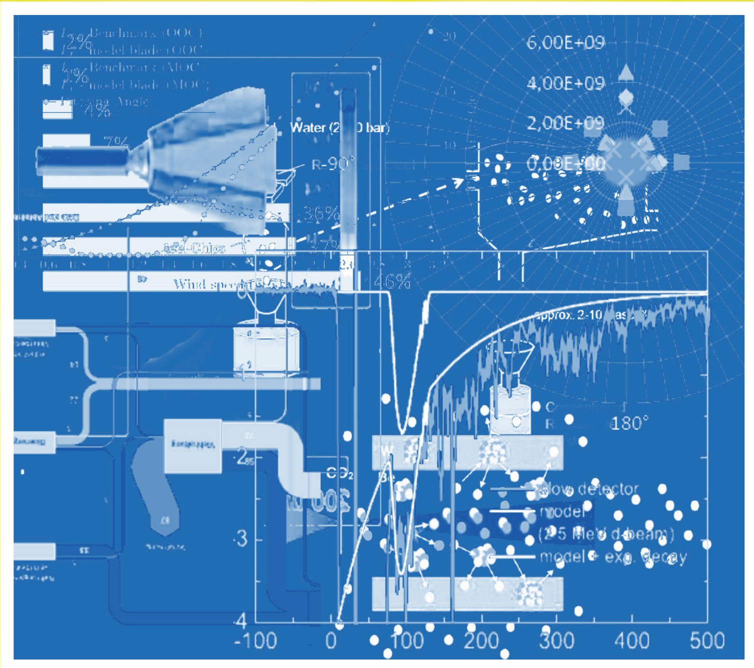
Deutsche Physikalische Gesellschaft DPG

Arbeitskreis Energie



Energiewende

Perspektiven und Instrumente

Vorträge auf der DPG-Frühjahrstagung
Rostock 2019

Herausgegeben von Hardo Bruhns

Arbeitskreis Energie in der Deutschen Physikalischen Gesellschaft

Vorträge auf der DPG-Tagung 2019 in Rostock

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Energie

Perspektiven und Instrumente

Energy

Perspectives and Instruments

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Arbeitskreis Energie in der Deutschen Physikalischen Gesellschaft

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Bad Honnef, 2019

Frühjahrstagung des Arbeitskreises Energie in der Deutschen Physikalischen Gesellschaft

Rostock, 11. bis 15. März 2019

Haupt- und Fachvorträge

Invited Talks

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These proceedings comprise written versions of invited talks given at the sessions of the Energy Working Group (AKE) during the Spring and Annual Conference 2019 of the German Physical Society held in the premises of the University of Rostock.

Viewgraphs of presentations (if provided by the speakers) can be accessed from the website of the Energy Group

https://www.ake.dpg-physik.de

(please follow the link to the archive of the Energy Group).

My thanks extend to all those who provided contributions to this volume.

Der vorliegende Band versammelt schriftliche Ausarbeitungen von Vorträgen des Arbeitskreises Energie auf der Frühjahrs- und Jahrestagung 2018 der Deutschen Physikalischen Gesellschaft in den Räumen der Universität Erlangen. Leider ist es nicht gelungen, von allen Vortragenden Manuskripte zu erhalten.

Die Präsentationsfolien von Vorträgen (soweit von den Sprechern zur Verfügung gestellt) können auf der Webseite des Arbeitskreises eingesehen werden über:

https://www.ake.dpg-physik.de

(von dort gelangt man zum Archiv des AKE). Allen, die zu diesem Sammelband beigetragen haben, sei an dieser Stelle sehr herzlich gedankt.

Düsseldorf, im August 2019 Hardo Bruhns

Introduction

Presentations at the sessions of the Energy Working Group (Arbeitskreis Energie, AKE) at the Spring Conferences of the German Physical Society (DPG aim at providing an overview of major ongoing developments towards sustainable energy supply and use. In a varying composition major strands of energy R&D and technology are being presented covering physical, chemical, biological geological, engineering and socio-economic disciplines. Following tradition these proceedings document part of the invited papers as well as abstracts of all talks given at the conference.

A first focus of this year's programme is on nuclear fusion where first significant results from the large Stellarator W7-X and developments at the National Ignition Facility (Livermore, USA) (AKE 1) will be reported. Nuclear fission will be phased out in Germany shortly (while internationally a strong development is being pursued). This requires technological developments and societal decisions for decommissioning of nuclear power plants and for the subsequent storage of radioactive waste (AKE 3).

Wind and Photovoltaics are on the way to provide the major share of energy supply. Being fluctuating they require back-up, novel grid technologies (AKE 10), large storage systems based on chemical energy (PV VI/AKE 7) and/or involving underground (geological) storage (AKE 11) as well as integration (coupling) of all sectors of energy use (AKE 6). While an impressive development is continuing with Si-based technologies, photovoltaics hold promises to win new applications with multi-band thin-film technologies based on novel materials (AKE 2). Off-shore wind technologies are progressing at a rapid pace. The dominant wind potential being located beyond shallow coastal waters, floating wind turbines gain increasingly attention (AKE 9).

Despite the advances in renewable technologies they remain uncompetitive as long as societal and environmental (external) costs of energy are not internalized, e.g. via a carbon tax (AKE 5). Bio-energy based on biomass is by far the dominant non-fluctuating renewable energy source. Technologies are being further optimized (AKE 8). Concurrently the development of synthetic (solar) fuels, in particular for mobility applications, is progressing along different tracks (AKE 4, AKE 12, see also proceedings of last year's presentations). Furthermore, a perspective for sustainable hybrid-electric aircraft propulsion is being investigated (AKE 4).

Mitigation of the global climate change has become the most distinguished task of energy research. Current observations of ice melting in the Antarctic and its far reaching consequences are being addressed as an exemplary aspect of climate research. Furthermore the societal considerations for a climate compatible development and its likely inconsistency with growth society are being investigated with regard to the potential technological and economical instruments to accomplish this transition in compliance with regulatory consequences of the Paris Climate Agreement with its legally binding path towards a zero-emission world within a much shorter time frame than so far understood. (AKE 13)

Novel technologies enter the renewable energy market via start-ups as well as established industry. In a joint symposium (SYIT/AKE 14) with jDPG and AIW examples are presented: a novel approach to hydrogen technologies with a liquid organic hydrogen carrier (LOHC), energy-related meteorological services and new technologies for wind turbines. The role of physicists in energy related industries is being addressed in a ensuing panel discussion folloWednesday by an open get-together.

The sequence of presentations is in part a consequence of constraints in speaker's availability.

Hardo Bruhns

Fachsitzungen / Sessions

AKE 1.1–1.3	Monday 10:30–11:45	Nuclear Fusion
AKE 2.1–2.1	Monday 11:45–12:15	Photovoltaics
AKE 3.1–3.3	Monday 14:00–15:30	Decommissioning of Nuclear Facilities and Final Repository
AKE 4.1–4.2	Monday15:30–16:45	Mobility: Hybrid-electric Aviation and Synthetic Fuels
AKE 5.1–5.3	Monday 16:45–17:45	Intermittent Renewable Energy Supply
AKE 6.1–6.3	Tuesday 16:15–17:45	Sector Coupling
AKE 7.1–7.1	Wednesday 9:00– 9:45	PV X: Chemical Energy Storage (joint session PV/AKE)
AKE 8.1–8.1	Wednesday 10:30–11:00	Bioenergy
AKE 9.1–9.1	Wednesday 11:00–11:30	Wind Energy
AKE 10.1–10.2	Wednesday 11:30–12:15	Distributed Energy Generation, Electrical Grids
AKE 11.1–11.3	Wednesday 14:00–15:15	Geological Energy Storage and Geothermal Energy
AKE 12.1–12.2	Wednesday 15:15–16:00	Artificial Photosynthesis, CO_2-Reduction
AKE 13.1–13.2	Wednesday 16:15–17:15	Climate Change
AKE 14.1–14.5	Thursday 10:30–14:00	Industrietag: Physiker in der Energietechnik (joint session SYIT/AKE)

Abstracts[1]

aller Vorträge der Erlanger Tagung des Arbeitskreises Energie in der DPG
of all presentations at the sessions of the DPG Energy Working Group

Invited Talk AKE 1.1 (21) Mon 10:30 U A-Esch 1

Wendelstein 7-X - Erste Ergebnisse auf dem Weg zum stationären Betrieb

*Torsten Stange und das W7-X Team — Max-Planck-Institut für Plasmaphysik, Wendelsteinstr. 1, 17491 Greifswald

Das weltweit fortschrittlichste Stellaratorexperiment ist Ende 2015 in Betrieb gegangen. Dem folgten zwei weitere Betriebsphasen. Neben der integralen Inbetriebnahme der sehr komplexen Anlage, die mit 70 supraleitenden Spulen ein Hochtemperaturplasma einschließt, dienten diese ersten Experimente dazu, herauszufinden, inwieweit bereits Aussagen über dem Design der Anlage zugrundeliegenden Optimierung gemacht werden können. Mit noch ungekühlten Wandkomponenten im Plasmagefäß war die Pulslänge zwar begrenzt. Es konnten jedoch bereits Plasmazustände erreicht werden, die für den Nachweis der Optimierung der Magnetfeldkonfiguration und den späteren Dauerstrichbetrieb notwendig sind. Dazu gehören Elektronen- und Ionentemperaturen bis knapp 4 keV und Plasmadichten jenseits der 1020 m−3. Zusammengenommen wurde sogar der bisherige Weltrekord für das Fusionstripelprodukt in Stellaratoren übertroffen. Der Vortrag berichtet über die ersten experimentellen Ergebnisse und erklärt deren Relevanz für das Erreichen stationärer Hochleistungsplasmen.

AKE 1.2 (16) Mon 11:00 U A-Esch 1

Systems Code for the Design of Fusion Power Plants – What they can and can not do

*Felix Warmer — Max-Planck- Institut für Plasmaphysik, Wendelsteinstraße 1, 17491, Greifswald

Fusion power plants will be complex technical devices containing a high temperature plasma which is the source for the fusion reactions and energy generation. The physics aspects are coupled to various complex subsystems which all have interdependencies and often nonintuitive interactions. In order to capture such a system in a holistic way, systems codes are employed. Systems codes are a framework of simplified yet comprehensive models which aspire to describe a whole fusion power plant in a complete, yet computationally tractable way. Such codes allow the study of the multidimensional physics and engineering parameter space to ascertain tradeoffs between different design parameters, performance and costs. The capabilites, advantages, as well as disadvantages of systems codes are reported.

Invited Talk AKE 1.3 (17) Mon 11:15 U A-Esch 1

Inertial Confinement Fusion - will Fast Ignition provide new progress?

*Markus Roth — Technische Universtät Darmstadt, Institut für Kernphysik, Schlossgartenstrasse 9, 64289 Darmstadt

Laser driven fusion experiments have made significant progress over the last years. Since the beginning of the ICF campaign at the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in California, although the fusion peak power during the experiments has exceeded 1 PW, there is a factor two to three to achieve a burning plasma

[1] An asterix in front of an author's name denotes the lecturer.

and sustainable self-heating. One alternate route not only to achieve ignition, but high gain is the concept of fast ignition. Laser driven ion beams are among the most intense particle sources available today. Due to their short pulse duration they could heat any material to high temperatures without hydrodynamic ambiguities. Heating of strongly compressed matter is interesting for two reasons: it explores a parameter space new to experimental access and addresses the question of fast ignition.

We have successfully performed experiments at the ORION and OMEGA facilities to use laser driven proton beams to heat a compressed target and are planning for an integrated experiment at NIF. While those experiments are of fundamental interest the concept also addresses the physics of proton fast ignition. We will present the status of fusion research, experiments and the preceding tests and introduce a route to a first real PFI experiment.

Invited Talk AKE 2.1 (24) Mon 11:45 U A-Esch 1

Photovoltaics: perspectives for new materials

*Susan Schorr — Helmholtz-Zentrum Berlin für Materialien und Energie, Germany

Materials are the fundamental basis for solutions to the most pressing issues in energy generation. In many cases, long-term solutions to these problems will depend on breakthrough innovations in materials. Meeting this challenge will require new materials and technologies for producing, storing and using energy with performance levels far beyond what is now possible. Photovoltaics (PV), the direct conversion of sunlight into electrical energy, plays a key role within the renewable energies. Thin film solar cells using compound semiconductors as absorber material are foreseen as one of the most promising and cost-efficient technology. To achieve further cost reductions in PV module efficiency must be increased beyond the single-junction limit (Shockley-Queisser limit).

The talk will present an overview on recent developments of new materials for solar energy conversion focusing on semiconductors which are potentially suitable for wide-bandgap applications such as mulitjunction solar cells. Three material groups will be presented: (1) organic (A) metal (M) halide (X) perovskites (AMX3), (2) quaternary chalcogenide semiconductors and (3) ternary II-IV-V2 nitrides, like ZnSnN2 and ZnGeN2.

Invited Talk AKE 3.1 (23) Mon 14:00 U A-Esch 1

Radioactive waste in Germany - current situation and future perspectives

*Clemens Walther — Institute of Radioecology and Radiation Protection Leibniz Universität Hannover, Herrenhäuser Str. 2, D-30419 Hannover

Asse, Morsleben, Konrad, Gorleben - names that are identified with the, some call it ”wicked”, problem of nuclear waste disposal. However, during the past five years, new concepts were elaborated – particularly concerning legal, political and participatory issues. The presentation will give an overview of the current situation from the technical side (how much waste will we have to handle? What are specifications and requirements for safe disposal?), elucidate the planned selection process according to the site selection act (How long will it take? Who will decide?) and will identify how research must continuously support this process.

Invited Talk AKE 3.2 (22) Mon 14:30 U A-Esch 1

Decommissioning of nuclear facilities

*Thomas Walter Tromm — KIT, Karlsruhe Institute of Technology

This presentation gives an overview on the KIT activities related to decommissioning of nuclear facilities. Our research aims are to standardize decommissioning procedures, to increase efficiency, to further minimize radioactive waste amounts, to reduce radiation exposure rates to staff, and to design autonomous and/or remote-operated decontamination techniques, which can be used in highly contaminated areas.

The standardization of the entire decommissioning process allows for an automation which reduces staff deployment and thus occupational radiation exposure. Those activities take place in close cooperation with industry and with research and education partners, such as the newly founded Decommissioning Competence Cluster coordinated by KIT. KIT researchers are strongly involved in German decommission ing working groups (e.g. within German Nuclear Society (KTG), Association of German Engineers (VDI)), in the international decommissioning network (IDN) of the IAEA, and are actively engaged i.e. in the organization of international workshops. In cooperation with the European Commission, the ELINDER (European Learning Initiatives for Nuclear Decommissioning and Environmental Remediation) initiative, which started in 2016, is being carried out, while having a regular exchange with international institutions (e.g. Fukui University, Japan).

Invited Talk AKE 3.3 (18) Mon 15:00 U A-Esch 1

The Nobel Prize in Physics 2018 and future applications for Laser-Driven Neutron Sources

*Markus Roth — Technische niversität Darmstadt, Institut für Kernphysik, Schlossgarten-strasse 9, 64289 Darmstadt

One of the pressing demands in our western society is the safety and maintenance of our nuclear legacy. In Germany the dismantling, safe processing and storage of nuclear waste have resulted in a multinational research program. Nondestructive testing methods and material selective imaging of compound large objects is possible using thermal and fast neutrons. Also, a powerful, safe, and compact neutron source is required. Since Donna Strickland and Gerard Mourou opened the path for ultra-intense lasers many applications have been investigated using the unique parameter of laser-driven secondary sources.

Recently, we have demonstrated the realization of a short-pulse laserdriven neutron source with beam intensities orders of magnitude above earlier attempts. Those sources can lead to a compact and potentially mobile neutron source with a large number of applications.

I will present the mechanism of creating an intense pulsed and highly directed beam of neutrons using ultra-intense lasers and the recent results using laser systems in the US and in Europe. I will focus on a few examples of using such sources for applications that are either important for the security of our countries or will have large economical potential in industrial applications. These range from the remote sensing of illicit nuclear material in cargo to the non-destructive analysis of large civil constructions using compact laser systems.

Invited Talk AKE 4.1 (31) Mon 15:30 U A-Esch 1

Innovation in aviation: the role of hybrid-electric aircraft

*Andreas Reeh — Siemens AG, Siemens eAircraft, Günther-Scharowsky-Str.1, D-91058 Erlangen

Distributed electric aircraft propulsion promises energy and emission saving as well as operational benefits for future aircraft. A key for realizing such new and unconventional concepts are lightweight and efficient hybrid-electric propulsion systems. The audience is introduced to the components of such systems, the characteristic performance parameters and the technological challenges in the optimization and implementation of such systems. The shown successful maiden flights and demonstrator projects pave the way for commercial applications.

Invited Talk AKE 4.2 (9) Mon 16:15 U A-Esch 1

Wind und Wasser zu Ammoniak - maritimer Kraftstoff und Energiespeicher für eine emissionsfreie Zukunft

*Angela Kruth — Leibniz Institut für Plasmaforschung und Technologie e.V., Greifswald

Ammoniak ist ein hervorragender Energiespeicher. Der hochdichte Energieträger kann aus Wasser und Luftstickstoff unter Einsatz erneuerbarer Energien hergestellt, leicht verflüssigt und mittels einer bereits verfügbaren Infrastruktur transportiert werden. Dadurch eröffnet sich die Möglichkeit einer emissionsfreien globalen Energiewirtschaft.

Für die Realisierung einer emissionsfreien Mobilität auf der Basis von Ammoniak sind innovative Konzepte im Bereich der Nanotechnologie für die Erzeugung und Nutzung von Ammoniak als Kraftstoff dringend notwendig. In diesem Beitrag werden wichtige dünnschichtbasierte Schlüsseltechnologien vorgestellt, die grüne Konzepte für etablierte traditionelle Verfahren wie den Haber-Bosch-Prozess und den Verbrennungsmotor ermöglichen, z.B. die Festkörper-Elektrolyse, Sauerstoff-Separation und Ammoniak-Reformer. Außerdem werden direkte Energiewandlungsprozesse wie die Festkörper-Ammoniaksynthese und Festoxid-Brennstoffzelle für die Ammoniak-Verstromung diskutiert. Das INP entwickelt seit mehreren Jahren Dünnschichten und Materialien für die Energietechnik und koordiniert das CAMPFIRE-Bündnis aus über 30 Partnern der Region Nord-Ost mit dem Ziel der Entwicklung von Technologien zur Erzeugung und Nutzung von grünem Ammoniak.

Invited Talk AKE 5.1 (3) Mon 16:45 U A-Esch 1

Decarbonization of the European energy system with strong sector couplings

Kun Zhu[1], Marta Victoria[1], Tom Brown[2], Gorm B. Andresen[1], and *Martin Greiner[1] — [1]Department of Engineering, Aarhus University — [2]Institute for Automation and Applied Informatics, Karlsruhe Institute of Technology

Ambitious targets for renewable energy and CO_2 taxation both represent political instruments for decarbonization of the energy system. We model a high number of coupled electricity and heating systems, where the primary sources of CO_2 neutral energy are from variable renewable energy sources (VRES). The model includes hourly dispatch of all technologies for a full year for every country in Europe. The amount of renewable energy and the level of CO_2 tax are fixed exogenously, while the cost-optimal composition of energy generation, conversion, transmission and storage technologies and the corresponding CO_2 emissions are calculated. Even for high penetrations of VRES, a significant CO_2 tax of more than 100 EUR/tCO_2 is required to limit the combined CO_2 emissions from the sectors to less than 5% of 1990 levels, because curtailment of VRES, combustion of fossil fuels and inefficient conversion technologies are economically favored despite the presence of abundant VRES. A sufficiently high CO_2 tax results in the more efficient use of VRES by means of heat pumps and hot water storage, in particular. We conclude that a renewable energy target on its own is not sufficient; in addition, a CO_2 tax is required to decarbonize the electricity and heating sectors and incentivize the least cost combination of flexible and efficient energy conversion and storage.

AKE 5.2 (14) Mon 17:15 U A-Esch 1

Geometric optimization of wind farms based on minimization of the Coulomb energy

Joakim Trane, Erik B. Joergensen, and *Martin Greiner — Department of Engineering, Aarhus University

Within a constrained wind-farm area, the wind turbines need to have sufficient spacing, so that the wind is able to recover in between the turbines. In this respect, wind turbines can be treated in analogy to equally charged particles, which arrange to have largest possible distances by minimizing the total Coulomb energy. This objective leads to a much faster spatial optimization of wind farms when compared to layout optimizations with dedicated engineering wind-farm models. For isotropic wind roses, the resulting Coulomb layouts lead to an increase of the wind-farm power efficiency by about 10% when compared to standard grid-like layouts. A further generalization of this optimization analogy to non-isotropic two-particle Coulomb interactions is also discussed and demonstrated to successfully deal with non-isotropic wind roses.

AKE 5.3 (1) Mon 17:30 U A-Esch 1

Von der Grundlastdeckung zur Lückenlastdeckung

*Helmut Alt — Eichelhäherweg 6, 52078 Aachen

Bei aller Euphorie, unsere Energieversorgung im Rahmen der politisch verordneten Zielvorgaben der "Energiewende" auf eine Stromerzeugungsbasis mit 100 % regenerativer Primärenergie umrüsten zu können, mögen einige Fakten aus der realen Bedarfsdeckung im Bereich der öffentlichen Stromversorgung Beachtung finden, um kostenbelastende Fehlentwicklungen zu vermeiden. Inzwischen treten die Wirkungen der als Panikreaktion auf die Fukushima-Katastrophe singulär in Deutschland gesetzten unsinnigen Zielsetzungen der politisch doch sehr hastig verordneten Energiewende hinsichtlich des überbordenden Ausbaus der fluktuierenden regenerativen Primärenergieträger mittels Wind- und Sonnenanlagen zur Deckung des deutschen Strombedarfes immer deutlicher zu Tage: Über 25 Mrd. € jährliche EEG Belastung! Es ist Daher angezeigt, in Demut zu ergründen, was geht und was unter bezahlbaren Randbedingungen nicht geht, um eine effiziente Weiterentwicklung der Energiewende mit realistische Zielsetzungen auf gangbaren Wegen zu ermöglichen nach dem Motto: "Das Bessere ist der Feind des Guten, aber was gestern gut war, muss auch heute noch brauchbar sein".

Invited Talk AKE 6.1 (5) Tue 16:15 U A-Esch 1

Die Energiewende geht in die nächste Phase - wichtige Merkmale der künftigen Energieversorgung

*Cyril Stephanos — acatech - Deutsche Akademie der Technikwissenschaften

Sollen die Treibhausgasemissionen drastisch reduziert werden, muss die Energieversorgung grundlegend umgebaut werden. War die Energiewende bisher vor allem auf die Stromerzeugung konzentriert, müssen nun in allen Sektoren die CO_2-Emissionen gesenkt werden. Dafür ist ein systemübergreifender Ansatz notwendig. Erneuerbare Energiequellen müssen ausgebaut, Effizienzpotenziale gehoben und Energieträger dort eingesetzt werden, wo sie am effizientesten sind. Doch welche Rolle spielen Energieträger wie erneuerbar erzeugter Strom, Wasserstoff, Gas und flüssige Kraftstoffe? Wie viele Speicher und regelbare Kraftwerkewerden in Zukunft für eine hohe Versorgungssicherheit notwendig sein? Und welche Entscheidungen muss die Politik heute treffen, welche Randbedingungen muss sie setzen? Diesen und weiteren Fragen hat sich die Arbeitsgruppe „Sektorkopplung“ des Akademienprojekts „Energiesysteme der Zukunft“ angenommen.

Es werden die zentralen Ergebnisse der Arbeitsgruppe vorgestellt und mit den Erkenntnissen aus anderen, systemübergreifenden Studien zum deutschen Energiesystem verglichen.

Invited Talk AKE 6.2 (6) Tue 16:45 U A-Esch 1

Die Rolle der Fernwärme bei der Umsetzung der Energiewende

*Marcel Krämer — swb Erzeugung, Bremen

Während im Stromsektor bereits erhebliche Fortschritte hin zu einer nachhaltigen Erzeugung auf Basis erneuerbarer Energien zu konstatieren sind, steckt der Wärmesektor in dieser

Hinsicht noch in den Kinderschuhen. Neben der Gebäudedämmung zur Verringerung des Energiebedarfs spielen die Technologien für die Bereitstellung von CO_2-arm bzw. CO_2-frei erzeugter Wärme eine wichtige Rolle. Fernwärme auf Basis von Kraft-Wärme-Kopplung kann hier einen wesentlichen Beitrag leisten und steht deshalb derzeit auch im Mittelpunkt verschiedener Förderprogramme der Bundesregierung. Anhand der Überlegungen, Planungen und Bauvorhaben eines städtischen Energieversorgers soll die Rolle der Fernwärme im Rahmen der Energiewende umfassend dargestellt werden.

Invited Talk AKE 6.3 (12) Tue 17:15 U A-Esch 1

WindNODE - Das Schaufenster für intelligente Energie aus dem Nordosten Deutschlands

*Markus Graebig — Wind-NODE

WindNODE richtet den Blick in eine Zukunft, in der unser elektrischer Energiebedarf nahezu vollständig aus erneuerbaren Quellen gedeckt wird. Gegenwärtig stammt bereits rund ein Drittel der elektrischen Energie in Deutschland aus ”Erneuerbaren”, allen voran aus den volatilen Quellen Wind und Sonne. Im WindNODE-Projektgebiet Ostdeutschland sind es bereits weit über 50%. WindNODE bringt über 70 Partner aus Industrie, Gewerbe und Wissenschaft zusammen, die gemeinsam Musterlösungen für die Systemintegration sehr großer Mengen Erneuerbarer entwickeln. Im Mittelpunkt stehen dabei Flexibilitäten (Lastverschiebung und Sektorkopplung) auf der Verbraucherseite - aus technischer, wirtschaftlicher, regulatorischer und sozialer Sicht. Der Vortrag präsentiert dieses ”Reallabor” der Energiewende, stellt erste Zwischenergebnisse vor und geht speziell auch auf die methodischen Aspekte dieses Großprojekts ein.

Plenary Talk AKE 7.1 (5) Wed 9:00 U Audimax

Chemical Energy Storage: a Key Element for a Sustainable Energy Future

*Ferdi Schüth — Max-Planck-Institut für Kohlenforschung, Mülheim an der Ruhr, Germany

Our energy systems are facing fundamental changes, caused by the depletion of fossil fuels and climate change. This requires increased use of renewable energy, which are typcially intermittent, such as solar radiation and wind energy. Storage of energy could thus become a key question in future energy systems, and methods for storage and different time and size scales are necessary. Chemical storage, including electrochemical systems such as batteries, have advantages compared to purely physical methods, since only chemical methods reach the required storage densities. The presentation will address the conditions, which future storage systems will have to meet and discuss different systems and their integration into the energy system. Main develeopment lines and the research needs associated with them will also be addressed.

Invited Talk AKE 8.1 (4) Wed 10:30 U A-Esch 1

Bioenergie in Deutschland: Historie, Stand und Perspektiven

*Michael Nelles — Universität Rostock -Agrar- und Umweltwissenschaftliche Fakultät - Professur Abfall- und Stoffstromwirtschaft — Deutsches Biomasseforschungszentrum (DBFZ) Leipzig

Die Energieversorgung Deutschlands muss im Sinne einer nachhaltigen Entwicklung in den nächsten Jahrzehnten vollständig auf erneuerbare Energien (EE) umgestellt und die Versorgung der Industrie mit organischen Grundstoffen in diesem Jahrhundert von petro- auf biobasierte Stoffe ausgerichtet werden. Dieses ambitionierte Ziel der langfristigen Integration von Biomasse in ein nachhaltiges

Energie- und Bioökonomiesystem ist nur erreichbar, wenn die Biomasse effizient, umweltverträglich und mit höchstmöglichem volkswirtschaftlichem Nutzen eingesetzt wird.

Schon heute nimmt die Bioenergie im Energiesystem eine besondere Stellung ein. Bezogen auf die Einsatzgebiete waren dies 2017 rund 1/4 der Bruttostromerzeugung aus erneuerbaren Energien sowie über 90 % der erneuerbaren Wärme und regenerativen Kraftstoffe. In den nächsten Jahrzehnten werden die Anforderungen und Rahmenbedingungen an die stoffliche und energetische Biomassenutzung im Zuge der Energiewende und dem Aufbau einer biobasierten Wirtschaft in Deutschland erheblich steigen. Eine optimierte Reststoff- und Abfallnutzung sowie die Verwertung neuer Reststoffströme aus Biomasse verarbeitenden Prozessen, z.B. der Chemieindustrie sowie das Schließen von Nährstoffkreisläufen eröffnen ergänzendeWertschöpfungspotenziale für intelligent integrierte Bioenergieverfahren.

Invited Talk AKE 9.1 (10) Wed 11:00 U A-Esch 1

Floating Offshore Wind - A state of the art review

*Frank Adam — University of Rostock, Chair of Wind Energy Technology, Rostock, Germany

Floating substructures for wind turbines are commonly credited for enabling the offshore wind industry, so far focused on fixed substructures, to expand into deeper waters. As per Arent et al. (2012), 77% of global offshore wind potential is located in water depths deeper than 60m. To reach areas with those water depths floating systems are needed. Compared to fixed offshore wind turbines or onshore wind turbines such solutions have different issues. The issues are e.g. higher motions of the whole system because of less foundation stiffness, wind farms far away from the coastline and longer grid connection to shore as well as dynamic cables to connect the devices with each other and the substation. The advantages of floating substructures are e.g., that they could be cost competitive in comparison to onshore renewable energy devices as well as that the need of huge installation vessels can be avoided because of an integrated installation procedure of the substructure and the wind turbine on top. The presentation will give a state of the art review of existing floating offshore substructures incl. a focus on current research and development topics. For example scaling effects for combined wind and wave tests with scales of 1:50 up to 1:100 are an issue. Other topics for the presentation will be the servo-hydro-aero-elastic coupled calculation methods and issues with regard to fabrication methods.

Invited Talk AKE 10.1 (2) Wed 11:30 U A-Esch 1

Wege zu einer sicheren und stabilen voll-regenerativen Elektrischen Energieversorgung

*Harald Weber — Universität Rostock, Institut für Elektrische Energietechnik

Im Zuge der Energiewende wird mehr und mehr elektrische Energie von Wind- und PV-Anlagen erzeugt. Diese Energie wird in großen chemischen Speichern gespeichert (Speicherkraftwerk). Diese neuen Player werden mit Umrichtern an das Drehstromnetz angeschlossen und weisen systembedingt keine Schwungmassen mehr auf. Die konventionellen Kraftwerke dagegen werden in ihrer Anzahl zurückgehen. Deshalb müssen die neuen Speicherkraftwerke alle Aufgaben der konventionellen Kraftwerke übernehmen. Das kann mit konventioneller Frequenzregelung oder aber mit neuartiger Winkelregelung geschehen.

AKE 10.2 (13) Wed 12:00 U A-Esch 1

Modellbasiertes IT-Sicherheitssystem für vernetze Komponenten zukünftiger Energiesysteme

*Kathrin Reibelt, Ghada Elbez, Oliver Scherer, Jörg Matthes, Hubert B. Keller und Veit Hagenmeyer — IAI, KIT, Karlsruhe

Cyberangriffe und auch nachfolgend Schäden haben allgemein in den letzten Jahren immer stärker zugenommen. Dies ist auch darin begründet, dass vernetzte informationstechnische Systeme in immer zentraleren, kritischeren Bereichen zum Einsatz kommen. Im Bereich der kritischen Infrastrukturen birgt dies ein erhebliches Risiko. Die Energieversorgung ist inzwischen zum häufigsten Ziel von Cyber- Angriffen avanciert. Dabei zeigt die Vergangenheit, dass klassische IT-Sicherheitsmaßnahmen über eine Analyse des Kommunikationsverkehrs (Traffic) nur unzureichend Schutz bieten. Beispielsweise können Angriffe basierend auf False Data Injection kaum detektiert werden. Ein neuer Ansatz nutzt Modellinformationen über den physikalischen Teil des Systems aus, um die kommunizierten Messwerte zu verifizieren und zu validieren. Im Fall eines Angriffs lassen sich über verschiedene Verfahren korrumpierte Komponenten lokalisieren, was gezielte Gegenmaßnahmen erlaubt. Gezeigt werden insbesondere Fortschritte seit der letzten DPG-Tagung, auf der der grundlegende Ansatz vorgestellt wurde. Die auf statistischen Verfahren basierende Lokalisierung wird mit zusätzlichen Modellinformationen ausgewertet, was zu einer verbesserten Detektion von Angriffen führt.

Invited Talk AKE 11.1 (11) Wed 14:00 U A-Esch 1

Potentiale und Möglichkeiten der untertägigen Energiespeicherung

*Sebastian Bauer, Bo Wang, Jens Olaf Delfs, Wolf Tilmann Pfeiffer, and Christof Beyer — Institut für Geowissenschaften, Christian-Albrechts-Universität zu Kiel

Zur verstärkten Nutzung erneuerbarer Energiequellen im Rahmen der Energiewende sind neue Technologien der Energiespeicherung erforderlich, um die zeitlich stark schwankende Energieproduktion aus erneuerbaren Quellen zu kompensieren. Geologische Energiespeicher bieten dafür sehr große potenzielle Speicherkapazitäten für Wärme und Massenspeicher. Zum Einsatz dieser Untertagespeicher ist ein grundlegendes System- und Prozessverständnis erforderlich, um die Realisierungsmöglichkeiten der einzelnen Speicheroptionen am jeweiligen Standort zu bewerten, die maßgeblichen Prozesse sowohl im Speicher als auch im Speicherumfeld zu quantifizieren und eventuell induzierte Auswirkungen vorherzusagen. Weiterhin sind Kenntnisse des geologischen Untergrundes und dessen Eigenschaften ebenso wie geeignete quantitative Modellinstrumente zur Speicherdimensionierung und Auswirkungsanalyse erforderlich. Im Rahmen dieser Präsentation werden die Potentiale und Realisierungsmöglichkeiten für geologische Energiespeicherung vorgestellt. Anhand von zwei geologischen Energiespeicheroptionen (Wasserstoffspeicherung und Wärmespeicherung) wird die Vorgehensweise, die geologischen Voraussetzungen, eine beispielhafte Speicherdimensionierung an einem synthetischen unterirdischen Speicherstandort sowie typische Abmessungen und Lade- / Entladegeschwindigkeiten näher erläutert.

AKE 11.2 (29) Wed 14:30 U A-Esch 1

Geologische Speicherung von Wasserstoff, Warum und Wie?

