 15% have been reported.

Since water management is not required, the operation of the HT-PEM fuel cell is considerably simplified. Start-up temperatures are around 130 °C. A long-term stability of more than 3,000 hours has been repeatedly demonstrated as of 2016.

The requirements for bipolar plates in HT-PEM fuel cells are:

- separation of reaction gases and cooling media,
- good electrical and thermal conductivity,
- robustness against chemical influences and
- resistance to mechanical contact pressure.

3.3 Direct Methanol Fuel Cell (DMFC)

Direct methanol fuel cells are, in principle, modified PEM fuel cells; instead of hydrogen gas, a methanol-water mix is used as fuel. This fuel consists either of methanol (CH_3OH) at a temperature of 80–90 °C or of methane vapour at 120–130 °C. The catalyst material typically is a mix of platinum and ruthenium. A methanol-water mix can be fed directly to the anode without the need for prior reforming. Carbon dioxide is the waste gas of the reaction.

DMFCs are easy to handle and refill. However, at room temperature, their power density remains far behind that exhibited by hydrogen systems. Also, the electrical efficiency of DMFCs is just 20–40%. Hence, they offer advantages only for the smallest of consumer devices.

Nevertheless, for the propulsion of vehicles, DM fuel cells are an interesting alternative to PEM fuel cells. The resistance of the noble metal catalysts (e.g. to poisoning by carbon monoxide and other intermediates) and the reliability of available membrane materials are still being studied. The aim of this strand of research is to prevent

the transverse diffusion of methanol to the oxygen (cathode) side.

In 2016, the DM fuel cell was still in its development stage. Research efforts focus on elucidating the mechanism of methanol oxidation: to improve the activity of the anode catalysts and to prevent methanol from passing through the membrane (crossover) and oxidising on the cathode, which causes losses in current and cell voltage.

By using a composite membrane developed by the Fraunhofer Institute, the crossover of methanol to the cathode can be reduced. However, methanol toxicity reduces its acceptability as a fuel (skin contact results in health risks). Furthermore, as methanol can be diluted by arbitrary amounts of water, separators, customary for gasoline or diesel, it would be ineffective in the case of leaks. On the other hand, methanol is readily biodegradable.

3.4 Alkaline Fuel Cell (AFC)

Alkaline fuel cells are low-temperature cells that usually operate at temperatures between 60 and 220 °C. The standard operating temperature is 80 °C.

AFCs use hydrogen and oxygen as fuel. The electrolyte consists of 30% potassium hydroxide solution (KOH). Air supplied to the cathode must never contain carbon dioxide. Otherwise, potassium carbonate may precipitate and clog the porous electrode. Other combustion gases may be used, provided they have been treated in suitable gas processing plants.

The theoretically possible efficiency of AFCs is 83%. Alkaline fuel cells offer great potential for development. In 2016, research mainly focussed on materials for membranes and electrodes.

3.5 Phosphoric Acid Fuel Cell (PAFC)

Phosphoric acid fuel cells use hydrogen or a hydrogen-rich gas as fuel. Concentrated and virtually water-free phosphoric acid is used as an electrolyte. The electrolyte is embedded into a matrix of silicon carbide. Together, they form the membrane through which the protons migrate. The catalyst is platinum or a platinum alloy such as platinum-ruthenium.

Using an acid as an electrolyte also allows for the use of carbon dioxide-containing gases as fuel, since carbon dioxide will not react with the acid. Thus, there is no need to separate the carbon dioxide produced during the reforming process. As a result, PA fuel cells are suitable for generating electricity from hydrocarbons. Due to their higher operating temperature of 135–220 °C, PAFCs are more tolerant to carbon monoxide (~1%) as well.

PA fuel cells are very sensitive to low temperatures. Below 42 °C, the phosphoric acid crystallises and the cell is irreversibly destroyed.

To date, PAFCs are the only kind of fuel cell that has been produced in significant quantities.

3.6 Molten Carbonate Fuel Cell (MCFC)

In molten carbonate fuel cells, the electrolyte consists of molten alkali carbonates, e. g. lithium carbonate (Li_2CO_3) or potassium carbonate (K_2CO_3). The electrolyte is chemically fixed and integrated into a highly porous ceramic matrix. These salts melt at a temperature above 200 °C. Operating temperatures are between 550 and 700 °C.

An MC fuel cell is based on relatively inexpensive materials such as nickel, nickel oxide, ceramic or steel. Due to its high operating temperature, platinum catalysts are not required – nickel and nickel oxide are sufficiently active electrode materials.

A mixture of hydrogen and carbon monoxide is fed to the anode as a fuel gas. The gas is reformed from a methane-containing energy carrier such as natural gas or biogas. The cathode is supplied with a mixture of air and carbon dioxide. The oxygen in the cathode side attaches to the carbonate ions in the electrolyte and as a group they migrate through the electrolyte. The

so-called hot anode (exhaust) gas is the real specialty of the MC fuel cell concept.

Since carbon dioxide is part of these cells' reactions, MC fuel cell are well suited for the conversion of carbon-containing fuel gases. The waste heat of the fuel cell stack is used for reforming the fuel gas into hydrogen and carbon dioxide (so-called internal reforming). MC fuel cells are, in principle, capable of directly processing diverse combustion gases (e.g. natural gas, carbonates, biogas).

Carbonate melts are highly corrosive. Carbonate melts attack many materials and the separating material between individual cells is particularly affected. Also, the cathode will dissolve even after relatively short exposure to carbonate melts. Therefore, the selection of suitable materials for MCFCs is crucial.

In 2017, the main issue with MC fuel cells is their short service life and lack of cycle resistance (cycle = heating-operation-cooling). Each start-up process reduces life expectancy by around ten percent.

3.7 Solid Oxide Fuel Cell (SOFC)

The electrolyte of this type of fuel cell is a solid ceramic material. On the anode side, oxygen reacts with a fuel gas, which can be hydrogen or carbon monoxide. Because of the reaction of oxygen with the fuel's hydrogen atoms, there is an excess of oxygen on the cathode side and a deficiency of oxygen on the anode side. This gradient allows oxygen to diffuse through the electrolyte to the anode side. The electrolyte is permeable only to oxygen ions. At the interface between the cathode and the electrolyte, each oxygen molecule receives two electrons, making it an ion, and then migrates through the electrolyte. On the anode side, the oxygen ion reacts again and releases the two electrons, generating a working current in the process.

Ceramic electrolytes made of yttrium-stabilised zirconium oxide conduct oxygen ions at temperatures of 450–1,000 °C. More modern designs using strontium- and magnesium-doped lanthangallium oxide (LSGM) allow for the operation of SOFCs at lower temperatures. These cells are called intermediate-temperature SOFC (IT-SOFCs) or medium-temperature SO fuel cells.

The anode on the fuel side generally consists of nickel oxide or nickel cermet and an electrolyte material that conducts oxygen ions. The cathode consists of ceramic lanthanum strontium manganite (also LSM), sometimes mixed with yttrium-stabilised zirconium oxide.

For the first time, a planar (flat) SOFC was able to run for 40,000 hours with an efficiency of 64% (five years of operating time) at a laboratory in Jülich, Germany. Up to 80,000 operating hours are expected for industrial applications.

Domestic applications require small plants ("BlueGen": 2 kW$_{el}$, 1 kW$_{th}$, efficiency: 60% $_{el}$ and 25% $_{th}$). In these systems, the hydrogen fuel is reformed from natural gas.

A tube concept (often referred to as the Westinghouse concept) consists of a supporting structure made of 0.5 to 1.5 m-long porous ceramic pipes, coated with anode cathode layers. The pipes themselves act as the electrolyte. Bundles of pipes are supplied with air from the inside and with fuel from outside.

The disadvantage of tube concepts is that only a small, annular surface is available for conducting electrical currents. Also, in planar SOFCs the electrode gas spaces can be more easily sealed.

Depending on the supporting structure, a distinction is made between metal-supported cells (MSC), anode-supported cells (ASC) and electrolyte-supported cells (ESC). 3-D printers, using ceramic particle ink, can realise the most diverse designs.

4 Small Cogeneration Units for Domestic Energy Supply

Between 2008 and 2012, a state-sponsored program called “Callux” supported the development of domestic combined heat and power (CHP) plants. In 2016, PEM and SO cells made for this purpose entered the market. More than 1,000 of these devices are expected to be installed annually.

These mini CHPs provide power and heat. Their hydrogen fuel is extracted from natural gas in a reformer. Depending on the manufacturer, the output of mini-CHPs ranges between 1.5 and 5 kW.

Figure 2: XellPOWER FC; source: Vaillan

5 Market Overview and Prospects

In 2016, as in previous years, the market for fuel cells was characterised by long development times and limited growth. While in 2015 the production of PEM fuel cells had more than doubled (to 180 MW) compared to 2014, the combined market for fuel cells in North America, Europe and Asia is only at 1% of the market for conventional power generation. Nevertheless, this technology is worth exploring and its development is worth observing. In addition to newcomers, established companies such as Siemens (also Siemens-Westinghouse) and GE are now beginning to enter the market.

Hydrogen generators (electrolysers) as well as storage and refuelling equipment are an integral part of fuel cell technology. Electrolysers are just as important as fuel cells themselves, particularly because their design resembles that of PEM fuel cells. Electrolysers with an output of up to 1.25 MW are now manufactured in series. These large-scale systems are intended for the production hydrogen gas from excess wind and solar energy, covering all the industrial demand while also being used for reconversion into electricity.

The production of large quantities of hydrogen increases the demand for large storage facilities. Hydrogen can be stored in both as liquid and as a gas. In its gaseous state, it is stored in tanks at a pressure of up to 800 bar. In Great Britain, large caverns are already being used as large-scale storage facilities. As of 2016, Germany has 51 gas storage facilities with a total capacity of 24.6 billion cubic metres.

Several alternative forms of storage are being investigated, including:

- metal hydride storage (a chemical compound of hydrogen and a metal)
- adsorption storage (hydrogen adsorbed highly porous materials)
- graphite nanofiber storage

List of Sources

E4tech: The Fuel Cell Industry Review 2015

Roland Berger Strategy Cunsultants (2015): Stationary fuel cells in distributed generation

Deutscher Wasserstoff- und Brennstoffzellen-verband

Netzwerk Brennstoffzelle und Wasserstoff NRW

6 Refuelling Infrastructure

The introduction of mobile fuel cells for passenger cars and busses depends on an adequate refuelling infrastructure. As of mid-2016, only 20 petrol stations in Germany, twelve of which were publicly accessible, offered hydrogen fuel. Companies including Daimler, Linde, Air Liquide, Vattenfall and EnBW, as well as the service station operators OMV, Shell and Total have devised an action plan in cooperation with the National Organisation for Hydrogen and Fuel Cell Technology (NOW). According to some participants, 100 hydrogen filling stations are to be built in the metropolitan areas of Hamburg, Munich, Berlin, Stuttgart, Rhineland and Franckfurt am Main over the course of the next four years. The planned investment totals around 350 million euros.

The hydrogen for these refuelling stations is supplied either by trucks from central production sites or – in remote locations – produced on-site by small electrolysers.

6.1 Passenger Cars

6.1.1 Market Development

Today, virtually all established car manufacturers are working on the development of fuel cell vehicles. Japanese and Korean manufacturers are the leaders in this technology. In 2013, Korea's automotive industry produced the first serially produced fuel-cell vehicle. In late 2015, Toyota presented their new fuel cell car, the production of which is expected to be ramped up to 3,000 units in 2017. Other manufacturers with serial production models are Honda and Hyundai. In 2018, as a result of current technological innovations, consumer prices for fuel cell cars are expected to drop by 43%.

In 2016, a fuel cell vehicle still cost about 45,000 euros. However, the consultancy firm Roland Berger concluded in a study of the costs of and the market outlook for fuel cell vehicles that the cost of fuel cells is likely to drop significantly by 2025. However, citing the high cost of platinum,

the authors believe that a broad breakthrough for fuel cells is far from realistic, even if production costs were reduced by 80%. The authors posit that until an alternative for platinum is found, fuel cell vehicles will remain a niche phenomenon.

6.1.2 Safety Aspects

Vehicle manufacturer's safety plans generally demand that the hydrogen tank, piping systems and valves on board a vehicle are leak-proof. Only vehicles that meet these requirements can be parked in a garage. In the event of a fire, the increased pressure inside the hydrogen tank (because of increased temperatures) must be released with a relief valve. The hydrogen released must be burned in the surrounding fire before an explosive mixture can build up.

For fuel cell vehicles, only gaseous hydrogen is used. Today in 2017, the problems surrounding the storage of gas in pressure vessels have been deemed solved. New materials have greatly reduced the loss of stored hydrogen through diffusion. Up until 2000, hydrogen tanks in the automotive sector typically operated at pressures of 200–350 bar. In 2016, typical tank pressures reached 700–800 bar. Today, tanks with pressures of up to 1,200 bar are technically possible. The latest generation of tanks (Type IV) consist of high-density polyethylene (HDPE) wrapped in carbon fibre. A complete HDPE tank system for passenger cars weighs just 125 kg. Only cylindrical tanks with spherical pole caps are used; other shapes have not been proven to be sufficiently reliable.

All tanks are equipped with pressure relief devices and melt fuses and respond to pressure and temperature. The feed-in system includes a pressure reduction valve, which reduces gas pressure from storage levels (700–800 bar) to the levels in the gas supply line, the fuel cell or the engine (0.2–0.3 MPa). If, during impact, the line is torn from the tank, only this reduced pressure in the supply line will affect the environment.

Some manufacturers also envelop the valve in a housing-like impact protection system or integrate this system into the pressure vessel itself. To keep the number of valves low and the supply lines short, manufacturers use as few tanks as possible. As a matter of principle, all piping should be welded.

The space in a vehicle where a hydrogen tank is to be installed must be vented as well as sealed and gas-tight from the vehicle's passenger compartment. In addition, vehicle hydrogen sensors are installed at the highest point in the passenger and engine compartments as well as above the tank. The drain line of the tank's overpressure relief system usually terminates in the car's underbody. This way, in the event of an emergency, hydrogen gas can be released and burned without danger of producing explosive hydrogen-air mixtures.

Tanks in commercial use in 2017 meet all safety requirements and have been approved by the TÜV. As of 2016, all the manufacturers have ceased to explore liquid hydrogen as a storage option for passenger vehicles.

All fuel cell vehicles have a lithium-ion battery that serves as an additional energy source for the electric motor. The battery can be recharged internally and externally. The combination of fuel cell and battery allows for a range exceeding 500 km. When all the hydrogen is used up, the charged battery provides for an additional 50 km of driving to find a petrol station.

6.2 Buses

In contrast to passenger cars and stationary fuel cells, Europe is the market leader in fuel cell buses. An interest group consisting of five European bus manufacturers in the cities of Hamburg, London and other municipalities is planning to produce and deploy up to 1,000 fuel cell buses by 2020. Fuel cell buses have been tested extensively, for example in the Hamburg and London metropolitan transport systems. Moreover, an "EU Fuel Cell Bus Coalition" with 83 members has formed with the aim of promoting the use of fuel cell buses.

35 transport companies from twelve countries are participating.

6.3 Forklift Trucks

In 2015, over 7,000 fuel cell-powered forklift trucks were used in the USA. In Europe, there were only 70. The retailer Walmart alone uses over 2,270 of these forklift trucks in the USA and Canada. BMW operates an estimated 400 fuel cells forklifts and 14 fuelling units at its plant in Spartanburg, South Carolina.

According to one study, around 47,000 electric forklift trucks will be used in North America by the year 2025. This number, however, includes both lithium-ion battery and fuel cell-powered vehicles. Reliable figures are not available for Europe. Various applications have been tested at the Frankfurt airport, but Germany and Europe are still at the proof of concept stage. Forklift manufacturers include Linde, Still and Plugpower/Axane (a subholding of the Air-Liquide Group).

6.4 Railway Engines with Fuel Cell Drive

Starting in winter 2017, electric railway traction units with fuel cell drive are to be operated on the Buxtehude-Bremervörde-Bremerhaven-Cuxhaven (Germany) route. The maximum speed of these trains will be 140 km/h and their range 600–800 km. The company Hydrogenics is to supply the fuel.

The regional transport companies of Lower Saxony have ordered a total of 14 trains. The federal states of North-Rhine Westphalia, Baden-Wurttemberg and Hessen have also expressed their intent to introduce this technology. The fuel cell trains are meant to replace diesel engines servicing branch lines not yet equipped with catenaries. In Germany, this currently affects more than 2,700 trains.

6.5 Stationary Installations

Japan and South Korea are pushing ahead the use of stationary fuel cell systems. Japan is a leader in domestic micro-CHPs. Around 140,000 of these units were installed in 2015. The Japanese government hopes to reach 1.4 million installed units by 2020 and 5.3 million by 2030.

Korea leads the way in power generation from fuel cell power stations. In 2016, these plants had a total estimated output of 220 MW. An additional 270 MW are planned.

In Europe, various manufacturers have attempted to sell stationary fuel cells with outputs around 0.5 MW. As of 2016, however, no manufacturer has managed to overcome small series production. Nevertheless, research and development are ongoing.

The Canadian company Ballard is building a 1-MW AFC power station at the AkzoNobel site in Bordeaux.

The Stade fuel cell power station in Lower Saxony with an expected output of 240 kW, designed by the British manufacturer AFC Energy, is nearing completion. The manufacturer has very ambitious plans: in Thailand, they are planning a 7-MW power station followed by a 50-MW power station in Korea and a 300-MW power station in Dubai by 2020.

First attempts at the commercial use of micro-fuel cells can be observed in Europe as well. For instance, nine European manufacturers currently offer micro-fuel cells for single-family homes. In the medium term, up to 10,000 units are expected to be sold across Europe. In 2015, approximately 500 units were installed as part of the “Callux” program. Within the European framework program “ene.field”, 1,000 units are to be installed throughout Europe by the end of 2017.

In the USA, a small number of manufacturers dominate the fuel cell market. These suppliers produce MC, PA, stationary and SO fuel cells in considerable quantities. It is rumoured that a single manufacturer has won a contract for SO fuel cells on the order of 40 MW or more, to be installed at 170 different sites. One average, sta-

tionary fuel cells with a total capacity of 200 MW are being produced in the USA each year.

The company FCES INC. in Connecticut is the manufacturer and operator of a 15-MW DFC fuel cell park in North America. FCES is also the supplier of the world's largest DFC fuel cell park in South Korea with a capacity of 59 MW.

6.6 Emergency Power Supply and Mobile Equipment

Fuel cells with an output of 100 W or more are ideal for supplying power in remote areas, sometimes combined with a lithium battery. New cells of this kind made by Turin Electro Power Systems will have a capacity of 2 MW per year. Possible applications range from camping to military use.

A German shipyard is currently producing a number of submarines that are powered exclusively by fuel cells.

For portable devices, low-temperature fuel cells of the PEM type (supply with hydrogen) or methanol fuel cells (see 3.3) are used.

Fuel cells are also excellent for emergency power supply. For example, Telecom India is a telecommunications company that employs 400,000 diesel generators and batteries all over India for USV emergency power supply. As an alternative, the company examined hundreds of methanol fuel cells in a recent field test.