*Johannes Hierold — Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum

Die Nutzung von fossilen Energieträgern verursacht große CO_2 Emissionen und wird als Hauptgrund der globalen Erwärmung gesehen. Der Ausbau der erneuerbaren Energien ist daher unumgänglich, um die Umsetzung die Ziele des Pariser Abkommens von 2015 möglich zu machen. Der zunehmende Anteil an erneuerbaren Energien führt jedoch auch zu größeren Fluktuationen in der Energiebereitstellung. Um diese verlässlicher zu machen, müssen große Energiemengen zwischengespeichert werden können. Das größte Potential zeigt hierbei die stoffliche Speicherung im Untergrund kombiniert mit dem sogenannten Power-to-Gas-Prinzip, bei dem Überschuss an erneuerbaren Energien genutzt wird, um durch Elektrolyse Wasserstoff herzustellen. Da nur wenig über das physikochemische Verhalten von Wasserstoff in der Untergrundspeicherung bekannt ist, gibt es großen Forschungsbedarf in diesem Bereich. Wie bei der Speicherung von Methan werden im Allgemeinen zwei Szenarien für Wasserstoff betrachtet. Die Nutzung von porösen Gesteinsformationen mit einem gasdichten Deckgestein, sowie die Speicherung in anthropogenen Salzkavernen.

Invited Talk AKE 11.3 (25) Wed 14:45 U A-Esch 1

Numerical modelling of shallow geothermal energy exploration process

*Haibing Shao — Helmholtz Centre for Environmental Research - UFZ, Permoserstr. 15, 04318 Leipzig, Germany

In the context of energy transition in German and all over the world, the extraction of shallow geothermal energy by Borehole Heat Exchangers (BHEs) is considered to be a technology with low carbon emission for building heating and cooling purposes. This talk will introduce the numerical simulation approach that has been applied to study the coupled physical processes caused by geothermal extraction from the shallow subsurface. Results from recent studies will be presented in order to answer following questions
1) What are the influencing factors for BHE efficiency?
2) How much energy can be sustainably extracted from the shallow subsurface?
3) What are the potential environmental impacts, e.g. on downstream groundwater temperatures?

Invited Talk AKE 12.1 (19) Wed 15:15 U A-Esch 1

Photocatalysis - a powerful tool for the generation of Sun Fuels from Water and Carbon Dioxide?

*Henrik Junge — Leibniz-Institut für Katalyse e.V. an der Universität Rostock

One of the central challenges of the next decades is the sufficient and sustainable supply of energy. The conversion of the almost unlimited available energy of sunlight into stored chemical energy by means of photo- or electrocatalytic water splitting into oxygen and hydrogen is a benign objective. Besides hydrogen, further value added products like e.g. carbon monoxide, formic acid, methanol or methane are of special interest. While multistep processes, consisting of a wind power plant or photovoltaic cells, an electrolysis cell and carbon dioxide hydrogenation to form these products are available at least at a small scale, the development of a one step process is pending and basic research is still necessary. Nevertheless, some significant progress has been already achieved. Due to lower costs, the replacement of noble metal catalysts by cheap 3d metals like iron, nickel and cobalt is of special interest for these fields. Within the presentation various relevant examples of catalyst development for these topics will be provided.

AKE 12.2 (15) Wed 15:45 U A-Esch 1

Photoelectrochemical CO_2 reduction as a negative emission technology

*Matthias M. May[1] and Kira Rehfeld[2] — [1]Helmholtz-Zentrum Berlin, Institute for Solar Fuels — [2]Universität Heidelberg, Institute of Environmental Physics

Current CO_2 emission rates are incompatible with the 2°C target for global warming. Negative emission technologies are therefore an important, but also controversial basis for climate policy scenarios. For this, energy is actively invested for the removal of dilute CO_2 from the atmosphere, followed by sequestration. We show that photoelectrochemical CO_2 reduction might be a viable, high-efficiency alternative to biomass-based approaches, which reduces competition for arable land [1]. To develop them, electrochemical reactions have to be optimised for CO_2 removal. This deviates from energetic efficiency optimisation in solar fuel applications and hence renders different carbon sink products attractive. Here, we discuss efficiency limitations of the approach.

[1] May and Rehfeld, Earth Syst. Dynam. Discuss., in review, 2018, DOI:10.5194/esd-2018-53.

Invited Talk AKE 13.1 (27) Wed 16:15 U A-Esch 1

The far reach of ice-shelf thinning in Antarctica

Ronja Reese[1,2], Hilmar Gudmundsson[3], Anders Levermann[1,2,4], and *Ricarda Winkelmann[1,2] — [1]Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany — [2]University of Potsdam, Potsdam, Germany — [3]Northumbria University, Newcastle upon Tyne, UK — [4]Lamont Doherty Earth Observatory, Columbia University, New York, NY, USA

Floating ice shelves, which fringe most of Antarctica’s coastline, regulate ice flow into the Southern Ocean. Their thinning or disintegration can cause upstream acceleration of grounded ice and raise global sea levels. So far the effect has not been quantified in a comprehensive and spatially explicit manner. Here, using a finite-element model, we diagnose the immediate, continent-wide flux response to different spatial patterns of ice-shelf mass loss. We show that highly localized iceshelf thinning can reach across the entire shelf and accelerate ice flow in regions far from the initial perturbation. As an example, this telebuttressing enhances outflow from Bindschadler Ice Stream in response to thinning near Ross Island more than 900 km away. We further find that the integrated flux response across all grounding lines is highly dependent on the location of imposed changes: the strongest response is caused not only near ice streams and ice rises, but also by thinning, for instance, well-within the Filchner-Ronne and Ross Ice Shelves. The most critical regions in all major ice shelves are often located in regions easily accessible to the intrusion of warm ocean waters, stressing Antarctica’s vulnerability to changes in its surrounding ocean.

Invited Talk AKE 13.2 (7) Wed 16:45 U A-Esch 1

Globale Klima-Governance: wie wird es nach mittlerweile 24 UN-Klimakonferenzen weitergehen?

*Felix Ekardt — Forschungsstelle Nachhaltigkeit und Klimapolitik, Könneritzstr. 41, 04229 Leipzig

Das Pariser Klima-Abkommen vom Dezember 2015 wird vielfach kritisiert, weil es unzureichend ist. Dies vernachlässigt jedoch sein sehr ehrgeiziges Ziel, das die rechtsverbindliche globale Erwärmung auf 1,5 bis 1,8 Grad im Vergleich zum vorindustriellen Niveau begrenzt. Dieser Vortrag zeigt, basierend auf Analysen von offenen Fragen für Klimaprojektionen in den Naturwissenschaften und Rechtsanalysen zu Paris- Abkommen und Vorsorgeprinzip, dass juristisch gesehen innerhalb kurzer Zeit weltweit Null-Emissionen geboten sind. Aus rechtlicher Sicht sind nur solche Politiken gerechtfertigt, die dazu beitragen können, die Temperaturgrenze mit hoher Sicherheit, ohne Überschreitung, ohne die 1,5-Grenze außer Acht zu lassen und ohne Geo-Engineering-Maßnahmen zu erreichen. Das IPCC-1,5-Grad-Sondergutachten vom Oktober 2018 erweist sich damit als in rechtlich unhaltbarer Weise als noch zu großzügig, denn statt der dort genannten drei Dekaden bis zu Nullemissionen weltweit in allen Sektoren (einschließlich Agrarbereich und Kunststoffe) wird es noch schneller gehen müssen. Dies stellt auch für die vermeintlichen Vorreiter der

Klimapolitik, Deutschland und die EU, eine große Herausforderung dar. Damit müssen die EU und Deutschland die Ambitionen in der Klimapolitik schnell und drastisch erhöhen

Invited Talk AKE 14.1 (1) Thu 10:30 U A-Esch 1

LOHC - wie Wasserstoff zum flüssigen Treibstoff bei Raumtemperatur wird

*Cornelius von der Heydt — Hydrogenious Technologies GmbH, Weidenweg 13, 91058 Erlangen

Die international vereinbarten Klimaziele und insbesondere die Ziele zur Reduktion der Mobilitätsemmissionen machen einen massiven Ausbau der erneuerbaren Energien und neue Lösungen notwendig. Wasserstoff wird hierbei eine zentrale Rolle spielen. Allerdings ist Wasserstoff mit heutigen Technologien (Druckspeicherung bis 500bar oder Verflüssigung bei -253°C) extrem aufwendig und nur sehr kostenintensiv zu speichern. Die von der Hydrogenious Technologies GmbH in Erlangen entwickelte Technologie zur Speicherung von Wasserstoff in flüssigen organischen Trägern (Liquid Organic Hydrogen Carrier - LOHC). Hierbei wird Wasserstoff chemisch an eine schwer entflammbare und nicht toxische Flüssigkeit gebunden. Dies ermöglicht die Speicherung großer Mengen an Wasserstoff bei Umgebungsbedingungen in der heutigen Kraftstoffinfrastruktur. Neben einer tieferen Erläuterung der Technologie und ihrer Vorteile wird auch auf das Spektrum möglicher Anwendungsgebiete eingegangen werden.

Invited Talk AKE 14.2 (2) Thu 11:10 U A-Esch 1

Energiewende können Physiker auch ?!

*Matthias Lange — energy & meteo systems GmbH

Die Integration großer Anteile Wind- und Solarenergie in die Stromnetze und Energiemärkte hat neue Geschäftsmodelle, wie die Direktvermarktung oder die Teilnahme von Erneuerbaren Energien am Regelenergiemarkt hervorgebracht. Für diesen sehr spannenden und dynamischen Teil der Energiewende stellt energy & meteo systems energiemeteorologische Dienstleistungen wie Vorhersagen der Leistungsabgabe von Wind- und Solaranlagen sowie Virtuelle Kraftwerke bereit.

Seit der Gründung des Unternehmens durch zwei Physiker, die ihre Doktorarbeiten über Energiemeteorologie geschrieben haben, hat sich energy & meteo systems erstaunlich erfolgreich entwickelt. Der Vortrag stellt das Unternehmen vor und die Motivation, es zu gründen.

Invited Talk AKE 14.3 (3) Thu 11:50 U A-Esch 1

Windenergietechnik als Arbeitsgebiet für Physikerinnen und Physiker

*Uwe Ritschel — Lehrstuhl Windenergietechnik, Fakultät für Maschinenbau und Schiffs-technik, Universität Rostock, 18051 Rostock

Windenergieanlagen erzeugen heute in Deutschland bereits 20 % des Stroms zu sehr niedrigen Gestehungskosten. Durch effizientere Anlagen und weiteren Ausbau vor allem der Offshore-Windenergie soll dieser Anteil künftig noch deutlich steigen und schließlich auch andere Sektoren wie Verkehr und Wärme mit Energie versorgen. In diesem Vortrag möchte ich einen Überblick über den aktuellen Stand der Windenergietechnik geben. Folgende Fragen sollen behandelt werden: Was sind die grundlegenden Wirkprinzipien bei modernen Windenergieanlagen? Wodurch unterscheiden sich die neueren Modelle? Was sind die Trends in der Windbranche und woran wird heute noch geforscht? Insbesondere möchte ich auch Themen behandeln, zu denen Physikerinnen und Physiker gut beitragen können, und in diesem Zusammenhang auch auf meinen eigenen Werdegang als Physiker in der Windindustrie und am Lehrstuhl für Windenergietechnik der Universität Rostock eingehen.

Lunch Talk AKE 14.4 (4) Thu 12:30 U A-Esch 1

Podiumsdikussion - Physiker in der Energietechnik

Anna Bakenecker[1], Hardo Bruhns[2], Cornelius von der Heydt[3],

Matthias Lange[4] und Uwe Ritschel[5] — [1]Universität zu Lübeck — [2]Arbeitskreis Energie in der DPG — [3]Hydrogenious Technologies GmbH — [4]energy & meteo systems GmbH — [5]Universität Rostock, Lehrstuhl Windenergietechnik

Wie können wir die Energiewende schaffen?! Die Podiumsdiskussion lädt dazu ein drei Physikern aus der Energietechnik nach technischen Lösungen für den Klimawandel zu fragen. Außerdem berichten die eingeladenen Referenten über ihren Werdegang und geben einen Einblick in unterschiedliche Berufsfelder in der Energietechnik.

Lunch Talk AKE 14.5 (5) Thu 13:15 U A-Esch 1

Get Together

— Anna Bakenecker[1], Hardo Bruhns[2] — [1]Universität zu Lübeck — [2]Arbeitskreis Energie in der DPG

Am Ende des Industrietags sind alle Zuhörer herzlich dazu eingeladen sich in geselliger Atmosphäre untereinander auszutauschen und kennenzulernen, sowie mit den Referenten in ein persönliches Gespräch zu kommen.

Die Energiewende geht in die nächste Phase – wichtige Merkmale der künftigen Energieversorgung

Cyril Stephanos[a*], Florian Ausfelder[b], Berit Erlach[a], Katharina Schätzler[c], Christoph Stemmler[a]

1. Einleitung

Deutschland hat sich anspruchsvolle Ziele gesetzt: Entsprechend dem Energiekonzept der Bundesregierung sollen die nationalen Treibhausgasemissionen bis zum Jahr 2050 um 80 bis 95 Prozent gegenüber 1990 reduziert werden [1]. Doch damit nicht genug. Denn bei dieser Zielsetzung sind die Ziele der Pariser Klimakonferenz von 2015 nicht berücksichtigt, zu denen sich Deutschland völkerrechtlich bindend verpflichtet hat. Und auch die Europäische Kommission drängt auf weitere Anstrengungen. In ihrer neuen Langfrist-Klimastrategie strebt die Kommission an, die Europäische Union bis zum Jahr 2050 in eine Volkswirtschaft mit Netto-Null-Treibhausgasemissionen umzuwandeln [2]. Vor dem Hintergrund, dass die Treibhausgasemissionen in Deutschland in den letzten 10 Jahren lediglich um 17 Prozent gesunken sind [3], sind diese Ziele eine enorme Herausforderung.

Rund 80 % der Treibhausgasemissionen sind energiebedingt [4]. Damit ist eine erfolgreiche Energiewende entscheidend, um die Klimaziele erreichen zu können. Um die Emissionen im Energiesektor zu senken, gibt es zwei wichtige Hebel: **Energieeffizienz**, um den Energiebedarf zu senken, und den Einsatz **erneuerbarer Energien**[2], um Energie möglichst emissionsarm zur Verfügung zu stellen. Technologien zur Abscheidung und Speicherung von Kohlendioxid („Carbon Capture and Storage“, CCS) können auch helfen, Kohlendioxidemissionen zu senken. Ihr Einsatz ist in Deutschland allerdings umstritten. Technologien, die CO_2 direkt aus der Luft entnehmen, wie beispielsweise „Direct Air Capture“ (DAC), sind hingegen technisch und ökonomisch noch nicht ausgereift [5].

Die Energiewende war bisher vor allem auf die Stromerzeugung konzentriert, wie ein Blick auf die historische Entwicklung der Emissionen zeigt: Während der Anteil erneuerbarer Energien am Bruttostromverbrauch im Jahr 2018 bereits 37,8 % betrug, lag er gemessen am Endenergieverbrauch im Wärme- und Verkehrssektor lediglich bei 13,9 % bzw. 5,6 % [6]. Tendenz: gleichbleibend. Gleichzeitig sank der Endenergieverbrauch im Wärmesektor zwischen den Jahren 2008 und 2017 lediglich um 1 %, im Verkehrssektor stieg er sogar leicht an [4]. Dies führt dazu, dass die Emissionen im Wärme- und Verkehrssektor kaum zurückgehen. Dabei sind diese beiden Sektoren für rund 80 % des Energieverbrauchs in Deutschland verantwortlich [4].

Eine Arbeitsgruppe des Akademienprojekts „Energiesysteme der Zukunft“ (ESYS) hat untersucht, wie die Energieversorgung in Deutschland ausgestaltet werden kann, damit Deutschland seine Klimaziele erfüllen und gleichzeitig eine zuverlässige Versorgung

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2 Der Begriff „erneuerbare Energien“ ist aus physikalischer Sicht nicht korrekt, da es sich nicht um erneuerbare, sondern um Energie aus Sonne und Umwelt handelt, die im Vergleich zu menschlichen Maßstäben „unerschöpflich“ erscheint. In diesem Artikel wird er aufgrund des gebräuchlichen Sprachgebrauchs dennoch verwendet.

sicherstellen kann. Die Arbeitsgruppe hat dafür die zur Verfügung stehenden Technologien analysiert und bewertet und Handlungsoptionen für politische Entscheidungsträger entwickelt. ESYS ist eine gemeinsame Initiative der deutschen Wissenschaftsakademien acatech – Deutsche Akademie der Technikwissenschaften, Leopoldina – nationale Akademie der Wissenschaften und der Union der deutschen Akademien der Wissenschaften. Ein klares Ergebnis: Ein „Weiter-so“ bedeutet, dass Deutschland seine Ziele deutlich verfehlen wird. Soll die Energiewende gelingen, muss sie in eine neue Phase eintreten. Es bedarf einer systemischen Herangehensweise, die das Energiesystem als Ganzes optimiert. Zentral dabei ist, die Sektoren Strom, Wärme und Verkehr stärker zu verknüpfen (Sektorenkopplung). Die Politik sollte jetzt handeln, um wichtige Gelegenheitsfenster nicht zu verpassen und die Kosten nicht deutlich nach oben zu treiben [7].

Zusammen mit dem Bundesverband der Deutschen Industrie (BDI) und der Deutschen Energieagentur (dena) hat die ESYS-Arbeitsgruppe ihre Ergebnisse mit den Ergebnissen der beiden Studien zur künftigen Energieversorgung von BDI und dena verglichen und die gemeinsamen Kernpunkte herausgearbeitet [8].[3] Wichtige Trends, die sich in allen drei Studien zeigen, können wertvolle Hinweise für die Ausgestaltung des künftigen Energiesystems geben.

2. Ausgewählte Ergebnisse der ESYS-Arbeitsgruppe

2.1 Methodik

Die Ergebnisse der Arbeitsgruppe (AG) basieren auf der Kombination dreier unterschiedlicher Ansätze. Erstens wurden relevante Technologien sowie ökonomische Rahmenbedingungen und Hemmnisse in zahlreichen **Expertendiskussionen und Workshops** analysiert und bewertet. Zweitens hat die AG relevante **Energieszenarien** aus Studien ausgewertet und im Hinblick auf Sektorkopplungs-Technologien verglichen. Drittens hat die AG mögliche Entwicklungspfade, wichtige Systemparameter und Wechselwirkungen im Energiesystem in **eigenen Modellrechnungen** untersucht. Die Ergebnisse der AG sind in der Analyse „»Sektorkopplung« – Untersuchungen und Überlegungen zur Entwicklung eines integrierten Energiesystems“ und der Stellungnahme „»Sektorkopplung« – Optionen für die nächste Phase der Energiewende“ veröffentlicht [5, 7].

Die Modellrechnungen wurden am Fraunhofer ISE mit dem Modellierungstool REMod-D durchgeführt. Für jeden Rechenlauf wurden jeweils Minderungsziele für die energiebedingten CO_2-Emissionen vorgegeben[4], jahresscharf vom Startjahr der Rechnungen 2014 bis 2050. Für diese Pfade berechnete das Modell dann die Zusammensetzung des Energiesystems, das heißt alle relevanten Erzeuger, Wandler, Speicher und Verbraucher, bei der die Gesamtkosten des Systems über die gesamte Zeit am niedrigsten sind (Kostenoptimierung). Dabei wurden auch die Kosten für die Infrastrukturen wie Netzausbau und Ladeinfrastrukturen als Kostenaufschläge berücksichtigt. Der Energieverbrauch wurde auf Basis heutiger Daten vorgegeben und musste jederzeit stundenscharf gedeckt werden. Sieben Rechenläufe mit unterschiedlichen Schwerpunkten wurden für die Studien ausgewertet. Diese sind in Tabelle 1 dargestellt.

3 Studien: „Klimapfade für Deutschland“ (BDI), s. Referenz [9]; „integrierte Energiewende“ (dena), s. Referenz [10].

4 Die Reduktion der CO2-Emissionen bezieht sich auf die energiebedingten Emissionen. Diese machen rund 80 % der gesamten Treibhausgasemissionen in Deutschland aus. Eine Reduktion der energiebedingten CO2-Emissionen in den Rechnungen bedeutet also eine Reduktion der THG-Emissionen in Deutschland um etwa 80 %.

Rechen-lauf	Reduktion energiebed. CO_2-Em. bis 2050	Schwerpunkt	Potenzial-obergrenze Wind + PV	H_2-Vol.-anteil im Gasnetz	Besonderheiten
60_offen	minus 60 %	--	500 GW	5 %	Keine Technologievorgaben
75_offen	minus 75 %	--	500 GW	5 %	Keine Technologievorgaben
85_offen	minus 85 %	--	500 GW	5 %	Keine Technologievorgaben
90_offen	minus 90 %	--	600 GW	5 %	Keine Technologievorgaben
85_H2	minus 85 %	Wasserstoff-Technologien	600 GW	30 %	▪ Pkw/Lkw: 100 % Marktanteile Brennstoffzellen in 2050
85_PtG	minus 85%	Power-to-Gas, Power-to-Fuels	600 GW	5 %	▪ Wärmepumpen auf 40 % beschränkt ▪ Pkw/Lkw: Marktanteile Batterie auf 50 % beschränkt ▪ Prozesswärmebedarf Industrie: Rückgang um 0,5 % / a
85_aktiv	minus 85%	Energie-einsparungen	500 GW	5 %	▪ Keine Technologievorgaben ▪ Verbrauch orig. Stromanwendungen.: Rückgang um 25 % bis 2050 ▪ Prozesswärmebedarf Industrie: Rückgang um 0,5 % / a ▪ Verdopplung Kapazität Strom-Grenzkuppelstellen ▪ Keine Must-Run-Bedingung für Kohlekraftwerke (→ früherer Kohleausstieg möglich)

Tabelle 1: Auflistung der verschiedenen Rechenläufe der ESYS-Arbeitsgruppe, zusammen mit den Schwerpunkten und einigen zentralen Annahmen. Als „Basisszenario" wird im Folgenden das grau unterlegte Szenario „85_offen" bezeichnet.

Einige zentrale Annahmen sind im Folgenden zusammengefasst (wichtige Ausnahmen sind in Tabelle 1 vermerkt):

- Der treibende Faktor für die Reduktion der CO_2-Emissionen in den Rechnungen ist der jahresscharfe Reduktionspfad, der stets eingehalten wurde.[5]
- Der Zinssatz für die Annuitätenrechnung betrug einheitlich 8 Prozent.
- Die Preise für Öl, Erdgas und Kohleimporte wurden als zeitlich konstant angenommen. Dazu wurde ein Wert aus 2016 gewählt, als die ersten Rechnungen begonnen wurden.
- Mit Ausnahme von „85_aktiv" wurde der Verbrauch der klassischen Stromanwendungen als konstant angenommen (481 TWh, Ausgangswert 2016).

5 Es ist möglich, den CO2-Preis, der für einen bestimmten Reduktionspfad notwendig ist, ex post zu berechnen. Vgl. hierzu Referenz [3], Seite 116f. In den Rechnungen wurde jedoch kein CO2-Preis veranschlagt.

- Für Hochtemperatur-Industrieprozesse wird nur Gas als Energieträger eingesetzt (Biogas, Erdgas, synth. Gas), jedoch kein Strom.
- Der Fahrzeugbestand im Verkehr wurde fortgeschrieben. Bis 2050 sinkt er leicht für Pkw (minus 5 %) und steigt für Lkw leicht an (plus 5 %).
- Die zur Verfügung stehende Biomasse blieb konstant auf dem Ausgangswert von ca. 300 TWh.
- CCS-Technologien wurden nicht berücksichtigt.
- Der Atomausstieg wurde wie von der Bundesregierung beschlossen umgesetzt (Abschaltung der letzten Kraftwerke 2022).
- Konventionelle Kraftwerke haben vorgegebene Lebensdauern in den Rechenläufen, die sich aus den kalkulatorischen Lebensdauern ergeben. Die Kraftwerke konnten weder früher zurückgebaut, noch länger genutzt werden.
- Kohlekraftwerke unterlagen teilweise einer Must-Run-Bedingung (zur Vermeidung von Kaltstarts und für KWK-Ergänzung).
- Leistung und Kapazität der Pumpspeicherkraftwerke blieben konstant auf dem Ausgangswert.
- Die Kuppelleistung zum Ausland blieb konstant bei etwa 15,5 GW.
- CO_2-Emissionen durch nichtenergetische Nutzung kohlenstoffhaltiger fossiler Rohstoffe (zum Beispiel in Stahl, Chemie) wurden nicht berücksichtigt.

Die Funktionsweise des Modells sowie alle wichtigen Annahmen der Rechnungen (u.a. Randbedingungen, Wirkungsgrade der Anlagen, Kostenkurven, Volllaststunden von EE-Anlagen, Mindestlaufzeiten für Kraftwerke, Potenzialgrenzen für erneuerbare Energien, Vorgaben für jährliche Zubaumengen) sind in Referenz [11] ausführlich dargelegt.

2.2 Wichtige Kennzahlen zur Energieversorgung der Zukunft

Der Großteil der Energie muss zukünftig aus erneuerbaren Energien bezogen werden. Da die Potenziale von Biomasse, Geo- und Solarthermie begrenzt sind, wird **Strom aus Wind- und Photovoltaikanlagen** zum dominierenden Energieträger. Er wird nicht nur für originäre Stromanwendungen gebraucht, sondern kommt auch im Wärme- und Verkehrssektor immer stärker zum Einsatz. Entsprechend steigt der Strombedarf an: In den Modellrechnungen variiert der Bedarf im Jahr 2050 je nach Rechenlauf zwischen rund 750 TWh („85_aktiv“) bis 1120 TWh („90_offen“). Zum Vergleich: Im Jahr 2018 lag der Bruttostromverbrauch in Deutschland bei rund 600 TWh [4]. Ergänzt wird die Energieversorgung durch **Bioenergie**, die dort eingesetzt werden kann, wo eine direkte Elektrifizierung nicht möglich ist. Dabei ist jedoch zu beachten, dass es aus ökologischen Gründen sinnvoll ist, langfristig auf Anbaubiomasse zu verzichten und vor allem Rest- und Abfallstoffe zu nutzen [12].

Um den steigenden Stromverbrauch decken zu können, müssen Wind- und Photovoltaikanlagen stark ausgebaut werden. Die **installierten Kapazitäten** liegen in den Modellrechnungen im Jahr 2050 zwischen 350 GW und 600 GW, wenn die energiebedingten CO_2-Emissionen um mindestens um 85 % reduziert werden (vgl. Abbildung 1). Dies entspricht der 3½- bis 6-fachen Menge der heutigen Kapazitäten von rund 100 GW (Stand 2018) [4]. Dafür wäre ein jährlicher Ausbau von 8-16 GW notwendig. Ein solcher Ausbau der erneuerbaren Energien – verknüpft mit dem dafür notwendigen Ausbau der Stromnetze auf allen Spannungsebenen – bedeutet neben den technischen Herausforderungen teils große Belastungen für die Bürgerinnen und Bürger und Veränderungen im Landschaftsbild. Ob ein solcher Ausbau in Deutschland von der Bevölkerung unterstützt würde, lässt sich heute nicht sagen.

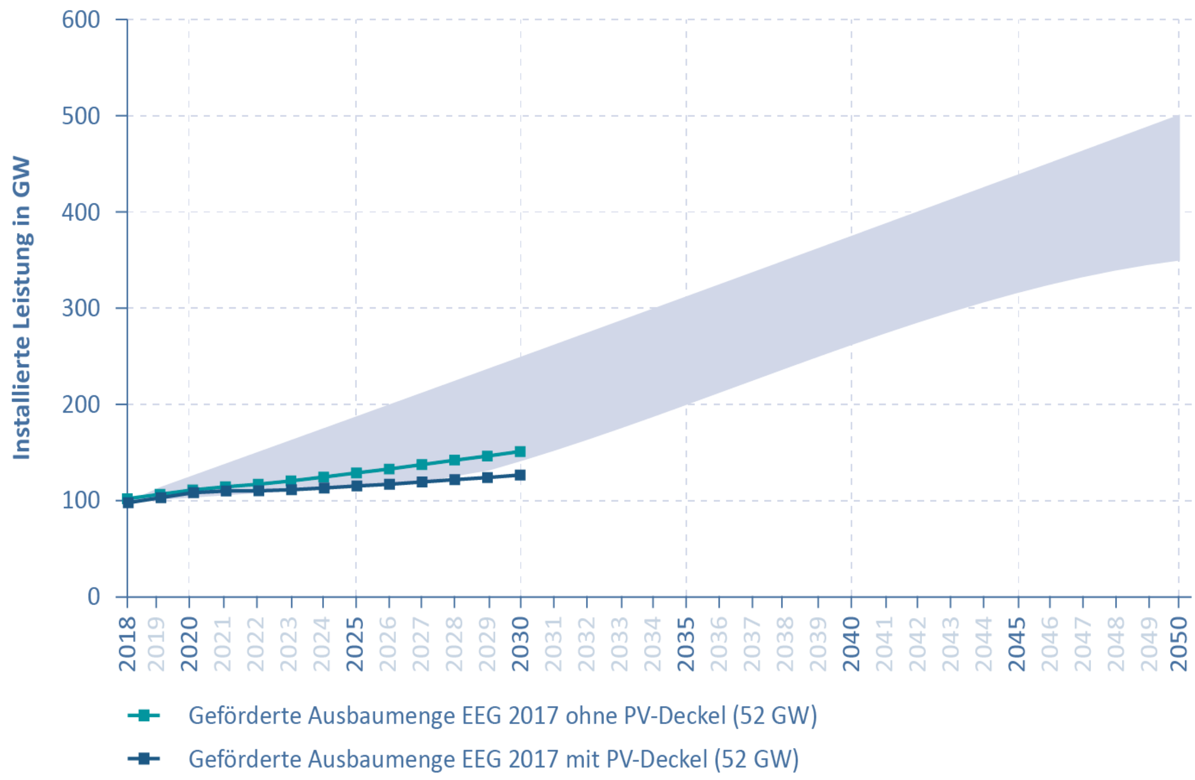

Abbildung 2: Installierte Kapazitäten an Wind- und Photovoltaikanlagen in den Modellrechnungen (Korridor). Der Korridor bestimmt sich durch die Mindest- und Maximalwerte aus Rechenläufen, in denen die energiebedingten CO_2-Emissionen um mindestens 85 % reduziert werden. Zum Vergleich sind die Fördermengen aus dem EEG2017 abgebildet, mit PV-Deckel (untere Linie) und ohne PV-Deckel (obere Linie). Graphik aus Referenz [7].

Doch auch **chemische Energieträger** bleiben unverzichtbar für die künftige Energieversorgung. Sie sind einerseits notwendig, um lange Zeiten ohne hohes Sonnen- und Windaufkommen zu überbrücken (sogenannte „Dunkelflauten). Andererseits werden sie für Anwendungen gebraucht, wo Strom nicht direkt eingesetzt werden kann, voraussichtlich etwa im Flug- und Schiffsverkehr, für bestimmte Industrieprozesse und gegebenenfalls auch für den Langstreckenverkehr. Als Energieträger kommen aufgrund ihrer vielseitigen Anwendungen vor allem Gas und Wasserstoff infrage. Als Gas kann zunächst Erdgas eingesetzt werden, das jedoch mit voranschreitender Zeit und mit steigenden Klimazielen sukzessive durch Biomethan und synthetisch erzeugtes Methan ersetzt werden müsste.

Synthetische Energieträger können in Deutschland oder in Ländern mit besseren Standortbedingungen hergestellt und nach Deutschland importiert werden. Der **Import synthetischer Energieträger** kann dazu beitragen, die Kosten der Energieversorgung in Deutschland zu senken. Allerdings ist ein solcher Import aus heutiger Sicht mit **politischen und wirtschaftlichen Unsicherheiten** verbunden. Durch den Import könnten neue Abhängigkeiten entstehen, teilweise vom Ländern, die politisch als wenig stabil einzuschätzen sind (vgl. hierzu Referenz [7], S 52).[6] Es müssten die Produktions- und

6 Demgegenüber ist zu bedenken, dass Deutschland auch heute noch rund 70 Prozent seiner Primärenergie importiert (Stand 2016) [13]. Prinzipiell ließen sich synthetische Energieträger aus vielen verschiedenen Ländern importieren, sodass sich Abhängigkeiten von einzelnen Ländern reduzieren ließen.

Logistikinfrastruktur für neue Importgüter mit den Produzentenländern abgestimmt und gemeinsam aufgebaut werden. Ob es gelingt, die globale Nachfrage zu bedienen, wenn viele Länder gleichzeitig ihre Energieversorgung auf emissionsarme synthetische Energieträger umstellen, ist heute schwer abzuschätzen[7]. Aus systemischer Perspektive wäre es zudem sinnvoll, dass Länder, die als Importländer infrage kommen, zunächst ihre eigene Energieversorgung umstellen, bevor sie synthetische Energieträger exportieren. In den Modellrechnungen waren solche Importbetrachtungen nicht möglich. Allerdings hat die Arbeitsgruppe abgeschätzt, wie hoch die Kostenersparnisse wären, wenn – ausgehend von dem 75-Prozent-Rechenlauf („75_offen") – hierdurch weitere 10 % der CO_2-Emissionen eingespart würden. Für die Abschätzung wurde fossiles Erdöl, das noch im System verwendet wird, durch einen erneuerbaren Kraftstoff substituiert, der importiert wird. Im Vergleich zum Rechenlauf „85_offen" wären die Kosten entsprechend dieser ersten Abschätzung um rund 530 Mrd. € für den gesamten Zeitraum bis 2050 günstiger (s. Referenz [5], S. 123f).

2.3 Die Rolle der Energieeffizienz

Ohne einen geringeren Verbrauch von Energie wird die Energiewende voraussichtlich nicht oder nur zu deutlich höheren Kosten gelingen. Es ist zum einen ein sparsamerer Umgang mit Energie, zum anderen eine höhere Effizienz beim Einsatz von Energie notwendig.

Die Endenergie nimmt in den Modellrechnungen bis zum Jahr 2050 deutlich ab: von rund 2500 TWh 2014 (Startjahr der Rechnungen) auf 1700 bis 1800 TWh im Jahr 2050, je nach Rechenlauf. Neben dem Einsatz effizienterer Technologien wird in den Modellrechnungen die Gebäudesanierung endogen bestimmt. Andere Effizienzmaßnahmen können exogen vorgegeben werden. Nur im Basisszenario wird verbrauchsseitig nicht von einem sinkenden Bedarf ausgegangen: Der Energieverbrauch der Industrie werden ebenso wie die jährlichen Personenkilometer und die Raumtemperatur in Gebäuden als konstant angenommen. Dies widerspricht zwar teilweise den Zielen der Bundesregierung [1]. Allerdings sind in den letzten Jahren kaum Erfolge im Bereich der Energieeffizienz zu verzeichnen, wie die Expertenkommission zum Monitoring-Prozess „Energie der Zukunft" kürzlich in ihrer Stellungnahme zum zweiten Fortschrittsbericht der Bundesregierung festgehalten hat [14]. Aus heutiger Sicht ist zunächst nicht davon auszugehen, dass Deutschland seine Effizienzziele in den nächsten Jahren erreichen wird.

Um den Einfluss von Energieeffizienzmaßnahmen zu untersuchen, wurden im Rechenlauf „85_aktiv" jedoch zwei wichtige Annahmen getroffen: Der Verbrauch der originären Stromanwendungen sinkt bis 2050 um 25 % und der Verbrauch der Industrie sinkt jährlich um 0,5 %, d.h. insgesamt um 17,5%. Beides trägt dazu bei, dass sowohl der Bedarf an Wind- und Photovoltaikanlagen als auch die Kosten der Energiewende deutlich sinken. Im Rechenlauf „85_aktiv" wurden zwar auch noch andere Annahmen getroffen, die sich positiv auf beide Aspekte auswirken, die Reduktion des Endenergieverbrauchs ist aber ein entscheidender Treiber[8].

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7 Ein kurzes vereinfachtes Rechenbeispiel: In Deutschland wurden im Jahr 2018 ca. 1200 TWh Mineralöl (Primärenergie) verbraucht. Sollte diese Menge synthetisch erzeugt werden, bräuchte es etwa die doppelte Energiemenge an Strom (vgl. Abbildung 2). Es müssten also rund 2400 TWh Strom bereitgestellt werden. Dies entspräche der 3,6-fachen Menge der Bruttostromerzeugung in Deutschland in 2018 beziehungsweise der 10,5-fachen Menge der Bruttostromerzeugung aus Erneuerbaren in Deutschland in 2018. Alle Zahlen aus Referenz [4].

8 Die Rolle der Energieeffizienz in den Rechnungen wird in Referenz [15] ausführlicher diskutiert.

2.4 Schlüsseltechnologien für die künftige Energieversorgung

Strom direkt einzusetzen ist technisch gesehen oft die effizienteste und kostengünstigste Lösung. Abbildung 2 veranschaulicht den Wirkungsgrad (vereinfachter) Wandlungsketten am Beispiel von Personenkraftwagen mit unterschiedlichen Antriebsarten, jeweils ausgehend von Strom als Primärenergieträger. Es wird deutlich, dass eine direkte Elektrifizierung wesentlich effizienter ist, als eine indirekte, bei der Strom durch verschiedene Wandlungsschritte in Wasserstoff oder andere chemische Energieträger umgewandelt wird. Hinzu kommt, dass Technologien wie Wärmepumpen und Elektromotoren, die Strom direkt verwenden, oft effizienter sind als Technologien, die auf der Verbrennung von chemischen Energieträgern basieren. Das bedeutet jedoch nicht, dass es nicht sinnvoll sein kann, stoffliche Energieträger aus regenerativ erzeugtem Strom herzustellen. Obwohl der direkte Einsatz am effizientesten ist, können andere Gründe (Speicherbarkeit, Energiedichte, Transportierbarkeit) für eine Umwandlung ausschlaggebend sein.

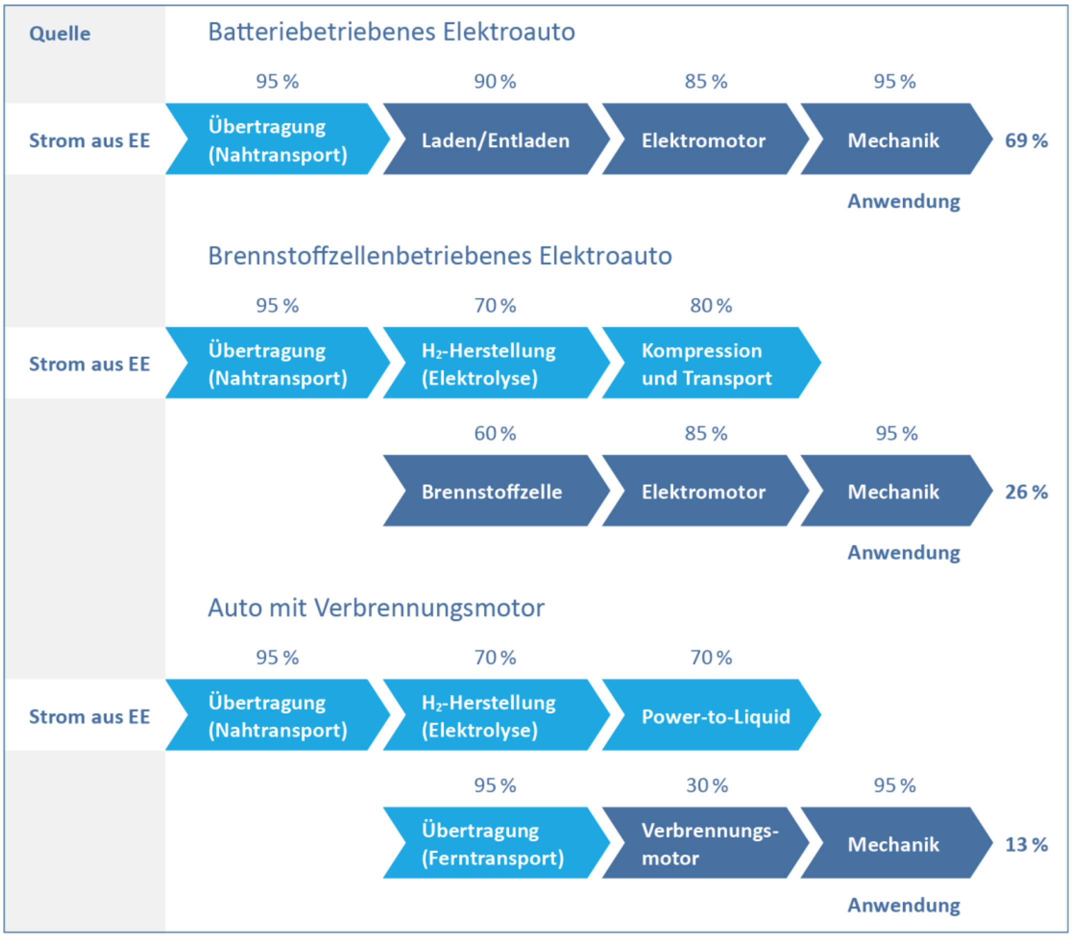

Abbildung 2: Gesamter Wirkungsgrad von Pkw ausgehend von Strom aus erneuerbaren Energiequellen als Primärenergiequelle, aufgezeigt anhand vereinfachter Wandlungsketten. Graphik aus Referenz [7].

Vor diesem Hintergrund erklärt es sich leicht, dass die **direkte Elektrifizierung** bei einer systemischen Betrachtung vorrangig wird: Wo möglich, und insofern keine anderen wichtigen Gründe dagegen sprechen, sollten Technologien, die Strom aus PV- und Windanlagen direkt nutzen, eingesetzt werden. Wärmepumpen für die Heizung von Gebäuden und Elektromobilität (vor allem in urbanen Räumen und im Kurzstrecken-Lieferverkehr) werden so zu Schlüsseltechnologien.

Doch da auch stoffliche Energieträger weiterhin für die Energieversorgung gebraucht werden, gleichzeitig aber fossile Brennstoffe sukzessive ersetzt werden müssen, gewinnen Technologien, die regenerativ erzeugten Strom in chemische Energieträger umwandeln, immer mehr an Bedeutung. In den Modellrechnungen kommen solche **Power-to-X-Technologien** schon früh (ab etwa 2030) und bereits bei moderaten Klimazielen zum Einsatz, wie Abbildung 3 zeigt. Das Herstellen synthetischer Energieträger lohnt sich aus systemischer Sicht also schon früh, um die schwankende Versorgung aus den Erneuerbaren zu ergänzen.

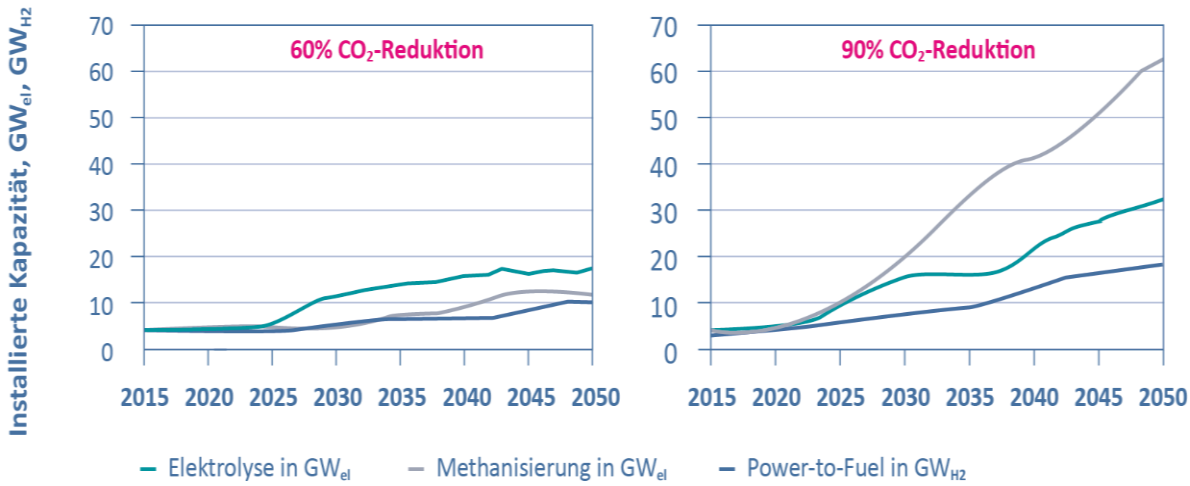

Abbildung 3: Zeitlicher Verlauf der installierten Kapazitäten von Power-to-X-Technologien in zwei Rechenläufe, bei denen die energiebedingten CO_2-Emissionen um 60 % (links) bzw. um 90 % (rechts) reduziert werden. Graphik aus Referenz [4].

Um die **Versorgungssicherheit** in Deutschland langfristig erhalten zu können, wird **Flexibilität** im Energiesystem zu einer Schlüsselanforderung – sowohl auf Verbraucher-, als auch auf Erzeugerseite. Neben intelligentem Lastmanagement („Demand Response") bei privaten und industriellen Verbrauchern werden **elektrische und thermische Speicher** für den kurzfristigen Flexibilitätsbedarf und **Reservekapazitäten** für länger anhaltende Dunkelflauten zukünftig eine wichtige Rolle spielen. In den Modellrechnungen werden Speicher selbst bei weniger ambitionierten Zielen stark ausgebaut zu einem integralen Bestandteil des Energiesystems (vgl. Referenz [4], S. 125f). Die Kapazität an regelbaren Kraftwerken bleibt hingegen – trotz des starken Ausbaus der erneuerbaren Energien – etwa auf den gleichen Stand wie heute (rund 100 GW) oder steigt sogar leicht an. Allerdings werden sie teilweise mit deutlich geringeren Volllaststunden betrieben als heute. Regelbare Kraftwerke werden in den Modellrechnungen langfristig hauptsächlich mit Gas (Erdgas, Biogas und synthetischen Methan) betrieben.

In den Modellrechnungen war es mit den im Basisszenario („85_offen") zugrunde gelegten Annahmen nicht möglich, die energiebedingten CO_2-Emissionen in Deutschland um deutlich mehr als 90 % zu reduzieren. Dies zeigt: Ohne weitere Maßnahmen, wie erhebliche Effizienzsteigerungen, Import synthetischer Energieträger und ggf. die Nutzung von CCS, wird es aus heutiger Sicht schwierig, die Energieversorgung treibhausgasneutral zu gestalten.

2.5 Kosten des Umbaus

Die Modellrechnungen erlauben es, die **kumulativen Gesamtkosten für die Energiewende** abzuschätzen. Es ist wichtig, anzumerken, dass Berechnungen dieser Kosten erstens mit großen Unsicherheiten verbunden sind und lediglich erlauben, eine Vorstellung der

Größenordnungen zu gewinnen. Zweitens werden die berechneten Kosten hier nicht mit denjenigen Kosten verglichen, die mit einem ungebremsten Klimawandel und den damit verbundenen Risiken einhergehen. Die Kosten, die hier betrachtet werden, beziehen sich nur auf den Umbau und den Betrieb des Energiesystems. Angesichts der wissenschaftlichen Erkenntnisse zu den Gefahren des Klimawandels[9] kann jedoch kein Zweifel daran bestehen, dass ambitionierter weltweiter Klimaschutz und damit auch die deutsche Energiewende notwendig sind, die Lebensgrundlagen der Menschheit zu erhalten.

In einem ersten Schritt werden die kumulativen Gesamtkosten aus den Modellrechnungen für die verschiedenen Rechenläufe bestimmt. Diese sind in Abbildung 4 abgebildet. Eingerechnet sind diejenigen Kosten, die für den Erhalt, den Umbau und Betrieb des Energiesystems von heute bis zum Jahr 2050 notwendig sind: Investitionen in Neuanlagen und Ersatz von Altanlagen, Finanzierungskosten für Investitionen, Kosten für die Energieträger sowie Betriebs- und Wartungskosten für alle Anlagen. Eingerechnet sind auch die Kosten für die energetische Gebäudesanierung. Nicht in der Darstellung enthalten sind hingegen externe Kosten, also Kosten, die sich heute nicht im Preis für die Endverbraucher widerspiegeln (beispielsweise Umweltschäden), von der Gesellschaft aber getragen werden müssen. Auch sind keine volkswirtschaftlichen Effekte einbezogen, wie etwa Wertschöpfungs- und Arbeitsplatzeffekte oder Exportchancen.

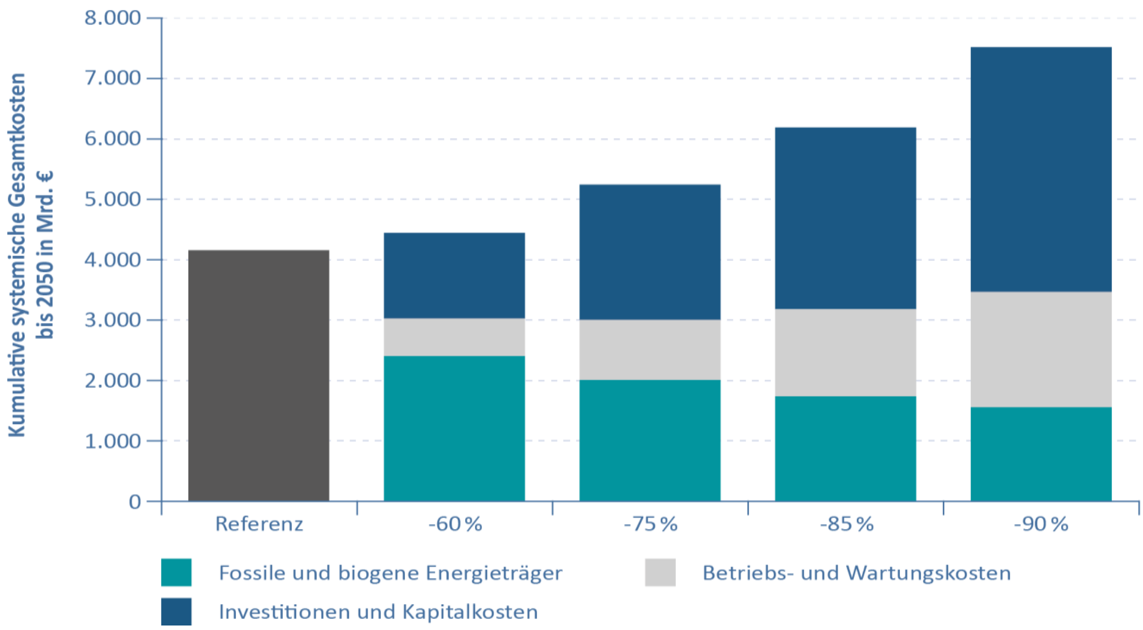

Abbildung 4: Kumulative systemische Gesamtkosten bis zum Jahr 2050 für Rechenläufe mit unterschiedlichen Reduktionszielen. Graphik aus Referenz [7].

In einem zweiten Schritt werden die Zusatzkosten mit einer „business-as-usual"-Entwicklung verglichen. Dafür wurde zusätzlich ein Referenzszenario berechnet, in dem die energiebedingten CO_2-Emissionen bis zum Jahr 2030 um 40 Prozent verringert werden und dann bis 2050 konstant auf diesem Niveau bleiben. Ein Vergleich der Kosten aus den Rechenläufen mit den Kosten aus diesem Referenzszenario ermöglicht es, die Mehrkosten abzuleiten, die notwendig sind, um die Klimaziele zu erreichen. Um die energiebedingten CO_2-Emissionen bis 2050 um 85 % zu senken, ergeben sich aus diesem Vergleich Mehrkosten bis 2050 von etwa 2 Billionen €. Dies entspricht mit rund 60 Mrd. € jährlich knapp 2 % des heutigen Bruttoinlandproduktes (Stand 2018). Sollen die energiebedingten

9 IPCC 1.5°C Special Report, Fünfter Sachstandsbericht des IPCC 2014.

Emissionen um weitere 5 %, also um insgesamt 90 % reduziert werden, würden die Mehrkosten um etwa 50% auf insgesamt rund 3 Billionen € wachsen. Die durchschnittlichen Kosten zur Vermeidung einer Tonne CO_2-Emissionen steigen also stark an. Dieser nicht-lineare Verlauf zeigt sich über alle Rechenläufe, wie in Abbildung 4 zu erkennen ist. Insgesamt lässt sich daraus ableiten: Je ambitionierter die Ziele, desto teurer werden die durchschnittlichen Vermeidungskosten. Oder anders gesagt: Die letzten Prozentpunkte zur Vermeidung von CO_2-Emissionen werden besonders aufwändig. An dieser Stelle sei noch einmal angemerkt, dass in den hier abgebildeten Rechnungen neben der Gebäudesanierung nicht von starken Effizienzmaßnahmen ausgegangen wird und der Import synthetischer Energieträger ausgeschlossen wurde. Beide Faktoren können dazu beitragen, die systemischen Kosten deutlich zu senken.

3. Ergebnisse aus dem Studienvergleich

ESYS, BDI und dena haben in einem gemeinsamen Studienvergleich die wichtigsten Treiber und Trends, die sich über alle drei Studien zeigen, herausgearbeitet. Durch die teils unterschiedlichen Annahmen und Herangehensweisen der Studien war es möglich, robuste Ergebnisse und Abhängigkeiten aufzuzeigen. Die Ergebnisse des Studienvergleichs sind in Referenz [8] veröffentlicht. Einige der Ergebnisse werden hier herausgegriffen und im Kontext der Erkenntnisse der ESYS-Arbeitsgruppe diskutiert.

3.1 Ausbau von Wind- und PV-Anlagen

Alle drei Studien kommen zu dem Schluss, dass Wind- und PV-Anlagen in Deutschland deutlich ausgebaut werden müssen, um die Klimaziele erreichen zu können. In Abbildung 5 sind die unterschiedlichen Ausbaukorridore aus den Studien dargestellt (für Rechenläufe, in denen die energiebedingten Emissionen mindestens um 85 % reduziert werden[10]).

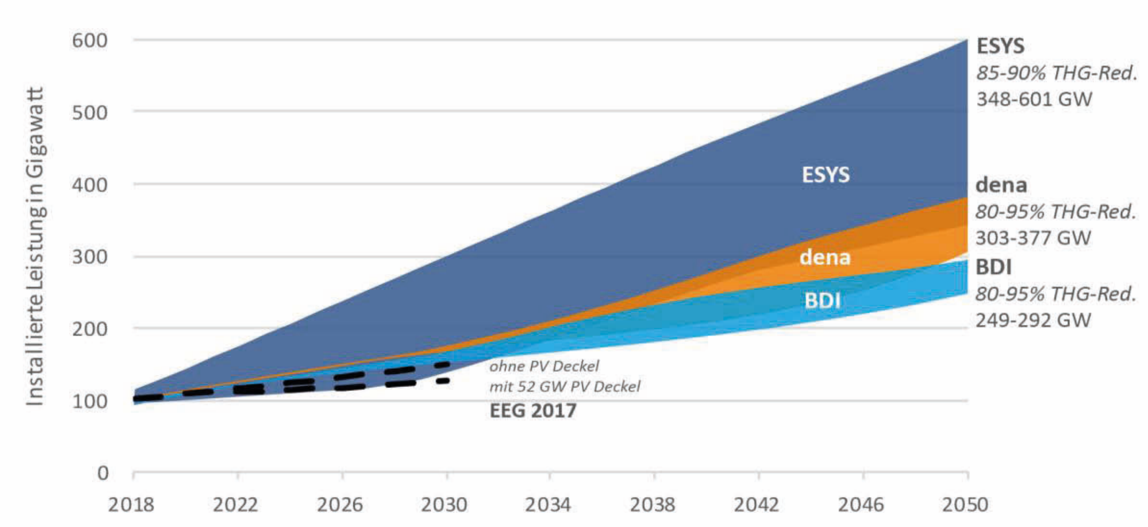

Abbildung 5: Notwendiger Ausbau von Wind und PV-Anlagen in Deutschland bis 2050: Installierte Kapazitäten von Wind- und Photovoltaikanlagen in den Studien von ESYS, BDI und dena. Graphik aus Referenz [8].

10 In den Studien von BDI und dena werden nicht nur die energiebedingten Emissionen, sondern die gesamten THG-Emissionen in Deutschland berechnet. Eine Reduktion der energie-bedingten CO2-Emissionen um 85 % entspricht etwa einer Reduktion der gesamten THG-Emissionen um 80 %.

Die installierten Kapazitäten reichen in den Studien von rund 250 GW (unterster Wert BDI) bis 600 GW (oberster Wert ESYS). Für die unterschiedlichen Ergebnisse gibt es zwei wichtige Gründe: Erstens wurde in den Studien von BDI und dena – anders als in der ESYS-Studie – explizit der Import von synthetischen Energieträgern zugelassen. Um die für die Energieversorgung notwendigen stofflichen Energieträger in Deutschland herzustellen, werden in der ESYS-Studie hohe Mengen an regenerativ erzeugtem Strom benötigt, was sich in den installierten Kapazitäten niederschlägt. Zweitens wird in den Studien von BDI und dena – ebenfalls abweichend von den verwendeten Szenarien der ESYS-Studie – von einem sinkenden Energiebedarf in Industrie und bei den originären Stromanwendungen ausgegangen (Diese sind bei ESYS allerdings im Szenario „85_aktiv" berücksichtigt). Dadurch sinkt der Energiebedarf in den Modellrechnungen, was sich wiederum auf die installierten Kapazitäten auswirkt.

3.2 Synthetische Energieträger (Power-to-X)

Ein klares Ergebnis aller drei Studien ist, dass Power-to-X-Technologien eine wichtige Rolle für die künftige Energieversorgung spielen werden. Synthetische Energieträger ersetzen sukzessive fossile Brenn- und Kraftstoffe, ihr Einsatz steigt stetig mit dem Ambitionsniveau der Klimaziele an. Sie werden unter anderem als Kraftstoffe im Verkehr, für Industrieprozesse und als Langzeitspeicher benötigt, dies um die Versorgungssicherheit in der Stromerzeugung zu sichern (vgl. auch Kapitel 1.1). Abbildung 6 zeigt die eingesetzte Menge an synthetischen Brenn- und Kraftstoffen in Deutschland, aufgeteilt nach in Deutschland hergestellten und importierten Anteilen. Die teils großen Unterschiede resultieren aus den unterschiedlichen Annahmen in den Studien, v.a. zum Bedarf an Energieträgern in den Anwendungsbereichen und zu den Kostenentwicklungen.

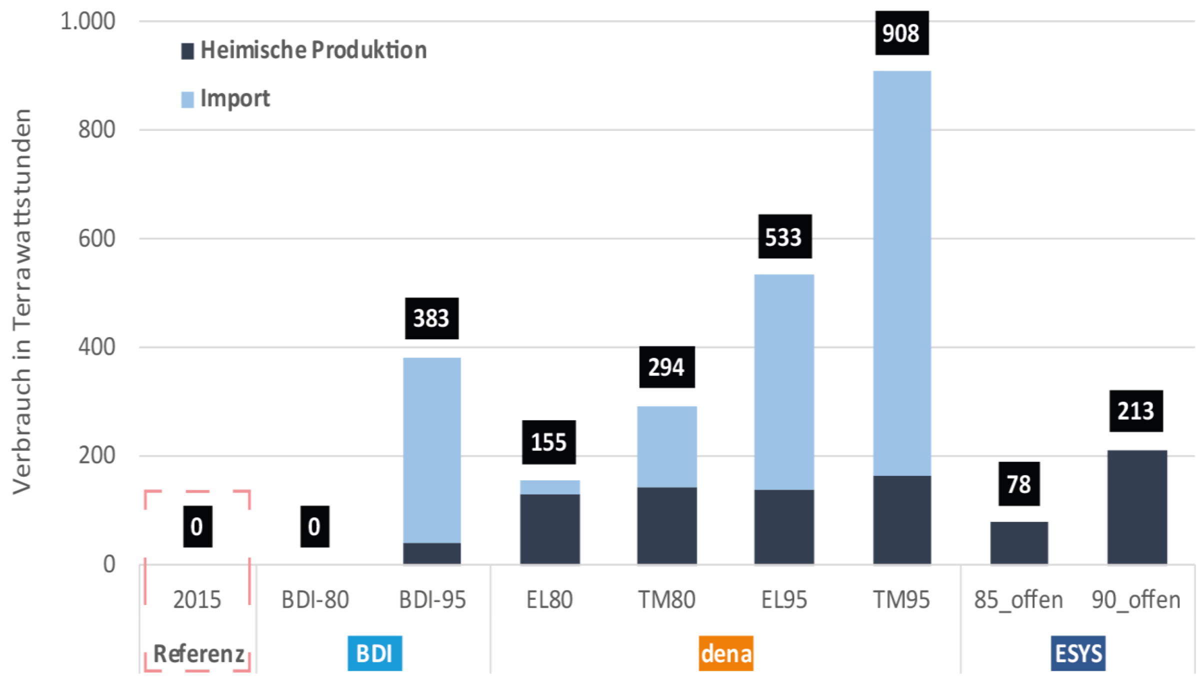

Abbildung 6: Nutzung synthetischer Energieträger bis 2050: Verwendete Energiemengen an synthetischen Energieträgern in Deutschland in den Studien von ESYS, BDI und dena, aufgeteilt nach Energieträgern, die in Deutschland hergestellt, und nach Energieträgern, die importiert werden. Graphik aus Referenz [8].

3.3 Technologien im Verkehrsektor

Der Verkehrssektor bildet das Schlusslicht der Energiewende, wie ein Blick auf die jährlichen Emissionen und den Anteil der erneuerbaren Energien zeigt: letzterer stagniert seit Jahren bei rund 5 % [6], während die Emissionen im Vergleich zu 1990 sogar leicht gestiegen sind [16]. Erfolge im Verkehrssektor sind also besonders wichtig.

Die **Elektromobilität** nimmt in allen drei Studien eine Schlüsselrolle ein, wie in Abbildung 7 zu sehen ist, die den Anteil der Elektrofahrzeuge im Pkw-Bereich im Jahr 2015, im Jahr 2030 und im Jahr 2050 zeigt. Weiterhin könnten **Brennstoffzellen-** und **gasbetriebene** Fahrzeuge eine Rolle spielen, sowie Kraftstoffe, die aus **Biomasse** hergestellt werden. Im Lkw-Bereich ist hingegen noch nicht klar, welche Technologie sich durchsetzen wird. Hier kommen die Vorteile chemischer Energieträger – die hohe Energiedichte und die gute Speicherbarkeit – stärker zum Tragen. Welche der Optionen sich durchsetzen wird – batteriebetriebene Lkw, Oberleitungen, Brennstoffzellen oder konventionelle Antriebe, die mit synthetischen Kraftstoffen betrieben werden – sollte sich in den nächsten Jahren abzeichnen. Zunächst sind weiterhin Forschung und Entwicklung sowie Demonstrationsprojekte notwendig. Wichtig ist jedoch, eine Entscheidung nicht zu spät zu treffen, damit die benötigten Infrastrukturen (auch in Absprachen mit den europäischen Nachbarländern) rechtzeitig aufgebaut werden können. Für den Flug- und Schiffsverkehr zeichnet sich ab, dass rein elektrische Lösungen auch im Jahr 2050 nicht verfügbar sein werden. Insgesamt ist also davon auszugehen, dass ein **Technologiemix** im Verkehr notwendig sein und bleiben wird.

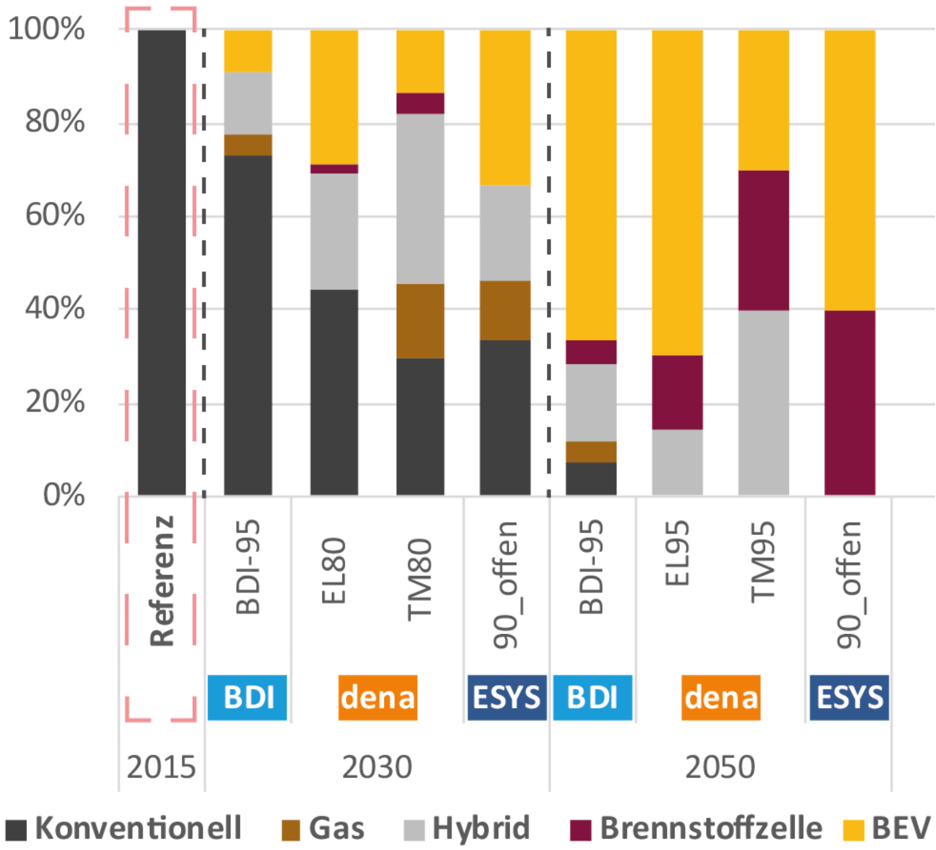

Abbildung 7: Anteil der Antriebsarten im Pkw-Bereich bis 2050: Antriebsarten in Rechenläufen in den Studien von ESYS, BDI und dena. Zu Hybriden zählen hier Plug-in-Hybride (konventionell oder Gas-betrieben). Graphik aus Referenz [8].

3.4 Sanierungsraten und Heizungstechnologien im Gebäudebereich

Um die Emissionen in der Wärmebereitstellung für Gebäude zu senken, gibt es zwei wichtige Hebel: Erstens den Ersatz von konventionell betriebenen Heizungen. In allen drei Studien kommen dafür vor allem **Wärmepumpen** und **Wärmenetze** zum Einsatz. Außerdem spielen **thermische Speicher** eine wichtige Rolle. Sie können Erzeugungsspitzen in der Stromerzeugung aufnehmen und Wärmelastspitzen bedienen und so die Flexibilität im System erhöhen. Der zweite Hebel ist die energetische **Gebäudesanierung**. Die Studien zeigen übereinstimmend, dass bis 2050 fast der gesamte Gebäudebestand saniert werden müsste, wenn die Klimaziele erreicht werden sollen. Dafür muss die Sanierungsrate laut allen drei Studien deutlich erhöht werden: von heute rund 1 % auf 1,4 % bis zu 2 % (vgl. Abbildung 8).

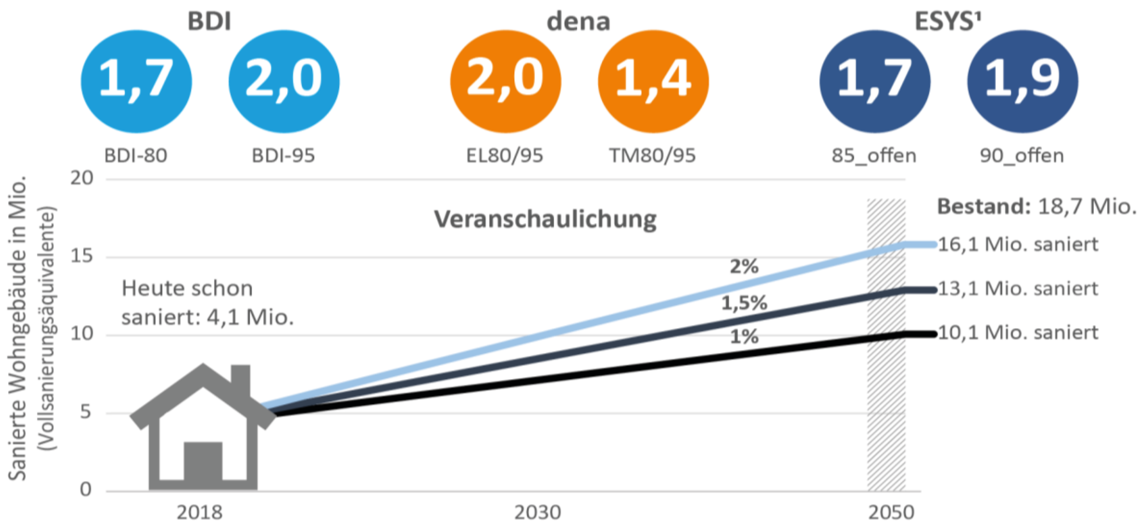

Abbildung 8: Notwendige jährliche Raten der Gebäudesanierung bis 2050 in den Studien von ESYS, BDI und dena. Die Sanierungsraten der beiden ESYS-Studien beziehen sich auf den gesamten Gebäudebestand, bei den beiden anderen Studien auf Wohngebäude. Graphik aus Referenz [8].

3.5. CO_2-Einsparungen im Industriebereich

Die Industrie ist für rund ein Viertel des deutschen Energieverbrauchs verantwortlich [4]. **Energieeffizienz** und ein **Wechsel auf emissionsarme Energieträger** sind notwendig, um die Emissionen zu senken. Hierfür kommen vor allem Biomasse und Biogas, Wasserstoff sowie Erdgas, das sukzessive durch synthetisches Methan ersetzt wird, infrage. Doch werden Effizienz und ein Energieträgerwechsel alleine nicht ausreichen, wie Abbildung 9 zeigt.