In Japan, Kawasaki City Airport will be supplied with electricity by a system consisting of photovoltaics (30 kW), USV batteries (350 kWh), electrolysers, hydrogen, water and fuel cells.

6.7 Large-Scale Electrolysers

The design of PEM electrolysers is identical to that of PEM fuel cells. In a proton exchange membrane, distilled water is split into hydrogen and oxygen by an electric current. The cathode side is coated with a porous electrode made of carbon and platinum as a catalyst. In addition, the PEM cell contains a gas diffusion layer (also GDL). On the anode side, this layer is coated with carbon and precious metals such as iridium and ruthenium. The active cell area is 1 m^2 and up.

An external current voltage is applied to the electrodes and distilled water is supplied on the anode side. The catalytic effect of the embedded metals leads to the break-up of the water on the anode side into oxygen, free electrons and positively charged H^+ ions. The ions (protons) diffuse through the membrane into the cathode side, where they capture free electrons (from the applied current) to form hydrogen. The membrane is gas-tight and allows for pressures of 100 bar and more. 10 litres of demineralised water yield one kilogram of hydrogen.

Each year, more than 600 billion cubic meters of hydrogen are produced worldwide, with more than 95% produced from a reformed carbon dioxide-intensive gas. Hydrogen produced from water and regenerative energy sources therefore has the potential to become a key element of sustainable electricity generation. Boston Consulting estimates that by 2030, over 150 billion euros will be invested in large-scale industrial carbon dioxide-free hydrogen generators.

Hydrogenics in the US, AREVA H_2Gen in France and Siemens in Germany rely on PEM electrolysis (e. g. for power-to-gas systems) to produce hydrogen. In contrast, Nel Hydrogen uses alkaline pressure electrolysis.

Electrolysers are suitable for high current densities and respond to mains fluctuations within seconds. Therefore, they offer the capability of absorbing excess energy from the electricity grid.

The produced hydrogen can be reconverted into electricity by PEM fuel cells or by gas turbines. The electricity is fed into the medium or high voltage network. Alternatively, the hydrogen can be made available as a basic raw material or as fuel for fuel cell vehicles. PEM electrolysers can produce hydrogen "on-site", at petrol stations for instance, without the need for long transport routes.

The potential future applications of hydrogen include:

- energy storage, particularly the storage of electrical energy from photovoltaics and wind,
- reconversion into electrical and thermal energy in fuel cells at a total efficiency of 90%, e. g. for network stabilisation and
- as fuel for fuel cell vehicles with local electrolysis.

In early 2017, the world's largest electrolysers to date were installed at the Energiepark Mainz. It has a capacity of 1.25 MW per stack, storage pressure up to 35 bar and a production rate of 225 standard cubic meters per hour. Beginning in 2018, large-scale electrolysis systems with 50 MW and more will be available.

Figure 3: At the Energiepark in Mainz (Germany) an electrolysis system based on PEM cells is installed. The plant has a capacity of 1.5 MW and produces between 60 and 90 kg of hydrogen per hour. The electrolysers are designed for a service life of 80,000 hours (≙ 10 years); source: Energiepark Mainz

7 Outlook

Until 2020, a significant increase in the production of fuel cell-powered automobiles and buses is to expected. During the same period, California's Air Resources Board expects to see more than 18,000 fuel vehicles on the world's roads. Other sources estimate about 35,000 vehicles – a Japanese manufacturer alone is planning to sell some 30,000 vehicles.

A public initiative in Japan appears realistic to be realistic; by 2020, around 40,000 fuel cell vehicles are to be approved and 160 hydrogen fuel stations to be put into operation.

In the power station sector, an increasing number of nuclear and coal-fired power stations are being shut down, opening up new market opportunities for fuel cell power stations. Public financial support has had a great influence on the realisation of fuel cell projects. However, this support is volatile, so market forecasts are necessarily uncertain and vague.

Regulations, Internet, Platforms and Literature

In October 2014, the European Commission published the "Alternative Fuels Infrastructure Directive" (2014/94/EU). In the future, updated ISO standards for the hydrogen sector, derived from this directive, are expected to be enforced. These standards will relate to the design of hydrogen filling stations, the hydrogen refuelling protocol, the geometry of the hydrogen filling nozzles and the quality of hydrogen gas. The requirements detailed in the directive are expected to be legally binding in the relevant member states by 2020 at the latest.

Further information

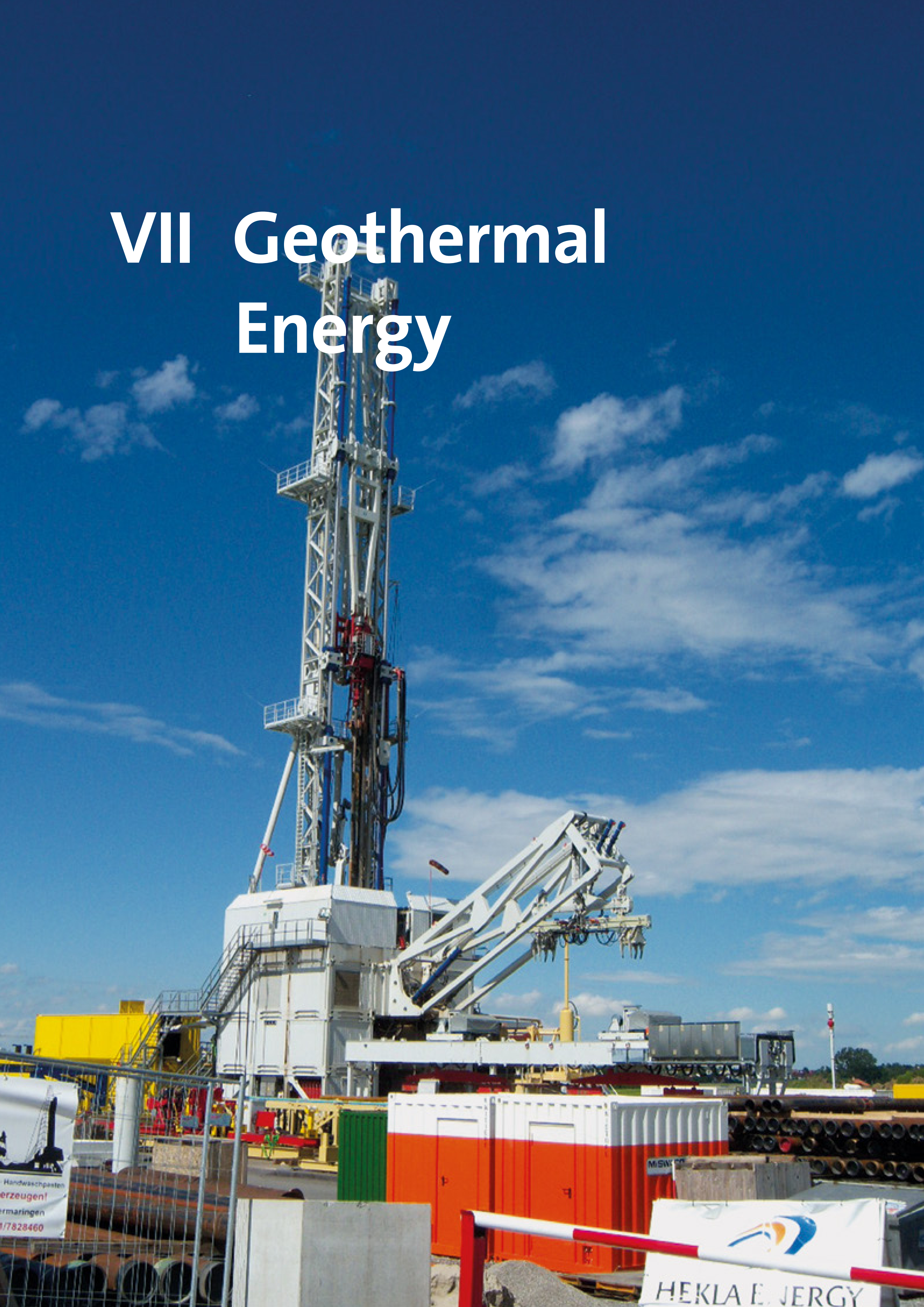
www.now-gmbh.de
Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie

www.eihp.org
European Integrated Hydrogen Project

Töpler/Lehmann: Wasserstoff und Brennstoffzelle, Verlag Springer Vieweg

Vogel: Zersetzungsmechanismen von Polymerelektrolytmembranen für Brennstoffzellanwendungen

VII Geothermal Energy



VII Geothermal Energy

1 Energy Potential

The thermal energy stored inside the earth is inexhaustible for human standards. It is available regardless of the time of day, season or climatic conditions. The technologies that exist today make the use of geothermal energy possible practically everywhere.

The deeper we go into the earth's interior, the warmer it gets. Today, we know that in the layers that are closest to the earth's surface, the temperature increases by roughly 3 °C per 100 m. According to the newest research, the earth's mantle has a temperature of 1,300 °C, and the earth's core is likely to be as hot as 5,000 °C. On the earth's surface, temperatures are almost exclusively determined by the sun. Since soil is a bad heat conductor, the heat from the sun cannot be detected at depths below 20 m.

Energy Stored in the Earth's Crust

Usually, human consumption of geothermal energy relies on the heat stored in rock or fluids (water or steam).

STORED GEOTHERMAL ENERGY AND WORLD ENERGY CONSUMPTION

Geothermal Energy (up to 3,000 m worldwide)	43×10^{24} joules
85% at T < 100 °C	36×10^{24} joules
World Energy Consumption (1987)	0.3×10^{21} joules/a
40% at T < 100 °C	0.1×10^{21} joules/a

If we compare the amount of geothermal energy stored in depths up to 3,000 m to the world's energy consumption, any worries about the world's energy supply appear unwarranted. Even with present-day drilling technologies, the energy stored in the earth's surface alone could meet the energy demand of humanity for the next 100,000 years. However, this idea is too simple; indeed, it's a fallacy:

- Only some of the heat stored inside the earth is usable.
- 85% of the geothermal energy at these depths exists at temperatures of less than 100 °C.

Even though at least 40% of world's energy consumption requires temperatures at this level or below, only consumers who have specific demands can actually use geothermal energy.

Among renewable energies, geothermal energy occupies a special position because of its properties: it is available day and night, regardless of the weather. Therefore, geothermal energy is a base load energy.

2 Types of Usage

Harvesting the earth’s thermal energy requires a means of transport, i. e. a medium such as steam, water or brine. We can distinguish types of usage based on whether a medium for transporting thermal energy is already present in the ground or needs to be injected. The following list is a selection of possible systems with fluid boundaries:

Petrophysical systems	use of energy stored in stone, e. g.		magma bodies
			Hot Dry Rock (HDR)
Hydrothermal systems with high temperatures	zones with high-pressure water steam systems hot water systems		
Hydrothermal systems with low temperatures	aquifers (aquiferous layers in the subsoil) with	hot water (> 100 °C)	thermal springs (> 20 °C)
		warm water (400–100 °C)	
		low-temperature water (25–40 °C)	
Surface geothermal systems (temperatures < 25 °C, depths < 400 m)	ground collectors geothermal heat probes groundwater drilling		
Other types of usage	deep geothermal probes (> 400 m) energy piles, concrete elements in contact with the ground seasonal storage aquifer store heat in mines and tunnels		

2.1 Near-Surface Geothermal Energy

In Germany, the average ground temperature near the surface varies between 7 and 12 °C. At a depth of approximately 10 m it hovers nearly constantly around 10 °C. Beyond that, towards the centre of the earth, it steadily increases at a rate of about 3 °C per 100 m. But even these relatively low temperatures can be exploited by small and medium-sized decentralised heating and cooling systems:

- single or multi-family houses, residential blocks, building groups
- public buildings such as administrations, hospitals, schools
- commercial enterprises, etc.

The use of near-surface geothermal energy is regulated in VDI 4640 “Thermische Nutzung des Untergrunds” (“Thermal utilisation of the subsurface”).

Since temperatures between 7 and 12 °C are too low for direct heating, ground-coupled heat pumps must raise them to the required levels (35–55 °C). For this purpose, the immense geothermal energy potential is exploited via geo-

thermal collectors, geothermal probes, groundwater fountains or concrete piles. In Germany, about 50% of all heat pumps are installed on geothermal probes, approximately 10% use groundwater. The remaining 40% use air as a heat medium and are not considered to be geothermal energy systems. By operating a heat exchanger in reverse, cooling can be provided during hot weather.

2.1.1 Operating Principles of Heat Pumps

In principle, a heat pump is an aggregate that absorbs heat energy at low temperatures and emits it at higher temperatures with the help of drive energy (mechanical energy or higher temperatures). The heat pump allows for the harvesting of geothermal energy near the earth's surface for heating purposes; heat is extracted from the earth at temperatures of about –5 to +10 °C and released for heating at about 35–55 °C. The lower the difference between temperatures (e. g. from 0 to 35 °C), the lower the required drive energy, i. e. the higher the energy efficiency.

In practice, heat pumps operate as a loop. A medium with a low boiling point at a low temperature is evaporated by adding heat. The resulting gas is then compressed and thus further heated with a compressor (up to 20 bar). This high-pressure medium then emits its thermal energy (heating water or an air stream). Below a certain temperature, it condenses and enters the part of the loop with low pressure through a throttling element (capillary tube, expansion valve). Here, it is again fed into the evaporator and the cycle starts all over again.

Most heat pump compressors are electric motors. For larger units (> 100 kW heating capacity), compressors powered by a gas or diesel engine are available.

2.1.2 Groundwater Heat Pumps

Depending on the location, groundwater can be fed directly to the heat pump from a well. However, the water must also be fed back into the ground. Therefore, in addition to an extraction well, a discharge well needs to be set up. Groundwater heat pumps can use heat sources of relatively high temperature. They prevent heat exchange losses in the ground with favourable effects on the heat production performance. In larger power stations, these systems are economically superior to geothermal probes.

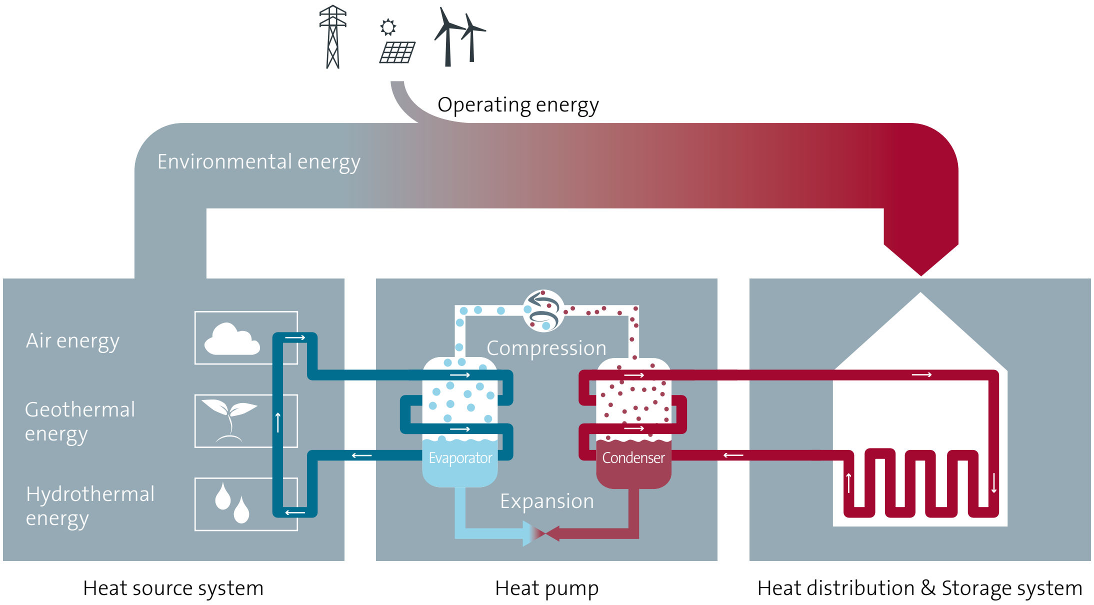


Figure 1: Working principles of Heat pumps; source: Bundesverband Wärmepumpe (BWP) e. V.

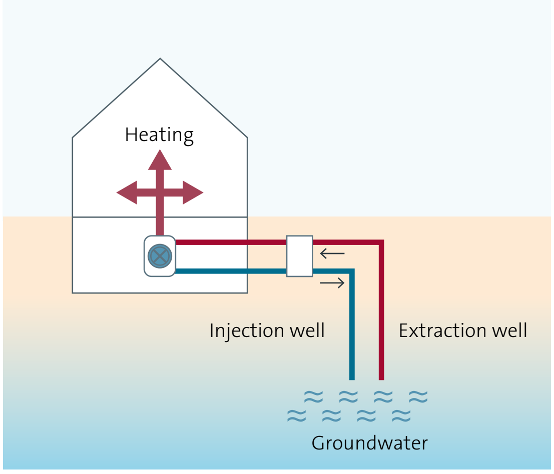


Figure 2: Groundwater heat pumps; source: ERGO

2.1.3 Geothermal Heat Collector

Geothermal collectors are usually laid horizontally, similar to a floor heating system, and typically at depths of 80–160 cm. In a closed pipe system, a water-glycol mixture is circulated as a heat transport medium. This medium takes up the ground's heat (stored from solar radiation and rain) and transfers it to the heat pump.

The use of geothermal heat collectors requires a sufficiently large area (~200–250 m^2 for a single-family house) and is influenced by the surface weather. Therefore, when coupled with a geothermal collector, a heat pump must deal with particularly unfavourable heat source temperatures during periods of high heat demand (i.e. in winter).

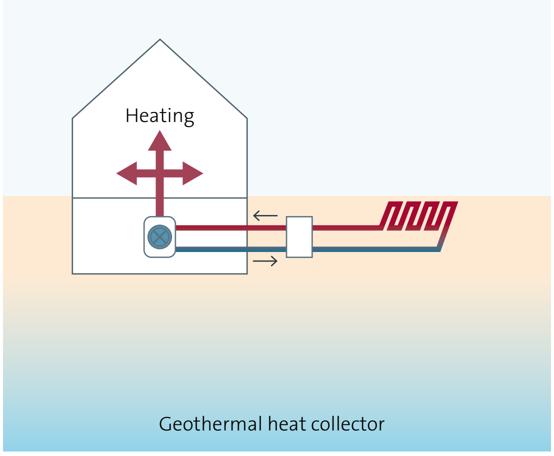


Figure 3: Geothermal heat collector; source: ERGO

2.1.4 Geothermal Heaters

Geothermal probes are the most common type of installation in central and northern Europe. Their surface area requirements are low and they provide access to a heat sources with constant temperatures. Geothermal heat probes are perpendicular or oblique drill holes, usually not more than 100 m deep in the case of single-family or two-family homes. Prior to drilling, the required dimensions and the soil texture must be determined. Depending on the soil class, the ground either saves and releases a lot of heat – or the opposite. Two plastic pipes are inserted into the drill hole. Inside them, a heat transfer fluid circulates absorbing heat from the soil and transferring it to a heat pump.

Geothermal probes work particularly well in winter because the temperature in the ground is nearly constant at depths of approximately 10 m and below.