Bei einigen Industrieprozessen, beispielsweise der Stahl- und Zementherstellung, entstehen zusätzlich prozessbedingt Emissionen, die mit den heutigen Verfahren nicht vermieden werden können. Diese **prozessbedingten Emissionen** sind heute für rund 7 % der Treibhausgasemissionen in Deutschland verantwortlich [4]. Sie können nur vermieden werden, wenn es gelingt, die Produktionen auf neue Prozesse umzustellen. Ein Beispiel ist die Stahlherstellung auf Basis von Wasserstoff. Gelingt es nicht, neue Verfahren rechtzeitig soweit zu entwickeln, dass sie ökonomisch konkurrenzfähig sind (ggf. unter Berücksichtigung eines entsprechenden CO_2-Preises) und für Großanlagen eingesetzt werden können, könnte die **Abscheidung und Speicherung von CO_2** („Carbon Capture and Storage“, CCS) als Brückentechnologie infrage kommen. Allerdings ist diese Technologie in Deutschland heute umstritten.

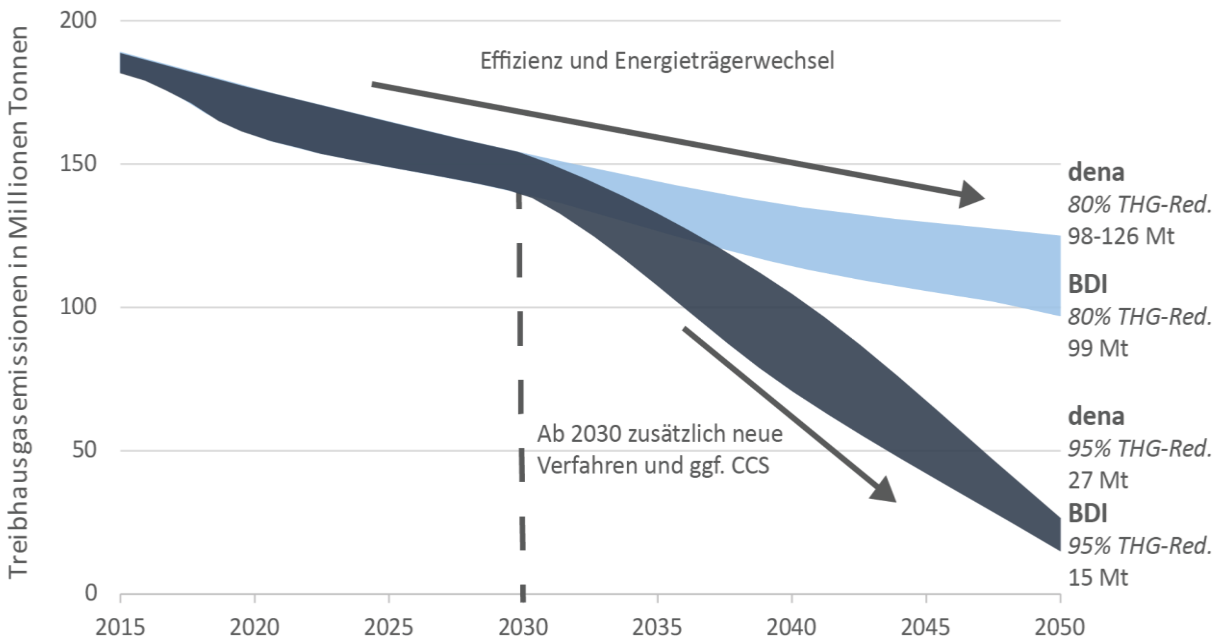

Abbildung 9: Notwendige Reduzierung der Industrieemissionen bis 2050: Korridor der Emissionen der Industrie in der BDI und dena Studie (energiebedingte und prozessbedingte Emissionen). In der ESYS-Studie wurden die Emission der Industrie nicht ausgewertet und prozessbedingte Emissionen nicht betrachtet. Graphik aus Referenz [8].

4. Fazit

Die Energiewende ist technisch machbar. Das haben die Ergebnisse der ESYS-Studie und der beiden Studien von BDI und dena gezeigt. Allerdings wird es notwendig sein, das gesamte Energiesystem grundlegend umzubauen – von den Erzeugungstechnologien und dem Ausbau der Stromnetze, Speicher und Reservekapazitäten bis hin zu neuen Anwendungstechnologien. Damit erneuerbare Energieträger in allen Sektoren zum Einsatz kommen und die Flexibilität des Gesamtsystems erhöht werden kann, müssen die bisher starren Grenzen zwischen klassischen Stromanwendungen, Wärmeversorgung und Verkehr überwunden werden. Das kann nur mit einem systemischen Ansatz gelingen, der das Energiesystem als Ganzes optimiert.

Ein klares Ergebnis der Studien ist zudem: wenn die Energiewende einen wichtigen Beitrag zur Abschwächung des Klimawandels beitragen soll, muss rasch gehandelt werden. Es gilt, wichtige Gelegenheitsfenster zu nutzen, etwa zum Austausch von Heizungen, Fahrzeugen, von Industrieanlagen und zur Gebäudesanierung. Gelingt dies nicht, können die langen technischen Lebensdauern dazu führen, dass späteres Handeln zu deutlich höheren Kosten führt.

4.1 Die vier Phasen der Energiewende

Eine Analyse der zeitlichen Entwicklung des Energiesystems ermöglicht es, die Energiewende in **vier strukturell unterschiedliche Phasen** aufzuteilen. Diese Phasen sind nicht trennscharf, aber unterscheiden sich durch spezifische Anforderungen und Charakteristika. Diese vier Phasen sind in Abbildung 10 dargestellt.

Die **erste Phase** ist inzwischen im Wesentlichen abgeschlossen. Sie war gekennzeichnet durch Entwicklungen im Bereich der erneuerbaren Energien und von Effizienztechnologien, sowie einem ersten Ausbau der Erneuerbaren in der Stromerzeugung. In der sich nun anschließenden **zweiten Phase** der Systemintegration gilt es, Technologien aufzubauen, die Strom direkt nutzen und die Flexibilität des Gesamtsystems durch Systemkopplung auf Erzeugungs- und Verbraucherseite zu erhöhen. Eine stetige Digitalisierung sowie die Entwicklung eines neuen Strommarkts, der die notwendigen Anreize für eine höhere Flexibilität im System setzt, sind dafür wichtig.

Die **dritte Phase** könnte zwar erst in 10-15 Jahren beginnen, aber es gilt, sie bereits heute vorzubereiten. Aufgrund des stetigen Ausbaus der erneuerbaren Energien werden zeitweise hohe Stromüberschüsse (negative Residuallasten) anfallen. Diese können für die großskalige Herstellung von synthetischen Energieträgern (Power-to-X-Technologien) genutzt werden, die wiederum im Verkehrs- und Prozesswärmesektor eingesetzt werden können. In der **vierten Phase** werden schließlich fossile Energieträger gänzlich aus dem System verdrängt werden. Aus heutiger Sicht erscheint es nicht zuletzt wegen des hohen Flächenbedarfs für Windkraft- und Solaranlagen und den damit verbundenen Akzeptanzproblemen unwahrscheinlich, dass die Energieversorgung Deutschlands mit weitgehend nur inländischen erneuerbaren Energiequellen machbar ist. Voraussichtlich wird es günstiger sein, regenerativ erzeugter Strom und synthetische Energieträger aus Ländern mit besseren Standortbedingungen zu importieren.

Alle vier Phasen werden begleitet durch einen stetigen Ausbau der erneuerbaren Energieanlagen, einer steigenden Energieeffizienz und einer immer stärkeren Kopplung der Sektoren Strom, Wärme und Verkehr.

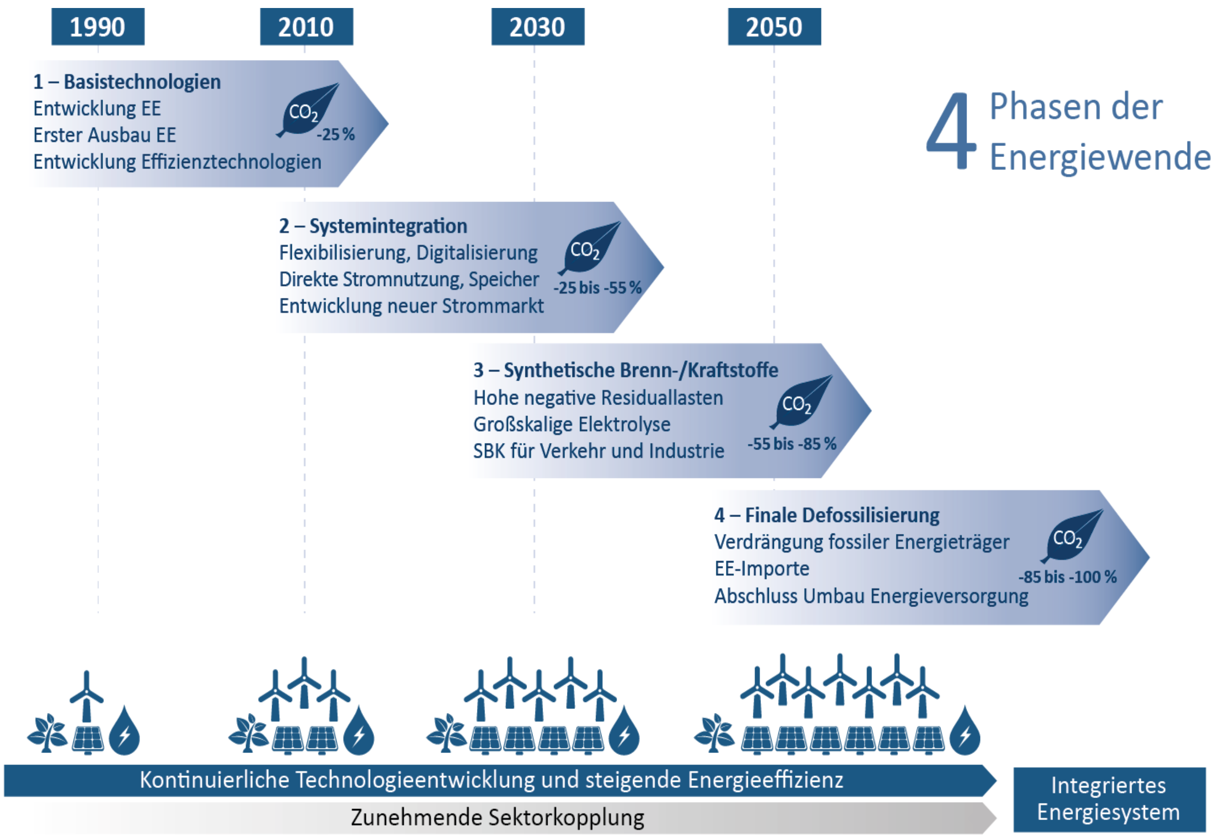

Abbildung 10: Die vier Phasen der Energiewende. Graphik aus Referenz [7].

4.2 Politische Umsetzung

Ein **einheitlicher, wirksamer CO_2-Preis auf alle Emissionen** ist das zentrale Steuerungselement für eine effiziente Klima- und Energiepolitik. Damit würde das eigentliche Ziel, CO_2-Emissionen zu vermeiden, in den Mittelpunkt gerückt. Gleichzeitig müssen Verzerrungen abgebaut werden: Die staatlich induzierten Preisbestandteile liegen bei Strom deutlich höher als beispielsweise bei Erdgas und Heizöl [5]. Das kann dazu führen, dass Strom perspektivisch weniger als für den Klimaschutz zweckmäßig zum Heizen und Fahren eingesetzt wird. Nur wenn das System an Steuern, Entgelten, Umlagen und Abgaben reformiert wird, können alle Energieträger über alle Sektoren hinweg konkurrieren.

Ein hoher CO_2-Preis ist jedoch kein Allheilmittel. Es bedarf ergänzender Maßnahmen: Förderung von Forschung und Entwicklung, (Ko-)Finanzierung von Infrastrukturen, Informations- und Weiterbildungskampagnen, Kompensationen für einkommensschwache Haushalte, für die die Lebenserhaltungskosten besonders stark ansteigen könnten, und weiterer Maßnahmen, die Strukturbrüche, etwa in Kohleregionen, abmildern können. Vor allem bedarf es einer hohen langfristigen Verbindlichkeit der Politik und entsprechender Maßnahmen, um Investoren, Unternehmen und der Bevölkerung Planungssicherheit und Vertrauen in die Umsetzung der Energiewende zu geben.

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Bioenergie heute und was kann/muss die energetische Biomasseverwertung bis 2030 bzw. 2050 leisten?[1]

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Zusammenfassung:

Bioenergie stellt in Deutschland und global den größten Anteil erneuerbarer Energien. Im deutschen Stromsektor liefert sie planbar und flexibel Energie und wird bereits marktorientiert bereitgestellt. In Bereichen der Wärmebereitstellung sowie im Verkehrssektor gibt es bislang keine etablierten sinnvollen Alternativen bzw. Ergänzungen zur Bioenergie. Eine deutliche Steigerung der globalen Biomasseproduktion wird als unrealistisch eingeschätzt. Der Erhalt der erzeugenden Ökosysteme erfordert eine Ausrichtung von Bioenergietechnologien auf Nachhaltigkeitsanforderungen. Ziel muss daher die Steigerung der Verwertungseffizienz sein. Große Optimierungspotentiale liegen in der umfassenden Integration von Bioenergie in das zukünftige Energiesystem sowie in die aufkommende Bioökonomie. Eine optimierte Kaskadennutzung, die Nutzung von Reststoffen und eine verbesserte Koppelproduktion stofflich und energetisch nutzbarer Produkte in einem Prozess bilden wichtige Leitplanken der weiteren Entwicklung von Bioenergietechnologien. In der Bioökonomie kommt Bioenergie die Rolle einer integrierten und emissionsfreien Bereitstellung von Prozessenergie zu. Auch die Erzielung negativer Emissionen (BECCS) wird langfristig als Entwicklungsoption gesehen. Ausblicke in die Zukunft (2030 bzw. 2050) sind aber naturgemäß mit hoher Unsicherheit verbunden.

Abstract:

Bioenergy accounts for the largest share of renewable energies in Germany and globally. In the German electricity sector, it supplies plannable and flexible energy and is already distributed today in a market-oriented manner. In some areas of the heat supply and in the transport sector, there are so far no usefully implemented alternatives for bioenergy. However, a further increase in biomass production seems to be impossible. The preservation of the producing ecosystems requires bioenergy technologies to be geared to sustainability requirements. The aim must therefore be to further increase the utilization efficiency of biomass. Great potential for optimisation lies in the comprehensive integration of bioenergy into the future energy system and into the emerging bioeconomy. An optimised cascade utilisation, the focus on residual materials as well as an improved coupled production of materially and energetically usable products in one process appear to be important guidelines for the further development of bioenergy technologies. In the bioeconomy, bioenergy plays the role of an integrated and emission-free provision of process energy. The achievement of negative emissions (BECCS) is also seen as a long-term development option. However, prospects for the future (2030 and 2050) are naturally associated with a high degree of uncertainty.

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[11] Dieser Beitrag ist auch im Tagungsband des Rostocker Bioenergie¬forums enthalten, das am 13. und 14. Juni 2019 an der Universität Rostock stattgefunden hat.

1. Aktuelle energetische Nutzung von Biomasse in Deutschland

1.1. Primärenergieverbrauch

Bioenergie ist die bedeutendste erneuerbare Energiequelle in Deutschland. 2018 stellte sie 8.5% des gesamten Primärenergieverbrauchs Deutschlands dar. Die anderen Erneuerbaren machten 5,5% aus. (AGEB 2019). Biomasse und dem biogenen Anteil von Abfällen stellen zusammen über 60% der Erneuerbaren Energien bereit.

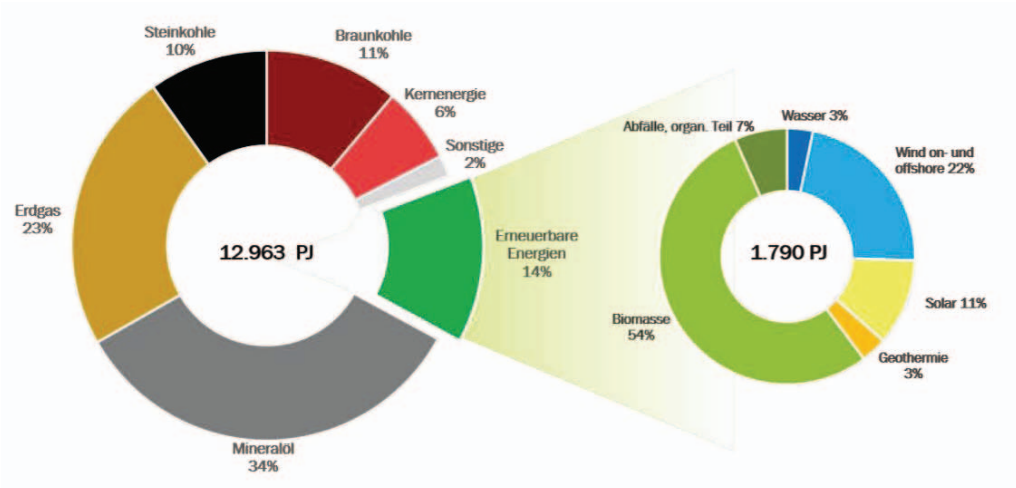

Abbildung 1: Energieverbrauch in Deutschland im Jahr 2018 (Zahlen vorläufig). Stand Februar 2019. Darstellung DBFZ, Daten: Arbeitsgemeinschaft Energiebilanzen e.V.:

Im Vergleich zum Vorjahr, konnte der Anteil Erneuerbarer Energien am deutschen Primärenergiemix um 1,1 % gesteigert werden. Dazu trug vor allem der Ausbau im Bereich Photovoltaik und Wind bei sowie die Extremwetterlagen mit 26% mehr Sonnenstunden als 2017 und sehr guten Windverhältnissen (AGEB 2019). Allerdings wurde aufgrund der Dürre auch 18% weniger Energie aus Wasserkraft gewonnen. Die Bioenergiebereitstellung ist mit -0,7% nahezu unverändert geblieben. Dies zeigt eine wichtige Eigenschaft, wetterunabhängig und vor allem planbar Energie bereitzustellen. Diese Stärke wird im zukünftigen Energiesystem eine wichtige Rolle spielen: Planbarkeit und Zuverlässigkeit bilden wichtige Kriterien bei der Preisgestaltung für Energie. Der damit verbundene Nutzen bei den Anwendern ist vielfältig und reicht von der Netzstabilisierung, Versorgungssicherheit im Strom und Wärmebereich bis zur detaillierten Planbarkeit z.B. von Produktionsprozessen.

Diese positiven Eigenschaften sind vor dem Hintergrund der deutschen Energiepolitik zu bewerten. Die Klimaschutzziele der Bundesregierung verfolgen eine Halbierung des Primärenergieverbrauchs in Deutschland bis 2050 (ggü. 2008) sowie einen Anteil Erneuerbare am Endenergieverbrauch von 60%. Der Anteil erneuerbaren Stroms soll zwischen 80 und 95% liegen.

1.2 Bioenergie im Wärme- und Kältesektor

Über 86% der erneuerbaren Wärme wurde 2018 aus Biomasse inklusive dem biogenen Anteil des Abfalls bereitgestellt (UBA 2019). Ihr Anteil ist damit im Vergleich zum Vorjahr leicht rückgängig. Solarthermie sowie Geothermie und Umweltwärme (Wärmepumpen) verzeichneten hingegen relativ große Zuwächse. Die Jahresschwankungen im Anteil Erneuerbarer am Endenergieverbrauch resultieren aus jeweiligen Wetterlagen.

Anteil EE am Endenergieverbrauch Wärme in %	
1990	2,1
2000	4,4
2010	12,4
2011	12,9
2012	14,2
2013	14,1
2014	14,2
2016	14,0
2016	13,5
2017	13,4
2018	**13,9**

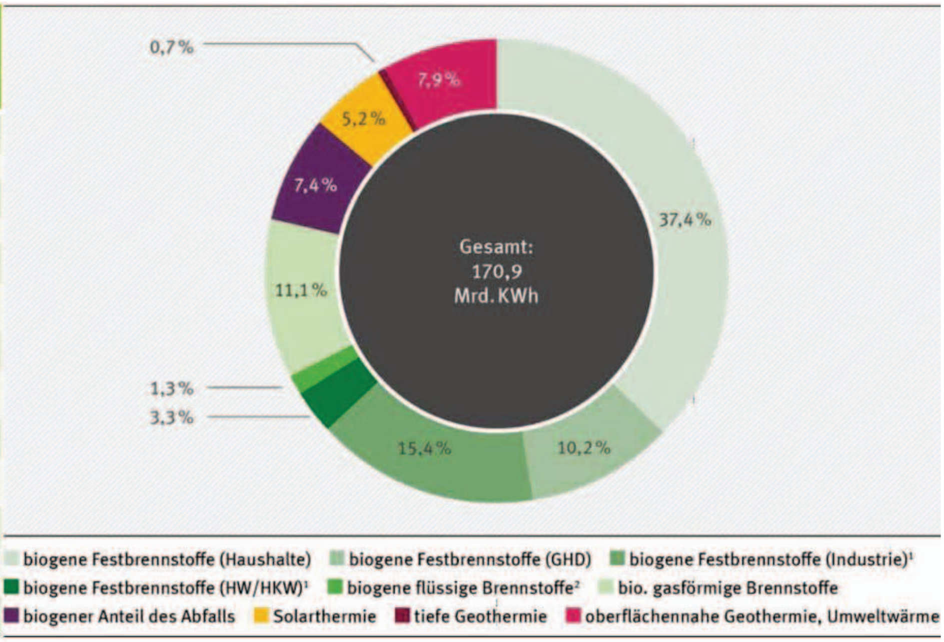

Abbildung 2: Endenergieverbrauch Wärme aus erneuerbaren Energien 2018. Zahlen für 2018 vorläufig. [1]inkl. Klärschlamm. [2]inkl. Biokraftstoffverbrauch in der Land- und Forstwirtschaft, im Baugewerbe und beim Militär. Modifiziert aus Umweltbundesamt (UBA) Hrsg./Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat) 2019.

Unterschieden werden muss in die Bereitstellung von Wärmeenergie zur Beheizung von Wohngebäuden, dem Gewerbe, Handel und Dienstleistungssektor (GHD) und industriell genutzte Wärme (Prozessenergie). Vor allem im industriellen Bereich ist die integrierte Bereitstellung von Prozessenergie (Dampf, Wärme, Strom) entscheidender Produktionsfaktor, der - in Hinsicht auf eine wachsende und politisch forcierte Bioökonomie - an Bedeutung gewinnen wird.

Im Raumwärmebereich wurden laut Deutschem Energieholz- und Pelletverband ca. 2,2 Mio. t Holzpellets abgesetzt, der Bestand an Pelletheizungen erhöhte sich auf 33.000 um 3% (UBA 2019). Auch die Wärmenutzung aus fast 9.000 Biogasanlagen ist erheblich. Alle Wärmeanwendungen haben dezentralen Charakter.

- **Biogene Festbrennstoffe**

Der Großteil biogener Festbrennstoffe wird zur Bereitstellung von Raumwärme und Warmwasser in privaten Haushalten und dem Sektor Gewerbe, Handel und Dienstleistungen eingesetzt (ca. 48%, vgl. Abb. 2). Die 2,2 Mio. t Holzpellets stammen vorwiegend aus Koppelprodukten der Sägeindustrie, rindenfreien Sägespan-Sortimenten. Dies ist ein Beispiel für eine wertschöpfende Verknüpfung von stofflicher und energetischer Nutzung von Biomasse im Sinne der Bioökonomie. Mit Abstand größter Energieträger ist Scheitholz mit ca. 80% des gesamten Brennstoffeinsatzes (vgl. Rönsch et al 2015). Dabei entstehen teilweise erhebliche Emissionen aus Einzelraumfeuerstätten, die im Rahmen der zukünftigen Entwicklung der energetischen Biomassenutzung in privaten Haushalten minimiert werden müssen. Auch die Menge der eingesetzten Biomasse ist mit Sicht auf die künftige

Ressourcenversorgung zu beachten: Im „Rohstoffmonitoring Holz“ ermittelt Mantau ein Volumen von fast 28 Mio. Fm Brennholz, welches 2014 genutzt wurde (Mantau et al. 2018).

Über 15% der erzeugten Wärme aus biogenen Festbrennstoffen entfällt auf den industriellen Sektor. Hier handelt es sich überwiegend um integrierte Industriekraft- bzw. Heizwerke, die in erster Linie Prozessenergie auf Basis von Holzbrennstoffen bereitstellen. Überwiegend wurde im Jahr 2016 knapp 49% Altholz als Brennstoff eingesetzt, Rinde, Sägenebenprodukt und sonstiges Industrierestholz machten zusammen fast 20% aus (vgl. Mantau et al. 2018). Vergleichbare belastbare differenzierte Zahlen für die Energiebereitstellung aus Koppelprodukten und Reststoffen (keine Festbrennstoffe) anderer Branchen wie der Nahrungsmittel- oder Chemieindustrie liegen derzeit noch nicht vor.

- **Biogas**

Die Wärme- und Kältebereitstellung aus Biogas und Biomethan erreichte 2018 einen Anteil von gut 11% des Endenergieverbrauchs an Wärme aus Erneuerbaren Energien (vgl. Abb. 2). Auswertungen der DBFZ Betreiberbefragungen zeigen, dass nach Abzug des Eigenwärmebedarfs der Biogasanlage die extern verfügbare Wärme einer oder mehrerer Nutzungen zugeführt wird (Denysenko 2019). Wichtige Nutzungen sind u.a. die Beheizung von Wohnhäusern und Warmwasserbereitung oder Ställen in unmittelbarer Nähe zur Biogasanlage oder für Trocknungsprozesse (bei ca. 37 % der Anlagen, vgl. Abb. 3).

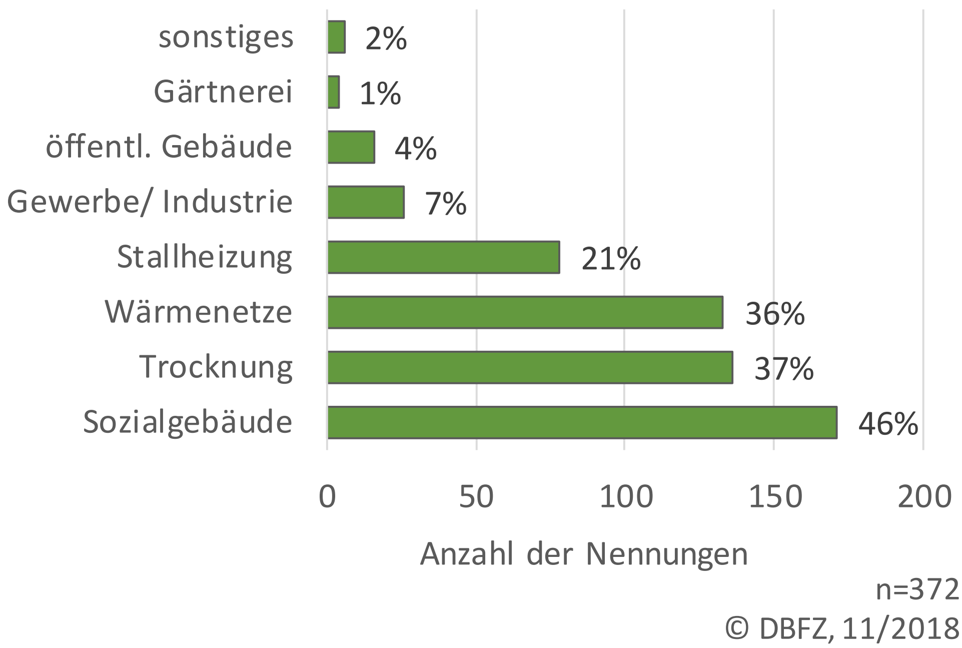

Abbildung 3: Rensberg et al 2019: Art der externen Wärmenutzung, absolute Anzahl der Nennungen und relative Häufigkeit bezogen auf die Stichprobe (n = 372) (Bezugsjahr 2017); Mehrfachnennungen möglich.

Rensberg et al. führen aus, dass die Bedeutung der Wärmebereitstellung über Wärmenetze bis 2016 (Nah- und Fernwärme) sowie die Wärmenutzung aus Biogas in Trocknungsprozessen in den vergangenen Jahren kontinuierlich zugenommen hat und die gestiegene ökonomische Relevanz der Wärmenutzung aus Biogas widerspiegelt.

1.3 Bioenergie im Verkehrssektor

Biobasierte Kraftstoffe machen 88% des Endenergieverbrauches erneuerbarer Energien im Verkehrssektor im Jahr 2018 aus (UBA 2019). Die AGEE-Stat verweist auf einen Absatzanstieg von Biodiesel um ca. 5% im Vergleich zum Vorjahrszeitraum auf ca. 2,2 Mio t. Änderungen der BImSchV in Bezug zur Treibhausgasquotenberechnung und geänderte Bilanzierungsvorschriften von Biodiesel führten zum Anstieg des Absatzes (UBA 2019). Mit Umstellung der energiebasierten Biokraftstoffquote auf eine Treibhausgasvermeidungsquote wurde die THG-Bilanz ein zunehmend relevantes Wettbewerbskriterium für Biokraftstoffe (3,5% ab 2015 & 4% ab 2017). Die im Rahmen der Zertifizierung anerkannte durchschnittliche THG-Bilanz der innerhalb dieser Quote eingesetzten Biokraftstoffe ist von 70 % in 2015 auf über 80 % in 2017 gestiegen. So konnten ca. 7,7 Mio. t CO_2 eingespart werden, was ca. 4% der Gesamtemissionen im Verkehr ausmacht. Trotz Anstieg der THG-Quote auf 4 % ist, aufgrund der parallel dazu zunehmenden durchschnittlichen spezifischen THG-Vermeidung, die eingesetzte Biokraftstoffmenge (Energieäquivalent) aber insgesamt weitgehend gleichgeblieben. Zum Einsatz kommen vor allem Biodiesel/FAME, Bioethanol sowie, zu deutlich geringeren Anteilen, HVO/HEFA und Biomethan (vgl. Lenz et al. 2019).

Die Elektromobilität verzeichnet erhebliche Zuwächse: 2018 stieg der Elektro-PKW-Bestand von 53.861 auf 83.175 Fahrzeuge, bei den Plug-in-Hybriden von ca. 42.500 auf 67.000 Fahrzeuge. In Relation zur gesamten Flotte in Deutschland von rund 47 Mio. Pkw sind dies aber nur die ersten kleinen Schritte zur Etablierung der Elektromobilität. Insgesamt werden 12% des Endenergieverbrauchs im Verkehrssektor über erneuerbarem Strom bereitgestellt, wobei der schienengebundene Verkehr hier einen großen Anteil hat.

Anteil EE am Endenergieverbrauch Verkehr in %	
1990	0,1
2000	0,5
2010	5,8
2011	5,7
2012	6,0
2013	5,5
2014	5,6
2015	5,2
2016	5,2
2017	5,2
2018	**5,6**

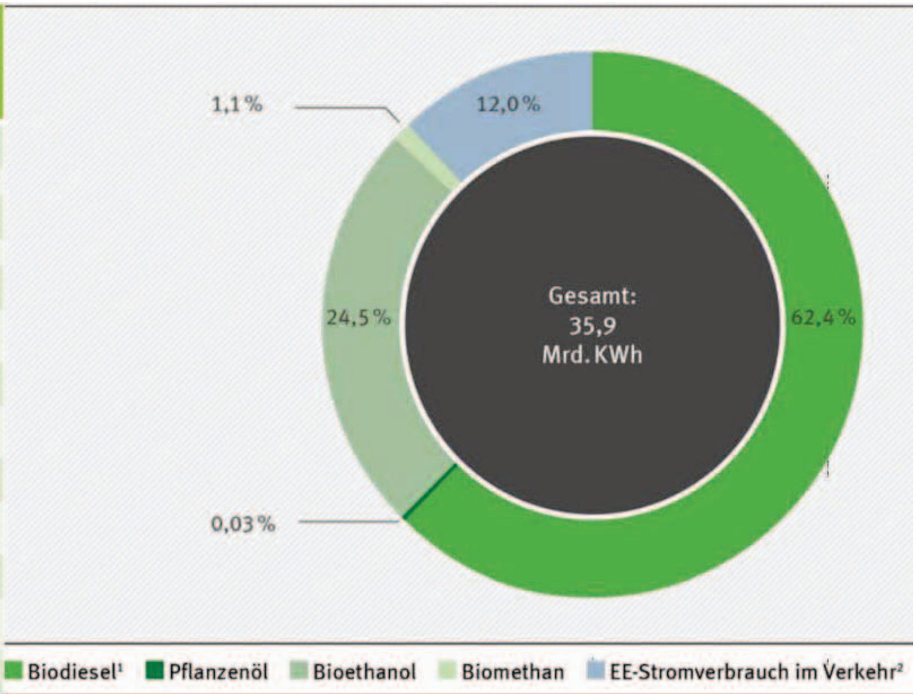

Abbildung 4: Endenergieverbrauch aus erneuerbaren Energien im Verkehrssektor 2018, Zahlen vorläufig. [1]Verbrauch von Biodiesel (inkl. HVO) im Verkehrssektor, ohne Land- und Forstwirtschaft. [2]berechnet mit dem Anteil erneuerbaren Energien am Bruttostromverbrauch des jeweiligen Jahres. Modifiziert aus Umweltbundesamt (UBA) Hrsg./Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat) 2019.

Ungeachtet dessen steht der Verkehrssektor vor besonderen Herausforderungen, Mobilität nachhaltig und klimaschonend zu ermöglichen. Und dies bei gleichzeitig steigenden Fahrzeugzahlen und zunehmender Gesamtfahrleistung, die zu steigenden Gesamtenergieverbräuchen führen. Einen wichtigen Rahmen für Klimaschutz und Erneuerbare Energien im Verkehr stellt die auf EU-Ebene verabschiedete Erneuerbare-Energien-Richtlinie II (kurz RED II) dar, deren konkrete nationale Umsetzung in Deutschland noch aussteht (siehe auch Beitrag „Die Bedeutung biomassebasierter Biokraftstoffe in der Erneuerbaren-Energien-Richtlinie (RED II) als Beitrag zum Klimaschutz im Verkehr“). Absehbar ist schon jetzt, dass Deutschland mit den bestehenden Maßnahmen und bei direkter Umsetzung der RED II die Klimaziele von 40-42% THG-Reduktion bis 2030 verfehlen wird.

1.4 Bioenergie im Stromsektor

Der Anteil an erneuerbaren Strom steigt seit vielen Jahren kontinuierlich an. 2017 trieb Wind das Wachstum an, 2018 die überdurchschnittliche Sonneneinstrahlung sowie neu an das Netz gegangene Windenergiekapazitäten. Die Trockenheit führte zu einem drastischen Rückgang der Stromerzeugung aus Wasserkraft (-18%). Die Stromerzeugung aus Biomasse lag mit knapp 23% ungefähr auf dem Niveau des Vorjahres (UBA 2019).