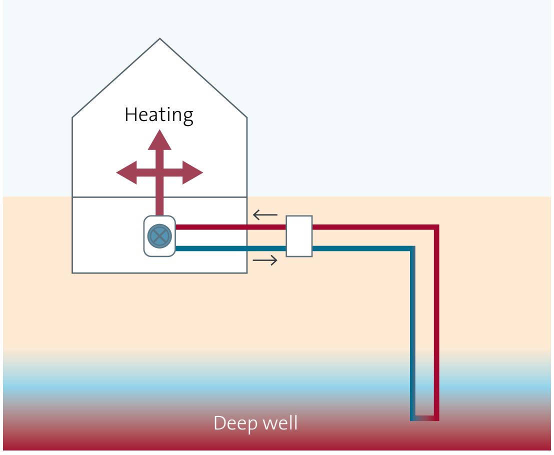


Figure 4: Geothermal heaters; source: ERGO

2.1.5 Carbon Dioxide Ground Probe

In this technique, the sump (the lower end of a pressurised earth probe) is filled with liquid carbon dioxide. Geothermal heat evaporates the CO_2, which then rises through the middle of the probe. At the upper end of the probe, the CO_2 gas condenses and releases heat to the cooling circuit of the heat pump. The condensed and cold CO_2 then sinks back into the depth of the of the probe, and the cycle starts over again. In contrast to conventional probe technology, no brine pump is required for carbon dioxide probes, since the evaporation-condensation cycle operates on its own.

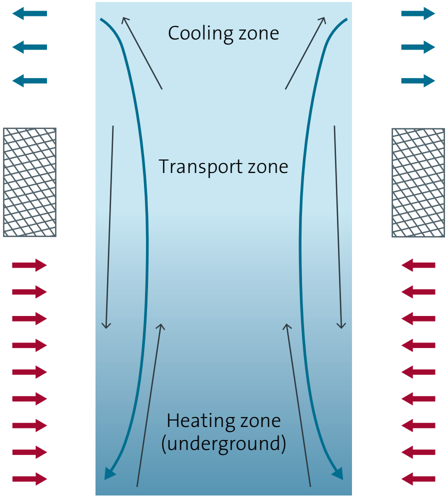


Figure 5: Carbon dioxide ground probe; source: ERGO

2.1.6 GRD Procedures

Another efficient way of extracting geothermal energy is the installation of geothermal probes by means of Geothermal Radial Drilling (GRD). In this method, several boreholes are drilled in different directions and at different inclinations from a small pit (1 m in diameter, 1 m deep), exploiting the whole surface area of a property. The inclinations range from 35–65 °C and the boreholes reach depths of 30–40 m. The advantage of this approach is its simplicity and low cost.

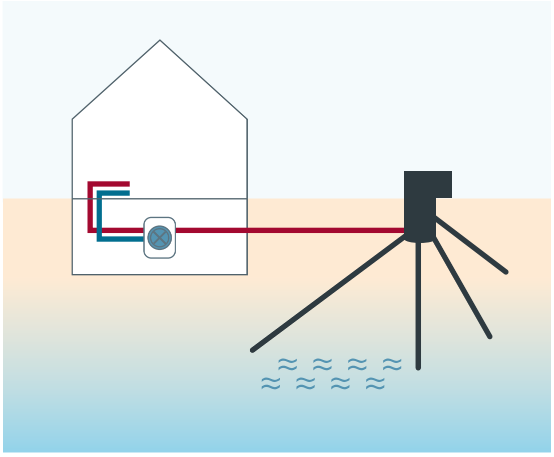


Figure 6: GRD procedures; source: ERGO

2.1.7 Grounded Concrete Components, Energy Piles

Concrete components can be used as more than just load-bearing or architectural elements. For this technology, the term “energy pile” has become a catchphrase. The term originates from the use of foundation piles for heating purposes. Essentially, any concrete surface in direct contact with the ground can be transformed into a heat source. However, the installation of heat exchangers can only take place while the building is being erected. Retrofitting into existing concrete surfaces is not possible.

Turning a building’s structural components into heat collectors requires relatively little effort. The economic advantage lies in the fact that the components used have to be constructed anyway. No additional drilling or laying work is required (as opposed to geothermal heat collectors or geothermal probes). In general, flexible plastic tubes are used as heat exchangers. The tubes are fixed to the reinforcement of a prefabricated or in-situ concrete pile, then grouted with concrete before the pile is erected.

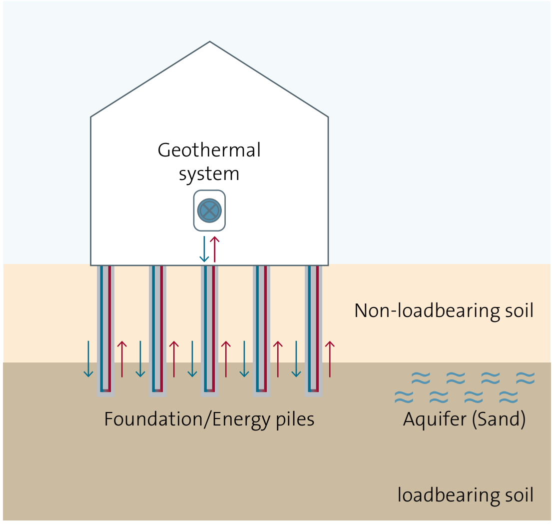


Figure 7: Building with Geothermal Energy Supply; source: ERGO

2.2 Principles of Hydrothermal Energy

In Germany, the supply of hydrothermal energy is limited; only a few regions have suitable thermal properties. These regions are found mainly in the Upper Rhine Plain near Wiesbaden and Landau and in the volcanic landscape near Bad Urach, south of Stuttgart. Other known hot water deposits can be found in the Bavarian Molasse Basin, as well as in the Eifel region, the Aachen region and in northern Germany.

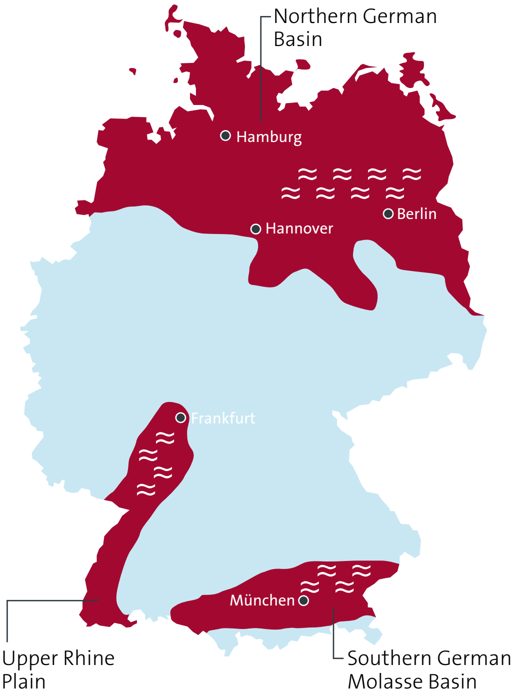


Figure 8: Hot water in Germany; source: ERGO

Hydrothermal energy is produced via the transport of thermal water from deeper ground layers to the surface through a borehole (extraction well). After heat transfer, the water is returned to the deep layer (duplicate principle) via a second borehole (re-injection well). Returning the water to the ground serves to maintain the hydraulic regime. Also, for environmental reasons, strongly mineralised water cannot be disposed of aboveground. The thermal water circuit between the extraction and injection wells is operated as a closed primary circuit. Heat is extracted from the thermal water with heat exchangers and supplied to the consumer via a secondary circuit.

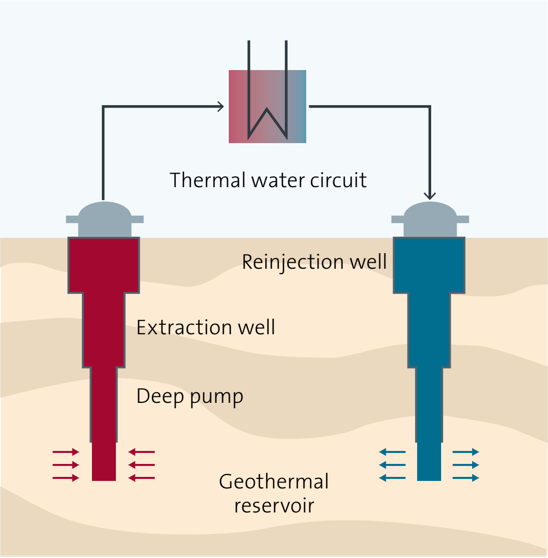


Figure 9: Principles of hydrothermal energy; source: ERGO

2.3 Hot Dry Rock Method (HDR)

Unlike hydrothermal deposits, the Hot Dry Rock (HDR) process does not necessarily require a water-rich rock layer. In this process, fissures in the ground are created by the injection of large amounts of water under high pressure (hydraulic stimulation). As a result, a circulation system is created between the extraction and injection wells. Water is used as the heat transfer medium and is either already present in the ground or supplied with strong water pumps. Achieving the temperatures required for economically viable operations at the respective depths is more of a financial than a technical problem. The existing knowledge of the stimulation of ground substrate that has been gained from HDR projects will be used to develop and improve hydrothermal deposits, reduce exploration risk and make geothermal energy less dependent on the geologic conditions.

After prelimary explorations in Rosemanowes Quarry (Great Britain), Bad Urach and Soultz-sous-Forêts (France) within the framework of a project funded by the European Union, Soultz-sous-Forêts was selected to be the location for an HDR project.

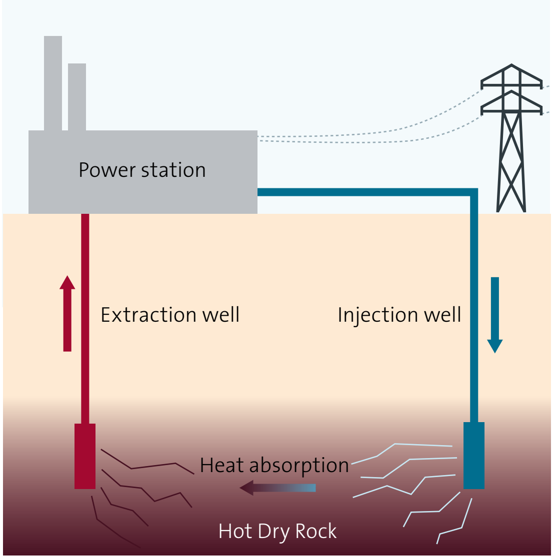


Figure 10: The HDR principle; source: ERGO

3 Design of a Hydrothermal Power Station

Deep geothermal energy projects require an explicit roadmap from the beginning that specifies such aspects as target horizons, development type and generation of electricity, heat or cooling. An overview of all necessary steps from planning to commissioning of the power station (or the district heating supply) is an absolute prerequisite.

The geology of the chosen site is of crucial importance for the success of a geothermal energy project. In other words, the design depends on the geological conditions. The success of the project therefore depends on the prospection and exploration phase.

To find a suitable exploration site, existing deposits or reservoirs must be detected during the prospection phase by means of suitable ground surveying methods (e. g. data collection with 3-D seismographs, geophysics, existing drilling sites, etc.). The data thus obtained must undergo a sound scientific evaluation.

During the subsequent exploration phase (local exploration and development of deposits), storage horizons must be evaluated, background temperatures measured, and, finally, the optimal drilling site and drilling paths determined.

The necessary planning steps include:

I Preliminary examination	II Feasibility study	III Exploration	IV Development
goals	detailed plan for preliminary exploration	commissioning a planning office	setting up surface installations
geoscientific background (geological sections running through the investigated area, seismic profiles)	investment costs, operating costs, profitability calculation	applying for a permit at the mining authority	production
depth of the water-bearing layers	risk analysis (risks of drilling, seismic activity, prospection, etc.)	planning and executing the drilling operation, stimulation measures (if required)	
rough technical model of the geothermal power station	project schedule		
development variants (duplicates, distance of the boreholes to each other, deflections)			
cost estimate			

3.1 Drilling

Geothermal drilling depends largely on developments in the oil industry. Due to the comparatively small number of geothermal drilling sites, special drilling technology for geothermal applications has not yet advanced considerably. However, the situation changed when geothermal power generation was included in the Renewable Energy Sources Act (EEG), changing the market conditions for the deep drilling industry. Now, technical innovations can be implemented profitably. The most important innovation of the last decades is directional drilling. Steering modules guide the drill head and drill string in a desired direction. With this technology, production and injection wells originating from the same drilling site can have different directions while maintaining the required minimum distance between the deep ends of the boreholes.

Drilling is much more complex for deep as opposed to near-surface geothermal energy development; deep boreholes are wider and exhibit different environmental conditions such as high pressures, heat and density of the rock. These challenges led to the development of various drilling techniques. The most common one today is rotary drilling.

3.2 Rotary Drilling

In the rotary drilling method, an electric motor drives a drill head. A hollow drive rod transmits the torque from a motor to the drilling head. As the drilling progresses, the drive rod is continuously lengthened. Drilling heads become blunt during a drilling operation, but cooling can extend their service life. To remove drill cuttings from the borehole, a drilling fluid is forced through the hollow drill string. In order not to waste expensive flushing agents, the drilling fluid is cleaned and reused once it has carried the drill cuttings to the surface.

3.3 Flushing Agents

Drilling fluids are used during the drilling operation to remove soil material (drill cuttings) from the space around the drill head. In addition, the borehole wall must be supported to counteract the rock pressure. For this purpose, the composition and the specific weight of the drilling fluid is adapted to the respective geology. Generally, a water-based suspension is used with a wide range of mineral or polymeric additives such as clay or concrete.

Without the supporting effect of the drill fluid deposits, loose rock layers would be pushed into the borehole, potentially impeding the drilling progress. Furthermore, the high-pressure drilling fluid could penetrate porous or even (drinking) water-bearing layers. To avoid this, the drilling liquid must be 'thickened' with suitable additives.

3.4 Pipes

With increasing depth, the support function of the drilling fluid decreases to the point where it can no longer ensure the stability of the borehole wall. Consequently, the walls must be secured against collapse at certain intervals by the introduction of steel pipes (casings). These pipes also act as a protection against torsion – an extended drill chuck, so to speak.

As the depth increases, the diameter of the casings decreases like a telescopic rod, while their thickness depends on the environmental conditions. The largest and smallest diameters of the casing depend on the total depth of the borehole. A borehole can be roughly divided into the following casing sections:

Surface Casing

The surface casing forms the first part of the borehole and has the largest diameter, for example, a 20″ pipe that extends to a depth of approximately 40 m. Its job is to establish a basic guide for the drill rod and to protect the drilling rig from undercutting. Normally, a standpipe is rammed into the ground. Like all the subsequent pipes, it is then joined to the wall of the borehole by pressing cement into the space between the borehole and the pipe (the so-called annulus).

Intermediate Casing

After fixing the standpipe, its cemented bottom is drilled at a smaller diameter (e.g. 17.5″) and sunk further into the ground. The intermediate casing anchors the drilling rod to its motor via a blowout preventer (BOP). The BOP is required to avoid sudden gas leakage. Furthermore, deeper deposits of potential drinking water are protected by the surface casing.

Production Casing

The production casing is the main part of the drilling structure. Inside this casing, the actual drilling happens all the way down to the target horizon. The production casing protects the borehole against collapse and, in the case of directional drilling, it also serves to take on the grinding loads at deflection points. At the end of the production casing, the drill head is driven forward into the target horizon.

If, after the drilling is completed or during normal operation, the flow rate does not meet expectations, the target horizon can be stimulated.

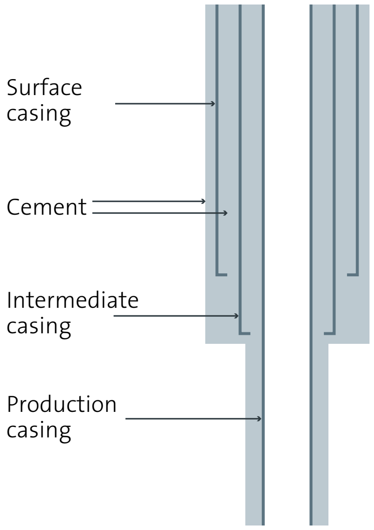


Figure 11: Piping; source: ERGO

Completion of the Borehole

The lower parts of a borehole can be completed in two different ways depending on the geological conditions. The first way – open hole completion – is used when the horizon is relatively stable with respect to its petrophysical properties, e. g. granite. In this scenario, an additional completion step is not required.

If, on the other hand, the horizon is brittle or unstable, pipes must be installed. To extract thermal water, these pipes (also known as liners) have slits and are pushed into the production zone by means of packers. This variant is called cased hole completion.

3.5 Drill Hole Measurements

Drill hole measurements are required to determine the important geophysical parameters, such as density, porosity and tectonic stress. In addition, borehole measurements also provide information about the quality of the drilling operations (e. g. inclination of the borehole) and the strength of the cementation. Borehole measurements include measurements during the drilling operation and measurements after the target horizon has been reached.

Measurements During the Drilling Operation

To take measurements during drilling, a probe is placed just behind the drill head. The use of these probes is particularly worthwhile during geothermal bores; the route of a directional borehole can be located by sending a pressure pulse into the drilling fluid, which is then detected by the probe on the drill head. A computer-based calculation can then determine where the drill head is located in the three-dimensional rock space.

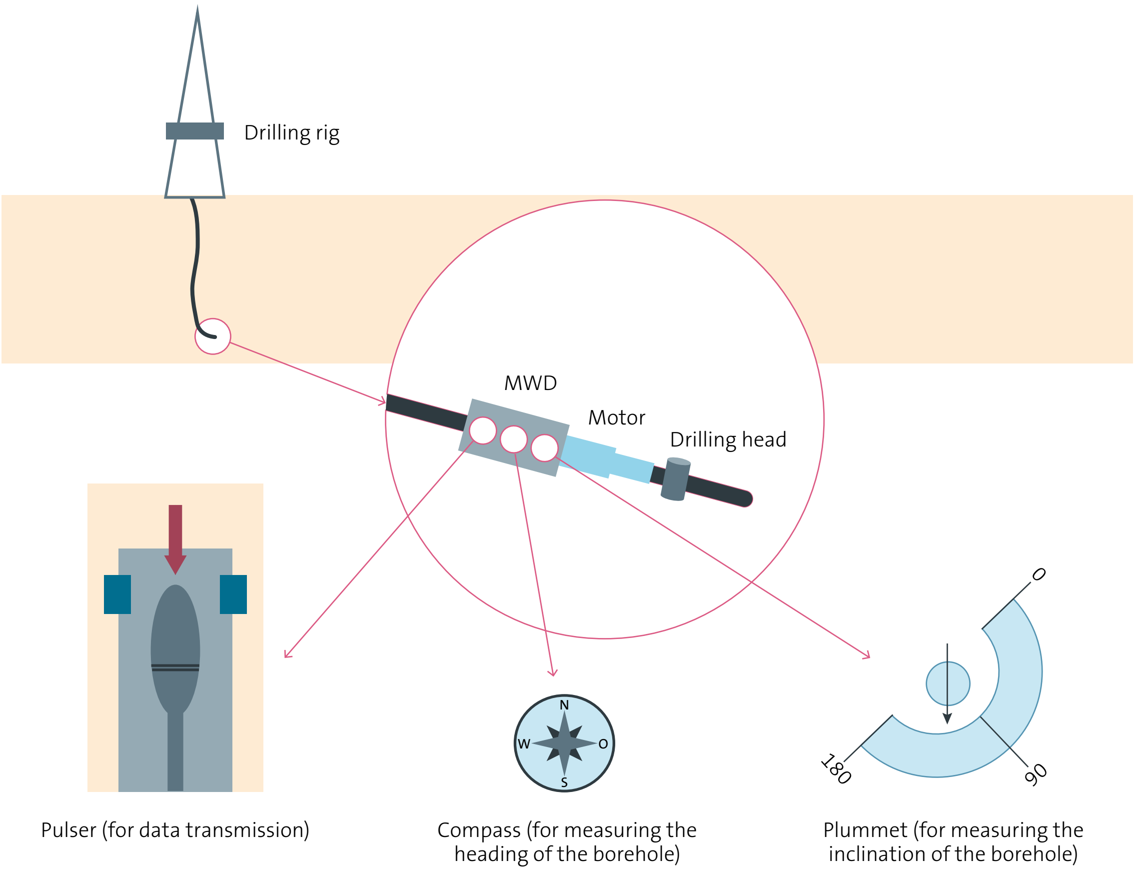


Figure 12: Measurement while drilling; source: ERGO

Mud Logging

The depth of the borehole can be determined by mud logging. The actual measurement happens on the surface: drill cuttings are examined under a microscope at certain temporal interval. By analysing fossil deposits and other constituents contained in the cuttings, the geological layers can be roughly mapped and the drill depth can be deduced.