Anteil EE am Stromverbrauch in %	
1990	3,4
2000	6,3
2010	17,0
2011	20,3
2012	23,5
2013	25,1
2014	27,4
2015	31,5
2016	31,6
2017	36,0
2018	37,8

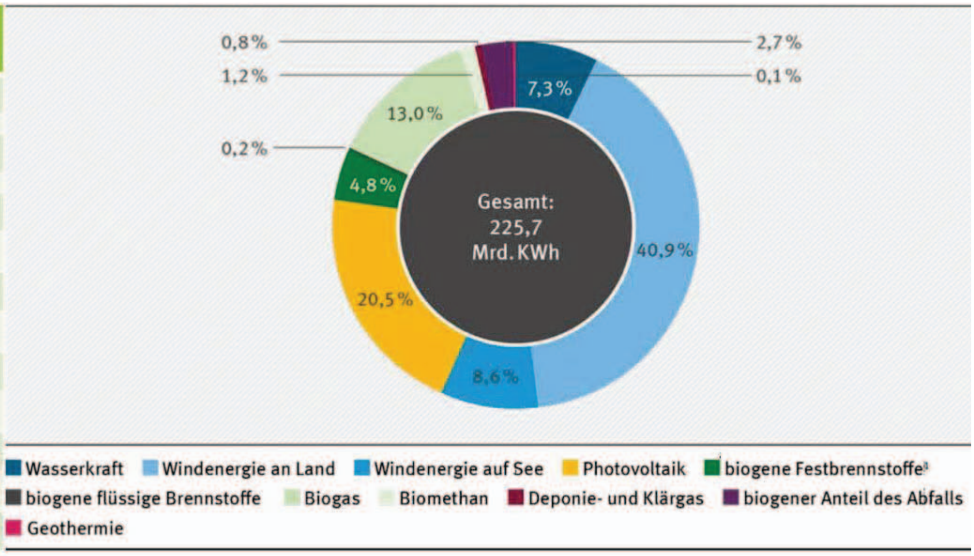

Abbildung 5: Stromerzeugung aus erneuerbaren Energien im Jahr 2018. Zahlen vorläufig. [1]inkl. Klärschlamm. Modifiziert aus Umweltbundesamt (UBA) Hrsg./Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat) 2019.

- **Biogas**

Im Biogasbereich wurde eine Leistung von 411 MW zugebaut, über 90% davon als Überbauung in an bestehenden Standorten. Mit ca. 80% befindet sich der Großteil der Anlagen in der Direktvermarktung.

Wie Denysenko et al. 2019 beschreiben, wurde mit der Novellierung des EEG im Jahr 2012 „die Flexibilitätsprämie für Anlagen, die Strom aus Biogas erzeugen eingeführt (EEG 2012, §33i) und mit dem EEG 2014 in Form vom Flexibilitätszuschlag fortgeführt (§ 54 EEG 2014). Es wurden Anreize geschaffen, zusätzliche installierte elektrische Leistung für eine bedarfsorientierte Stromerzeugung bereitzustellen. Dies kann durch Installation eines oder mehrerer zusätzlicher BHKW (Überbauung) oder den Austausch eines Alt-BHKW durch ein größeres BHKW erfolgen. Mit Hilfe der Flexibilitätsprämie sollen die notwendigen Investitionen für einen flexiblen Anlagenbetrieb teilweise refinanziert werden. Zusätzliche Einnahmen können durch eine Verlagerung der Stromproduktion in hochpreisige Zeiten erreicht werden, wodurch Erlöse oberhalb des monatlichen Durchschnittspreises an der Börse für kurzfristige Strommarktprodukte (EPEX SE) generiert werden können.

Bezogen auf die installierte elektrische Leistung erhalten gegenwärtig rund 15% der Biogasanlagen die EEG-Festvergütung, während die restlichen 85% den erzeugten Strom direkt an der Börse vermarkten. Seit 2014 zeichnete sich ein Anstieg der Flexibilisierung bestehender Biogasanlagen ab. Im Zuge der Novellierung des EEG 2014 erfolgte insbesondere im Juni/Juli 2014 ein starker Anstieg der Anmeldungen zur Flexibilitätsprämie, der als Vorzieheffekt aufgrund großer Unsicherheit hinsichtlich der EEG-Novellierung 2014 interpretiert werden kann.

Zum Stand 09/2018 wurden anhand der Daten der Bundesnetzagentur und Übertragungsnetzbetreiber durch Auswertungen des DBFZ rund 2.678 Biogasanlagen mit einer Gesamtleistung von 1.715 MW_{el} zugeordnet, für die die Flexibilitätsprämie gewährt wurde. Darüber hinaus wurden ca. 155 Biomethan-BHKW mit einer Leistung von 161 MW_{el} flexibel betrieben. Insgesamt erhielten demnach mehr als 2.900 Biogas- und Biomethan-BHKW mit einer gesamten installierten Anlagenleistung von mehr als 2,02 GW_{el} Flexibilitätsprämie bzw. -zuschlag“ (Denysenko et al. 2019).

- **Anlagen zur Vergärung von Bioabfällen**

Ende 2018 sind in Deutschland 136 Abfallvergärungsanlagen in Betrieb (Lenz et al. 2019). „Dies umfasst Vergärungsanlagen, in denen Bio- und Grünabfälle aus getrennter Sammlung eingesetzt werden, als auch Anlagen, in denen gewerbliche organische Abfälle (Lebensmittel, Speisereste aus Großküchen, Kantinen und Gastronomie, Fette und Flotate), Abfälle aus der Nahrungsmittelindustrie oder sonstige organische Abfälle eingesetzt werden. In etwa 90 Abfallvergärungsanlagen werden Bio- und Grünabfälle aus getrennter Sammlung eingesetzt – mit sehr unterschiedlichen Anteilen am Gesamtinput. Auswertungen der Datenbank des DBFZ zeigen, dass rund 70 Anlagen Vergärungsanlagen gemäß §27a EEG 2012/§45 EEG 2014/ §43 EEG 2017 sind. 2018 sind zwei neue Vergärungsanlagen auf Basis von Bioabfällen aus getrennter Sammlung neu in Betrieb gegangen. Die Behandlung der Grün- und Biogutmengen erfolgt mit rund 7,4 Mio. t (Frischmasse) derzeit zum Großteil in Kompostierungsanlagen. Ein kleiner Anteil der getrennt erfassten Bioabfälle (ca. 20%) wird zur Vergärung und Biogasproduktion eingesetzt, zunehmend in kombinierten Anlagen (Kompostierungsanlagen mit Vergärungsstufe), wie Scholwin et al. 2018 darlegt (Denysenko et al. 2019). In Abbildung sind die Standorte der Abfallvergärungsanlagen differenziert nach Betriebsstatus und Substratinput dargestellt. Seit der Einführung der gesonderten Förderung der Vergärung von Bioabfällen mit Inkrafttreten des EEG 2012 sind in Deutschland rund 30 Abfallvergärungsanlagen in Betrieb gegangen. Rund die Hälfte der seit 2012 neu in Betrieb gegangenen Abfallvergärungsanlagen sind als sogenannte Vorschaltanlagen (vorgeschaltete Vergärung des Bio- und Grünabfalls vor der Kompostierung) an bestehenden Kompostierungsanlagen integriert worden. Ende 2018 sind in Deutschland mehr als 50 Vergärungsanlagen mit einer nachgeschalteten Kompostierung in Betrieb (Denysenko et al. 2019).

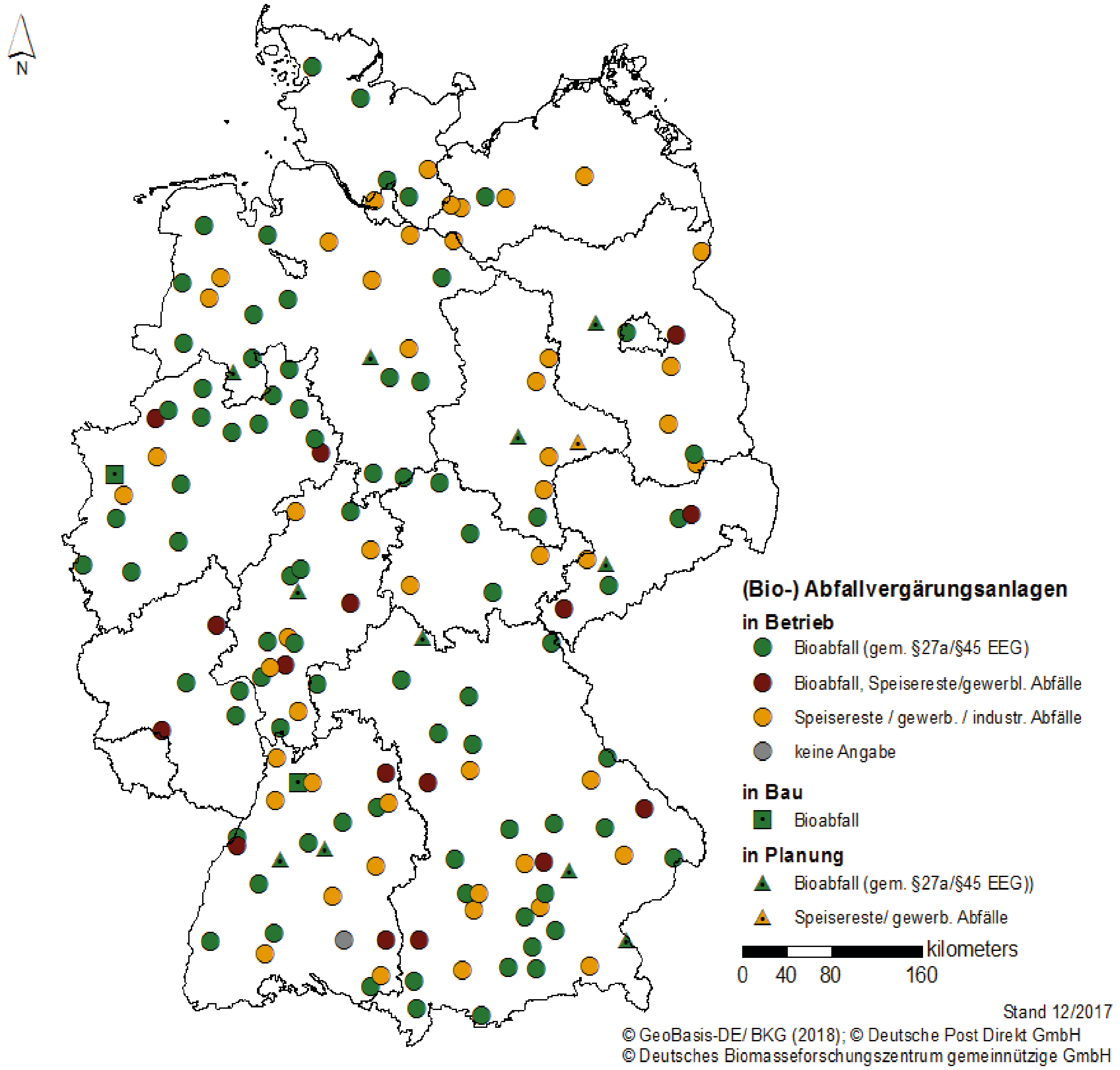

Abbildung 6: (Denysenko et al. 2019) - (Bio-)Abfallvergärungsanlagen in Deutschland differenziert nach Betriebsstatus und Substratinput.

Die gezielte Umlenkung von reinen Kompostierungsanlagen zu Kompostierungsanlagen mit Vergärungsstufe (Anforderungen TA Luft) zur kombinierten stofflichen und energetischen Verwertung der Reststoffe ermöglicht eine effizientere Nutzung der Reststoffe und Einsparungen von Treibhausgasemissionen. Ausgewählte Stoffströme der Grün- und Biogut-Mengen, die bisher in reinen Kompostierungsanlagen verwertet werden, sollten perspektivisch auch für die Vergärung in Biogasanlagen eingesetzt werden. Weitere Potenziale ergeben sich aus der konsequenten Umsetzung der Sammlung und Verwertung getrennt erfasster Bioabfallmengen sowie perspektivisch aus der Erfassung des Organik-Anteil im Restabfall (Denysenko et al. 2019).

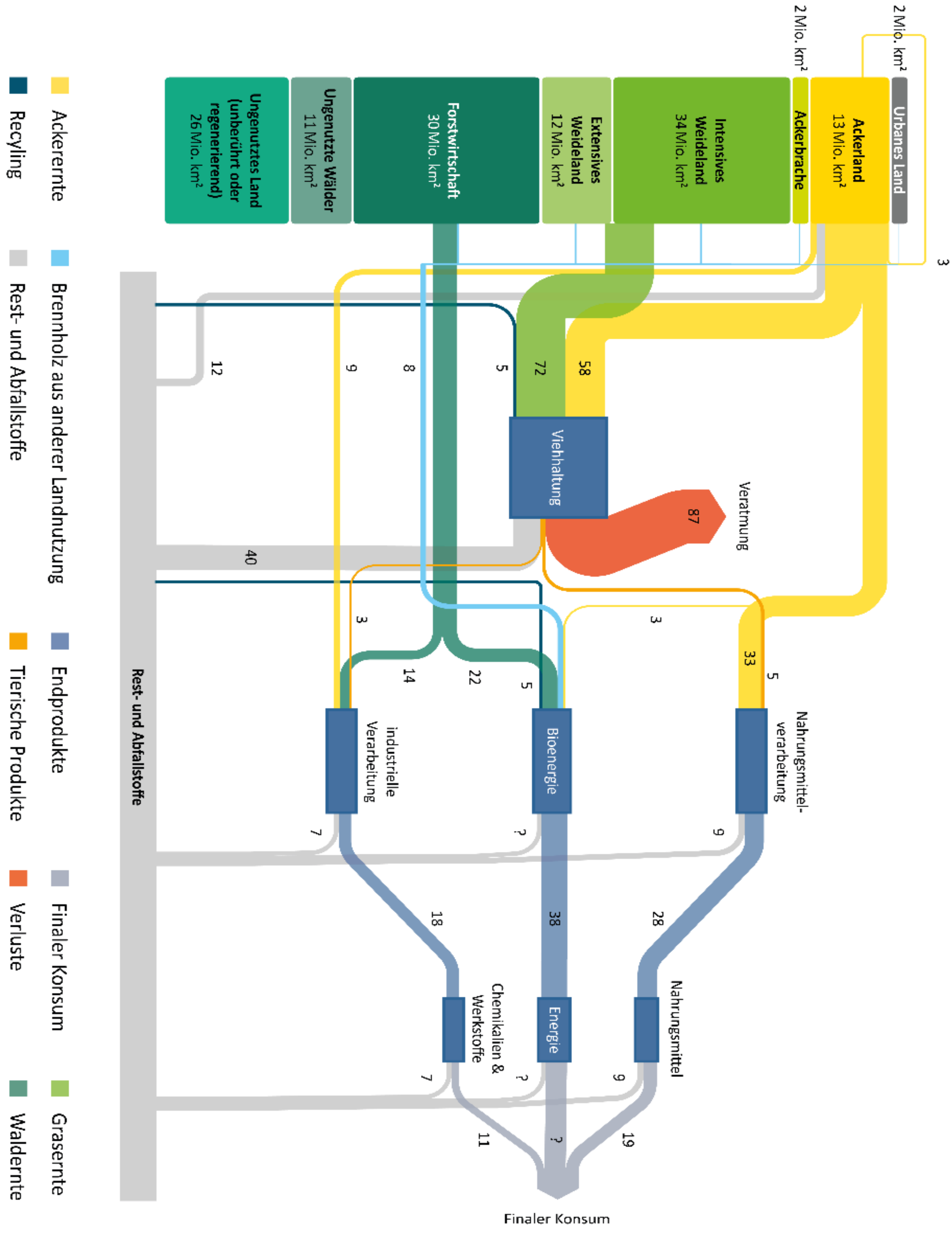

Abbildung 7: Klepper, Thrän 2019: Globale Nutzung der geernteten Biomasse in Exajoule/Jahr. Flussdiagramm der globalen Biomasseflüsse in Exajoule/Jahr mit Zahlen für das Jahr 2000 (Dies ist das letzte Jahr, für das konsistente Biomasse- und Landbilanzen schon vorhanden sind). Die linke Spalte illustriert die gegenwärtige globale Landnutzung.

- **Festbrennstoffe**

Integrierte Anlagen aus der Sägeindustrie konnten bei der letzten EEG-Ausschreibungsrunde Zuschläge erhalten, wie das Holzzentralblatt am 5. Mai 2019 berichtet. So schätzt der Deutsche Säge- und Holzindustrieverband (DeSH) das Instrument als wichtige Anschlussperspektive für EEG-Bestandsanlagen ein. Jedoch werden die Flexibilisierungsforderungen als hinderlich beschrieben. Alleine die Sägeindustrie betreibe derzeit ca. 2.000 Holz-Feuerungsanlagen für Wärme (notwendig für die Bereitstellung von Prozessenergie), teilweise mit Stromerzeugung in KWK. Hinzu kommen ca. 70 Altholz(heiz)kraftwerke in Deutschland (HZB 2019).

2. Energetische Biomassenutzung weltweit

Neueste Schätzungen gehen von einer Bioenergieproduktion weltweit von ca. 51 EJ im Jahr 2015 aus. 87 % davon sind holzbasiert, 10% aus der Landwirtschaft, 3% aus der biogenen Fraktion des Hausmülls (Klepper, Thrän 2019). Die energetische Nutzung entfällt zu über 2/3 auf traditionelle Nutzungsformen in offenen Feuerstellen zum Heizen und Kochen mit extrem niedrigen Wirkungsgraden. Das in Abbildung gezeigte Flussdiagramm weist die Biomasseflüsse im Jahr 2000 aus. Die gesamte vom Menschen geerntete Biomasse stammt zu 50% aus Kulturpflanzen (Ackerbau), ca. 33% aus von Tieren gefressenem Weidegras und zu 16% aus der Holzernte. Ca. 60% der gesamten Biomasse (130 EJ) werden als Tierfutter genutzt, wovon 3 EJ (weniger als 2,5%) der menschlichen Ernährung zur Verfügung stehen. Der größte Teil wird bei der Umwandlung in tierische Proteine veratmet. Ca. 10% der Kulturbiomasse wird direkt als Nahrungsmittel verwendet.
Global betrachtet, wird somit der größte Teil der geernteten Biomasse derzeit mit geringen Effizienzgraden in der Viehwirtschaft eingesetzt oder verbrannt.

Abbildung 8 zeigt den pro-Kopf-Primärenergieverbrauch von Deutschland im globalen Vergleich. Hervorzuheben sind die relativ hohen Nutzungsanteile von Biogas und flüssigen Bioenergieträgern ebenso wie die Verwertung von Abfällen. Hier liegen in der globalen Betrachtung noch erhebliche Potentiale, die gehoben werden können.

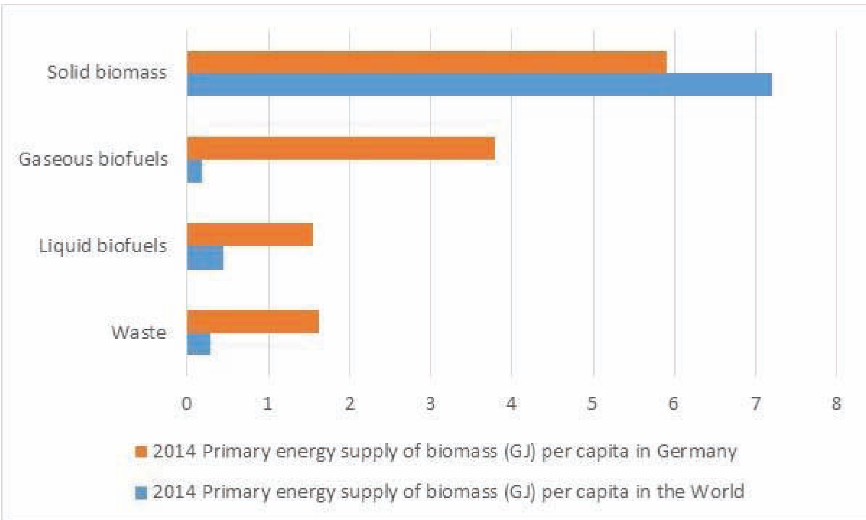

Abbildung 8: Vergleich des Primärenergieverbrauchs pro Kopf global und in Deutschland 2014. Die Werte für gasförmige Bioenergieträger enthalten auch Klärgas. Pfeiffer, Thrän 2018.

Eine substantielle Steigerung der weltweiten Biomasseproduktion erscheint als unwahrscheinlich. Die Analyse der Leopoldina / acatech „Biomasse im Spannungsfeld zwischen Energie- und Klimapolitik“ (Klepper, Thrän 2019) vergleicht verschiedene Studien zur Potenzialabschätzung für Ackerland, Wiesen und Weideland, Wald und Reststoffen. Sie zieht das Fazit, dass ohne ernst zu nehmende ökologische Auswirkungen eine weitere Steigerung der weltweiten Biomasseproduktion unrealistisch erscheint. Auswirkungen durch Klimawandel auf die Produktivität der Anbauflächen inkl. Wald oder die wachsende Weltbevölkerung sind hierbei noch nicht berücksichtigt. Die gegenwärtige Diskussion zum Artensterben aufgrund gegenwärtig praktizierter Anbaumethoden und der abnehmenden Biodiversität lassen eine deutliche Steigerung ebenfalls als unwahrscheinlich erscheinen. Intakte Ökosysteme, wie z.B. naturnahe bewirtschaftete Wälder, benötigen zudem funktionierende Destruentensysteme, die Waldrestholz mineralisieren, Nährstoffe zirkulieren und wichtige Nahrungsketten speisen.

3 Anforderungen an die künftige energetische Biomassenutzung

Einen Ausblick über das Jahr 2020 hinaus bietet u.a. die umfassende Studie „Meilensteine 2030 – Elemente und Meilensteine für die Entwicklung einer tragfähigen und nachhaltigen Bioenergiestrategie“ (Thrän, Pfeiffer 2015). Sie analysiert modellbasiert verschiedene Szenarien der Bioenergienutzung in den Bereichen Ressourcen und Märkte, Ressourcen und Landnutzung, zu ökobilanziellen Bewertungen, ökologischen Auswirkungen, regionalen und internationalen Effekten und Rückkopplungen. Auch in der aktuellen Analyse der Leopoldina/acatech „Biomasse im Spannungsfeld zwischen Energie- und Klimapolitik“ (Klepper, Thrän 2019) werden die Entwicklungsoptionen für die energetische Biomassenutzung für 2050 differenziert dargestellt.

Im Folgenden werden basierend auf diesen beiden Studien und dem oben vorgestellten Status Quo wesentliche Anforderungen und mögliche Entwicklungsrichtungen der Bioenergienutzung knapp zusammengefasst:

- **Nutzung knapper Biomasseressourcen und höchstmögliche Effizienz**

Eine weitere Erhöhung der globalen Biomasseproduktion erscheint, wie oben dargelegt, als kaum realistisch. Die steigende Weltbevölkerung und die in vielen entwickelten Ländern verfolgte Umstellung auf eine Bioökonomie wird die Nachfrage nach Biomasse noch deutlich erhöhen. Hinzu kommen zunehmend Nachhaltigkeitsanforderungen, um die Ökosysteme - und damit auch unsere Produktionssysteme für Biomasse - leistungsfähig zu erhalten. **Alle Nutzungspfade von Biomasse müssen mit höchstmöglicher Effizienz erfolgen**. Dies betrifft vor allem die gegenwärtige Form der traditionellen Bioenergienutzung in sich entwickelnden Ländern, wo ein Großteil der weltweit eingesetzten Festbrennstoffe für Kochen und Heizen mit minimalen Wirkungsgraden von ca. 10% verbraucht werden. Wie Klepper und Thrän 2019 anführen, wird der mit Abstand größte Teil der produzierten Biomasse in der Viehhaltung als Futtermittel eingesetzt. Dieses Potential dient der Erzeugung tierischer Proteine und Nahrungsmittel. Eine fleischreduzierte Ausrichtung Lebensmittelversorgung vor allem in den entwickelten Ländern könnte hier zu einer erheblichen Freisetzung zusätzlicher Biomassepotentiale beitragen. Denn zwischen der Produktion einer vegetarischen und einer fleischlichen Kalorie liegt der Effizienzfaktor 10!

Eine umfassende Ausrichtung der Biomasseverwertung an Nutzungskaskaden in der angestrebten Bioökonomie wird zu einer **wesentlich umfassenderen energetischen Verwertung biogener Rest- und Nebenproduktströme führen.** Effizientere Technologien bei der Abtrennung, Kreislaufführung und Energiebereitstellung sind erforderlich.

- **Integration in das Energiesystem und die Bioökonomie**

Die **bessere Verknüpfung und Integration stofflich und energetisch verwerteter Stoffströme in Koppelproduktion** sowie den zugehörigen Technologien wird von entscheidender Bedeutung sein. Die energetische Nutzung von Biomasse muss in das zukünftige Energiesystem sowie die Bioökonomie gleichermaßen integriert werden. Dabei sind die Stärken von Bioenergie als planbare und speicherbare Energiequelle intelligent einzusetzen (Dotzauer et al. 2019). Nutzungskonkurrenzen müssen aufgehoben bzw. reduziert werden. Sektoren, für die sich bislang keine sinnvollen erneuerbaren Alternativen abzeichnen, bestehen vor allem im Bereich der Prozessenergie (Industrie), im Verkehr insbesondere in der Luft- und Schifffahrt sowie dem Langstrecken-schwerlastverkehr sowie bei der Beheizung größerer oder schlecht zu dämmender Gebäude (vgl. dazu auch Klepper, Thrän 2019).

Bislang kaum betrachtet sind die Synergien und integrativen Ansätze, die sich aus dem Zusammenspiel der einzelnen erneuerbaren Edukte und Produkte ergeben. Dabei spielt Smart Bioenergy nicht nur für die Energiewende im Stromsektor eine wichtige Rolle, sondern auch in der Vernetzung mit dem Verkehrssektor und der stofflichen Nutzung von Biomasse. Dazu eröffnet das Feld nachhaltiger SynBioPTX-Produkte aus biomasse- und strombasierten Ausgangsstoffen für die stoffliche und energetische Verwertung neue Perspektiven für einen erfolgreichen Wettbewerb, auch international (vgl. Müller-Langer in Naumann 2019.).

Bioenergietechnologien können im landwirtschaftlichen Bereich in die Schließung z.B. von Nährstoffkreisläufen integriert werden, bzw. diese ermöglichen.

- **Minimale Umweltauswirkungen: Emissionen und Nachhaltigkeitskriterien**

Die energetische Biomassenutzung muss langfristig „emissionsfrei“ erfolgen. Dies erfordert die Entwicklung entsprechender Verbrennungs- und Abscheidertechnologien, inklusive dafür notwendiger Katalysatoren. Methanemissionen müssen aufgrund des vielfach höheren Treibhausgaseffektes gänzlich vermieden werden – im Vergärungsprozess ebenso wie beim Betrieb von Motoren oder Turbinen mit Biogas/Biomethan.

Strikte Nachhaltigkeitskriterien müssen für alle Nutzungsformen von Biomasse gleichermaßen gelten. Dies schließt die stoffliche Nutzung ebenso wie die Erzeugung von Lebensmitteln und Bioenergie ein. Durch entsprechende Anbausysteme ist sicherzustellen, dass u.a. die Biodiversität und Bodenfruchtbarkeit erhöht werden.

- **Umfassende Nutzung aller Nebenprodukte von Bioenergieanlagen**

Integrierte Bioenergietechnologien ermöglichen eine Vielzahl von Systemleistungen im Energiesystem, in der Bioökonomie, der Kreislaufgeführten Wirtschaft und zur Erreichung von Klimaschutzzielen. Neben den oben angeführten Optionen zur Kreislaufschließung, Netzstabilisierung durch bedarfsgerechte Energiebereitstellung kann Bioenergie grünes CO_2 zur Verfügung stellen. Dieses kann z.B. in der Chemieindustrie genutzt (BECCU – „Bioenergy Carbon Capture and Utilization“ oder zur Erzielung negativer Emissionen (BECCS - „Bioenergy Carbon Capture and Storage“) dauerhaft der Atmosphäre entzogen werden. Langfristig werden diese Technologien als eine weitere Option zur Erreichung der gesetzten Klimaschutzziele beitragen können. Wirtschaftliche Umsetzbarkeit und gesellschaftliche Akzeptanz müssen jedoch eingehend untersucht werden (vgl. Klepper, Thrän 2019).

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Review of inertial confinement fusion and Fast Ignition driven by intense, laser generated proton beams

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Abstract

Inertial confinement fusion has achieved significant progress over the last couple of years. Different laser pulse shapes to drive the x-ray flux inside a hohlraum and new ablator materials have boosted the fusion output to new record values. Still there is some way to go to achieve self-sustaining burn in ICF. The concept of Fast Ignition in fusion targets is a technique to significantly reduce the constraints to the driving laser or ion beam systems and to simultaneously enhance the gain of the fusion yield. While, fast Ignition by intense beams of electrons meanwhile has been investigated over three decades the discovery of intense laser driven proton and ion beams has introduced the idea using those beams to ignite a pre-compressed fusion target.

Introduction

In conventional inertial fusion ignition a propagating burn occurs when there is a sufficient temperature (5-10 keV) reached within a sufficient mass of DT fuel characterized by a density-radius product greater than an alpha particle range $(\rho r)_0 > 0.3$ g/cm^2. The necessary conditions for propagating DT burn are achieved by an appropriate balance between the energy gain mechanisms and the energy loss mechanisms. Mechanical work (PdV), alpha particle energy deposition, and, to a much smaller extent, neutron energy deposition are the principal energy gain mechanisms in deuterium-tritium fuel. Electron heat conduction and radiation are the principal energy loss mechanisms. When the rate of energy gain exceeds the rate of energy loss for a sufficient period of time, ignition occurs. Because of the short burn time and the inertia of the fuel the contribution of expansion losses are negligible.

The onset of hydrodynamic instabilities and the less than optimum power deposition of the x-ray drive on the capsule so far has prevented fusion to deliver more energy that used by the driver.

After the discovery that a significant part of the fuel is escaping compression due to Rayleigh-Taylor instabilities and the failure to reach fusion conditions the concept of the “High foot campaign” achieved significant insight in the problem [37]. In this campaign the intensity of the first driving laser pulse was increased to generate a much hotter plasma and a stronger shock wave driven into the capsule. The initial imperfections in capsule manufacturing and local inhomogeneity’s in the drive flux were smoothed by the hotter plasma temperature and thus the imploding capsule suffered from much less material mix. However, this campaign came at the cost of driving the entire capsule at a higher adiabate, meaning that the increased thermal pressure caused by the first strong shock was prohibitive to achieving the required compression and ignition. So, the campaign was mainly focused on the investigation of the instabilities and less on achieving the highest neutron numbers from fusion.

A more recent approach was to change the outer material of the fuel-containing capsule from CH to high density carbon (HDC). The increased density of the material and the enhanced strength allowed for a thinner ablator, a reduced ratio of total mass to payload, a shorter compression time and resulted in record neutron numbers at much reduced laser energy. This allowed for two additional improvements to enhance fusion. First, as the time to compress was reduced the expansion of the gold hohlraum walls was less of a concern and thus the backfill gas pressure in the hohlraum could be reduced. With less backing pressure also the unwanted parametric instabilities of laser beams travelling in a plasma environment could be reduced.

Second, the lower required laser energy allowed for an increase in hohlraum size as now the laser had enough headroom to drive a larger hohlraum to required temperatures. This was beneficial as it enhanced the radiation field symmetry on the capsule.

Encouraged by the recent results, research with HDC capsules is currently ongoing at the National Ignition facility where meanwhile the fusion energy output exceeds the energy of the imploding shell of the target capsule [40].

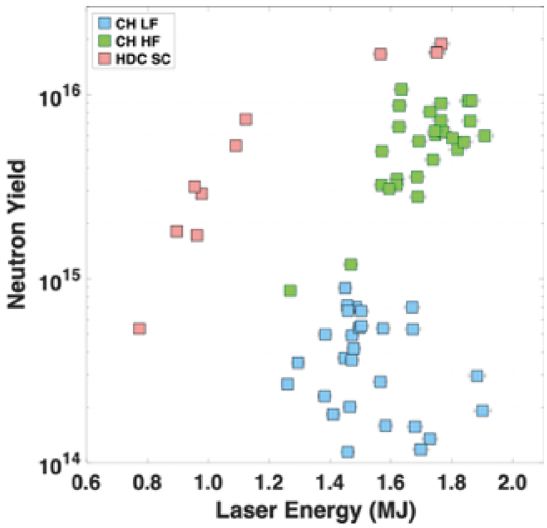

Figure 1: Neutron yield versus laser energy for different campaigns. CH targets were used with low-intensity first shock (low-foot, LF), high-intensity first shock (high-foot, HF) and high-density targets were used HDC, also in a larger hohlraum (figure courtesy of LLNL).

Fast ignition (FI) [1] was proposed as a means to increase the gain, reduce the driver energy, and relax the symmetry requirements for compression, primarily in direct-drive Inertial Confinement Fusion (ICF). The concept is to pre-compress the cold fuel and subsequently to ignite it with a separate short-pulse high-intensity laser or particle (electron or ion) pulse. Fast Ignition is being extensively studied by many groups worldwide [2], using short pulse lasers or temporally compressed heavy-ion beams. There are several technical challenges for the success of laser-driven FI. Absorption of the ignitor pulse generates copious relativistic electrons, but it is not yet known whether these electrons will propagate as a stable beam into the compressed fuel to deposit their energy in a small volume.

For indirect drive, the use of a laser ignitor is prohibited by the absorption of the laser light in the hohlraum wall and the ablation plasma (see [3] for details of a NIF-style indirect drive target). In principle, ion beams can have advantages for FI. A focused ion beam may maintain an almost straight trajectory while traversing the coronal plasma and compressed target [4], and ions have an excellent coupling efficiency to the fuel delivering their energy in a well-defined volume due to the higher energy deposition at the end of their range (Bragg peak) [5]. However, a major problem for ion fast ignition driven by conventional accelerators is to achieve the necessary beam brightness (small spot size, short pulse length) required to deposit sufficient energy for igniting the fuel. To heat a pre-compressed fusion target the beam energy must be deposited into an area similar to the size of the desired hot spot and cover the alpha-particle range. Thus, a beam spot of around 30 μm will be required, which is hard to achieve by conventional ion beams due to space charge effects. The required deposited energy of around 10 kJ asks for an extremely high beam current, worsening the space charge problem and finally the energy has to be delivered in a time shorter than the hydrodynamic response time of the sample. The latter is given by the sound speed of compressed hydrogen at roughly 100 eV and about 1000 times solid density and the radius of the hot spot. To summarize the beam has to deliver around 10 kJ in about 20-30 ps into a spot of roughly 30 μm using ions, that are being stopped in that volume.

Transport of the ion beam over a path of a few meters inside a reactor chamber before reaching the target will result in a larger than optimal beam spot size, which will require a higher ion pulse energy than necessary for heating the desired deposition volume to the ignition temperature.