3.6 Stimulation Measures

After the drilling operation and the measurements are completed, the hydrothermal parameters are essentially fixed. If they do not meet the expectations defined in the geological feasibility study, stimulation methods can be used to improve the outcome. A method commonly used in the Molasse Basin is acid stimulation. A highly-concentrated acid is injected into the target horizons to dissolve and break up minerals. Pure hydrochloric acid, citric or acetic acid or mixtures thereof are pressed into the borehole. Acid stimulation achieves considerable production improvements in calcareous deposits.

3.7 Multilateral Drilling

In the case of multilateral drilling, a side branch is drilled from the production bore into another target, increasing the number of contacts with the reservoir. Since both boreholes are open, both can be used independently for production. This method is often used when the primary borehole has not ended up in the right direction.

4 Risks of Drilling Technology

Today, almost all geothermal deep drilling is carried out under difficult conditions. Since geological conditions differ from one location to the next, there is no ‘standard recipe’ for mastering deep drilling. A drilling technique comprises the drilling type (e.g. directional drilling), the drill rig, various tools for use inside the borehole, the composition of the drilling fluid, and the cementation of the annulus. All these drilling components must be individually adapted to the geological conditions to achieve the best possible result.

4.1 Technological Risk

Directional drilling may have to be deflected in an unfavourable rock formation. This can lead to angular deviations, losses of drilling fluid and strong deviations in very hard rock formations. All of this can result in a slow progress of the drilling operation, potentially leading to increased costs. Furthermore, the deflection pressure at a deflection point can lead to cavitation of the rock, which makes the later installation of the pipes more difficult since the lateral support is lacking.

A further technological risk is torn drill rods caused by excessive torsional forces. As a result, a chain reaction can occur in the borehole and, in the worst case, the unlined bore wall can partly collapse. Then the borehole may have to be laterally deflected above the collapsed region, continuing in parallel to the one already sunk and grouted. A delay may ensue at a considerable additional cost.

If drill heads are not carefully chosen with regards to the geological conditions, the bore wall may become structurally damaged and lose stability. If the lower part of the bore wall collapses, the drill head can become stuck, which may cause the rod connecting to the running motor to be sheared off due to torsional forces. Moreover, the flawed selection of a drill head can lead to faster wear and frequent replacement. In these scenarios, delays in the progress of the drilling operation causing considerable increases in cost are virtually unavoidable.

The wrong composition of the drilling fluid represents another technological risk. If the fluid is insufficiently thixotropic, the stability of the borehole cannot be ensured during tool changes and the unlined part of the borehole may collapse.

The incorrect composition of the annulus cement can also have negative effects. The cement may not harden as planned, so that casings are insufficiently filled in one or another section. In these hollow sections, the pipe may not support the radial and axial forces of the rock. The consequences during subsequent operation are material fatigue or hydraulic or pneumatic leakage.

4.2 Geological Risks

Geological risks depend on the hydraulic characteristics of the rock, the prevailing temperatures and the geological conditions. Drilling risks are encountered, for instance when trying to control overpressure (met in certain geological horizons) when drilling fluid is lost (e. g. in disturbances), hydrocarbons are released or the drill string breaks.

4.3 Deformation

Irrespective of geological and technical questions, slow drilling progress represents an additional risk. In slow drilling, lateral rock pressure can deform the unlined borehole, which may then take on an oval shape. In this case, all attempts of recapturing the drill head are futile. As a result, that section of the borehole must be abandoned, the drill head cut off, the borehole section filled (cemented) and the section above laterally deflected.

4.4 Salvage Operations

Recovering drilling equipment or measuring tools is a complex and costly endeavour. The cost of keeping drilling equipment and a drilling team on stand-by is approximately 50,000 euros per day. The cost of a salvage operation can be as high as one million euros. A potential sidetrack involves costs on the same order of magnitude. The loss of high-sensitivity measuring tools can increase expenses by an additional one million euros.

4.5 Exploration Risk

The risk that the thermal water is not of the expected temperature and quantity has a decisive influence on the investment potential in geothermal projects. As a rule of thumb, as the scope of exploration grows, the risk drops. Predicting temperatures for a defined target horizon is less problematic than estimating production rates. In the case of high drilling costs, this risk is substantial. The predicted parameters are mass flow, temperature and the length of the period of thermal water production. One approach has been to financially hedge this risk with a state-initiated insurance fund. These funds were designed to keep the risk for the insurance industry predictable until sufficient statistical data is available to accurately calculate actual risks. Geological and technical risks are not covered by this insurance.

Exploration risk insurance covers the damages incurred when the borehole cannot be used for the intended purpose despite stimulation measures. The maximum claim size comprises the cost for the drilling operation and the stimulation measures. The exploration risk is defined by the flow rate and temperature parameters.

- For the conclusion of an insurance contract, the following information must be available:
- geological and hydrogeological expert opinions on the planned project
- feasibility study on the planned project
- project plan
- reference data set (adjacent drillings with test results)
- drilling plan, including stimulation measures and costs
- definitions of insured events

5 Thermal Water Circulation

The thermal water from an extraction well is transported to a machine house and from there in heat-insulated pipes, usually underground pipes, to an injection well. The thermal water in northern Germany used for power generation is very salty. Its salt concentration depends on the depth and can reach over 300 g/l (sea water contains an average of 35 g/l). In thermal water, small amounts of dissolved gases can be found which consist predominantly of nitrogen (N_2), carbon dioxide (CO_2), occasionally hydrogen sulfide (H_2S) and methane (CH_4), as well as traces of helium (He). Waters containing this mix of gases are very corrosive to most metals. Thus, thermal water circuits must be protected against corrosion. Since the composition of the thermal water cannot be altered, corrosion protection measures are limited mainly to the selection of the pipe material and coating. If temperatures and pressures in the power station permit it, glass-fibre-reinforced plastic (GFRP) or cross-linked plastic are used. This applies, for example, to the piping inside the borehole or the connecting pipe on the surface, both of which are typically made of GFRP. Simple steel pipes are usually not suitable.

The thermal water circulates at a pressure of up to 16 bar. To prevent oxygen from entering the thermal circuit, all components that come into contact with the thermal water are pressurised with a so-called inert gas (e.g. nitrogen). This applies to the annulus and the pressure control systems. This is to prevent the entry of oxygen and subsequent oxidation and corrosion. Also, the redox potential changes during the contact between thermal water and oxygen, which can lead to considerable problems, especially with re-injected water. To be in a position that allows a swift response to changes of the oxygen content, the injection water should be examined at regular intervals.

Additional filters are present in the thermal water circulation aboveground. A filter system immediately downstream of the extraction probe retains particles conveyed along during drilling. The filters protect the aboveground power station components; for example, against sediment deposits in sections of lower flow velocity. The particles can originate from the production horizon itself or from probe installations, the pump or the piping. Another filter system, equipped with finer mesh filters, is installed inside the injection well upstream of the site of re-injection of the thermal water. This filter system prevents the introduction of very fine particles from the production horizon and chemical precipitation products into the injection site and thus into the thermal water reservoir. The number of solid particles captured by these filters is small compared to the flow rate of the thermal water.

The slop system (collection tank) absorbs thermal water produced during maintenance work on the heat transfer medium or during filter replacement. Here, waters end up that leaked through sealing elements or that were flushed from the borehole and the thermal water circuit during start-up of the power station. A heat exchanger transfers the heat extracted from the ground to a secondary circuit that supplies a heating system or a power station. Both circuits are physically separated. For each circuit, the hydraulics are designed and materials are selected independently. Thus, the requirements listed above only apply to the thermal water circuit.

6 Geothermal Power Stations

Various processes are available for converting geothermal into electrical energy; however, they all involve a turbine that drives a generator via a shaft. These turbines operate based on either the classic steam power process (Clausius Rankine process) or the open gas turbine process. The extracted fluid (thermal water, steam or a mixture of both) either serves directly as a working medium or transfers heat to a secondary fluid in a heat exchanger. The type of geothermal power plant that is best suited depends on the properties of the site, including temperature, pressure, the content of non-condensable gases, the mineralisation and the amount of a geothermal waste:

- Systems for the direct use of the extracted fluid operate at temperatures of 150 °C and above. All involved processes benefit from low levels of non-condensable gas and mineralisation.
- Binary plants are used at reservoir temperatures of 80 °C and above. Higher temperatures improve efficiency considerably. Each temperature level demands a slightly different working medium for optimal efficiency. Here, engineering problems typical for geothermal power stations are limited to the thermal water circuit. Therefore, binary power stations are used for deposits that, because of their steam content and temperature, would theoretically be suitable for direct extraction, but are highly mineralised or contain high proportions of non-condensable gas.

6.1 Organic Rankine Cycle (ORC)

Considering its individual components, the Rankine cycle with an organic working medium is similar the classic Rankine cycle:

The working medium is preheated, evaporated, superheated and then expanded in the turbine. It then condenses and the feed pump increases its pressure again. The main difference lies in the parameters of pressure and temperature. Both lie far below the values typical for steam power stations. The materials that can be used depend on the temperature of the available heat source. The working medium should be evaporated at rela-

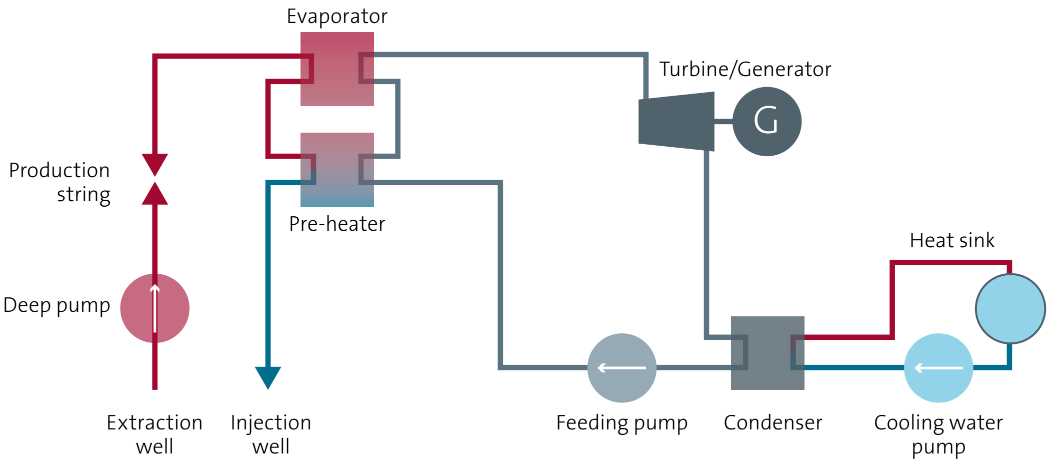


Abbildung 13: Operational principles of the Organic Rankine Cycle (ORC); source: www.asue.de

tively low temperatures. It should be nontoxic and have no environmentally damaging effects. At present, short-chain hydrocarbons (e.g. pentane) and so-called azeotropic mixtures (ammonia/water in appropriate proportions) are used. The thermodynamic properties of the working medium should optimally match those of the heat source. ORC systems with a typical output of 0.5–1.5 MW have been operated safely and reliably worldwide for more than 15 years.

When organic working media are used, various technical questions arise:

- Turbines are typically custom-built since the working medium differs considerably from water (molecular weight, lower specific heat capacity).
- The medium is often aggressive, so the surfaces of the turbines and the heat transfer system must be protected against corrosion, e.g. with a coating.
- The sealing of the circuits is complex and therefore not as easily realisable as for water based circuits.

6.2 The Kalina Cycle

In the Kalina cycle, mixtures of two substances (e.g. ammonia/water) are used as working media. The special advantage of the Kalina process lies in its better heat transfer ratios during evaporation and condensation. In contrast to the Rankine process, neither change in state is isothermal. Rather, in each case the properties of the mixture are exploited: its temperature can be changed by changing its relative concentration water and ammonia, while the total concentrations and the pressure stay constant. Under continuously rising temperatures, the mixture evaporates, and under constantly decreasing temperatures, it condenses. The costliness of ammonia decomposition product disposal is still considered to be a major technological challenge.

A significant advantage of the Kalina cycle over ORC systems is its increased thermodynamic efficiency, especially at low temperatures (< 140 °C). Depending on the scenario, improvements of up to 50% can be expected.

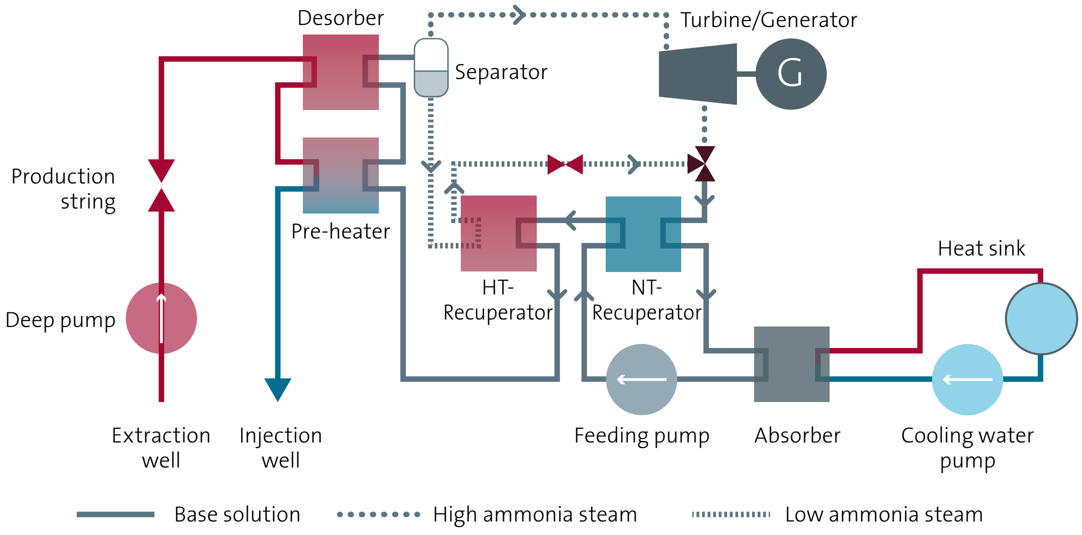
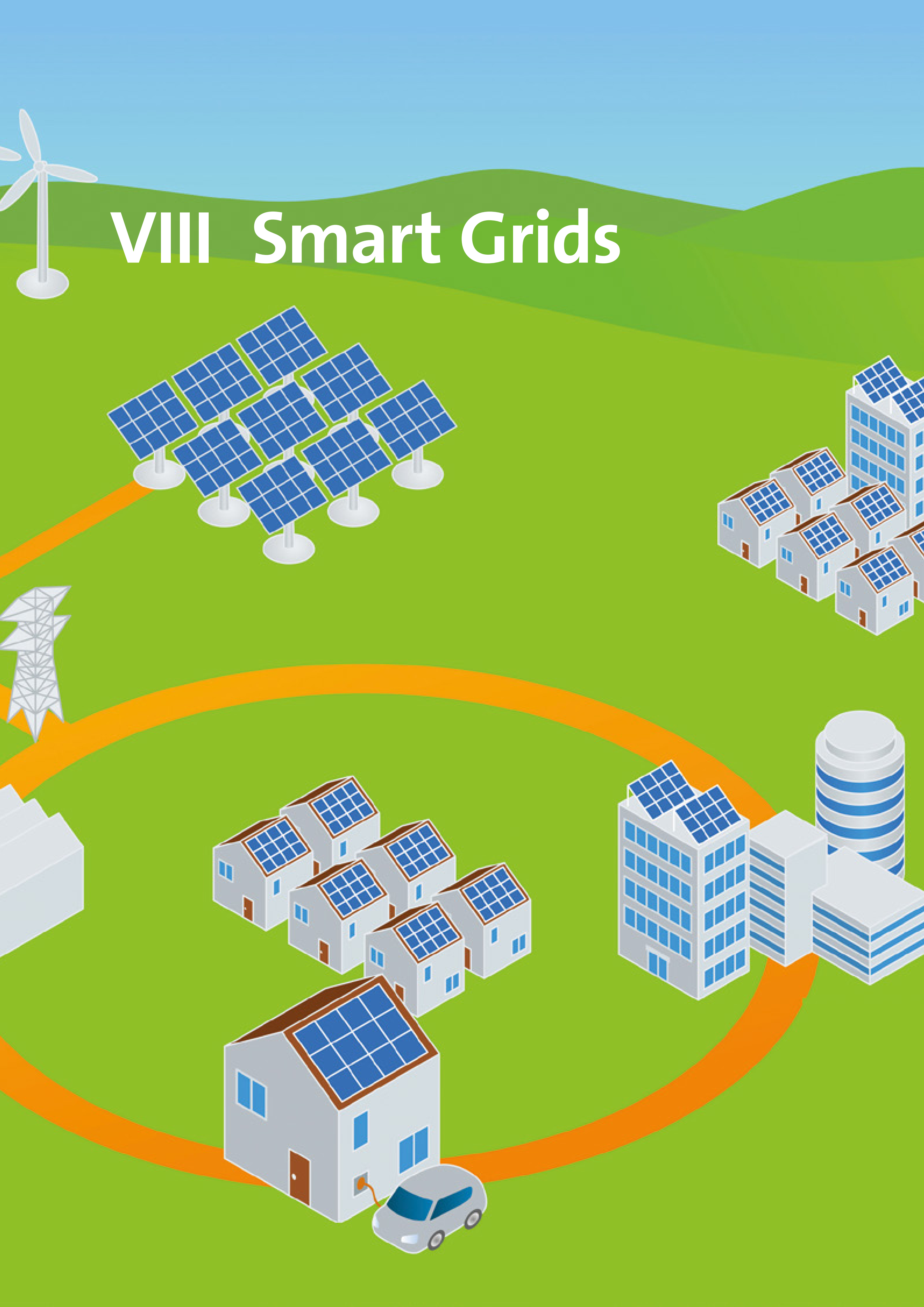


Abbildung 14: Operational principle of the Kalina cycle; source: Kalina cycle according to Leibowitz and Mlac www.asue.de

VIII Smart Grids



HOSPITAL

VIII Smart Grids

Introduction

The term smart grids refers to so-called intelligent power grids and encompasses the organisation and regulation of the electricity grid, producers and consumers, i. e. of all components of a power infrastructure.