An interesting alternate route towards Fast Ignition was triggered by the discovery of intense, short, energetic, directed beams of protons off the rear surface of solid targets irradiated by ultra-intense lasers [6]. The initial idea of FI already dealt with the problem, that laser light is stopped and absorbed at a point along the rising slope of the density, orders of magnitude below the density region required to ignite the compressed fuel. So, for the Fast Ignitor there is the need for energy deposition in a small volume (the hot spot) in a short time, by particles that can be created by e.g. the laser and are not likely to be subject of instabilities or other uncontrollable phenomena. With the discovery of those intense, short, energetic bursts of ions with excellent beam quality the idea of using these beams for FI was introduced [7,8].

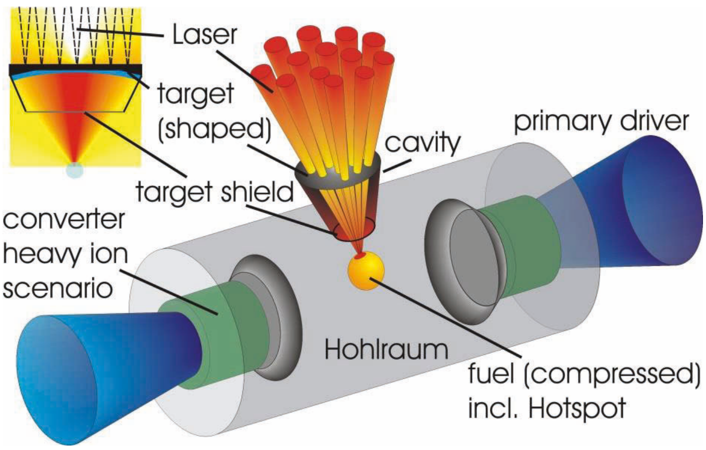

Figure 2: Initial idea of indirectly driven fast ignition (from Ref 5) using a laser accelerated proton beam (not to scale). The rear surface of the laser target is shaped to focus the ion beam into the spark volume.

Protons do have several advantages compared to other ion species [9] and electrons. First, because of their highest charge to mass ratio, they are accelerated most efficiently up to the highest energies. They can penetrate deeper into a target to reach the high-density region, where the hot spot is to be formed, because of the quadratic dependence of the stopping power on the charge state. And finally, they do, like all ions, exhibit a characteristic maximum of the energy deposition at the end of their range, which is desirable in order to heat a localized volume efficiently. As sketched in Figure 2, the basic idea is to use multiple, short pulse lasers irradiating a thin foil. The protons are accelerated off the rear surface of the foil and, because of its parabolic geometry, are focused into the compressed fuel. The detailed acceleration mechanism will be discussed in the next section. The higher mass and the neutralized space charge due to accompanying electrons make them less likely to be subject of instabilities compared to electron beams. As has been shown, the ion beams have an excellent beam quality e.g. emittance [10], that allows for the focusing into a small volume, the pulse duration is short and the particle numbers are high.

Status

After some years of research, what is the current experimental and theoretical status of the prospects for proton fast ignition (PFI)? Based on experimental and theoretical results over the last years the prospects are quite promising. There has been no show-stopper found so far and progress in the experimental results is encouraging.

In this field of research, the main objectives can be summarized:

- Deliver proton or ion beams of matched energy distribution and intensity to reach ignition of a pellet compressed by moderate primary driver energy.
- The transporting and focusing of the beam energy into the fuel to the required density.
- Develop a system that works under realistic ICF conditions and that is technically compatible with the requirements of a power plant.

So far, for the generation of intense ion beams by ultra-intense lasers the following mechanisms have been proposed and, to some extend, experimentally investigated:

- Protons and heavier ions accelerated by the Target Normal Sheath Acceleration (TNSA) mechanism that exhibit a Maxwellian energy distribution [5,11,19].
- "Quasi-monoenergetic" ion beams that are delivered by the same driving mechanism, but are generated by means of intelligent target chemistry [12,13] and / or temporal pulse shaping of the short pulse laser [14].
- Ion beams driven by newly proposed and partly experimentally confirmed mechanisms, like the Shock Breakout Afterburner (BOA) [15], or the Radiation Pressure Dominated Regime (RPD) [16].
- Ion beams driven by the Skin Layer Ponderomotive Acceleration (SPLA) mechanism [17]

The first two mechanisms meanwhile have been studied for some years and therefore some theoretical and experimental expertise has been established. For the two last mechanisms initial experiments have been performed, but it might be too early to quantify their usability for a PFI concept at this time. Nevertheless, the prospects of the new mechanisms are such that further investigation will be carried out in the near future and a future review will address those concepts in more detail. In the following the TNSA based ion acceleration will be reviewed for its usability in PFI.

The generation of fast protons from laser irradiated solid surfaces by the TNSA mechanism is attributed to electrostatic fields produced by hot electrons [18,19]. Relativistic electrons generated from the laser-plasma interaction, having an average temperature of several MeV, envelope the target foil and form an electron plasma sheath on the non-irradiated rear surface. The electric field in the sheath can reach $>10^{12}$ V/m, sufficient to field-ionizes atoms on the rear surface and accelerates the ions very rapidly normal to it. Protons, having the largest charge-to-mass ratio, are preferentially accelerated with respect to heavier ions over a distance of a few microns, and up to tens of MeV. They form a collimated beam with an approximately Maxwellian energy distribution at kT = 5-6 MeV.

Following the initial experimental introduction of laser accelerated proton beams for FI theoretical studies have not only quantified the required beams parameters [20,21], but also recently allowed to devise sophisticated scenarios that greatly relax the required beam parameters. A recent study proposed a combination of two spatially shaped proton beam pulses with a total beam energy which might be available from laser systems in the not too distant future [22,23] (see Figure 3).

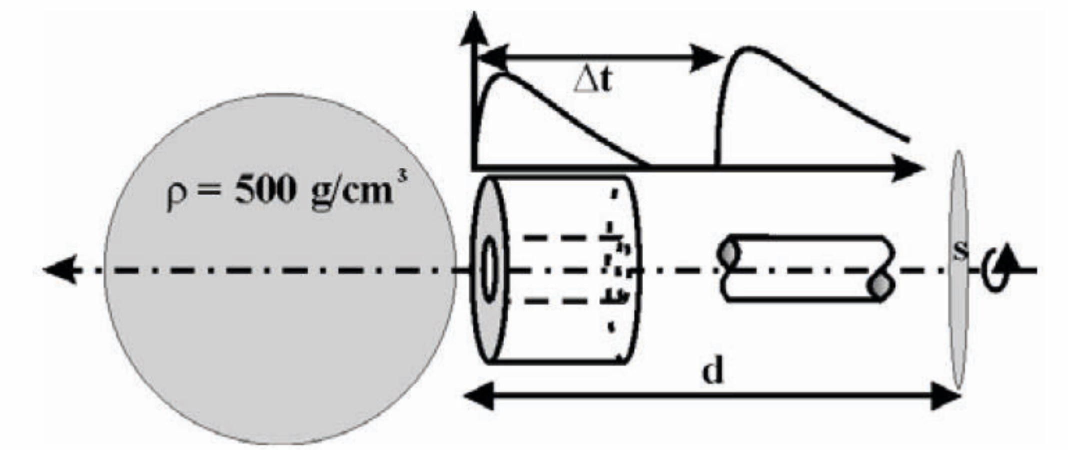

Figure 3: (Courtesy of M. Temporal) Sketch of the beam-fuel configuration using an initial ring-shaped (hollow) proton beam followed by a high energy ignition pulse, separated by about 20 ps (see top sketch of the time evolution). The outer diameter of the ring-shaped pulse is about 20 µm, whereas the inner diameter of 10µm matches the diameter of the second beam pulse.

One of the requirements for PFI is the possibility of focusing the proton beams into a small volume. It has recently been demonstrated experimentally that proton beam focusing is indeed possible down to spot sizes well below 50µm [24]: a LLNL group lead by P. Patel has measured a 32µm spot diameter containing more than 80% of the proton beam. This is still larger than required by PFI, but this also depends on the geometry of the experiment. In future high-energy short-pulse laser experiments computer simulations predict even smaller focal spots getting close to the required 10 to 15µm.

The pulse length was already of the right order of magnitude for PFI as indicated in first experiments on ion acceleration [25]. The protons were found not to be monochromatic, but to have an exponential energy distribution. Initially, this seemed to be a concern for two reasons. First, because of the different energies, the dispersion of the proton pulse along the path from the source to the target stretches the pulse and therefore a maximum distance on the order of only a few millimeters must not be exceeded in order to keep the energy deposition of the PFI beam within the disassembly time of the hot spot region. The close distance to the pellet on the other hand raises concerns whether the thin metallic foil, that is to be the source of the protons, can be kept cold enough to avoid the development of a density gradient at the rear surface, as this would diminish the accelerating field generated by the laser via ponderomotoric effects. A second concern is related to the stopping power. Differences in initial kinetic energy of the protons relate to their energy deposition over a larger volume and slower protons are stopped earlier and they do not contribute to the creation of the ignitor spark.

For the concern on the hydrodynamic stability of the proton source foil the proposed usage of a cone target similar to the one proposed for electron fast ignition [26, 27] has solved most of the problems by shielding the foil from primary soft x-rays generated in the compression of the capsule (see Figure 4).

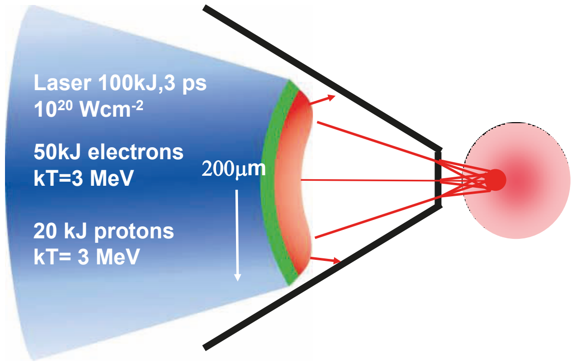

Figure 4: (Courtesy of Mike Key (LLNL)) Proposed concept of using cone-guided proton fast ignition.

Furthermore, it was demonstrated that small-scale plasma density gradients at the rear side of the proton source target caused by target preheat have no significant (less than 10 %) impact on the TNSA mechanism [26]. Still the dispersion of the proton beam energy causes undesirable pulse lengthening and therefore should be kept to a minimum. It was agreed that there is a trade-off between the minimization of the source to hot spot distance and the source area required for providing a sufficient amount of protons for ignition. A possible adjustment parameter might be the manipulation of the proton spectrum which is subject of current research.

Since the time the concept has been first presented a deeper understanding of the underlying physics has been achieved. Detailed numerical simulations have been carried out taking advantage of increasingly sophisticated and realistic computer modeling.

A big surprise was that a monochromatic proton beam is actually not the optimal concept for heating a hot spot in a fusion target. Numerical simulations [27, 36] have shown that one has to take into account the decrease of the stopping power in the nuclear fuel with increasing plasma temperature during the beam interaction. Rather as mentioned above, an exponential energy spectrum, like the one that is actually generated in experiments appears to be the most favorable one due to the following mechanism. The first protons with the highest energies penetrate deep into the fuel. By the time the impinging proton number increases and the target temperature rises, the stopping power is reduced, thereby compensating for the lower (initial) energy of the incoming protons. Thus, the majority of the protons deposit their energy within the same volume. A further improvement of this concept has been proposed by spatially shaping the proton beam and applying two consecutive beams, which brings down the required beam energy to 6kJ [23]. This is an important fact, because not only a realistic proton spectrum was assumed, but also, assuming already experimentally confirmed laser to proton beam conversion efficiencies, the primary laser energy is in the ballpark of facilities which are currently designed for FI (see Figure 5).

The use of a cone-guided geometry, like in conventional FI has been considered to be of great advantage. The source foil can be shielded from the radiation caused by the primary drivers, the source to hot spot distance can be tailored precisely and the pellet can be protected from heat during the injection into the target chamber.

Conversion efficiency from laser energy into proton beam energy is still an important question that directly affects the feasibility of the whole concept. Initially, a conversion efficiency exceeding 6% into protons above 3 MeV has been reported [28]. Those numbers are not far from those required by current PFI concepts, but still need to be improved. Recent new target designs [29,30] and laser pulse shaping experiments resulted in highest conversion efficiencies of 15 % in the ballpark of required fusion experiments [31].

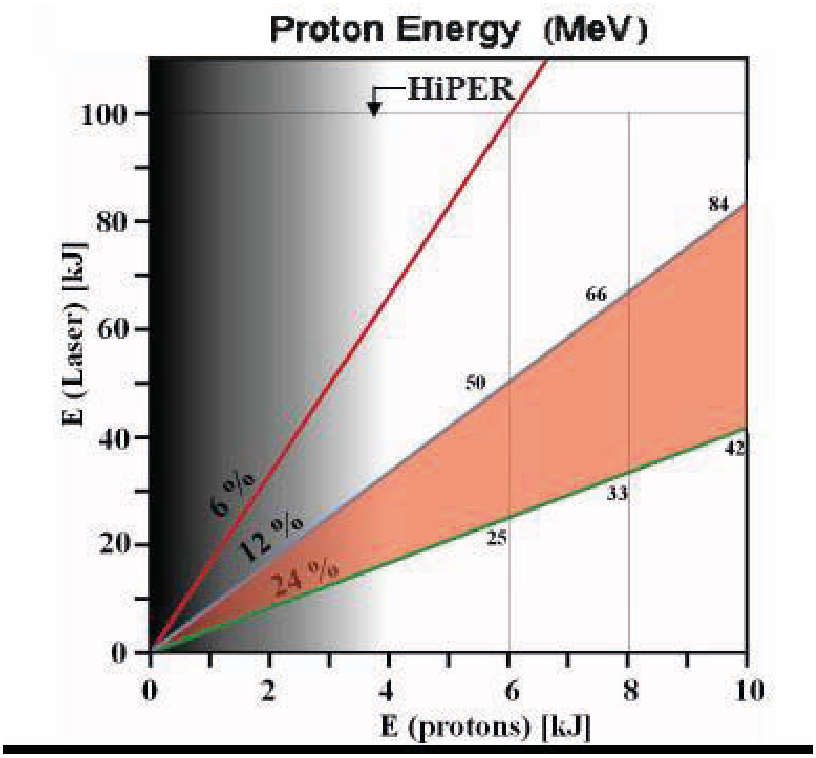

Figure 5: Courtesy of M. Temporal. Energy requirement of the laser system to achieve ignition versus energy stored in the proton beam. For confirmed conversion efficiencies of 6% the latest design [17] was in range of the once proposed HIPER laser system.

There have been also experiments for a proton focusing design which includes the walls of the cone and the transmission through the cone tip. Energy loss in the cone tip, scattering and spot enlargement as well as the influence of electron interaction with the cone, guiding and instabilities were addressed experimentally as well as numerically. Using the Orion laser system at AWE in the UK, delivering a peak intensity of $1x10^{21}$ Wcm^{-2}, we measured a spectrally broad focused component between 10 and 30 MeV, with a clear annular structure in the proton beam's spatial distribution measured near the cut-off energy. An auxiliary laser-driven proton beam, generated using a second short pulsed beam, was used to transversely probe the target, to characterize the field structure responsible for the focusing. To close in on a realistic PFI scenario, multiple long pulsed beams were used to induce plasma expansion around the cone walls, to measure the effect of a dense, long scale-length plasma on the focusing of the proton beam.

Still, a realistic hydrodynamic design for the survival of the cone and proton foil rear surface during pre-compression has to be established and tested.

Outlook

In addition to protons, carbon ions or even heavier ions have been considered as an interesting alternative. Due to the dependence of the stopping power on the ion charge squared they have to have much higher initial particle energies. This might be harder to achieve, but the benefit is a lower number in particles required for the ignition energy, a more pronounced Bragg-peak (if still present in such plasmas) and beams with even higher rigidity that will maintain their trajectories on their way to the hot spot due to less straggling. One interesting experimental finding was that for heavy ions the initial beam divergence was actually lower that the one for protons [32].

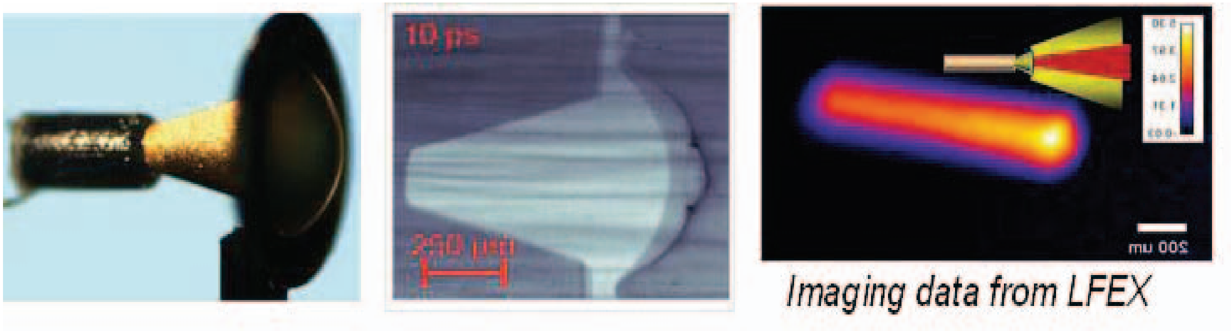

Figure 6: Experimental data from ORION (AWE,UK)(left, middle), and LFEX (ILE, Japan) (right). A copper foam was heated using focused, laser-driven ion beams and the k-alpha radiation imaged onto a detector. Fast proton radiography revealed the electric fields around the target.

Still quite some challenges remain until a more detailed concept can be proposed with some confidence. While predictive modeling has much advanced [38] there is an urgent need to better understand the stopping power of ions in ICF relevant plasmas, especially the presence or absence of the beneficial Bragg-peak should be addressed. Experiments should be planned to measure the energy loss of ions in such extreme plasmas. Here facilities like the Omega EP facility may become an important role-player for their ability of compressing a target and to simultaneously accelerate ions in decent numbers.

Finally, an interesting question not only for PFI is the superposition of multiple petawatt type beams at pulse durations of many picoseconds. Will there be a chance to smoothly overlap those beams in order to maintain and preserve the required intensity for ten picoseconds? What will be the influence of beam filamentation, self-focusing in the preformed plasma or misalignment of the beams, which may result in much higher intensities and therefore electron temperatures? Also, we know that laser imprint does have an effect on the quality and shape of the accelerated ion beams [33]. Those questions must be addressed urgently and finally, as expected the verification of different numerical codes that are used to simulate PFI as well as ICF in general is an important task to further gain more confidence in the different scenarios.

With all the encouraging results it should be noted that currently there are plans for building multi-kilojoule short pulse laser systems in the US, Japan and in the EU. So, finally, the chances are high for demonstrating PFI as an alternative way to achieve ignition and to further explore this fascinating field of research.

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NEUTRON GENERATION BY LASER-DRIVEN PROTON SOURCES

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Abstract

Ultra-intense lasers have demonstrated the capability of accelerating short pulses of intense ion beams. These ion beams have been used to generate short bursts of neutrons by irradiating a converter in close distance to the source, making this scheme a very compact and bright source of neutrons up to more than 100 MeV in energy. Using novel laser ion acceleration mechanisms directed beams of neutrons can be generated, which increases the brightness of these sources compared to previous attempts. We review the recent research and present experimental data using a mechanism based on relativistic transparency to drive the most intense laser driven neutron source and use them for first applications.

Key Words: Ultra intense lasers, neutron sources, ion beams, relativistic transparency

1. Introduction

There is a growing need for small and medium sized neutron sources of high brightness [1] and ranging from thermal to multi-MeV particle energies. Applications include basic research, the use in material sciences and further industrial and medical applications. Since the advent of ultra-intense lasers, the acceleration of intense ion beams has been one of the most exciting fields of research over the last decade. Those laser systems can accelerate ion beams using fields six orders of magnitude above the highest conventionally available fields and therefore have reduced the required accelerator length from meters to sub-millimeters.

The basic concept of laser driven neutron sources is to replace large conventional accelerator structures by compact laser driven ion sources and use a small converter design to form a compact neutron source. Thus, one combines the large cross section for neutron evaporation and related nuclear processes with the spatial and temporal advantage of a laser driven source.

The most widely used mechanism had been discovered in 1999 and is known as the target normal sheath acceleration (TNSA) [2,3]. This mechanism is based on the charge separation at the rear surface of thin, micrometer-sized solid foils and results in short bursts of ions up to energies of 60 MeV in an exponential spectrum [4]. The ion beams usually contain protons as the predominant species as those have the highest charge to mass ration and are accelerated most efficiently by the quasi electro-static potential.

The short pulse duration of the ion beam results in a short burst of neutrons with highest brightness and allows for techniques not accessible with conventional drivers.

2. Prior research

Shortly after the discovery of laser driven proton beams by the TNSA mechanism those have been used to generate neutrons. Early experiments include the Li(p,n)Be reaction [5] and obtained $3x10^{8}$ n/sr^{-1} using the CLF Vulcan laser in the UK and 70 J of laser energy. They also observed an anisotropy with an increased yield in the backward direction towards the laser.

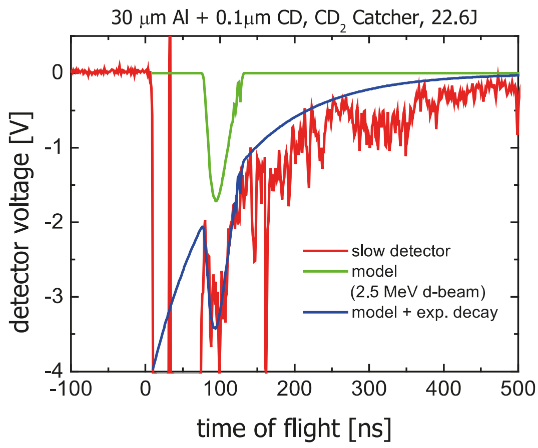

Figure 1: one of the first nTOF measurement for neutron generation by laser driven deuterons (2000) at LULI. The neutron peak at 2.45 MeV is clearly visible in the decaying signal caused by the x-ray flash.

Experiments of our group at the LULI laser system in 2000 resulted in 4×10^8 neutrons using d-d fusion reactions when irradiating a deuterated plastic block with deuterons (see Figure 1). A clear mono-energetic peak at 2.5 MeV was observed, which was boosted in energy in the forward direction by the beam fusion kinetics.

In 2010 Higginson et al. continued the work on neutron production using the LLNL TITAN laser system [6] and obtained 1.8×10^9 n/sr^{-1} using LiF as a converter and 120 J of energy. They calculated those numbers to be sufficient enough for neutron resonance spectroscopy as a possible application. A year later the same group succeeded in getting 8×10^8 n/sr^{-1} via the same reaction using 360 J of laser energy on the same facility [7]. This time they also increased the neutron energy up the 18 MeV and observed a forward peaked intensity distribution. At a smaller laser system, but at a high repetition rate, the university of Michigan also obtained a directed neutron emission up to 1×10^8 n/sr^{-1}, energies up to 16 MeV and a conversion efficiency of 10^{-5} from laser to neutron energy using 10^{21} W/cm^2 pulses [8]. Here the group used a deliberate deuterium contaminant layer at the rear surface to enhance the neutron production via the TNSA mechanism. As all the cross sections and the directionality of the emitted neutrons are energy dependent and the use of deuterium instead of protons is advantageous due to the additional neutron present in the latter a novel mechanism was investigated to enhance the neutron emission.

3. Relativistic Transparency

Relativistic transparency occurs, when the motion of the electrons in the laser results in an increased inertia caused by the relativistic mass increase as the electrons approach the speed of light. As the electrons are no longer able to follow the laser oscillation and their number is decreasing due to the expulsion by the ponderomotive force of the laser the target becomes transparent for the laser frequency. More precisely, a target becomes relativistic transparent when $N/\gamma \leq 1 < N$ with $N = n_e/n_{cr}$ the normalized target electron density and $n_{cr} = m_e\omega_0^2/(4\pi e^2)$ the critical electron density.

At this point the laser interacts with the entire target volume and efficiently accelerates the bulk material [9]. In contrast to the TNSA now all the ions are accelerated, which opens the possibility to use the most efficient neutron conversion reaction.

Two important developments were required to experimentally confirm this new mechanism, the reliable production of sub-micrometer free standing target foils [10,11] and the enhancement of the laser contrast, i.e. the ratio of unwanted light prior to the main pulse [12,13,14]. This mechanism, the so-called Break Out Afterburner (BOA), has been predicted using large scale 3D simulations on the first PFLOP computer at the Los Alamos National Laboratory (LANL) [15,16] and has meanwhile experimentally demonstrated at several laser facilities.

4. Neutron production

The most promising neutron generating reactions are the Be(p,xn)B reactions, widely used in conventional accelerator driven sources [17,18]. A highly efficient converter is therefore made of beryllium, where the length of the converter matches the range of the incoming ion beams. To further enhance the converter performance and to increase the directionality the Be converter is often surrounded by a cylinder of tungsten. If initially the proton beams is replaced by a deuteron beam the additional neutron generating breakup reaction of the deuteron yields a directed neutron beam in addition to the isotropic Be(p,n)B reaction.

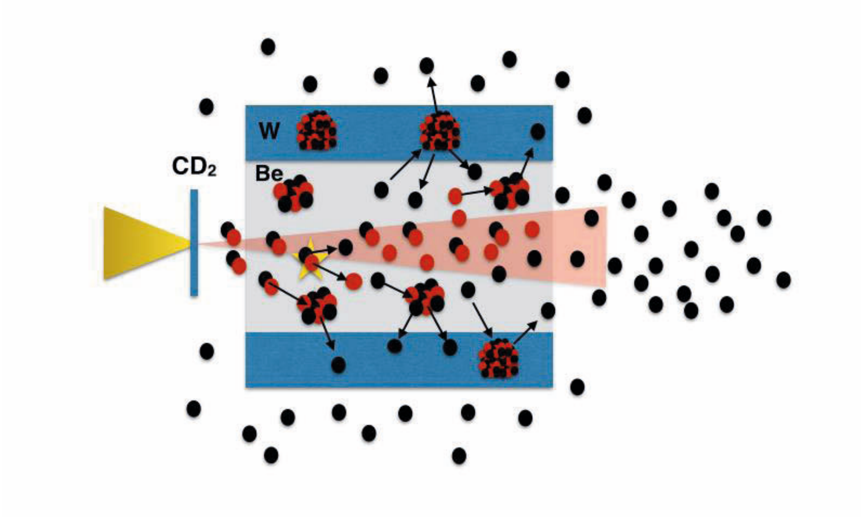

Figure 2: nuclear reactions in the converter. In addition to the energy loss there are breakup reactions, nuclear excitation via (d,xn), (p,xn) and (n,xn) reactions in Be and W. The tungsten cylinder also reflects some of the neutrons back into the forward emission cone.

The conversion of the incident ion beam into neutrons therefore is governed by the following processes (see Figure 2): 1. breakup of the deuteron as it enters the converter material, 2. neutron emission due to the Be(p(d), xn)B processes according to the energy dependent cross sections, 3. energy loss of the ions inside the converter material, 4. pre-compound reactions in the converter material for the highest neutron energies, 5. neutron scattering and W(n,xn)W reactions in the tungsten wall of the converter casing.

5. Recent Experiments

Whereas initial experiments on neutron production using the TNSA mechanism have resulted in neutron numbers that made them suitable for resonance spectroscopy, a higher conversion efficiency is needed for more demanding applications.

Recently, our group used the BOA mechanism to generate an intense beam of energetic deuterons from the bulk of deuterized plastic foils at the LANL Trident facility. The BOA mechanism also offers the possibility to efficiently accelerate ions independent of their charge to mass ratio, preferential for accelerating deuterons [19]. Different converter materials were tested, starting with copper and then changed to an encapsulated beryllium target, about 5 mm behind the plastic foil. The BOA mechanism required a precise target thickness control as if the target is too thin the target becomes transparent too soon, before the laser pulse reaches maximum intensity and the interaction is inefficient. If the target is too thick the regime of relativistic transparency cannot be reached and the ions are accelerated by the less favorable TNSA mechanism [20] (see also Figure 5). A typical experimental setup is shown in Figure 3. A short focal length off-axis parabolic mirror (e.g. F/1.5) is used to focus tens of Joules of one micrometer laser light of a few hundreds' femtosecond pulse. The on-target focus is a few µm in radius ($1/e^2$-condition, containing >60% of the laser energy) with a peak intensity of up to 1×10^{21} W/cm^2. The laser pulse duration and beam parameters have to be carefully recorded during the whole campaign. Thin, free-standing, plastic (CH2) and deuterized plastic (CD2) foils with thicknesses from 200 nm to 3.2 µm were then used to generate proton and deuteron beams.

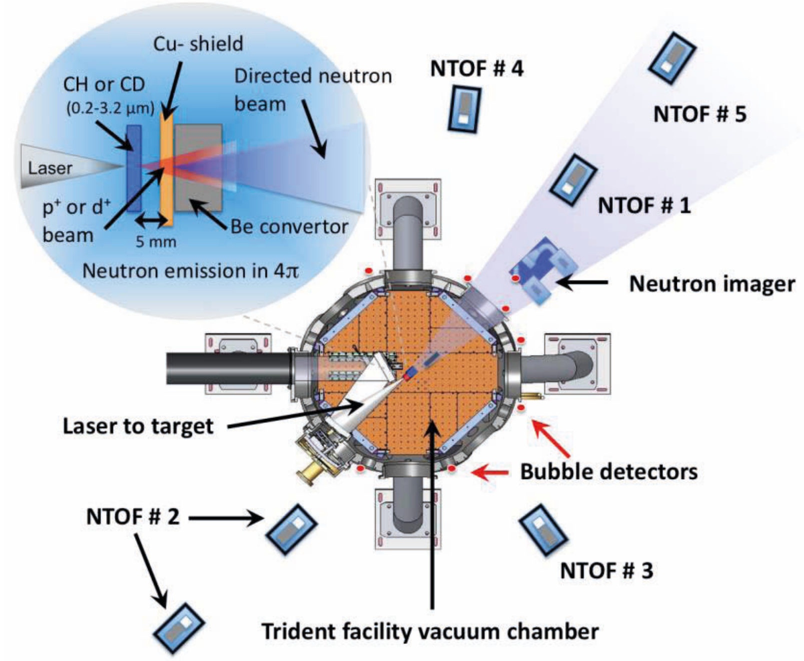

Figure 3: Experimental setup at the LANL TRIDENT facility. The accelerator length in this case was 5 mm to the converter (upper inset). The neutron emission was monitored with NTOF detectors and bubble detectors in different directions to get energy resolved, absolute, spatial neutron distribution function.

Evaluation of the neutron generation performance requires detailed knowledge of the driver in terms of energy distribution, particle numbers and energy content, as well as beam divergence. Ideally one uses several independent diagnostics to characterize the driving ion beam for these parameters including an ion Wide Angle Spectrometer (iWASP) [21], Radiochromic Film Imaging Spectroscopy (RIS) [22] and Nuclear Activation Imaging Spectroscopy (NAIS) [23]. During the experiments at LANL in 2012, the optimum target thickness was approximately 650 nm for the CH and CD targets at which peak energies of up to 150 MeV have been measured for protons and deuterons, respectively. With thinner or thicker targets, particle energies and numbers drop rapidly (for more details, see Ref. [24]).

Neutrons can be measured using activation techniques in different materials (In, Cu, Ag), neutron time-of-flight (nTOF) methods in different directions, neutron imaging camera systems [25,26] and BTI bubble detectors [27,28,29]. Details about our experimental setup can be found in [30].

According to the requirements in the previous chapter, the neutron converter has to have a sufficient length according to the stopping range of the deuterons, but not too long in order not to scatter or absorb too many neutrons in the desired forward direction.

Laterally, the converter can be limited in order to maintain a small source size, e.g. for point projection imaging using high energy neutrons, but this reduces the total amount of neutrons, as the ion beam diverges and more deuterons start to miss the converter material.

The neutron yield and distribution is made of two parts. a) The 4π emission of neutrons from the $^{9}Be(p,n)^{9}B$ reaction for lower energetic protons and the $^{9}Be(p,2n)^{8}B$ reaction at higher proton energies. b) the forward peaked emission from the breakup if deuterons were used.

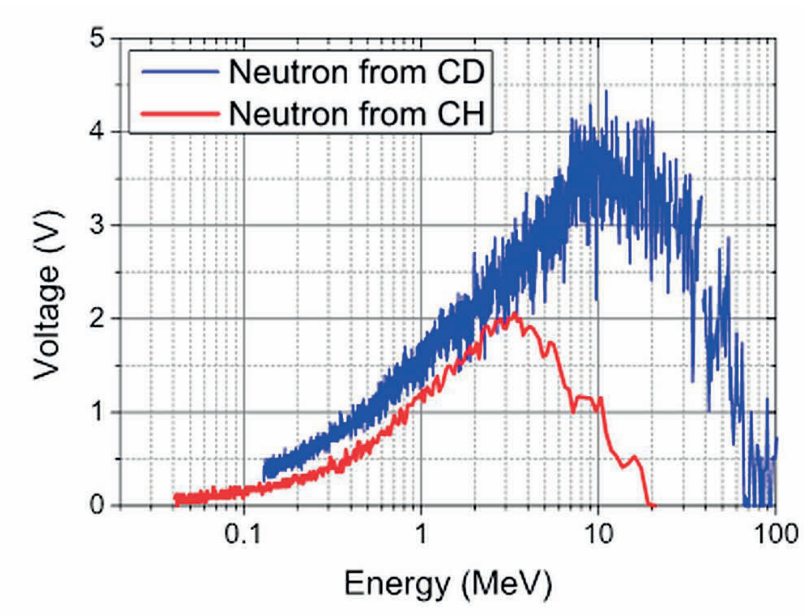

Figure 4: Neutron spectra from a 400 nm CH foil (red) and a 480 nm CD foil (blue), measured with an nTOF detector.

As can be seen in Figure 4 the efficiency in forward neutron emission as well as the neutron energy strongly increases with the use of deuterium instead of protons. For the deuteron breakup experiments we have measured almost one percent conversion efficiency and around 0.2 percent for the proton reaction.

Figure 5 shows a result that clearly demonstrates the difference of efficient deuterium acceleration if the thickness of the target matches the optimum for the BOA mechanism with a strongly peaked neutron emission in the forward direction (0°).

6. Results

So far, recent experiments have measured record neutron yields close to 3 x 10^{10} n/sr (data from 2014), energies well exceeding 100 MeV and a strongly directed neutron beam [31,16]. It is important to note that due to the compact generation of the neutron beam and the ultra-short pulse duration of the driving ion beam the neutron pulse is extremely short. As the ion beam is generated and accelerated within a few picoseconds and the total length of the system, accelerator and converter structure is less than 15 cm the total pulse duration is only a few nanoseconds for the entire pulse. In fact for the ion energies between 100 MeV and 4 MeV(e.g. required for activation) the pulse in forward direction has a total length of 6.5 ns.