Smart grids are geared toward the future design of networks and the link between energy production and energy consumption. The implications of smart grids are not limited to Germany; on the contrary, in view of climate change and corresponding new regulations, they are of global importance.

1 Current Situation

In Germany and throughout Europe, the electricity sector is adapting to a major transformation. The rapid expansion of renewable energies, in particular wind and solar power, has resulted in substantial fluctuations in the electricity grid caused by weather-related fluctuations that impact electricity production. Prior to the expansion of renewable energies, electricity was generated centrally in large power stations. Today, however, electricity production is often decentralised. At the same time, distances between the sites of production and consumption remain large.

Among renewable energies, wind energy plays by far the strongest role – particularly in the northern part of Germany. This role is reinforced by the expansion of offshore wind energy. Yet, a large percentage of the demand for the energy produced in the North comes from in the southern regions of Germany. Because of this imbalance, a significant expansion of the electricity grid will be indispensable if renewable energy is to be consumed in regions where it is clearly needed.

A major effect of the expansion of renewable energies is that it has made the operation of certain conventional power stations uneconomical. Many older power stations that in operation today are antiquated. Their operators would like to shut them down, but decommissioning them requires the approval of the Federal Network Agency. Also, grid stability still depends on the availability of these power stations. Consequently, the planned abandonment of nuclear power in Germany calls for renewed action if a reliable and stable supply of electricity is to be maintained in the future.

2 The Electricity Market: Future Conditions and Framework

The European climate policy has set the framework for the future European energy market. Its expressed aim is to reduce greenhouse gas emissions by 40% and to simultaneously increase in the share of renewable energies to 27% of total electricity production by 2030. The German government aims to go even further by reaching the 40%-target by 2020 and achieving a reduction of greenhouse gas emissions of 80–95 % by 2050 (as compared to the levels in 1990). These targets were already defined in the Energy Plan from 2010. They are meant to be achieved mainly by expanding renewable energies, by gradually removing a total of 2.7 GW of coal-fired power from the grid and by increasing overall energy efficiency. In addition, an Action Plan on Climate Protection was developed to advance the decarbonisation of electricity production. By 2020, these measures are expected prevent 62–78 million tonnes of greenhouse gas emissions.

Today, three main methods of generating electricity can make achieving these targets possible: nuclear power, thermal power with ‘Carbon Capture and Storage’ technology (CCS), and renewable energies. The availability of energy storage also plays a major role.

In addition, considerable efforts are required to adapt the electricity grid to these challenges. Finally, it is important to control the consumption side of the energy equation, at least in part.

Figure 1: New high voltage mast; source: Teko

2.1 Energy Production

The technical challenges of producing energy from coal, gas, nuclear power and renewable energies are well understood. The feeding volumes of these energy sources can already be controlled by grid operators. Here, technological innovations and their integration with existing technologies will be examined.

2.1.1 Battery Storage

Batteries have been widely available for many years. They help power a wide range of applications, such as vehicles or telephones. However, the range of sizes of today's batteries and their associated problems is a newer development. Large batteries allow for the storage and retrieval of electricity from renewable energy sources. The energy stored in batteries can be fed back into the grid when necessary. However, before the required storage capacity and economic framework are established, further research is needed. Currently, the world's largest electricity storage device has a capacity of 32 MW.

Larger quantities of energy have so far only been stored in pumped-storage power stations. In these power stations, water is pumped into a reservoir during phases of low electricity demand. When the demand rises again, the stored water can be drained through turbines, thus recovering electricity.

Here, we illustrate battery storage using the example of a project at Aachen University (RWTH).

5 MW Battery Storage

Aachen Technical University (RWTH) and their partners built a battery storage power station (M5BAT) with a capacity of 5 MW that went into operation in September 2016. With this storage system, they hope to develop a sound understanding of the costs and savings potential of battery storage power stations.

Project Data

Project status	In operation
Typical power station size (energy)	5 MWh
Typical system size (power)	5 MW
Storage loss	About 0.1%/day
Service life of the power station	Up to 20 years, depending on the technology
Response time when power is supplied	About 100 ms
Efficiency (AC/AC)	Up to 10,000 cycles, depending on the application and battery type
Cycle stability	Up to 10,000 depending on the application and battery type
Typical discharge time	45 to 60 min
Typical time between storage and evacuation	From seconds to several hours – highly application-dependent
Example applications	Integration of renewable energy, regulation of power, electricity trading
Project term	July 2013 to June 2017

M5BAT stands for 'Modular multi-megawatt multi-technology medium-voltage battery storage system'. The special feature of the M5BAT is the modular design of its medium-voltage storage. Inside it, different battery technologies are combined. Lithium-ion batteries are used as short-term power accumulators, high-temperature batteries are used for storage periods of several hours, and lead-acid batteries allow for short and medium discharge times.

During construction and operation, scientists have determined the technical and economic potential for optimisation of this type of storage. In addition, they have developed so-called target cost estimates for storage applications, such as primary and secondary control. With these estimates, the minimum revenue required for battery power stations to operate economically can be determined. Decreasing cost trends have already been taken into account. The results also specify which regulatory incentives should be put in place. The findings have been summarised in a manual for battery power stations, which is meant to help with cost planning for and the operation of a battery power station.

Optimisation of the Battery Storage Power Station during Operation

The M5BAT power station is designed and built to offer access to reliable information regarding service life, costs and potential applications. Apart from the actual costs for the battery cells, these comprise peripherals for the installation of the battery system, such as battery assembly, their management, diagnostic systems, central system control and thermal management. The researchers at the M5BAT project continually examine and optimise the interplay of different battery types for different application profiles. In addition, an energy management system is to be created for the batteries, inverter and control technology.

An interesting aspect of electrochemical accumulators is that they do not depend on geographic conditions, which is the case for compressed-air accumulators and pumped-storage accumulators. Also, comparatively short planning periods can be expected for their construction. It is therefore necessary to ascertain the development of skills for cost-effective design, optimised operation and comparative technology assessment. Furthermore, the performance of various technologies must be tested under realistic operating conditions.

New Types of Batteries

Redox flow cells store electrical energy in chemical form. In this respect, they are like batteries, but with one decisive difference: in a redox flow cell, the electrochemical storage and the energy converter are not inseparable. Redox flow batteries store energy in electrolyte solutions in which dissolved salts absorb and release electrons from and to membranes. The energy content of this type of accumulator is determined by the tank volume for the electrolyte.

2.1.2 Carbon Capture and Storage

Carbon Capture and Storage (CCS) refers to technologies that allow carbon or, more precisely, carbon dioxide (CO_2) to be permanently stored in the ground.

The legal basis for CCS is the Law for the Demonstration and Use of Technologies for the Deposition, Transport and Permanent Storage of Carbon Dioxide, passed on August 17, 2012 (Gesetz zur Demonstration und Anwendung von Technologien zur Abscheidung, zum Transport und zur dauerhaften Speicherung von Kohlendioxid – BGBl. I p. 1726). The law implements Directive 2009/31/EC on geological carbon dioxide storage.

On this legal basis, power stations based on CCS technology are to be built and tested in Germany. Applications for storage permits had to be submitted by the end of 2016. These demonstration projects are limited both in operation time and in number. The maximum planned storage volume for these projects is 1.3 million tonnes of CO_2 per year. Within the scope of these projects, a total of four million metric tons of CO_2 per year can be injected into underground storages. The earth's crust is still being investigated for its suitability as long-term storage of carbon dioxide, in part to avoid a negative impact on humans and the environment.

The aim of this technology is a significant reduction of CO_2 emissions from industrial processes, energy generation and natural gas production. It could significantly contribute to achieving climate protection targets.

Technologies for CO_2 Capture

There are various ways to separate CO_2 in power stations.

During pre-combustion, solid fuel is gasified and CO_2 is separated. In this manner, fuel gas is produced and compressed, for instance from coal. During subsequent purification, the CO_2 is dissolved out of the gas before it is passed through a gas turbine.

Another option is the oxyfuel process, which is based on the addition of pure oxygen. A solid fuel is combusted and the resulting carbon dioxide CO_2 is subsequently separated.

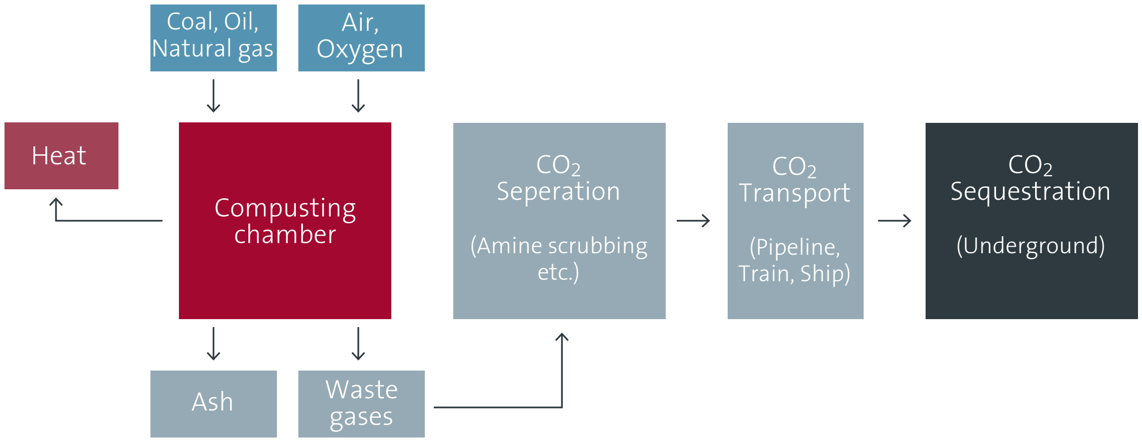


Figure 2: CO_2 storage process; source: Teko

A third possibility is the post-combustion process, which is based on conventional methods of energy generation. In this case, resulting smoke gases are cleaned. Today, all power stations clean their smoke gas, not for the reduction of CO_2, but of nitrogen oxides. CO_2 can be separated in an additional cleaning step.

The development of other methods for the CO_2 reduction is to be expected. These could be used for the reduction of CO_2 emissions in all areas of industry. Current research is aimed at increasing the efficiency of these processes.

Separated CO_2 is stored in suitable soil layers. For this purpose, the experience gained in the oil industry can be applied.

The potential usage of stored CO_2 is a challenge considered to be complementary to that of storage.

2.1.3 Conversion of Energy into Gas (Power to Gas)

The World's First Industrial Power-to-Gas Power Station

In the WOMBAT project, researchers explored the idea of linking electricity and gas networks. Excess electricity from renewable sources is used to produce hydrogen, which is in turn combined with CO_2 in a biogas power station to form methane, the main component of natural gas. This process allows for the exploitation of the whole complex infrastructure of the gas industry, from transport to storage.

Project status	Project completed
Typical power station size (energy)	capacity of the natural gas network
Typical power station size (power)	6 MW
Volumetric power density	Same as natural gas network
Efficiency AC/VN CH_4	54 ± 3%
Service life of the power station (one cycle/day)	Target value: > 20 years
Response time when power is supplied	30 s
Typical discharge time	Variable due to very high power generation in the grid
Typical time between insertion and removal	Arbitrary due to location- and time-independent storage
Areas of applications (examples)	Supply of e-gas for mobility, using electrical surplus energy, can be used as secondary control power
Project term	July 2012 to September 2016

The name WOMBAT is derived from the German phrase for 'degree of efficiency optimisation for methanation and biogas power station technology'. At the facility in Werlte, a municipality in Lower Saxony, scientists work on optimising the entire process chain from electrolysis and methanation. This includes the technical optimisation of all employed systems as well as a systematic analysis of feedback provided by network operators and mobility providers. Marketing strategies are also being investigated. The researchers hope to show how this technology as a whole can become profitable while contributing to the optimisation of sustainable energy use, including in the mobility sector.

WOMBAT is the world's first power-to-gas pilot power station on an industrial scale. It offers rare insights into the characteristics of the ongoing operation of such a system.

Synergies

The synergies realised at the biomethane power station of the project partner EWE are one focus of current research. Scientists are investigating the extent to which the efficiency of a combined biomethane/power-to-gas power station (PtG power station) can be increased by a specific heat management system, as compared to the operation of the two separate power stations. This approach appears promising, since a PtG system offers various exploitable heat sources such as the electrolyser and the methanation unit. Niomethane power stations, on the other hand, require heat in several processing steps, for example for the hygienic management of waste, for heating the fermenter and for the separation of CO_2. Consequently, the transfer of heat between two of these power stations appears to be reasonable idea. However, challenges arise from the intermittent operation of PtG power stations, as biomethane power stations require continuous heating.

A large proportion of the stored synthetic methane is meant to be used as a fuel in natural gas-driven passenger vehicles. The project's goal is to find ways to optimise revenues for renewable methane as well as the cost of bringing the gas to market. Research is conducted to demonstrate how PtG power stations can be operated and developed in a cost-effective fashion in a market economy prior to the emergence of energy-related economic necessities.

The optimisation of the combined biomethane/PtG power stations is meant to be accompanied by and documented through comprehensive monitoring. To this end, a detailed technical plan is being developed to record and analyse material and energy flows at a high temporal resolution throughout the duration of the project. The PtG system is operated with additional personnel since different operating strategies must be analysed under varying conditions, such as the condition of the electricity grid, changing weather, etc. The goal is to optimise the PtG system with respect to different criteria: stability of the electricity network, unused electricity, profitability, total ecological impact of the PtG power station, stability of electrolysis/methanisation. The goal is the development of effective and stable control algorithms.

Optimising the use of the stored energy requires a systematic investigation by means of traditional life-cycle assessments and scenario analysis.

PtG power stations will be adopted to provide their system services only if overall economic viability can be proven and the distribution of PtG technology via appropriate investments appears possible. Therefore, a special focus lies on the analysis and optimisation of those variables that have the greatest impact on costs and revenue.

Regular Operation Since the End of 2013

In May 2011, it was decided that an industrial power-to-gas power station would be built in the Emsland region right next to an existing biomethane power station. The partners of this collaboration are the power-to-gas manufacturer SolarFuel (today: ETOGAS) and the operator of the biomethane power station, the energy supplier EWE. The CO_2 derived from biogas treatment is to be used for methanation.

The PtG plant started regular operation in late 2013. At this plant, pioneering work took place in the fields of monitoring of heat management, current reference, life cycle analysis and marketing of the energy carrier e-gas. Furthermore, this

year's plans include the optimisation of measures, which are designed to ensure an improved supply of highly concentrated CO_2 to the e-gas system. After start-up of the e-gas system during summer, the monitoring system will collect the first data and later the first technical optimisation measures of the operation of both power stations can be implemented. For 2014 and subsequent years, ecological as well as economic optimisation in the operation mode of both power stations are planned, particularly in light of the availability of substrates for the biogas power station and the specific grid situation (electricity and gas) at the Werlte power station.

2.2 Electricity Grid and Infrastructure

The German electricity grid is strongly ramified and well developed. The network is divided into

a) transmission networks (maximum voltage)

and

b) high-voltage, medium-voltage and low-voltage distribution networks.

One of the responsibilities of German network operators is to develop the grid with regard to the prevailing conditions and to ensure safe operation. The German Energy Industry Act (EnWG) defines these responsibilities. In addition to the responsibility for safe operation, maintenance and modernisation, network operators have to ensure open access to the grid for electricity producers.

The German transmission network is currently operated by four companies: TenneT, 50Hertz Transmission, Amprion and TransnetBW.

Transmission networks allow for the transport of currents over long distances with relatively little transmission loss. These networks distribute electricity all over Germany and into the networks of other European countries. The whole network comprises about 35,000 km of power lines. So far, the electricity in this network is transmitted as a three-phase current at a maximum voltage of 220 kV or 380 kV. In the future, a new high-voltage direct-current transmission line will transmit electricity at up to 525 kV.

The distribution networks are used to transfer electricity from the transmission networks to the end user. Not all the electricity takes this route, as some producers feed directly into the distribution network.

These different voltages are used to transport electricity with minimal losses. The voltage level depends on the transport route. Substations and transformer stations convert the voltages up or down between networks.

The high-voltage grid is operated at 60–220 kV. The whole network has a total length of about 77,000 km.

Medium voltage refers to the range of 6–660 kV. This network is about 480,000 km long.

The task of the low-voltage network with 230 V or 400 V is to provide electricity to private households and to commercial or municipal consumers, apart from those in the minority that are connected directly to the high-voltage or medium-voltage network. The low-voltage network has a total length of about 1,123,000 km.

Future Requirements for Power Grids

As the foundations of energy production are changing, there is a growing need to prepare all electricity networks for these changing conditions. With renewable energies, the fluctuations in production have grown. Today, electricity production correlates more with environmental conditions than with demand. In addition, in Germany the production of electricity is often situated far away from areas of high consumption. For example, most of the wind energy is produced in the North, while a large proportion of industry is located in southern Germany. The expansion of transmission grids is therefore enormously important for future network operation and requires a considerable financial investment.

The issue is aggravated by the expansion of offshore wind power. To harmonise of the expansion of offshore electricity production with the expansion of onshore transmission networks, new rules and regulations are vital.

The advantage of offshore power generation is its increased reliability: in the North and Baltic Sea, power generation is more predictable than on land due to more uniform wind speeds.

Appropriate sites are 20–40 km off the coast in the so-called ‘exclusive economic zone’ (EEZ). Other European countries operate at sites considerably closer to the coast.

Wind energy generated in the Baltic Sea is converted to a three-phase current. In contrast, in the North Sea a direct current is generated, which is more suitable for long-distance transmission.

Every two years, the Federal Network Agency specifies in the offshore network development plan (O-NEP) which offshore connection cables are to be built in subsequent years. Usually, the agency will confirm the onshore network development plan (NEP) at the same time. On this basis, transmission system operators can take necessary development measures.

The load on the networks is increasing due to increasing numbers of small units and feed-in points and the use of German networks for electricity trading between European partners.

Only new transmission lines at the highest voltage level can solve the problem of large distance transmission between production sites (northern Germany) and consumption centres (southern Germany). The legal prerequisites for this expansion have been defined in the Power Grid Expansion Act (EnLAG) and the Grid Expansion Acceleration Act (NABEG).

An energy management system controls and coordinates the various decentralised operating components. These so-called virtual power plants (VPP) or regenerative combined-cycle power plants will substantially expand the possibilities for demand-oriented energy supply. It is not enough, however, to cover energy demand; the operation of the grid must also be actively supported by ancillary services (AS). The energy industry calls these properties of regenerative energy carriers power plant characteristics.

The term indicates that production must be controllable and reliable in accordance with the system requirements. Furthermore, all involved power stations must support the electricity grid in the event of a malfunction. If renewable energies, particularly wind energy, are to generate the entire load of the grid, the output of conventional power stations will have to be phased out. In this scenario, the systems services of regenerative energy systems must ensure grid stability.