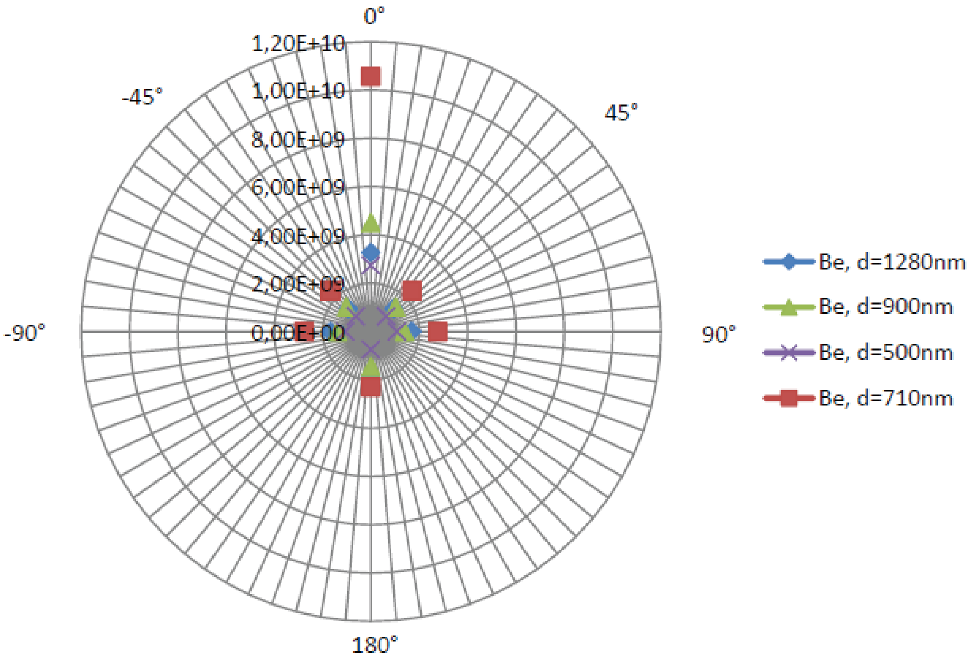

Figure 5: Neutron production from different targets. Whereas the isotropic part is not that much sensitive, the efficient deuteron acceleration is strongly correlated to the target thickness. In this case for 10^{21} W/cm^2 at TRIDENT 710 nm was close to the optimum for the BOA mechanism. The neutron emission exceeds 1x10^{10} n/sr.

But more important, the pulse duration for the beamed neutron part originating from the deuterium breakup is different as the neutron emission closely follows the initial deuterium kinetics. Thus, the pulse is strongly chirped in energy having an excellent time to energy correlation and resembling the initial ps pulse duration. This would allow for excellent energy resolution for fast neutron resonance spectroscopy as one possible application.

7. Applications

The high brightness, directionality and compact format of the neutron source opens up a multitude of applications.

Radiography with neutrons.—With such an intense, directed and ultra-short neutron beam available a first laser-driven neutron image of a structured object was demonstrated [31]. The main detector for neutron radiography was a fast scintillating fiber array gated neutron imager, developed by LANL for fusion experiments at the National Ignition Facility (NIF) [26]. Neutrons, impacting into a 5 cm thick fiber array generate light that is transported through the fibers, down collimated by a coherent fiber taper, amplified by a gated micro-channel plate and finally detected in a high resolution cooled CCD camera. The scintillator is also sensitive to the large number of x-rays being produced during the initial laser target interaction. With a decay constant (1/e) of 2.5 ns, the x-ray contribution can be used for radiography or excluded from the measurement choosing a specific timing. Moreover, gating the detector well past the decay of the scintillating light caused by the prompt x rays and limiting the gate width allows for easy selection of the neutron energies, which is of special interest as this allows for the radiography of material imaging different neutron energies similar to recently observed neutron bursts using electrons as a driver [32], but with much higher neutron numbers. By varying the delay between the laser pulse and the exposure window of the imager, one is able to distinguish between the contribution of instantaneous hard-x-ray emission from the primary target and the exposure due to neutrons from several discrete energy intervals.

As right behind the converter material the neutron flux is around 10^{20} N/(cm^{2}s) the source is an excellent tool for tests on neutron damage of materials.

One application that has recently been tested successfully is the active interrogation of sensitive nuclear material using neutron activation. This application can serve in security and safeguarding environments as well as to detect nuclear material that has been lost, buried or is not directly accessible (e.g. due to destruction in accidents).

Nuclear, fissile material is exposed to the short burst of neutrons and the subsequent neutron emission is detected. Because of the short pulse duration, the secondary neutron emission can be monitored shortly after the probe pulse and therefore very early in the exponentially decaying signal. Moreover, the delayed neutrons from the subsequent decay chain can be monitored as well as the response to thermal and epithermal neutrons, thus allowing for the detection of different isotopes, like ^{235}U, ^{238}U and ^{239}Pu. A first experiment has been carried out in 2012 and 2014 and will be published elsewhere. This method of detection is quite insensitive to high Z shielding and therefore can be used in real environments, like container transport or behind radiation shielding.

8. Summary

The generation of neutrons using laser driven ion beams has made significant progress in the recent years. The initial experiments using the TNSA mechanism to drive an ion beam have been followed by new acceleration mechanisms based on relativistic transparency of solids with the advantage of selected ion species at very high brightness. Using the most favorable reaction of deuterium on beryllium high brightness neutron sources driven by laser systems of a few Joules of energy have been realized and the unique neutron beam characteristics have been measured. First applications like neutron radiography, the test of detector systems and the use in active interrogation have opened the field to those compact sources. As this states the very early results of this new technique and given the rapid development of short pulse laser systems this will become an exciting field of research with many useful applications.

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A SAFE, RELIABLE AND REGENERATIVE ELECTRICAL ENERGY SUPPLY TO POWER THE FUTURE

Harald Weber and Nayeemuddin Ahmed, University of Rostock

Abstract

Today, three phenomena are developing into critical global problems, requiring urgent attention from leaders all over the world. The first of these is the increase in carbon dioxide (CO_2) emissions due to the escalated use of coal, resulting in the gradual increase of the Earth's average temperature. The second is the continually diminishing fossil fuel resources, e.g. oil and natural gas, which are the primary sources of energy for vital services like transportation and domestic heating. The third is the unforeseen and rapid "world population boom" since the beginning of the 19^{th} century after the invention of the steam engine by James Watt.

The combination of these three factors signals imminent danger. With the increase of the world population, there is a subsequent rise in the usage of both electrical and non-electrical types of energy. At the same time, not only are the sources of these energy forms, i.e. the fossil fuels, depleting because they are non-renewable but their usage is also severely detrimental to the environment. Therefore, it is of utmost importance to reduce the dependency on fossil fuels and switch to renewable or even nuclear resources as alternatives, in order to prevent an impending climate disaster. Hence, taking the aforementioned problems into account, a method is proposed in this paper to create a safe, reliable and regenerative electrical energy supply system using renewable wind and solar energy as well as hydrogen storages.

Introduction

In figure 1, a picture developed by two National Aeronautics and Space Administration (NASA) data visualizers is presented, showing the world illuminated by city lights during the night. As can be seen easily, North America, Europe, Japan and South-Korea are brightly lit.

Figure 1: The Earth lights at night. This a composite image of hundreds of pictures made by the orbiting Defense Meteorological Satellite Program (DMSP) satellites, [Mayhew & Simmon, 2000].

These regions are the ones with the highest standards of living. In Europe this means that a two-person household consumes approximately 3.5 MWh of electrical energy per year, ["Household composition statistics", 2017]; [Morris, 2015, 2018]; [Thalman & Wehrmann, 2019]. Described in gasoline equivalents, this is roughly equal to filling a 100-liter car tank 3.5 times per year. Taking Europe's population and its total energy usage into account, an annual consumption of about 37 MWh per capita can be calculated, as displayed in table 1, [Eurostat -Statistics Explained, 2015). In the United States of America (USA) this value is approximately doubled, i.e. 78 MWh per capita per year. This means that every person in the USA consumes almost twice the energy compared to a resident in Europe on an annual basis. The next largely illuminated regions which can be seen on the map are China and India. These so called "emerging countries" have increased their energy consumption drastically in the recent years, leading to annual figures of about 25 MWh and 8 MWh per capita respectively.

Table 1: Comparison of the energy consumption per capita between different regions of the world

Regions	**Energy Consumption** (million toe)[1]	**Energy Consumption** (MWh)[2]	**Population** (millions)[3]	**Energy Consumption per capita** (MWh)
United States	2,188.3	25449.9	325.7	78.1
EU-28	1,629.5	18951.1	508.5[*]	37.3
China	2,973.3	34579.5	1390	24.8
India	851.1	9898.3	1260	7.9
Australia	125.3	1457.2	22.25	65.5
South Korea	272.7	3171.5	49.09	64.6
Russia	709.7	8253.3	144.5	57.1
Japan	429.8	4998.6	136.7	36.6
World	13,647.4	158719.3	7383[**]	21.5

[1]Eurostat - Statistics Explained, 2015; 1 toe = 11.63 Megawatt-hour (MWh), [2](Wikipedia contributors, 2018); [3]("People > Population in 2015: Countries Compared", 2015); [*]Eurostat - Statistics Explained, 2018; [**]Worldometers, 2019

Countries such as Russia and Australia also have high annual energy consumption per capita of roughly 57 MWh and 66 MWh respectively. However, only certain parts of these areas appear brightly lit in Figure 1 owing to their massive size and nature of the population distribution. In contrast, regions like Africa are nearly completely dark, despite possessing a high population. This is also true for many countries in South America such as Bolivia and Peru. This confirms the fact that the "Earth Night Lights" are not a reflection of the world's population distribution, but instead represent the quality of life in different areas of the world. Unpopulated regions like deserts and large forests are not taken into account in this case.

The trends from figure 1 are also reflected in figure 2 which represents the Gross Domestic Product (GDP) per capita of the different regions of the world in the year 2000. Here, the sizes of the regions are adapted according to their total GDP. From this depiction, it can be observed that North America, Europe, Japan and South Korea have the highest GDP per capita values of more than 20,000 US$ per capita. Today, these values are much higher; greater than US$ 50,000 for North America and Australia, around US$ 40,000 for Europe and

Japan and close to US$ 30,000 for South Korea, (World Bank, 2017). This indicates a clear link between the electrical consumption per capita and distribution of global wealth.

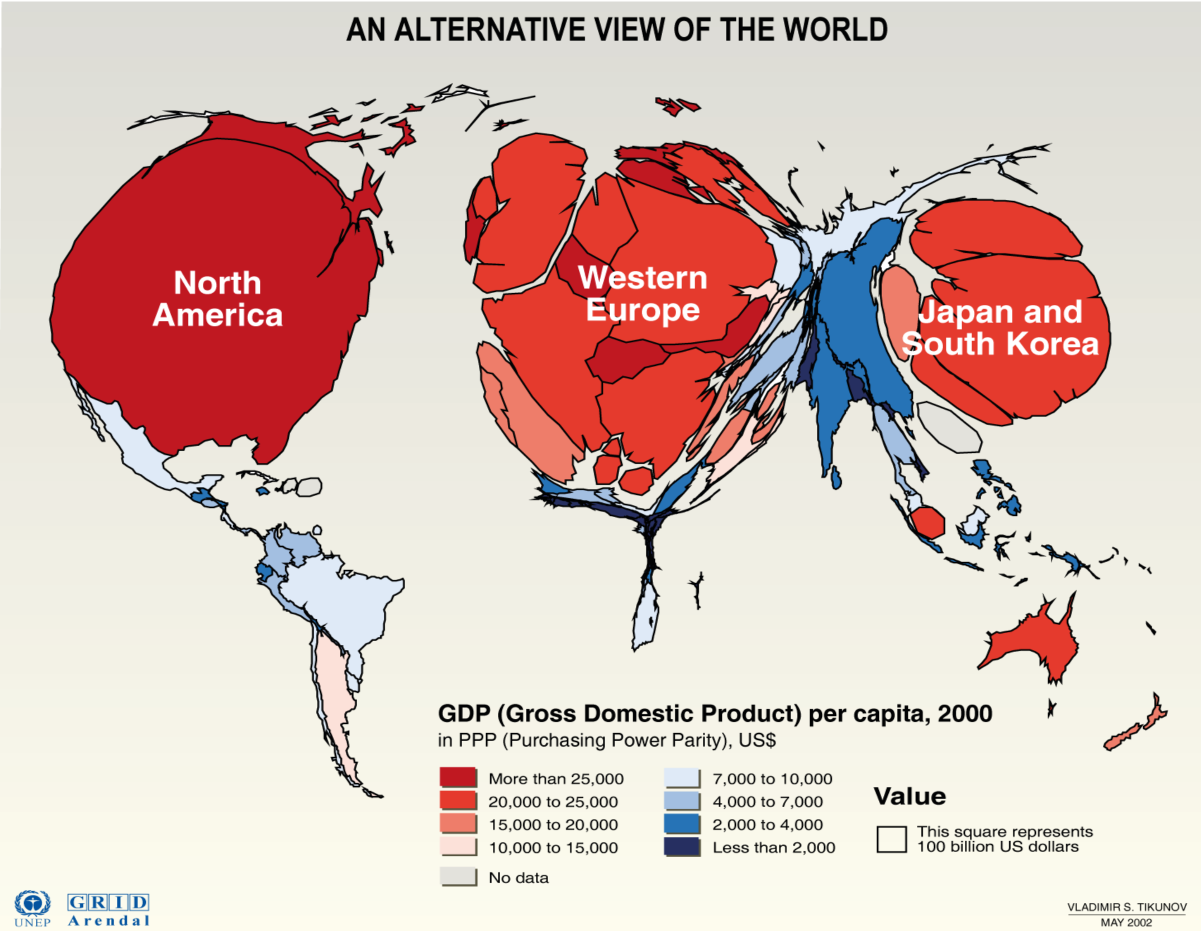

Figure 2: The GDP per capita of different regions of the world in PPP in the year 2000, [Tikunov, 2000].

The Role of Fossil Fuels in Global Overpopulation and Climate Change

When it comes to ensuring the distribution of the global wealth, one invention was of paramount importance as driving force. This was the Steam Engine (shown in figure 3) designed by James Watt. The Scotsman received the patent for his machine in 1769, [Watt, 1781]. This contributed to the onset of the first industrial revolution, a significant turning point in the human history, roughly within the next 50 years, [Wikipedia contributors, 2019]. In figure 4, using the example of threshing, it is nearly impossible to describe the benefit of this invention for mankind. In the past, threshing was done manually for weeks on the farmyard, after the rise of the steam engine, the same work could be done in a matter of hours. However, not only were farming techniques revolutionized as a result, but also transportation, irrigation, production of medical products and of course military needs experienced a dramatic boom. Now, heavy and daunting manual work was reduced for the working class. A Consequence, being valid till today, is the rise of two other nightmares; the rapid increase in global population and the overuse of fossil fuels resulting in the CO_2 driven greenhouse effect leading to the gradual increase of the average global temperature.

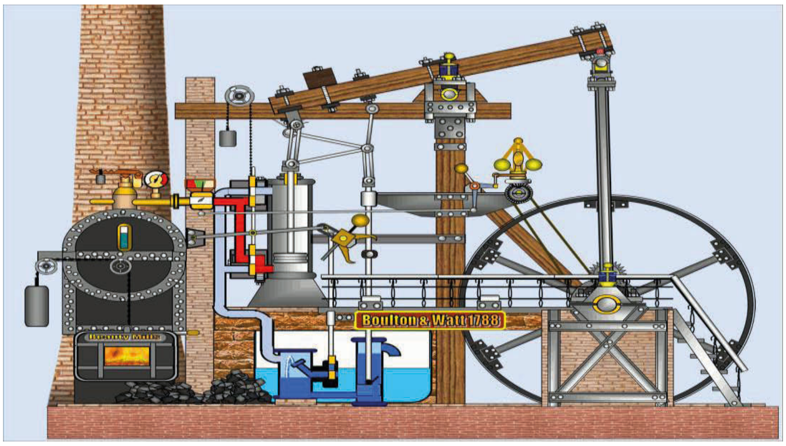

Figure 3: The Steam Engine of James Watt and Mathew Bolton, [“Dampfmaschine / Dampfkraftmaschine - Funktion, Aufbau & Animation”, n.d.].

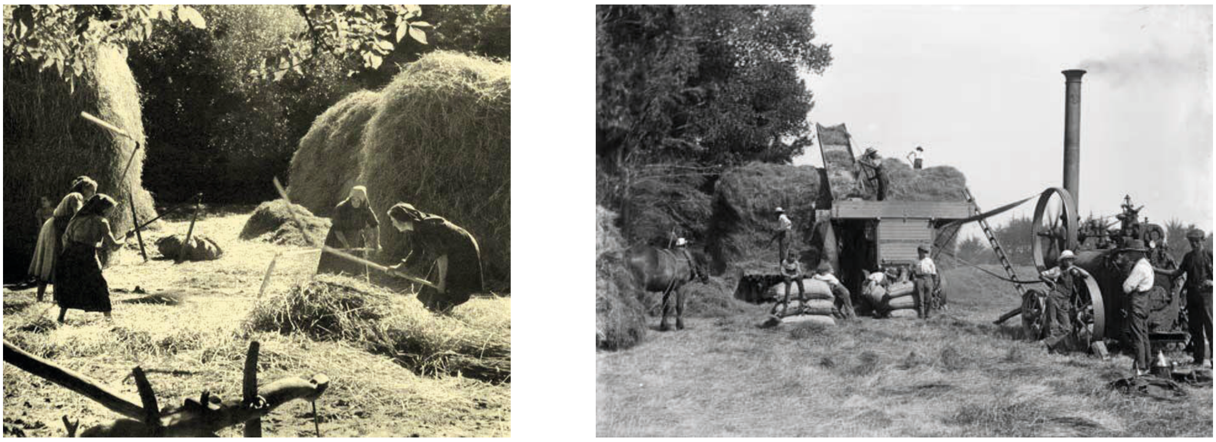

Figure 4, Left: Threshing via manual labor, (“Treading and Threshing”, n.d.). Right: Threshing by using a threshing machine, [Watson, 2008].

Figure 5 portrays the change in world population through time. As predicted in the diagram on the left, more than eight billion people will live on the globe in the year 2025. The primary reason for this, as exhibited in the zoomed figure on the right, is the accelerated population growth at the beginning of the 19th century. This was the time when not only were the number of steam engines increasing drastically but also operating reliably. The red arrow on the figure gives an estimate of the evolution of the total world population if this invention would not have been made. Less than one billion people would live on the planet today!

The possibility of harvesting energy from fossil fuels, based on their current rate of usage, is only expected to continue for approximately 200 more years, [“Years of fossil fuel reserves left”, 2016]. Before the inception of such extensive usage of fossil fuels, all the energy was originating from humans, animals as well as wind and water forces. Once the non-renewable fossil sources will be depleted, only these traditional energy sources along with the prospect of photovoltaics (PV) and nuclear energy will be available. So in the end the all-important question arises: How can energy be provided to the future generations? Surely, the answer to this question will play a crucial role in the continued existence of life as we know it. While searching for a possible answer, one must also anticipate the possible energy supply and demand in the future. Figure 5 displays such data representing the expected growth of electrical energy in Europe and the entire world until 2040, forecasting an increase of 8% and 61% respectively. Thus, it cannot be expected that the use of electrical energy will be reduced in the future.

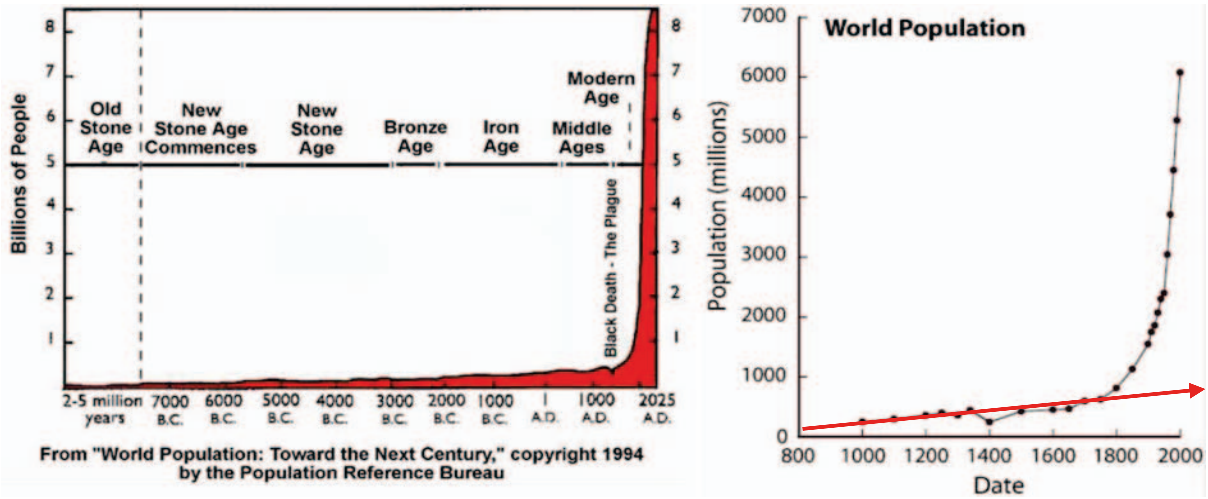

Figure 5, Left: World population growth through history, ["World Population: Toward the Next Century", 1994]. Right: Zoomed view of the global population over the last millennium, ["Population, problems and progress", 2013].

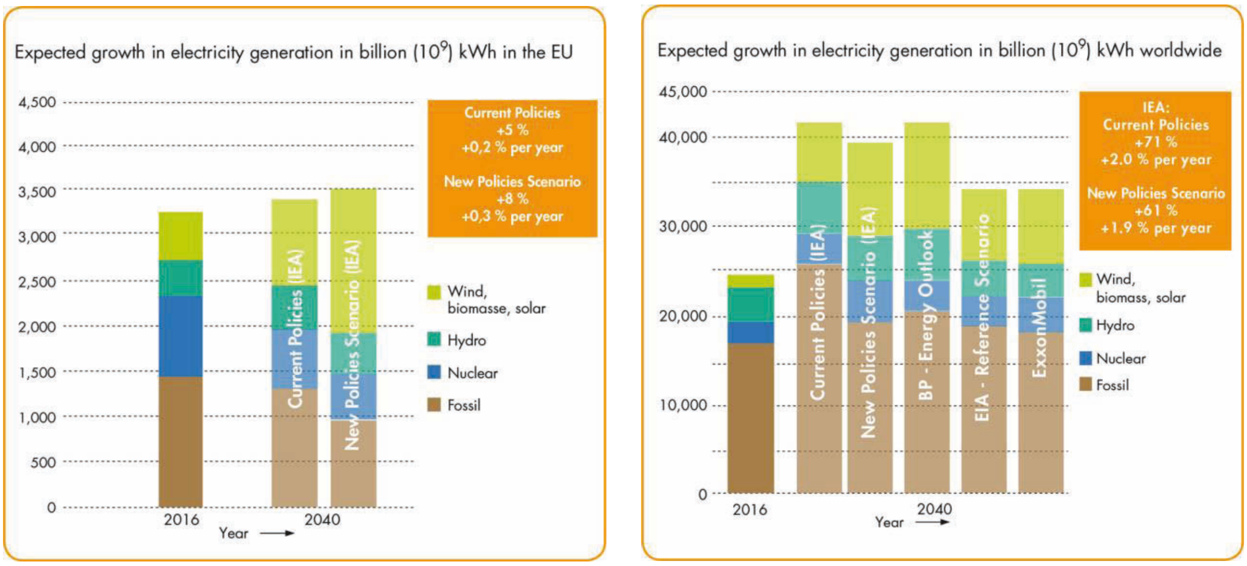

Figure 6: Predicted electrical energy production increase in the EU (left) and the World (right), [IEA, EU Commission, VGB (own calculations), 2018].

Table 2: Various fossil reserves and resources along with their projected lifetimes taking their current rate of usage into account, (own calculations, 2015)

Fossil fuel types	**Reserves**			**Resources**	
	Reserve (B tHCU)	Consumption (B tHCU)	Lifetime (years)	Reserve (B tHCU)	Lifetime (years)
Coal	907.3	4.9	185	3,963	1,264
Mineral Oil	1147.7	28.5	40	120	24
Natural Gas	175.8	2.6	68	235	87
Uranium	-	-	50	-	-
Oil sand, oil shale and heavy oil	-	-	-	451	90
Coal gas, gas hydrate	-	-	-	1660	607

Table 2 lists the different forms of fossil fuel reserves, their consumption rate and their predicted lifetimes. The data required for the first two parameters was accumulated from different sources and then used to calculate the lifetime values. As can be seen, only coal is expected to exist for nearly the next 200 years. Oil, natural gas and uranium reserves could come to an end within half a century. As reserves only those fossil energy sources, the extraction of which are economically viable, are considered. In contradiction, fossil fuel resources such as deep grounded coal, oil sand and shale etc. are energy sources which cannot be mined easily owing to geological, economic and technological limitations. The exploration of such types of primary energy would not only be very expensive, but also environmentally detrimental. Additionally, bearing in mind the current alarming increase in the atmospheric density of CO_2, it would be best to discourage the extraction and subsequent usage of such resources.

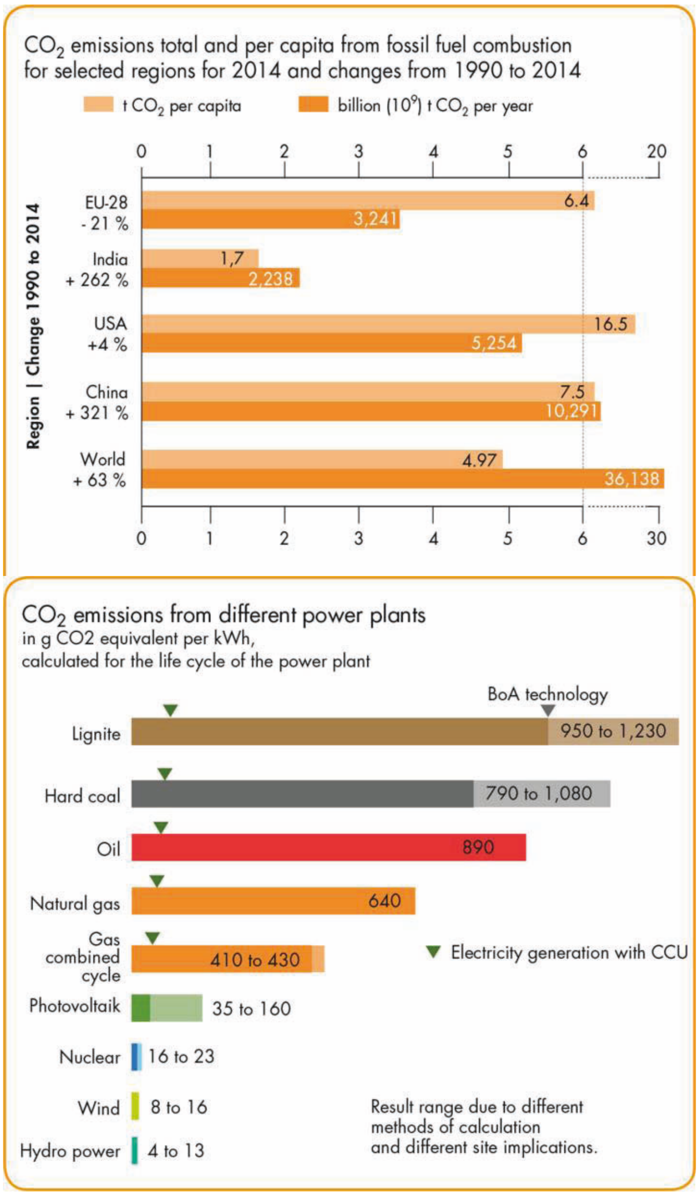

Figure 7: Carbon dioxide (CO_2) emissions in selected regions of the world (top) and from different types of power plants (bottom), [U.S. Department of Energy's (DOE) Environmental System Science Data Infrastructure for a Virtual Ecosystem (ESS-DIVE), 2018; Scherrer, Institute (PSI)- Switzerland, ESU-services, VGB (own calculations), 2018]

Figure 7 (left) represents a horizontal bar chart signifying the total and per capita CO_2 emissions due to the burning of fossil fuels in different regions. The percentage change in the emissions between the years 1990 and 2014 is also shown for each region. As can be seen, the largest increase is in China and India which are the countries with the largest populations in the world. Only Europe has reduced its CO_2 emissions by 21%, while for USA the figure is nearly unchanged (4%). On the figure to the right, the production of CO_2 from different power plant types is shown. Here of course lignite plants are the greatest producers, but emissions from natural gas powerplants are also quite high. Thus in the long run, combined cycle gas plants are the best option as power plants running on non-renewable fossil fuels. In the end, though, considering the ultimate effect of CO_2 and other greenhouse gases on the climate and environment, PV, wind, nuclear and hydropower are the best and outright options for electrical energy generation.

Transformation of the Electrical Energy System

So taking these issues into account, for Germany the goals shown in Table 3 must be met. Similar targets also hold true for other countries since solving the world's energy crisis and at the same time tackling an impending climatic disaster requires a global effort.

Table 3: Incentives, goals and future challenges for the energy sector of Germany

Motivation

- Replacing fossil fuels with renewable energy sources
  - Massive reduction of carbon dioxide emissions
- No further production of radioactive waste
  - Eliminating risks of nuclear accidents such as in Fukushima, 2011

Goals:

- Reduce carbon dioxide emissions in Germany by 80% by 2050
- Nuclear power phase-out by 2022
- Increase the share of renewable energies from 18% today to 40% in 2020 and to 80% in 2050

Challenges:

- Maximum possible direct use of regenerative energy
- Maximum utilization of existing potentials
- Problems caused by the transmission of power over long distances
- Balancing the intermittent feed-in with thermal power plants
- Ensuring security of power supply and system stability

Development of Wind and Solar Resources in Germany

Table 4, displays the magnitudes of electrical power and energy generation from wind and PV resources in Germany between the years 2010 and 2025. The maximum electrical load in Germany is 80 GW and this value is expected to remain constant in the near future. On the other hand, the production of power from the renewables is projected to reach 100 GW in 2020. As a result, a significant part of the society believes that further installations to harness renewable power are unnecessary. This often results in strong opposition towards construction of new PV power stations or wind farms. However, analysis regarding the electrical energy requirement for the country leads to completely different conclusions. Germany needs about 600 TWh of electrical energy per year, (Federal Ministry of Economic Affairs and Energy, 2014), but the renewable sources can only generate about 200 TWh. It is predicted that the maximum amount of energy which can be harvested from renewable resources will be limited to 1000 TWh in the country due to limitation of free space. However, the total final consumption of energy currently per year is 2600 TWh, ["Total Final Consumption (TFC) by source, Germany 1990 – 2016", 2016]. Hence, there is still a significant difference between consumption and production.

Nevertheless, basing the operation of the electrical energy supply solely on wind and solar resources is also not possible since it introduces additional problems in the electrical grid. An overview of this is presented in figure 8. Here, the projected total consumption and corresponding generation of electrical power is shown in Germany for a duration of four weeks in May 2020. As can be seen, the power generation from resources consisting of hydropower, wind onshore and offshore, combined heat and power, as well as photovoltaics is completely unrelated to the load demand. Hence, this means some storage power plants (SPP) are needed to bridge the gap between consumption and production.

Table 4: Projected installed power capacity and energy output of wind and solar resources in Germany till 2025, (Ziems & Meinke, 2012)

Year	Power Generation (GW)				Energy Generation (TWh)			
	Wind		PV	Sum	Wind		PV	Sum
	Onshore	Offshore			Onshore	Offshore		
2010	27.2	0.3	17	44.5	58	1	12	71
2011	28.2	0.8	23	52	61	2.8	24	87.8
2012	29.8	1.2	29	60	64.6	3.8	30.5	98.9
2013	31.2	2.3	32	65.5	67.6	8.4	33.5	109.5
2014	32.3	3.5	35	70.8	69.2	13.8	37	120
2015	33.6	4.4	38	76	72	19.8	39.8	131.6
2016	34.1	6.1	41.2	81.4	73	26.8	43.2	143
2017	34.6	7.7	44	86.3	75.7	31.3	46	153
2018	35.6	10.3	46.4	92.3	76.3	42.7	48.7	167.7
2019	36.2	12	49.2	97.4	79	50	51.5	180.5
2020	**36.9**	**14.3**	**51.9**	**103.1**	**80**	**59**	**54.3**	**193.3**
2021	**37.8**	**14.8**	**53.8**	**106.4**	**81**	**63**	**56.3**	**200.3**
2022	38.2	17	55.5	110.7	82	72	58.2	212.2
2023	38.4	18.8	57	114.2	83	80.8	59.8	223.6
2024	39	20.7	59	118.7	84	87	61.8	232.8
2025	39.5	21.7	60.2	121.4	84.8	92	63.2	240

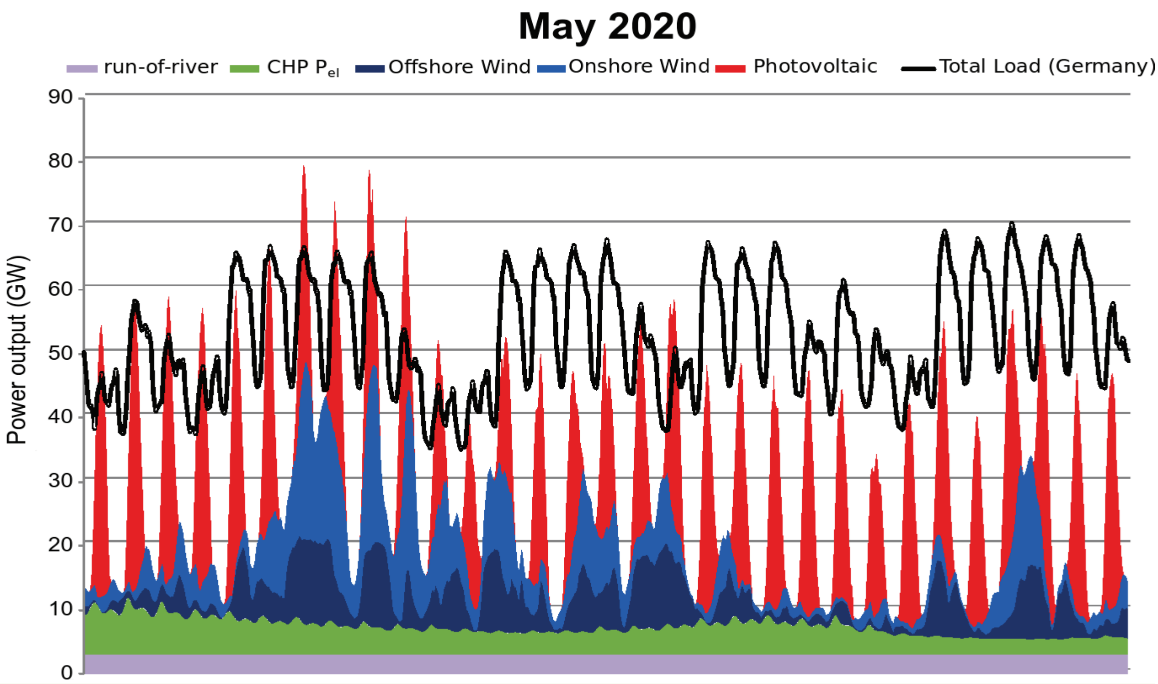

Figure 8: The projected electrical power demand and corresponding generation from intermittent as well as non-dispatchable sources during May 2020, (Ziems & Meinke, 2012)

Operation of a Storage Power Plant (SPP)

The SPP consists of converters and storages. The power plant does not contain any flywheels or rotating masses. Similar to wind turbines and solar panels, the SPP is connected to the grid via power electronic converters and hence does not have any inertia. However, in order to function effectively in the current electrical network, the SPP converter systems have to adapt to the rotating masses and respective frequency of the conventional power plants (CPP). This can be done by synthetically generating rotating inertia and primary reserve power. To achieve this, the converters have to measure the instantaneous active power at the connecting node so they can properly feed their angle-oriented regulating power into the grid. This way, these new converter systems can also function as power plants and can hence be integrated into the grid.