Systems services include control systems (frequency maintenance (primary control performance), secondary control performance and minute reserve), reactive supply of power (voltage maintenance) and network bottleneck management. Other systems services, like black start capability, are important but do not represent major challenges. The main challenges are indeed the control of active and reactive power in all connected installations and the maintenance of proper behaviours, such as fault-ride-through, in the event of line faults.

Control energy is the energy required by a network operator to compensate for unforeseen fluctuations in the power grid. A distinction is made between positive and negative control energy. In the case of a sudden increase in demand and insufficient supply, we speak of **positive control energy** – more electricity must be fed into the network. On the other hand, the compensation of increased supply or sudden reduced demand is called **negative control energy** – electricity must be removed from the grid. The supply of negative control energy must not be confused with the compulsory regulation of power generators as part of feed-in management.

The transmission network operators 50Hertz Transmission GmbH, Amprion GmbH, EnBW Transportnetze GmbH and TenneT TSO GmbH

are responsible for offsetting power imbalances in their respective control zones. They are not allowed to simply negotiate these adjustments among themselves. Instead, they must put the required control energy out for tender. The procedure and the results can be found at www.regelleistung.net. Invitations to tender are published for both positive and negative control energy and for

- **Primary control energy** (required for rapid stabilisation of the grid within 30 seconds),
- **Secondary control energy** (must be fully available within five minutes) and a
- **Minutes reserve** (used to release secondary control energy, must be supplied within a lead time of up to 7.5 minutes and at constant level for a minimum of 15 minutes).

Ground Cables in the Transmission Network

The planned North-South overhead electricity link in the transmission network has encountered resistance from the public. In response, the federal government opted to lay the legal foundations for underground transmission cables. In the future, high-voltage direct current transmission lines (HVDC lines) are to be used on the so-called Stromautobahnen (e.g. SuedLink). Due to a lack of experience with a three-phase current in the transmission network, a direct current will be used. The three-phase current in a so-called meshed three-phase system is a new technology and still presents technical challenges that must be overcome before deployment in order to avoid reduced reliability of energy supply. First practical experiences with this technology are currently being acquired in a pilot project in the region of Raesfeld in North Rhine-Westphalia.

2.3 Power Consumers

There are private, commercial, industrial and municipal consumers.

Electricity consumption is subject to daily and seasonal fluctuations that are partially predictable. In addition, certain devices can defer their energy demands. These devices include heat pumps or private freezers. The effects can be two-fold.

One the one hand, by controlling this process, supply can be matched to demand. In practice, this will be difficult to achieve. Nevertheless, this approach shows of lot of potential for increasing efficiency.

On the other hand, the consumer has the advantage of being able to buy electricity when it is cheap. Participating homes would have to be equipped with so-called **smart meters**. These electricity meters feature a data transmission system and thus allow for the flexible response to fluctuating electricity prices throughout the day.

This approach can also be adopted by companies. They can help ensure a reduced demand and contribute to grid stability with targeted shutdowns (load shedding). These can also be short-term shut-offs, for example, in periods of little wind. Thus, instead of requesting additional production capacity, the demand is adjusted to the supply. This variant has the additional advantage of reducing energy losses due to transmission. However, any reduction in the demand must be accompanied by interventions on the supply side. On its own, the management of demand will not be sufficient to compensate for the fluctuations caused by renewable energies.

These load shifts have the same effect on the adjustment of supply as for storage power stations: increasing the load during current surges corresponds to charging an electricity storage and load reduction corresponds to discharging the storage. Therefore, load shifting can also be described as a form of 'virtual storage'.

3 Impact on the Insurance Sector

From this transformation process, i.e. from the combination of new and existing technologies, new risks for the insurance industry will likely emerge.

Technical insurance providers are of course particularly affected by risks caused by technological innovation. However, liability insurers may also need to adapt.

The operating modes of conventional power stations are changing. Operating hours are decreasing and the number of start-ups is increasing. The resulting deterioration of profitability is countered by the reduction of maintenance measures or by increasing maintenance and inspection intervals. Ultimately, the economic situation can lead to high losses and decommissioning. In addition, because they were never designed for such volatile conditions, transmission and systems technologies will have to be replaced. These factors lead to a considerably increased damage risk in terms of damage to property and damages caused by interrupted operation.

Under these changed operating modes, the current regulations for revision intervals after certain operating hours are no longer appropriate. Increased loads caused by a larger number of start-ups are not recorded. If network operators cannot manage to keep the grid voltage constant, these fluctuations can cause unplanned shutdowns with considerable damage to conventional power generation systems.

On the other hand, there are also opportunities for new revenue streams. The invitations to tender in the field of control energy may mean additional revenue for the operators of conventional power stations. Control energy is distributed by the network operators for a certain period of time in accordance with a fixed procedure. Calls for tender are separated between primary and secondary control energy and the minute reserve. Producers can then submit offers including their prices and provided quantities. The network operator then chooses the most favourable offers and the producers receive the corresponding remuneration. The results are then published at www.regelenergie.net.

The invitations to tender are published for both the positive and the negative control energy. Positive control energy refers to producing more electricity and negative control power refers to reducing consumption. This also results in fluctuations for companies that do not produce energy. These companies can also receive remunerations for reducing their demand when needed. The shares of the revenue thus obtained may be included in the insurance sums of the business interruption insurance even though they have nothing to do with energy production.

The consequence for insurers is an increased probability of damage due to higher loads on power stations during start-up and shutdown an as well as cost savings for maintenance and repair. On 27 October 2016 an article was published in the VDI Nachrichten with the title ‘Power Plants Operated for Wear’. In the field of business interruption insurance, risk assessment and calculation of losses from possible failures are much more difficult and confusing. One consequence of the altered operational modes is a much more uneven distribution of revenue throughout the year with strong fluctuations. In addition, the supply of control energy is hard to monitor. The tendering process and the volatility of the demand means that more variables need to be considered.

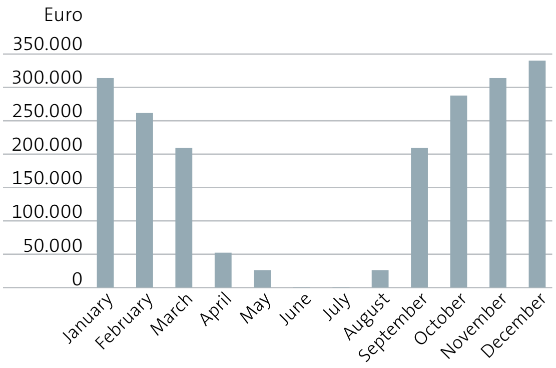


Figure 3: Annual distribution of the insurance sum; source: Teko

The merit order effect limits the use of conventional power stations for the benefit of renewable energies. The priority feed-in of electricity generated from renewable energies into the grid is legally binding.

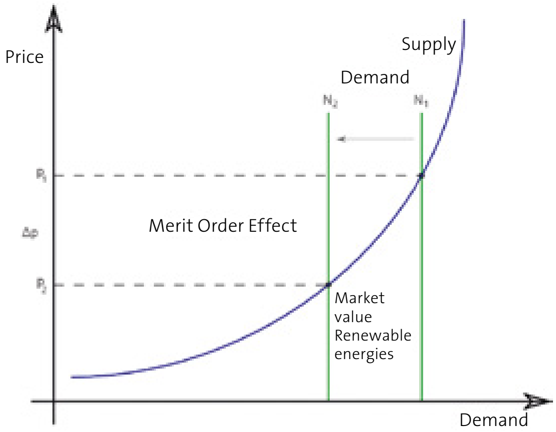


Figure 4: "Merit Effect" by Andromedus – own creation; source: Wikimedia Commons

Another new issue is the partial exemption from grid costs for electricity-generating companies. This exemption depends on the amount of the electricity purchased and the duration of use.

Companies with an electricity purchase of more than 10 GWh/a may apply for reduced grid charges, according to §19 of the Stromnetzentgeltverordnung (StromNEV).

The regulation provides for the following rates:
20 percent of the net charge at > 7,000 operating hours per year
15 percent of the net charge at > 7,500 operating hours per year
10 percent of the net charge at > 8,000 operating hours per year

Exempted companies pay a smaller portion of the net charge depending at the applicable exemption level. If, however, the total electricity purchase turns out to be lower than promised at the end of the year, the normal net charges apply retroactively. In case the highest level of exemption has been set up in advance, this can amount to a ten-fold increase of the network charges.

This scenario can be triggered, for instance, by substantial damage to the production facilities. The failure of continuous production due to machine damage for a period of 42 days can already lead to the withdrawal of the exemption.

Example: A power station plans a 98.4 GWh/a current purchase with a peak power of 12 MW and during a provisional period of 8,200 operating hours per year. Due to machine damage, the system is interrupted for two weeks. In this period, 3.6 GWh less of electricity are consumed than was planned, reducing the total consumption to 7,900 operating hours per year. As a result, the conditions for the highest exemption level are no longer met, despite the fact that the total consumption remains well over 10 GWh/a.

If the reduced power charge at the 10% exemption level was 500,000 euros, it will now double to 1,000,000 euros at the 20% level. And in the case of a complete loss, network charges will increase to 5,000,000 euros.

The adjustment of grid charges is shown in the table on the next page.

	Annual Usage Period = 2.500 h/a			
Connection to	**Performance price EUR/kW/a Net**	**Performance price EUR/kW/a Gross**	**Commodity price Ct/kWh Net**	**Commodity price Ct/kWh Gross**
High-Voltage network	40.61	48.32	0.07	0.08
Including transformation	43.92	52.27	0.33	0.39
Medium-Voltage network	44.34	52.76	0.56	0.67
Including transformation	54.74	65.15	0.46	0.55
Low-Voltage network	39.93	47.52	1.36	1.62

Source: Teko

The relevance for the insurer lies in the fact that further damage will be added to the actual production loss, representing a separate risk that should be considered.

The same applies to companies that are exempt from the EEG levy. These are companies with an electricity consumption larger than 1 GWh/a. If their consumption drops below 1 GWh/a, the exemption will be waived. This is regulated in Sections 40 et seq. of the Renewable Energy Sources Act (EEG).

Due to the increase in these levies, electricity prices for the consumer have been rising. In 2017, the EEG levy will rise to 6.8 ct/kWh.

As a result, instead of feeding their electricity into the grid, many producers are now mainly trying to cover only their own consumption. This is the case particularly for companies that need electricity in order to manufacture products. Their advantage then lies in a more cost-effective production. Only in the event of an interruption due to damage must the electricity be drawn from the grid, resulting in higher costs for the company (additional costs).

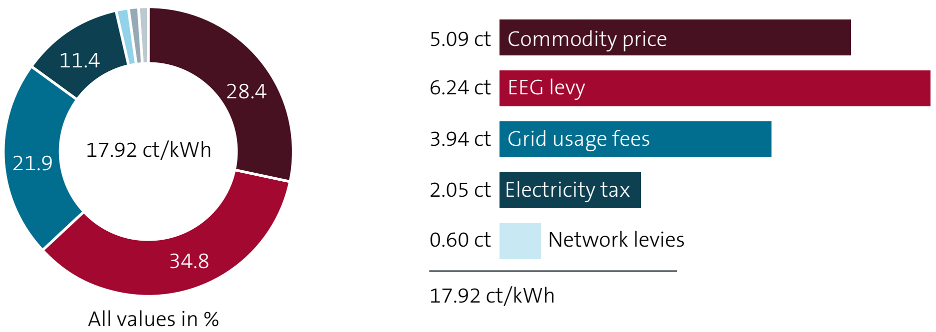


Figure 5: Composition of the price of electricity per kWh; source: Teko

Another worthwhile topic is the generation of revenue in regional electricity production by avoiding network usage. Paragraph 18 of the StromNEV Act specifies the relevant regulations and prerequisites for this scenario. Regional electricity producers who do not receive subsidies under the EEG and who generate electricity receive a remuneration if their electricity is consumed nearby and is therefore not passed through the grid or, rather, through all levels of the grid. The amount of remuneration depends on which networks are used. When a producer feeds their electricity only into the low-voltage network, they will receive the highest possible remuneration. If instead they also feed into the medium-voltage network, the compensation is reduced since only the high-voltage network can be avoided. However, the remuneration depends not only on the grid level but also on the self-generated peak power in May and the peak power of the upstream grid operator in November. Peak power is the maximum power measured in a period of 15 minutes. The remuneration is therefore time-independent and can be influenced only partly by the producer. Depending on the producer, the remuneration for the avoided use of the grid can reach seven-digit figures (in euros). This is the case, for example, for some municipal utility companies. For business interruption insurers, this represents a top risk due to the unpredictable character of short outages with these companies. The insurer's information requirements are therefore much more stringent with regard to these risks.

4 Conclusion

Because of the increasing importance of renewable energies, climate change and the phasing-out of nuclear power, the electricity sector is undergoing changes that involve considerable expenditures. Changes to the energy market not been this incisive since the establishment of the Federal Republic of Germany. However, their effects are not limited to Germany and will cause significant changes throughout Europe as well.

Many stakeholders consider this to be the project of our century. The changes are significant for all involved parties and pose continual challenges due to their long-term character.

The creation of the so-called 'intelligent networks' is the attempt to adapt to this process of change.

Due to the increasing interconnectedness of electricity supply, transport and demand (with linked control systems), networks are also becoming much more vulnerable to cyberattacks. Criminal operations will find it easier to collect extortion fees. And, by simulating an increased demand, a subsequent increase in electricity production could bring the whole grid to a collapse.

Technical innovations will catalyse additional changes and a respective need for adaptation. However, not all the solutions for problems relating to this ongoing transformation have been found. The maintenance of power supply and grid stability is still a dream of the future, a dream of a world without conventional energy sources.

The insurance industry and particularly the field of technical insurance is faced with the great task of accompanying this transformation. Being an active player is clearly the goal, but also presents major challenges for German insurance companies, as was the case with the Code of Conduct in offshore wind energy.

The ongoing changes are becoming increasingly complex and challenging; potential interruptions can no longer be solved by single risk bearers.

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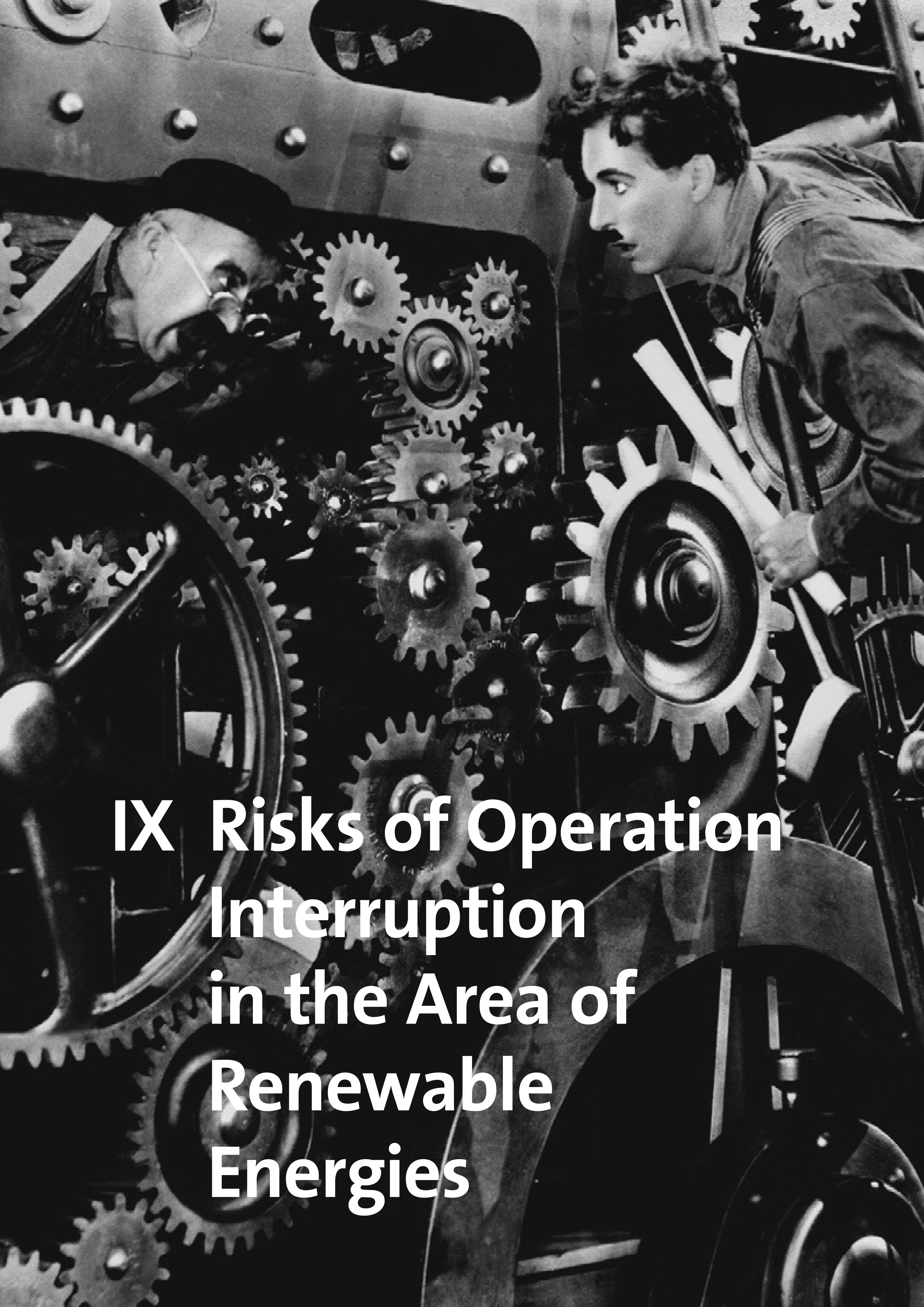

IX Risks of Operation Interruption in the Area of Renewable Energies

IX Risks of Operation Interuption in the Area of Renewable Energies

Introduction

Apart from liability risks, operators of renewable energy power stations face two difficulties. First, in the event of damage, their power stations must be restored and second, during outages they may not be able to realise the anticipated energy yield.

The planned revenues from power station operation must include financing, expenses and a profit margin. After the power station has been paid off, the profit margin can be increased. Due to higher maintenance costs, the share of expenses may increase as well.

These aspects must be included in any business plan and must be considered in all phases of the power station's service life. The same applies for fluctuations in revenue. Although remuneration rates are enshrined in the Renewable Energy Sources Act (EEG), the production volume and the costs of production will fluctuate.

In accordance with the Renewable Energy Sources Act (EEG), remuneration rates are continuously falling. As a result, the pressure to optimise the design of renewable power stations is increasing.

Human error plays an important role in any technology. Incorrect installation, maintenance or adjustment of equipment regularly results in damage. Though the human factor is significant, it is not an issue specific to renewable energies or to any of its technologies. For these reasons, human error will not be discussed here.

The effects of these individual aspects depend on the area of renewable energy. However, technologies are not the focus of this chapter since they have been individually discussed in preceding chapters. Instead, the general status quo in the field of renewable energies will be summarised here. Each subchapter is dedicated to one type of renewable energy.

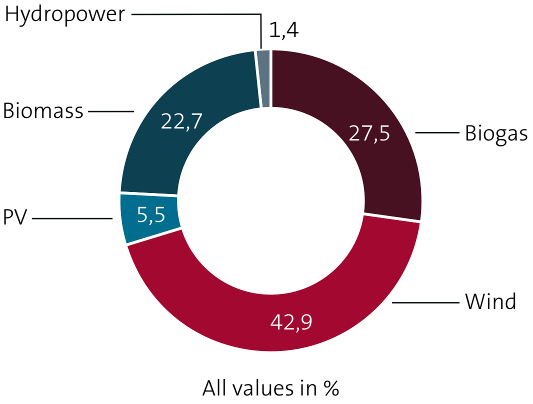

Figure 1: Distribution of remuneration in the renewable energies sector; source: Teko

1 Wind Power Stations

The greatest share of renewable energy is produced by wind power stations. In considering the risks, a distinction must be made between onshore and offshore wind power stations. Each of these two areas is characterised by very different risks, not only because of the size of the involved investments but because conditions on land and at sea differ.

Figure 2: Wind turbine damaged by fFire; source: Teko

1.1 Onshore Wind Energy

In the year 2015, onshore wind energy power stations produced a total of 77.1 TWh of electricity. The number of installations was 25,980 with a total installed capacity of 41.7 GW. Onshore wind energy power stations vary considerably in size and are installed either individually or in wind farms.

Operators of wind power stations must manage risks of diverse origin, including operational interruption, failure of technology, weather conditions, cost management and the legal side of grid access.

Feed-in tariffs determine the revenue and are regulated in the Renewable Energy Sources Act (EEG). However, revenues and earnings can also be increased through direct marketing. At this point, apart from these two, there are no further options for generating revenue.

The high share of renewable energies, and of wind power in particular, led to an adjustment of the Renewable Energy Sources Act (EEG) with respect to feeding. The rules regarding the safety of grid connections had to be changed. On windy days, grid operators may have to shut down their wind power stations, which is possible thanks to wind turbine control. Since wind power has become the single largest source of renewable energy, network operators have started demanding direct access to wind farm control systems, so they can regulate the electricity input from this source as required. The EEG 2009 Act obliges operators of wind power stations with more than 100 kW output to equip their power stations with the technical or operational capability to remotely reduce the feeding capacity during periods of grid overload. Furthermore, they must be capable of monitoring feeding levels in real time. The German federal government also issued a Regulation For The Improvement of Grid Integration For Wind Power Plants. It specifies the requirements for:

- the behaviour of the equipment in the event of a fault
- frequency stability
- detection methods
- the restoration of energy supply
- voltage stability and supply of control energy
- the expansion of existing wind farms (as well as for old power stations)
- retrofitting of older power stations in existing wind farms

1.1.1 Technical Risks

Certain risks originate from the periphery and the grid connection of wind power stations.

Compared to other influences, variable natural conditions (wind conditions) represent a significant risk for a wind power station due to the

high loads generated. Correspondingly, the requirements for the durability of components are stringent. Not all components will reach the expected service life of a wind turbine (20 years) and damage to these components often results in long operational interruptions. The longest delivery times are usually experienced for gearboxes, generators and transformers. In addition, the number of cable damages has increased.

Fires usually cause an overloading of the electrical systems resulting a total loss of the wind power station. Possible causes for a fire are failing brake systems or a lack of lubricant in the generator or a gearbox.

An extinguishing system is not usually installed inside the gondola. This and the inaccessibility of gondolas to the fire brigade usually leave operators with the sole option of letting the power station burn down in controlled manner while ensuring that no further damage is caused from falling parts. These types of damage are relatively rare, but their financial consequences can be all the greater.

Downtimes depend on repair times, delivery times for the damaged or destroyed parts, the weather and the availability of truck-mounted or crawler cranes.

1.1.2 Natural Hazards

The most typical types of damage to wind power stations are caused by lightning strikes. Generally, these damages are limited to the rotors. Incorrect or insufficient lightning protection can lead to damage to other components, including a total loss of the power station due to a fire.

Furthermore, although damage from heavy winds or floods is rare, it cannot be ruled out. Particularly in the event of a storm, a failure of the braking systems can cause a fire or overspeed damage.

1.1.3 Official Requirements

If the damage to a wind power station is so great that it must be replaced, certain official requirements must be fulfilled. The permitted type of power station is specified in the certificate of approval for the construction of a wind power station. Also, if the operator’s permission is no longer valid or no authorisation for repowering is issued, he is not authorised to install a new power station on the site of the old one. In both cases, a new and often lengthy approval procedure must be endured, extending the interruption period.

1.1.4 Maintenance Contracts

Maintenance contracts can limit the risks the operator must take on. There are different types of maintenance contracts, from those limited to normal maintenance operations to full maintenance contracts. The manufacturer Enercon was the first to introduce a full-service contract in collaboration with its partner, Konzept. Other manufacturers have since followed suit. Today, a number of independent companies also offer maintenance contracts.

The difficulty in evaluating maintenance contracts lies in their diverse focus points. Therefore, their contents must be examined very carefully. A full-service contract may contain several restrictions that exclude certain risks. These exclusions may refer to components, or they may define limitations with respect to point systems or maximum limits. All exclusions of individual risks must be determined. As a rule, external hazards are excluded. Damages caused by wind speeds within the operational range specified by the manufacturer are usually covered.

Unfortunately, full maintenance contracts are quite diverse as well. As a result, basic knowledge of the contract type does not necessarily entail a reliable understanding of the actual insurace coverage.

Independent maintenance companies face the additional difficulty of being forced to maintain stockpiles of spare parts to repair potential damages.

Full maintenance contracts include defined times of availability of the wind power station or the wind farm in question. The availability is calculated based on various factors, including planned shutdowns, outages outside the control area of the maintenance company, standstills due to repairs and other factors. No uniform definition exists for these calculations. The defined availability generally lies between 95–97%. If maintenance reduces the availability beyond a certain predefined limit, compensation payments to the operator are due.

Any risk of damage that is not covered by a maintenance contract remains with the operator.

1.1.5 Damage Assessment from the Machinery Loss of Profits Insurance Perspective

Due to their variable nature, the aforementioned factors represent major challenges for insurers. This applies to both the insurance coverage and the calculation of losses.

Depending on the incurred damages, individual factors will enter the calculation of the compensation. For instance, the missed energy production during an outage will depend primarily on the wind conditions.

In this case, an adjacent identical power station can be taken as a reference. Of course, in the relevant period the reference power station should not have been damaged or remain out of service due to maintenance operations. If no reference power station is available, the process of determining the wind pressure and thus the energy that could have been produced during the respective time period will be considerably more complex.

Apart from these factors, the failure of a wind power station can also be caused by damage to a substation or to the cabling outside the wind farm. In particular, damage to a substation can result in the failure of a whole wind farm. This type of damage (retroactive damage) can be insured as well.

The expansion of a wind farm may require the linking of new power systems to older ones. In this case, the failure in the older system may lead to the failure of new power stations. The required insurance against this scenario is similar to the insurance against substation failure. Differences can result from the ownership structure of individual wind power stations.

Onshore wind power stations produce hardly any variable costs. Variable costs can therefore be ignored during loss assessment.

1.2 Offshore

Figure 3: Trianel offshore wind park Borkum West II; source: Teko

1.2.1 Special Features of Offshore Sites

At sites in the most promising coastal areas, wind power stations deliver an annual performance of about 25–30% of what is theoretically possible at full load. Due to stronger and more constant winds at offshore sites, offshore wind farms are expected to yield 45–50% (3,942 to 4,380 full-time operational hours) of their theoretical maximum output. Thus, the electricity yield can – theoretically – still be increased by 66%. Start-up wind speeds for wind turbines are usually at 2.5–4.0 m/s, while shutdown is usually initiated at 20–25 m/s. Rated power can already be reached at wind speeds of 12–15 m/s.

It must be considered that the transformer and the cable to the mainland can cause considerable losses, reducing the amount of remunerated feeding.

For offshore wind parks, an onshore reserve is indispensable to ensure the availability of the power stations.

Depending on the size of the wind farm and its distance to the feeding point on the mainland, the electricity is transported onshore either directly via a land cable or via a substation in the wind farm.

Sea cables must be protected against damage from external events. For this reason, they are embedded into the sea floor. In hazard-prone areas, such as crossings with shipping lanes, rock beds or special mats offer additional security. Cables are laid by specialised ships. Only a few companies have the required expertise. If crossing cables already laid sea or a dyke along the coast, particularly difficult methods such as horizontal directional drilling (HDD) must be carefully planned and performed by the commissioned companies.

Offshore power stations are not always accessible due to the highly variable weather conditions. Moreover, specialised maintenance (crane ships, jack-ps, cable distributors) are not always available. For extensive retrofitting or damage recovery measures, it can therefore be beneficial to bring the entire gondola onshore to allow the necessary work to be carried out under weather-independent conditions.

Offshore power stations feed into the 380-kV grid. The grid connection is one of the main risk components of an offshore power station. Provided there are no redundancies, in the event of a damage, all connected wind turbines will be disconnected from the grid. The same applies for today’s centralised cable routes that connect offshore wind farms to the feeding points of the onshore distribution network. Here, planning must strike a balance between redundant and simple solutions. Technical innovations are required to connect individual wind power stations with distances of 500–1000 m with sea cables. A wind farm can be of rectangular or square shape, with an edge length of, for example, 10 km. If a wind farm with these dimensions consists of, for instance, 120 power stations, they will cluster in subgroups. Each subgroup connects to its own medium voltage switching station. These switching stations in turn all connect to a single substation. In the medium-voltage range, wind power stations can cluster to groups of five or ten in stub ring circuits. This has the advantage of limiting the number of power stations affected by a failure of one of the stubs or ring circuits. In the event of failure of the central connecting cable, the number of affected power stations is significantly higher.

Today’s onshore high-voltage grid is working to capacity on most days. As a consequence, it may not be able integrate additional offshore power. Thus, the additonal wind power that is planned for the period from 2012 to 2020 will have to be transported via a high-voltage direct current transmission (HVDC) to the southern metropolitan and consumption areas, where it is then fed into the regional network (Verbundnetz). For this purpose, transmission capacities in the center and the south of Germany will have to be expanded significantly.

It is economical for larger wind farms to transmit electricity to the mainland at a higher voltage and, if appropriate, as a direct current. This way, transmission losses are minimised. The required technology is kept on a separate platform.

In order to keep the number of submarine cable connections to onshore network nodes as small as possible, network operators group wind farms into clusters and provide a large substation platform for each cluster, which in turn receives the electricity from smaller platforms within each cluster.

The site of this platform is determined by the environmental conditions. Due to its central importance for the operation of the wind farm, usually a location is selected that is exposed as little as possible to shipping traffic. In addition, on the platform for the substation, common rooms for maintenance personnel can be provided as well as a space for the emergency power diesel generators for the wind farm. In the event of a dis-

ruption of the land connection, the diesel units ensure an energy supply for the functions of the entire wind farm that are critical to its continued performance.

If the distances to the mainland are long, a high-voltage direct current (HVDC) is used to transfer electrical power in order to minimise transmission losses. The required rectifiers also have to be accommodated on the substation platform. This technique is now being used for the first time on the BorWin Alpha platform to minimise transmission losses in a cable that runs over 125 km via Norderney and Hilgenriedersiel to the mainland. Experiences with HVDC systems could already be gained from the power supply to large oil drilling platforms.

In large wind farms, a separate substation platform receives electricity from individual wind power stations and converts it from medium (~30 kV) to high voltage (110 kV or higher) before transferring it to the feeding station of the transmission grid operator. The topside and jacket are usually prefabricated on land.

1.2.3 Assessment from the Machinery Loss of Profits Insurance Perspective

Some factors that may have a significant negative effect on the operational disruption at sea have already been presented in the preceding chapters. At this point, four of these factors will be highlighted that must be regarded as essential. They are, however, not meant to detract from other causes that can lead to considerable operational interruptions as well.

Delayed Repairs Due to the Restricted Availability of Specialised Vessels

The large number of offshore projects that are being realised in parallel implies the reduced availability of those specialised repair vessels. They feature large cranes, lifting platforms and cable distributors. By commissioning their own ships, manufacturers and project managers have already started responding to anticipated bottlenecks, which are, however, expected to disappear in the medium term. To assess the operational risk of interruption, the availability of specialised vessels to wind farm owners or operators will play a decisive role. The risk is aggravated in the event of simultaneous damage to several wind farms, for instance due to a natural hazard or series of damages.

Delayed Repairs Due to Maritime Environmental Conditions

Maritime environmental conditions can prevent access to a wind power station over long periods of time. If a single wind power station becomes inoperable, the financial damage remains within ‘reasonable’ limits. However, if several power stations fail for longer periods, the resulting interruption losses can become unsustainable. It is thus understandable that, apart from weather conditions, transport ships and specialised ships are of central importance in this context.

If possible, the personnel and material required for a repair must be transported safely to the wind power station (including both transport at sea and transfer/loading onto the wind power station).

In this context, it should be kept in mind that, due to a lack of practical experience, many repair companies are dealing with difficult boundary conditions, such as sea waves more than two metres high. Some repairs are likely not to be performed in a speedy manner, due to other physiological boundary conditions (e. g. nausea).

Some wind power stations also allow repair personnel be transferred by helicopter, either by landing on the power station or by abseiling. Experience has shown, however, that abseiling in extreme conditions (e. g. strong winds) from a helicopter is a high-risk activity for humans. Nevertheless, this approach offers a considerable advantage for German offshore projects: transport times are much shorter, so even short windows with favourable weather can be used.

Damage to the AC Substation

In the event of a failure of the substation platform itself or parts of its technical equipment, for example the transformers, the feeding capability of the entire wind farm is affected. Typically, a ‘bottleneck’ situation will emerge, which can bring the entire farm to a halt. Whether the operation of a wind farm can be sustained at least in part depends on the number of mutually independent strings in which the voltage conversion takes place. For instance, instead of single large components (e.g. transformers), which are difficult to replace and have long delivery times, two parallel units with reserve capacity can be installed.

With this design, damages like the one experienced at the offshore wind farm Nysted can be avoided. In June 2007, during the warranty period, the substation failed after a fault in the main transformer. The 140-tonne, four-year-old transformer from an Italian manufacturer had to be dismantled and brought ashore. The transformer was the one central feed-in point for 72 wind power stations with a capacity of 2.3 MW each. Until the repair of the transformer was completed several months later, none of these 72 power stations could feed into the grid.

Damage to the HVDC Substation Platform

An HVDC substation can process the electricity generated by up to three wind farms. This, however, also means that, in the event of a loss of the HVDC platform, the individual wind farm operators can experience substantial losses. In the case of major damage to the HVDC substation, the recovery can take up to 24 months, during which the lost feeding remunerations alone can amount to hundreds of millions of euros per year. Like natural hazards, this scenario entails high accumulation potential for the insurance industry.

Damage to Sea Cables

The second scenario which may cause a major interruption to the operation of a wind power station is damage to a sea cable. How important a particular sea cable is to a wind farm’s operation depends on whether the cable belongs to the internal or external cabling.

While internal cabling bears the risk of being damaged due to improperly anchored service boats or by transport/repair vessels (e.g. jack-up vessels), external cabling is exposed to other risks, e.g. emergency anchorage manoeuvres performed by large ships.

The effects of damage to a sea cable are diverse. The consequences range from the operational interruption of individual wind power stations and the failure of individual production strings (wind power stations connected in a series) if the internal cabling is affected to the failure of the entire wind farm in the event of damage to the external cabling. In an offshore wind farm with 80 power stations with an output of 5 MW each, damage to the external cabling can lead to revenue losses of approximately 800,000 euros per day.

Repairing a damaged sea cable can take a long time. Apart from specialist personnel, ROVs (remote operating vehicle), suitable vessels and sufficient replacement cables must all be available. Even if these conditions are met, the operation still requires a window of suitable weather.

Business interruptions hold the greatest loss potential for offshore wind farms. Contingent Business Interruption losses (CBI losses) due to the failure of services provided on land cannot be ruled out. Also, in the case of an excessively large supply of electricity, transmission system operators have the power to intervene and reduce the feeding capacity. The electricity not generated due to such measures is remunerated with 90% of the relevant feed-in tariff.

2 Photovoltaic Power Stations

Figure 4: Photovoltaic system; source: Teko

In the field of photovoltaics, we distinguish between ground systems and roof systems.

Depending on the location of the power station, the possible proportion of annual full load hours is 10–20%.

The technology in roof and ground systems is fundamentally the same. However, the respective hazards are different.

Since other types of solar power stations currently play a minor role in electricity production, they will not be considered here.

2.1 Roof Systems

The generation of energy with roof systems depends on the available roof area. In January 2012, the electricity prices were higher than the feed-in tariffs for the power stations, resulting in a change in usage. Until then, photovoltaic power stations were built to benefit from higher feed-in tariffs defined in the Renewable Energy Sources Act (EEG). Since 2012, however, photovoltaic power stations have increasingly been used to cover their operator's own electricity consumption. Additional battery storage can be installed that makes it possible to buffer and consume the generated electricity at the appropriate times. To what extent electricity is stored also depends on the targets of the operator. If he or she wants to be as independent as possible from external power sources, the operator can use the option of storage, in contrast to the operator who aims at saving electricity costs. In both cases, the investment in the storage is balanced against the savings it creates. Lithium and lead batteries are commercially available. In addition, they can accept a direct current (DC), alternating current (AC) or both. This also depends on the system being used.

2.1.1 Technical Risks

The failure of a photovoltaic system or of an essential part can significantly increase losses, particularly if the damaged parts can no longer be purchased. Many manufacturers have disappeared from the market and a replacement with modules from a different manufacturer is not always straightforward, since all other components would still be tuned to the original module type. Without being adjusted to the overall system, foreign modules can cause additional damages.

The greatest risks still lie in poorly executed installations, the incorrect laying of cables and a failure to observe safety regulations.

The additional components used for storage have been increasing the total risk of failure. Which technology – photovoltaics or electricity storage – is less susceptible to, cannot be said for certrain, based on today's limited experience.

2.1.2 Natural Hazards

Natural hazards do not only comprise the weather conditions. Damage is also caused by animals; cables especially are often bitten by martens. The installation of protective devices is highly recommended, particularly in areas full of animals.

Damages caused by hail are tending to increase due to the increasing frequency of thunderstorms and large hailstones (stronger impacts suffered by photovoltaic modules).

Two more hazards are snow pressure and ice loads. In winters with a lot of snow and longer

periods of frost, this risk is increased, as seen in the winter of 2009–2010. Snow can melt from sunlight during daytime and turn into a layer of ice during the night. Additional snowfall may then exceed the maximum loads, causing rows of modules to collapse.

Both direct and indirect lightning strikes carry enough energy to cause damage to photovoltaic power stations. In the worst case, a lighting bolt can create a fire that destroys the entire power station and the building.

Storm damage is also a significant risk factor. Damage to solar modules can be caused by inadequately secured components, by parts of the roof or by tree branches that are hurled around.

2.1.3 Theft

Theft is a major risk in the field of photovoltaics. Modules and inverters are often stolen and sold.

2.1.4 Buildings

The building itself or the objects stored therein can also present a risk to photovoltaic power stations. For example, if a fire damages the building, even an undamaged photovoltaic system may not be operable. The goods stored in a building can pose an increased fire risk. For instance, straw or hay stored in a barn is a significant fire hazard.

2.1.5 Damage Assessment from the Electronics Loss of Profit Insurance Perspective

The integration of electricity storage into photovoltaic power stations has rendered calculating the losses caused by an operational interruption significantly more demanding. The amount of energy that could have been generated depends on the season and the weather conditions in the respective year. For instance, modules that are covered with snow cannot generate electricity at all. Also, a power station's performance declines with age. Finally, contamination can lead to a further loss during feeding.

Whereas in previous years, only the lost feed-in tariff was relevant for the calculation of losses, now, the extent to which the electricity would have been used by the producer himself, either directly or from storage, becomes a separate question.

In the case of fire damage, the failure time can take a few days up to a year or longer.

Insurers have developed models to simplify the processing of claims as much as possible. The year is divided into so-called summer and winter remunerations.

As a result, the calculated losses can turn out to be considerably off the actual figures. In most cases, the difference is small compared to the effort that could have prevented the failure in the first place. It is even more difficult to calculate the costs saved from using an electricity storage system. If only the storage fails, the amount of damage is limited to the proportion of the produced electricity that could not be saved. However, that electricity could still have been fed into the grid. Thus, the difference is a function of the size of the storage and usually remains relatively small. The loss can, however, increase due to changing electricity prices for private households and changes to the feed-in tariffs, as detailed in the Renewable Energy Sources Act (EEG).

In the event of a failure of the photovoltaic system itself, the interruption damage increases if no storage is installed.

The losses can be estimated from the power consumption of the household or the company before and after the damage period.

The topic is still relatively new. A widely used system has not yet been established.

In any case, it is necessary to include these risks when applying for insurance because otherwise, revenue in the form of saved energy costs will not be covered.

EXAMPLE OF DAMAGES

Due to a voltage surge, 1,010 photovoltaic modules were damaged. This resulted in a failure of 24 strings with 20 × 195 Wp modules as well as 52 strings with 20 × 190 Wp modules, reducing the output of the solar power plant by 291.20 kWp

The bypass diodes of the affected modules were replaced and the modules were then tested for any other damage. 111 modules with 190 Wp as well as 29 modules with 195 Wp showed irreparable damage. These modules were disassembled and replaced with intact modules from the same power station, which meant that in the end only seven strings (each with 20 modules) with a capacity of 27.16 kWp were out of service. Then, the 140 damaged modules were replaced. Since then, the photovoltaic power station has been running at full capacity. The total losses caused by the interruption in operation amounted to 14,000 euros.

2.2 Ground Systems

The overall performance of ground based systems is many times higher than that of roof systems. The hazards are often the same as for roof systems, but there are also differences. In the following sections, only these differences will be considered.

2.2.1 Natural Hazards

The risk of flooding is considerably higher with ground systems than for roof systems. Damages from natural hazards show an increasing trend as a result of changing weather conditions.

2.2.2 Theft

Ground systems are a more rewarding target for thieves than roof systems. This is due to the smaller number of parts that have be removed and the simpler disassembly of these parts. Thieves will not have to climb on a roof, the power stations are usually in the countryside, with few people around, and security measures are often insufficient. The cost-effectiveness of an installation can boil down to the investment – or lack therefore – in security facilities.

2.2.3 Damage Assessment from the Electronics Loss of Profits Insurance Perspective

In the insurer's view, missing or insufficient protective measures represent a significant risk with a potentially strong impact on the operator. The required protective measures, as identified from the insurer's claims experience, must be explicitly stated by the insurer as neccessary conditions for insurance coverage. Interruption losses resulting from theft are relevant due to their extent and duration.

When an installation is affected by flooding, the extent of the interruption can be minimised by shutting down the power station early enough and completely drying and cleaning (where appropriate) all components before recommissioning. Specialised companies offer this service.

Ground systems usually generate revenue from the feed-in tariffs, detailed in the Renewable Energy Sources Act (EEG). Larger battery storage power stations, however, are becoming increasingly popular. The difference between them and roof systems is a question of ownership. Battery storage power stations are usually run by specially founded companies which market the electricity stored in their batteries. The situation is to be viewed in the same way as in the case of roof systems: the operator of a photovoltaic system and the insurer have no influence on the damage to the battery. The resulting CBI losses represent the interruption losses for the operator of the ground installation.

If electricity from a ground system is fed into a private substation, this can also cause CBI damage. The same situation can arise when the power station is connected to a public substation (built and operated by the grid operator). However, the risk of failure is lower in this case.

3 Biomass

Both solid and liquid substances are used as biomass. If biomaterial is used to produce gas, then the applied technology is called a biogas power station. However, if the substances are used directly as fuels, then the installation is a biomass power station.

3.1 Biogas Power Stations

Biogas power stations generate and treat gas. Some of them utilise it straight away in a combined heat and power unit (CHP). The treated biogas can also be fed into the gas network.

3.1.1 Technical Risks

Motors in the combined heat and power unit hold the greatest technical risk potential. The varying quality of the produced biogas can lead to high stress on or damage to the unit's engine. Damage to agitators, often due to excessive sulfur contents, and damage to the gas treatment system must also be considered.

Damage is often provoked by ignoring maintenance intervals. The same applies for missed or insufficiently performed examinations of the engine lubrication oils. This can also cause fire damage.

3.1.2 Natural Hazards

Damage caused by natural hazards does not play an overly important role for biomass power stations. Only a few cases of damage due to storm or hail have been reported.

3.1.3 Damage Assessment from the Machinery Loss of Profits Insurance Perspective

The insurer must examine the entire process, from the delivery of the raw materials to the production of energy and the disposal of residual material. Any obligations for acceptance or delivery must also be determined. The electricity fed into the grid is remunerated according to the levels specified in the Renewable Energy Sources Act (EEG). It should be kept in mind that after relatively short downtimes, the insurer will base his refund on the lowest remuneration level, even if a higher level is achieved during the rest of the year. The operator can also generate revenue from the supply of heat, for example to a greenhouse. These revenues are included in the insurance with the appropriate figures. If a delivery obligation exists, the operator of the biogas power station has to bear the resulting additional costs for an alternative heat supply. The extent of this obligation (in full or in part) is set out in the delivery contract.

It must also be determined whether the acceptance of biomass deliveries is obligatory (fully or partly). If such an obligation exists, this can result in increased costs in the event of a longer failure, when storage capacities are met and the biomass is sold and transported to another customer.

As a rule, the operator of a biogas power station has to pay for the disposal of fermentation residues. This aspect and particularly the costs of disposal must be examined.

Re-procurement options should be determined if delays are to be insured that are caused by a damage-related dysfunction of the biological process in a fermenter.

EXAMPLE OF DAMAGES

In a fermenter with a capacity of 2,500 m^3 along with the maize silage an iron rod entered the fermenter and damaged the agitators. The iron rod had served to secure a foil that was stretched over the maize silage. The fermenter fed a total of three combined heat and power stations with a total output of 1,100 MW.
The broken agitators had to be replaced. The resulting downtime was 43 days. The business interruption loss amounted to 130,000 euros.

3.2 Biomass Power Stations

Figure 5: Biomass power plant; source: Teko

Most biomass power stations process wood of varying quality (A1 to A4).

3.2.1 Technical Risks

In biomass power stations, most of the damage is observed in the combustion chamber or the turbine area. Inhomogeneous fuels can cause an irregular combustion process, resulting in caking and abrasion due to increased waste gas velocities caused by deposits. Water of poor quality can damage conventional turbines. The higher incidence of damage to biomass power stations is also due to the lack of safety equipment and insufficient qualifications of the operators.

3.2.2 Natural Hazards

For biomass combined heat and power stations, damage caused by natural hazards plays only a minor role.

3.2.3 Damage Assessment from the Electronics Loss of Profits Insurance Perspective

Interruption losses can arise from faults of the combustion technology. Often the root cause is less than optimal fuel treatment (partiality, residual moisture) or the fact that the biomass is not suitable for the respective firing technology.

As for biogas power stations, all processes of the operation of the combined biomass heating and power station should be examined.

The electricity fed into the grid is remunerated as detailed in the Renewable Energy Sources Act (EEG). The insurance sum is this renumeration minus all costs that are no longer incurred due to the interruption. Revenues from heat supply may have to be added. If the operator has an obligation to supply heat, the costs for alternative heat generation, for example with gas boilers, must be added to the insurance sum. All obligations are spelled in the heat supply contract.

It must also be determined whether an acceptance obligation (part or full) exists for purchased biomass. If this obligation exists and the storage capacity is insufficient, a longer period of failure can cause increased costs. In this scenario, the unused biomass will have to be sold and transported to another customer.

The costs of ash disposal must be deducted.

EXAMPLE OF DAMAGES

Shortly after the commissioning of a steam turbine, after revision and repair of the generator, the turbine automatically turned itself off due to strong bearing vibrations. The vibrations were caused by a broken tooth on the sun pinion of the load transmission. After the turbine ran for about eight hours in its slewing bearing, this caused a defect on the turbine rotor. These two mutually independent material damages were caused by a material defect in the sun pinion, the inappropriate operation of the coupling and insufficient removal of water from the turbine before reassembly after the revision had been completed.

The gearbox was provisionally fixed and the turbine could be operated again. After eight months, the damaged sun pinion was replaced. The business interruption loss amounted to 1.2 million euros.

Figure 6: Torn sun pinion with broken teeth; source: Teko

4 Geothermal Energy

In Germany, geothermal energy is being exploited in two areas. The first is the heating of buildings: near-surface geothermal energy uses the heat in depths up to approximately 400 m and temperatures up to 25 °C for the heating and cooling of buildings, technical installations or infrastructure facilities. The heat is extracted from the ground, from near-surface rock or from ground water.

The second area is deep geothermal energy: deep geothermal reservoirs that are developed at depths of more than 400 m. It is possible to exploit the heat that is stored in deep and dry rock, or in hydrothermal layers, i.e. mixed rock and ground water layers.

In Germany, exploitable geothermal layers are found in depths of 1,000–5,000 m. The great depths make the exploitation of these layers quite challenging. Drilling is expensive and if it does not result in success, the interest quickly vanishes. The number of setbacks caused by such failures can lead to a reduced demand.

These hurdles highlight the prospecting risks. The drilling itself is not a simple risk and not finding the expected parameter values is an even greater one. This risk is referred to as the prospecting risk.

In Germany, 15 sites are currently being used to generate electricity from geothermal energy. Altogether, there are 34 sites that use deep geothermal energy. Their total output is 37.69 MW of electrical and 280.68 MW of thermal energy.

4.1 Prospecting Risk

The prospecting risk, i.e. the probability of not finding the projected values for the temperature and quantity parameters of thermal water, has a decisive influence on the willingness to invest in geothermal projects. As a rule, the more effort that goes into site exploration, the lower the prospecting risk will be. The temperature predicted for a target horizon is less problematic than the predicted production rates. For this parame-

ter, the risk is significant given the high drilling costs. Significant are the parameters mass flow, temperature and sustainability, i.e. the possible duration of use. Recently, a state-initiated insurance fund has been discussed as an option for offsetting this risk. This fund would be intended to bridge the time until usable statistical data are available and to render the prospecting risk 'predictable' for the insurance industry. Geological and technical risks are not part of the possible insurance coverage.

The insurance provider Munich Re initiated an 'actuarial pilot project': it was intrepid enough to conclude the first private-sector insurance contract for a deep geothermal borehole in Unterhaching in Germany. Further projects have followed.

Productivity risk insurance covers the losses incurred if, despite stimulation measures, a borehole cannot be used for the intended purpose. The maximum loss is composed of the drilling costs plus the cost of stimulation measures. The prospecting risk is defined by the parameters of flow rate and temperature.

For the conclusion of a productivity risk insurance plan, the following information must be made available:

- geological and hydrogeological expert opinions on the planned project
- a feasibility study on the planned project
- a project plan
- reference data (close-by drillings with test results)
- a drilling plan, including stimulation measures and costs
- a definition of insured events

4.2 Failure of a Geothermal Power Station

4.2.1 Technical Risks

Apart from the high risks involved in drilling, the normal risks of operating a power station must taken into account.

4.2.2 Natural Hazards

The thermal water poses challenges to the water cycle of the system. The composition of thermal waters often leads to damage to the technology. In particular, depth pumps are very vulnerable and must be replaced regularly.

4.2.3 Damage Assessment from the Machinery Loss of Profits Insurance Perspective

The operating risk is more manageable than the development risk. ORC turbines with up to a 5 MW output generate the electricity. Turbine damages can also take several months to repair.

Geothermal power stations can be operated fairly continuously throughout the year; 8,000 operating hours can be achieved.

5 Hydropower

5.1 Technical Risks

Hydropower technology is well-established; however, the opportunities to expand this technology are limited, at least in Germany. As a result, the market is not particularly innovative. A variety of small and medium-sized facilities exists.

Power stations that are integrated in dams and operated by one of the major energy producers are not considered here. These power stations produce the largest share of energy in this area and are usually not insured by technical insurers.

5.2 Natural Hazards

In this area, water hazards are of the highest significance. In response to past experiences, these hazards have become largely manageable.

5.3 Damage Assessment from the Machinery Loss of Profits Insurance Perspective

The biggest issue from an insurer’s point of view is the fact that most hydropower power stations are old and are often operated as a side project. Most of these power stations are not very big and have a manageable performance and thus a limited yield.

These systems are not always adequately maintained and revised, resulting in damages that can take several months to fix.

6 Outlook

The updated Renewable Energy Sources Act 2017 will instigate further developments in the field of renewable energies. The next invitation to tender will likely reveal exciting innovations. It remains to be seen whether the invitation will also result in ‘savings’ that negatively affect the reliability and/or service life of components.

The field of geothermal energy shows strong potential for continued development. However, it remains to be seen to what extent the legal framework will support the development of new geothermal sites.

The challenges for the industry remain high. Apart from technical challenges, the topic of energy storage and availability is also a question of possible implementation speeds.

7 Conclusion

Renewable energies will continue to gain in importance. In the foreseeable future, the relative contribution of the various areas of renewable energy will not change significantly. It remains to be seen to what extent the industry will be able to benefit from the phasing-out of nuclear power and the decline of fossil fuels.

The overall goal should be independence from fixed remuneration rates for the production of electricity, since in the long term the operation of renewable energies will depend on competition.

The insurance industry must respond to the changes experienced in all areas of renewable energy and track these changes as closely as possible. Insurers have proven their willingness to take on these challenges. Recently, they presented the first code of conduct for the field of offshore wind energy. Renewable energies will benefit from this commitment.

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X List of Abbreviations

AC	Alternating Current
AF	Air Forced
AFC	Alkaline Fuel Cell
AN	Air Natural
AS	Ancillary Services
ASC	Anode-supported Cell
BtL	Biomass to Liquid
BDEW	Bundesverband der Energie- und Wasserwirtschaft (Federal Association of the Energy and Water Industry)
BOP	Blowout Preventer
BWP	Bundesverband Wärmepumpe (Federal Association for Heat Pumps)
CBI	Contingent Business Interruption
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CMS	Condition Monitoring System
CTV	Crew Transfer Vessel
DC	Direct Current
DEFC	Direct Ethanol Fuel Cell
DGS	Deutsche Gesellschaft für Sonnenenergie e. V. (International Solar Energy Society, German Section)
DIBt	Deutsches Institut für Bautechnik (German Institute for Construction Engeneering)
DMFC	Direct Methanol Fuel Cell
DVGW	Deutscher Verein des Gas- und Wasserfaches e. V. (German Association for Gas and Water Applications)
DWW	Druckwasserwäsche (Pressurised Water Scrubbing)
EEG	Erneuerbare-Energien-Gesetz (Renewable Energy Sources Act)

EEZ	Exclusive economic zone
EnLAG	Energieleitungsausbaugesetz (Power Grid Expansion Act)
ENS	Einrichtung zur Netzüberwachung mit Schaltorganen (Islanding Protection System)
EnWG	Energiewirtschaftsgesetz (Energy Industry Act)
ESC	Electrolyte-supported Cell
EVA	Ethylene vinyl acetate
EWTC	European Wind Turbine Committee
EZE	Zertifikat für Erzeugungseinheiten (Certificate for Generation Unit)
FC	Fuel cell
FET	Stahl-Fundamenteinbauteil (Foundation component)
FGW	Fördergesellschaft Windenergie und andere Erneuerbaren Energien e. V. (German Society for Wind Power and Other Decentralised Energy Sources)
GDL	Gas Diffusion Layer
GDV	Association of German Insurers
GFRP	Glass-fibre Reinforced Plastic
GRD	Geothermal Radial Drilling
GU	Generalunternehmer (General Contractor)
HDD	Horizontal Directional Drilling
HDPE	High-Density Polyethylene
HDR	Hot Dry Rock
HVDC	High-voltage, Direct current
IGBT	Insulated-gate Bipolar Transistor
INDCs	Intended Nationally Determined Contributions
IP	International Protection
ISET	Institut für Solare Energieversorgungstechnik (Institute for Solar Energy Supply Technology)
LBO	Landesbauordnung (German building regulations)

M5BAT	Modular Multi-Megawatt Multi-Technology Medium-Voltage Battery Storage System
MCFC	Molten Carbonate Fuel Cell
MEA	Membrane electrode assembly
MPP	Maximum Power Point
MSC	Metal-supported Cell
MWD	Measurement While Drilling
MWS	Marine Warranty Surveyor
NABEG	Netzausbaubeschleunigungsgesetz Übertragungsnetz (Grid Expansion Acceleration Act)
NawaRo	Nachwachsende Rohstoffe (Renewable Resource)
NEP	Netzentwicklungsplan (Network Development Plan)
NOW	Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie (National Organisation Hydrogen and Fuel Cell Technology)
OCoP	Offshore Code of Practice
O-NEP	Offshore-Netzentwicklungsplan (Offshore Network Development Plan)
ORC	Organic Rankine Cycle
OSS	Offshore substation
PAFC	Phosphoric Acid Fuel Cell
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
PID	Potential-induced degradation
PSA	Pressure swing adsorption
PTFE	polytetrafluoroethylene, trade name: Teflon
PtG	Power to Gas
PV	Photovoltaic
PVT	Photothermie
ROV	Remote operating vehicle

SMA	Service & maintenance agreement
SOFC	Solid Oxide Fuel Cell
STC	Standard test conditions
StromNEV	Stromnetzentgeltverordnung (Electricity Network Fee Regulation Ordinance)
TA Luft	Technischen Anleitung zur Reinhaltung der Luft
TCO	Transparent conducting oxide
TP	Transition piece
TÜV	Technischer Überwachungsverein (Technical Inspection Association)
UNFCCC	United Nations Framework Convention on Climate Change
VDEW	Verband der Elektrizitätswirtschaft e. V. (Central Association of the German Electrical and Information Technology Industry)
VPP	Virtual Power Plant
ZVEH	Zentralverband der Deutschen Elektro- und Informationstechnischen Handwerke (Central Association of the German Electrical and Information Technology Industry)