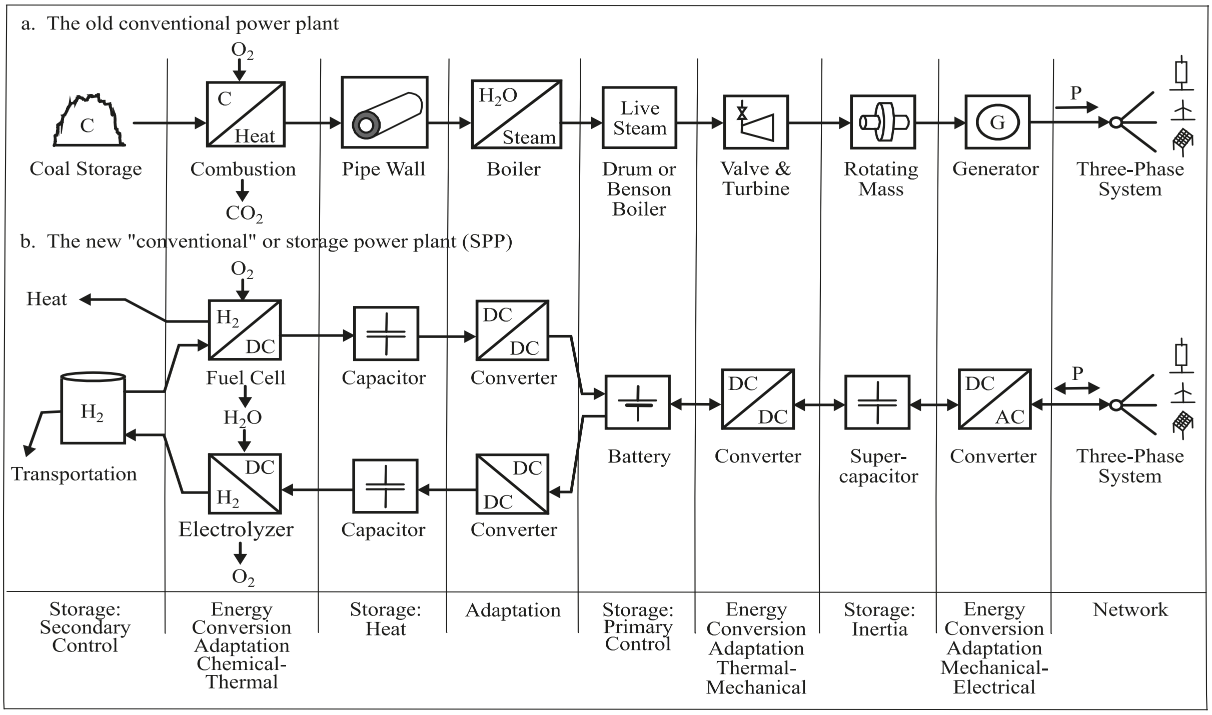

Figure 9: Comparision between (a) the existing fossil fuel based and (b) new storage power plant (SPP) [Weber et al. 2018b]

In the future, when the number of CPP reduces significantly in the electrical power supply due to the lack of fossil fuels, the need for such power converters to adapt to rotating masses will diminish and frequency control may become obsolete. A new method of grid control can then be introduced, known as the nodal voltage angle control, [Weber et al., 2018a]. Under this control method, the SPP can function either in grid-forming or grid-supporting mode with a constant grid frequency. All the fundamental principles of electrical energy supply and power system control, which are satisfied today with the CPP running on fossil fuels, can also be met by the SPP. An overview of this is presented in figure 9 where the component chains of the two types of power plants are compared. The mode of operation of a SPP operating in grid-forming mode is explained below and compared with the output response with a CPP when there is a step increase in the active power requirement in the network:

- Conversion/adaptation: The step increase in the active power requirement at the DC/AC converter with a constant nodal voltage angle (grid-forming) leads to an instantaneous increase of three-phase AC current and therefore also an instantaneous increase of direct current on the DC side of the adjacent converter.

- Storage: The supercapacitor instantaneously accesses its stored electrical energy and supplies this as output power. A capacitor is chosen for this purpose since it can immediately supply large magnitudes of power. As a result, the voltage of the supercapacitor decreases, which signifies the amount of its stored energy. These features are similar to that of the spinning reserve in a CPP, which is provided by the decrease in the speed of the rotating masses in the system.
- Conversion/adaptation: The downstream DC/DC converter's governor (between the battery and the supercapacitor in figure 9b) has to keep the capacitor voltage constant. To this end, it accesses the battery increasing the battery output power within a few seconds. As a result, the capacitor charging current increases and this recharges its energy storage. These properties are similar to that of the primary control of thermal power plants where the opening of the steam valve in the boiler is adjusted to increase the flow of live steam, restoring the speed of the turbine prime mover.
- Storage: Due to the increase in battery output power there is a decrease in battery voltage resulting in a decline in the amount of stored energy as well.
- Conversion/adaptation: The DC/DC converter, on the upper branch between the fuel cell and the battery, adjusts the required voltages enabling the charging current to flow from the fuel cell to the battery. The fuel cell's control unit increases its activity and synthesizes more water from hydrogen and oxygen and in the process produces more energy to replenish the battery storage as well as satisfy the power demand in the network.
- Storage: The fuel cell's control unit accesses the hydrogen storage within a few minutes and increases the fuel input mass flux. The amount of hydrogen in the storage decreases. It may be refilled autonomously by the plant via the electrolyzer. This is similar to secondary control in a CPP where the fuel governor accesses the coal store to increase the fuel input. However, the coal storage cannot be reloaded automatically by the plant. The capacitor between the DC-DC converter and the fuel cell stores some energy and this is analogous to the heat stored on the pipe walls inside the boiler of a steam power plant.

During steady state operation, the required power is effectively transferred from the hydrogen storage to the three-phase network. The battery or the capacitor storages only act, when the consumption or production in the network changes suddenly, to instantaneously respond and provide the necessary ancillary services autonomously. Contrary to current power plants, which are only able to reduce their output to a certain minimum, this new type of power plant can actually reverse its output. In case of a production surplus from renewable sources or decrease in load demand, there is a shock-free transition from fuel cell to electrolyzer operation to store the excess energy. The corresponding converters adjust the voltage of each component, while the electrolyzer produces hydrogen of the required pressure, which can also be used later for automobiles.

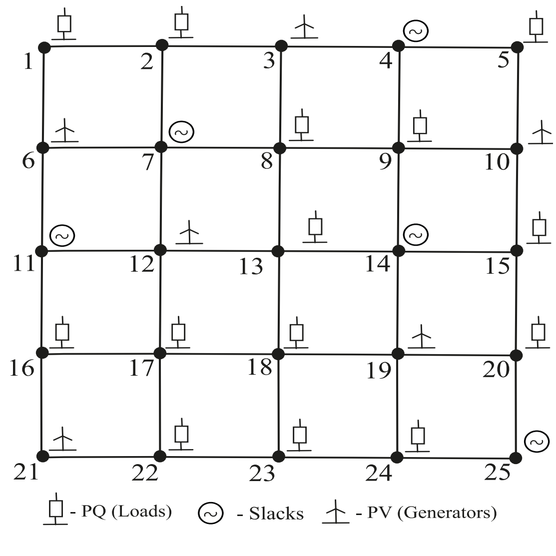

Figure 10: example network with 25 nodes

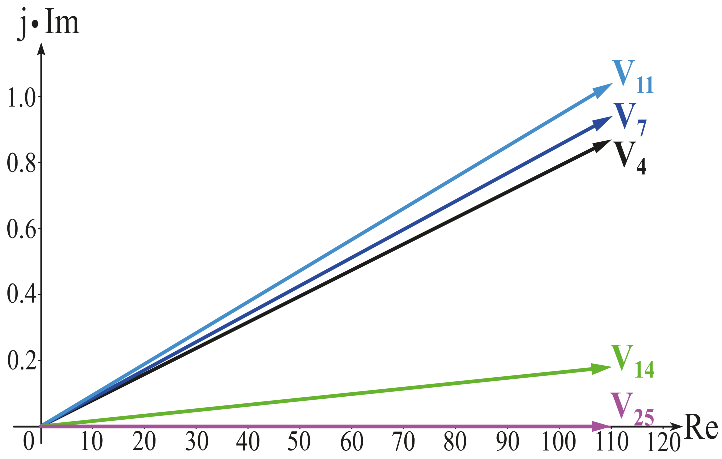

Figure 11: Voltage phasors of storage power plants after initial loadflow

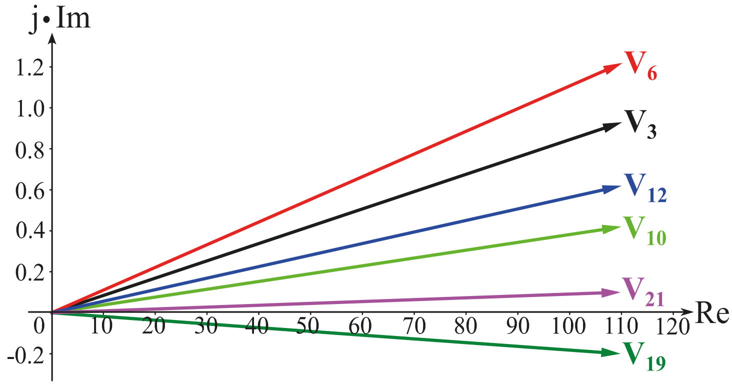

Figure 12: Voltage phasors of PV generators after initial loadflow

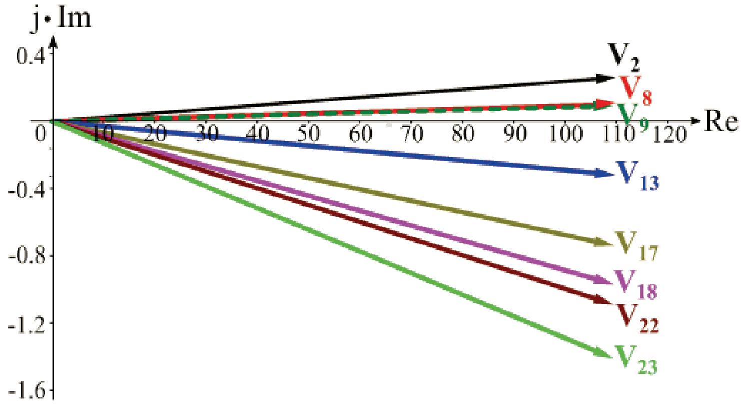

Figure 13: Voltage phasors of PQ loads after initial loadflow

The three-phase supply can be operated at a constant frequency, for instance at 50 Hz. The tasks of grid control like spinning reserve and primary control can be fulfilled using the nodal voltage angle at the storage power plant's connection point. The grid itself with its admittance matrix and voltage angles operates as a coordinating unit. All the required information is provided using the given load flow. Storage power plants can operate either in grid-forming mode, as slack power plants (voltage source), or in grid-supporting mode, as PV (constant active power and voltage magnitude output) power plants (current or power source). These features are present in the current conventional power plants with a certain time delay from either an integral acting angle control (slack behavior) or active power control (PV behavior). To that end, all power plants have to know the current voltage angle at their connected terminal with reference to the 50 Hz angle standard of their control area via an accurate radio controlled quartz clock. This clock can be synchronized via the time signal transmitter, DCF77, of the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany once each day.

The mode of operation of this new type of grid control is best explained with an example network shown in figure 10. The grid consists of 25 equidistant nodes, each connected to either a generator or a load. The nodes are connected via transmission lines, each 50 km long and at a voltage level of 110 kV. The line impedances are identical and each has a magnitude of 0.3 Ω/km, with the resistance to reactance ratio being 0.1.

There are 11 power plants, of which 5 are slack storage power plants. The other 6 are PV power plants i.e. generators at terminals where the active power (P) being supplied and the voltage (V) has a known constant value. The remaining 14 nodes are each connected to a PQ consumer, i.e. loads at terminals where the active (P) and reactive power (Q) being consumed are known and constant.

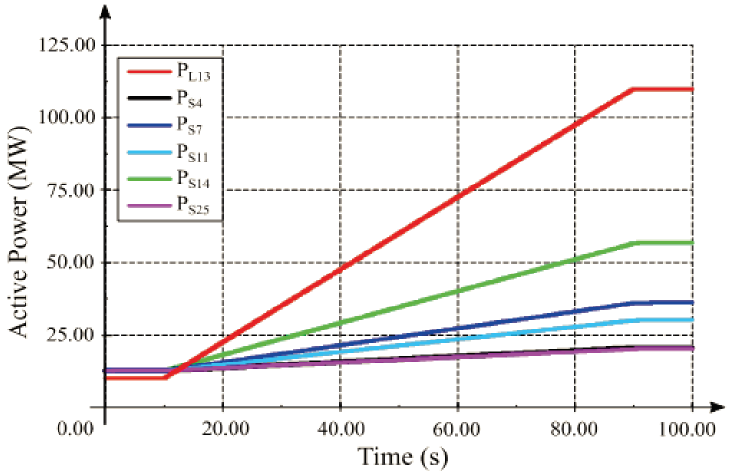

Figure 14: Active power of slack nodes and changing load at node 13

It is assumed that each of the 14 loads consumes 10 MW of active power. The total consumption of 140 MW is equally shared by the 5 Slacks and the 6 PV Generators each producing 12.7 MW to meet this demand. Each load also consumes 3.33 MVAR of reactive power which is supplied later by the generators. The modeling and simulations are carried out in the software DIgSILENT PowerFactory. The slack and PV generators are modeled as AC Voltage Sources along with necessary control loops to represent the behavior of power electronic converters replacing the conventional synchronous or asynchronous generators.

Figures 11, 12, and 13 show the voltage phasors of the initial load flow calculations respectively, for slack storage power plants, PV power plants, and PQ consumers. As shown in the diagrams, the PQ consumer's voltage phasors follow the surrounding voltage phasors of slack and PV power plants, ensuring the load flow from the generators to the consumers. For the sake of clarity in voltage angles, the imaginary axis is shown in an overstretched manner in this depiction.

Figure 14 shows the power increase of the consumer at the central node 13 and the corresponding reaction of the constant voltage slack storage power plants. The depiction shows how each of the slack storage power plants supply the additional required power according to their electrical proximity to the consumer.

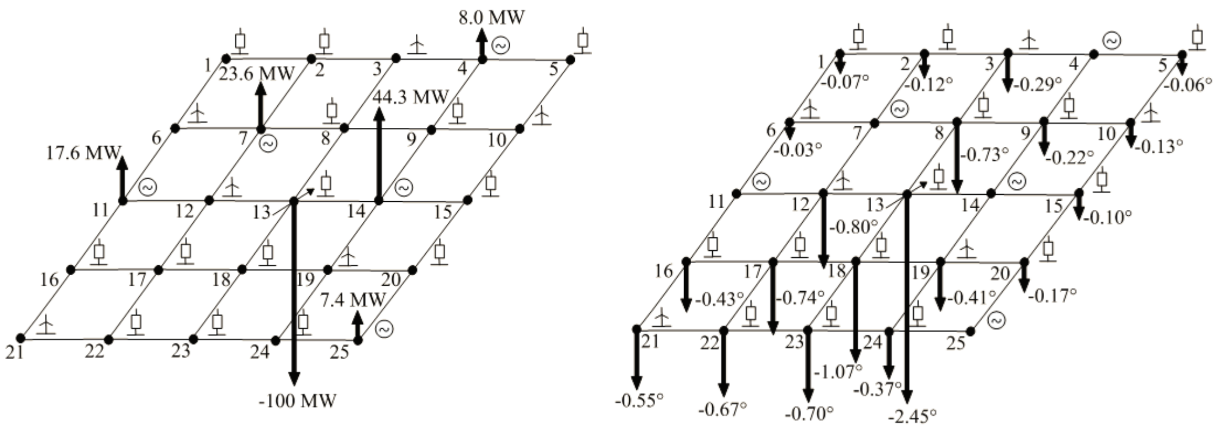

Figure 15: Left: Increase in power consumption by load at node 13 and the resulting increases in the generation of every slack power plant. Right: Angle changes in PV Generators and PQ consumers during the increase in load power consumption at node 13.

These results are further supported by figure 15 (left), which shows the maximum power increases of the consumer and storage power plants, depicted as bars. Consumption is shown as a negative value, and generation as positive values. Due to the resistance in the transmission lines, there will be some losses during the power flow and the total additional power supplied will be slightly greater than the additional demand of 100 MW. Such behavior of storage power plants is analogous to the combined effect of spinning reserve and primary control. This type of primary control is load flow oriented, since the neighboring storage power plants have a greater load to bear than the remote ones. Hence, in the event of a disturbance, the load flow mainly emerges at that location while remote storage power plants contribute little in terms of power supply.

Figure 15 (right), exhibits the angle torsion of all the non-slack nodes in the investigated grid. All angular changes from their initial operating point are depicted. The voltage angle of the load in node 13 has a maximum decrease of −2.45º owing to the large increase in power consumption. The resulting angle torsions in the rest of the grid due to this power decrease are required by the slack power plants to provide the necessary additional power.

In the next case of investigation with the 25 node network, a ramp is implemented at the PV generator in node 12 to increase its power output from 10 MW to 110 MW in a duration of 80 s. This depicts a situation that could possibly arise from the increase in power generation of wind turbines in a particular region due to an increase in wind speed. The response of the five slack storage power plants to this change is then analyzed.

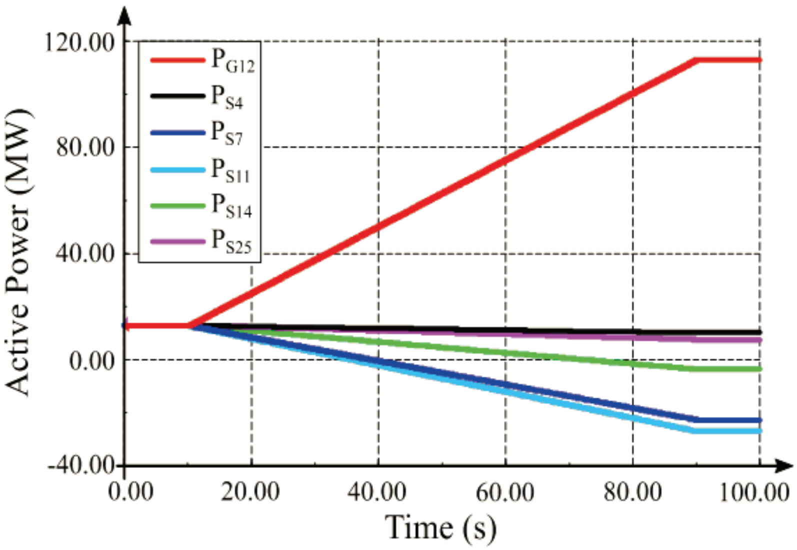

Figure 16: Active power of slack nodes and increasing generation at node 12

Figure 16 depicts how each of the slack storage power plants reduce their power generation or increase their power storing capability due to the generation of additional power in the system. Once again, the response of the slack storage power plants are according to their electrical proximity to the node with changing power, in this case node 12. This is also supported by figure 17 (left). These results show that not only can slack storage power plants increase their power generation during increased load demands, but they are also able to store active power if there is excessive generation from renewable sources in the system. This truly exhibits the possibility of bidirectional active power flow for the slack storage power plant system, as shown in figure 9b.

Figure 17 (right), depicts all angular changes of the non-slack nodes from their initial operating point. Since the grid is organized in such a way that there are more slacks to its northern and eastern part, the angular torsions have higher values in the zones with fewer slacks, i.e. the southwestern part of the grid. The voltage angle of the generator in node 12 has a maximum increase of 2.26º owing to the large increase in its power generation. The resulting angle changes in the nodes due to the power increase in node 12 are used by the slack power plants to reduce their output and accordingly store the excess energy to counter the presence of additional power in the system.

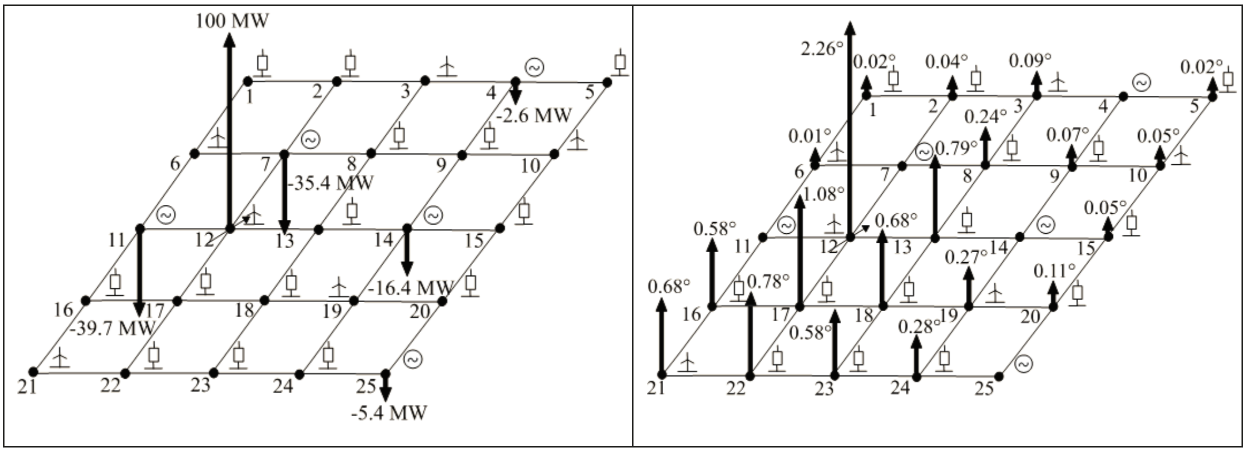

Figure 17: Left: Increase of power production by PV generator at node 12 and the resulting decreases in the generation of every slack power plant. Right: Angle changes in PV Generators and PQ consumers during the increase in power generation at node 12.

What Could be the Consequences of Ignoring Reason?

From the information provided till this point, it is clear that the problems mentioned previously have to be solved not only to ensure a reliable energy supply in the future but also for the overall development of our planet. The use of fossil fuel energy resources has to be reduced and, if possible, even stopped in the future. The consumption of energy should not significantly increase any further and the growth of the world population needs to be limited. To achieve all these, it is necessary that a significant part of the younger generation is not only aware of these issues but is also able to understand them and offer possible solutions to tackle these problems.

Figure 18: A 1:10 scale model of the ship on display at the Vasa Museum, ("Vasa stern color model", 2015)

What can happen when decisions are taken driven by inadequate motivations and thereby ignoring facts can be exemplified with the incident of the "Vasa" warship sinking in the year 1628 in Stockholm, Sweden during the Thirty Years' War. To construct this ship, an equivalent amount of money close to the entire Gross Domestic Product of one year in Kingdom Sweden was used, to gain warfare advantage in the Baltic Sea against Poland.

In figure 18 a model of the ship can be seen, now present in a museum in Stockholm. Initially, it was decided that the ship should only have one deck of canons. However, King Gustav Adolf recommended to install a second set in an additional higher deck. Due to this decision, the center of mass of the warship became too high and the ship was unstable. As a result of the death of the initial Dutch constructor during the construction phase, new unskilled people took over the job. After finalizing the construction of the warship, a stability test was performed with 30 sailors running back and forth from port to starboard five to ten times. During this time, it was observed that the ship was inclining sideways beyond expected limits and thus the test was stopped. The two new contractors understood the problem and could conclude that the ship would sink immediately if it was allowed to sail. However, neither of them informed the King nor did anything stop the maiden voyage. Under this situation, the only solution would have been to inform the responsible authority and dismantle the ship in order to salvage its parts so a better one could be constructed later. However, this did not happen and thus the ship started its voyage from the shipyard as can be seen in figure 19. After about 20 minutes, there was a strong gust of wind and the glamorous ship tilted sideways allowing water to flood the open lower gun deck causing the ship to sink rapidly.

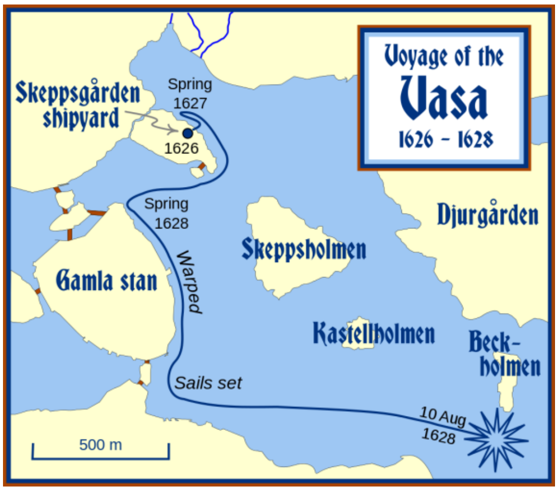

Figure 19: The maiden journey of the Vasa, ("Voyage of the Vasa", 2016).

Today, we might be close to a similar situation concerning our energy supply, CO_2 emissions, global warming and the increasing global overpopulation. We know the problem, we know that the current system is unstable and we know the possible alternatives to using fossil fuels. Thus, it is completely in our own hands whether we opt not to make any changes and continue in our present course or whether we decide to take action against such impending threats and give to future generations a chance of living on this planet with at least the same standards of living as ours.

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Numerical modelling for the layout of shallow geothermal energy systems

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Technical Background

In the shallow subsurface (<200 m depth), the soil temperature is often assumed to be a constant. The amount of geothermal energy stored there is increasingly employed for heating and cooling of buildings through the Ground Source Heat Pump Systems (GSHPS). In the heating mode, the general principle of a GSHPS is to extract heat from the shallow subsurface by circulating heat carrying fluid through single or multiple borehole heat exchangers (BHE), which are typically operating at a relatively low temperature. The energy carried by the circulating fluid is then lifted by heat pump to a level suitable for domestic applications (see the illustration in Figure 1). For cooling applications, the system can be reversed, and the excess heat can be removed from the building and stored in the ground. As the temperature in the shallow subsurface remains constant, GSHPS are very efficient in comparison to other technologies. For example, if 1 kWh of energy is required to heat the building, only 0.25-0.3 kWh of electricity are consumed to drive the heat pump. The substitution of coal and gas burning boilers by GSHPS will not only reduce fuel costs, but also lead to substantially lower emission of CO_2 and air pollutants. Therefore in the context of energy transition, GSHPS have become a very attractive technology for reducing the CO_2 emission in the domestic heating sector.

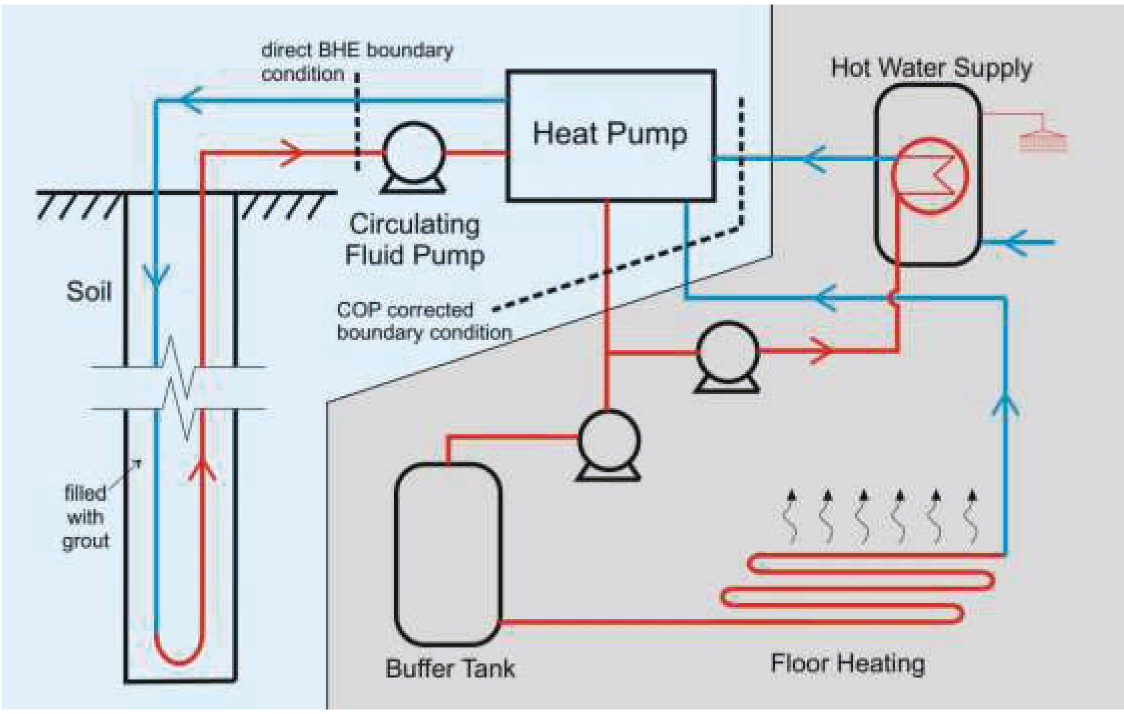

Figure 1: Illustration of shallow geothermal energy extraction through borehole heat exchangers

2. Quantification of Sustainably Exploitable Shallow Geothermal Energy

For policy makers and city planners, it is important to know how much thermal energy can be sustainably extracted from the shallow subsurface. Traditionally, such kind of evaluation was carried out via a volumetric approach. Putting into simple words, the evaluation was conducted by multiplying the subsurface volume with the heat capacity of the soil and also by assuming a uniform temperature drop of 2-6 °C in the aquifer. Although this approach has been carried out widely, the 2-6 °C of temperature drop is considered an empirical parameter and its sensitivity on the extraction of heat and other parameters remains to be investigated.

Recently, researchers from the Helmholtz Centre of Environmental Research – UFZ have conducted a more comprehensive study for answering the above question. As shown in Hein et al. (2016), a numerical model has been constructed to reproduce the operation of ground source heat pump systems over a long period of time. Numerical experiments have been performed by simulating the evolution of the subsurface temperature field. As illustrated by the simulation results in Figure 2, the change of subsurface temperature distribution in a 150 deep domain is subject to the operation of a 100 m long borehole heat exchanger. The shallow subsurface was composed of different layers with varying parameters such as thermal conductivity and groundwater flow velocity. The concept of equivalent temperature drop is proposed as an auxiliary quantity for the subsurface. With the help of this parameter, a procedure has been established to quantify the shallow geothermal potential for BHEs. Following this approach, a realistic equivalent temperature reduction is found to be from -1.8 to -4.4 °C in the subsurface over a period of 30 years. This can be translated to an annual extractable geothermal energy value in a unit surface area, ranging from 3.5 to 8.6 kWh per square meter per year.

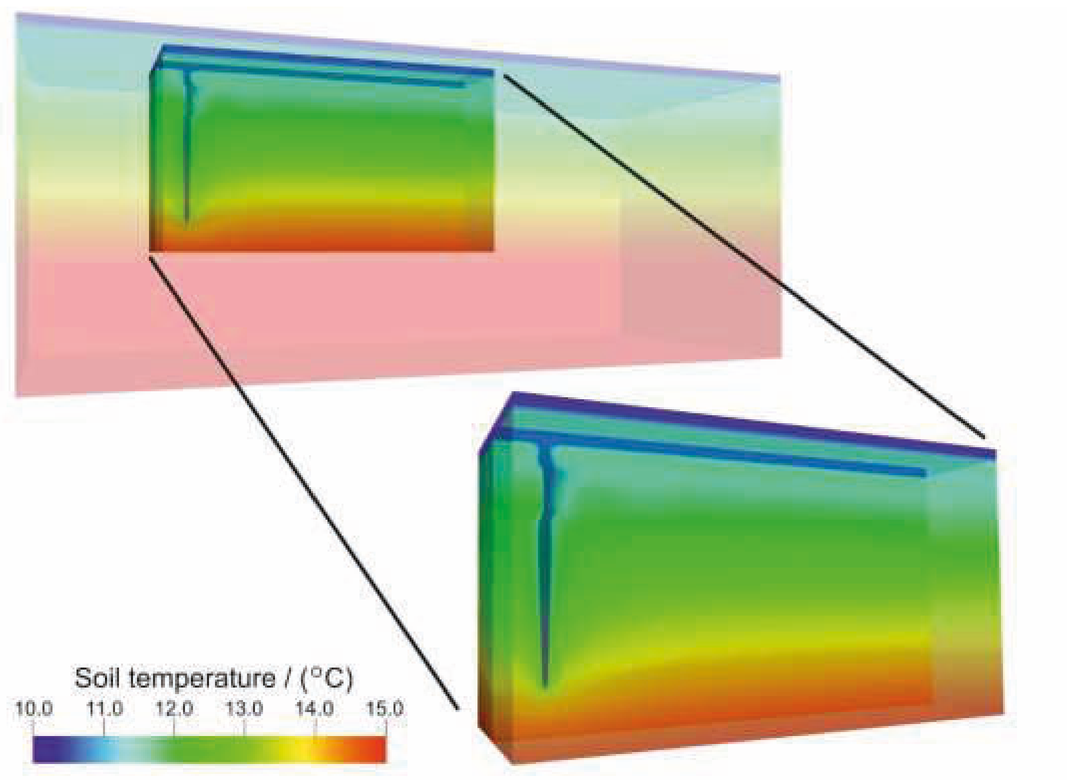

Figure 2: Numerically simulated temperature distribution in the shallow subsurface due to geothermal energy extraction

3. Environmental Impact of Shallow Geothermal Energy Utilization

According to the current trend, the shallow geothermal energy is utilized in a more extensive way to help cut CO_2 emission in the building heating sector. It is interesting to the researcher that, if the subsurface energy is continuously extracted over a long period of time, what kind of environmental impact will it be with regard to the downstream groundwater? In this context, a suburban neighborhood in Cologne, Germany was chosen as the study area. In this neighborhood where the ground water temperature is around 11,55°C, high-density Ground Source Heat Pump systems have been installed for the heating and cooling of houses with an average heat demand of 9.6 kW. Figure 3 illustrates the position of the GSHP systems and their respective types (open or closed loop). In total, there are 51 GSHP installations, of which 47 are closed loop BHEs while the remaining 4 are open systems. Different from the 100 m long BHE in the above section, the maximum borehole depth in this neighborhood is only 30m limited by the thickness of the first groundwater reservoir. All the installed GSHP systems are at least used for heating during the winter. The minimum distance between adjacent installations is about 10 m, which is quite typical in German urban settings.

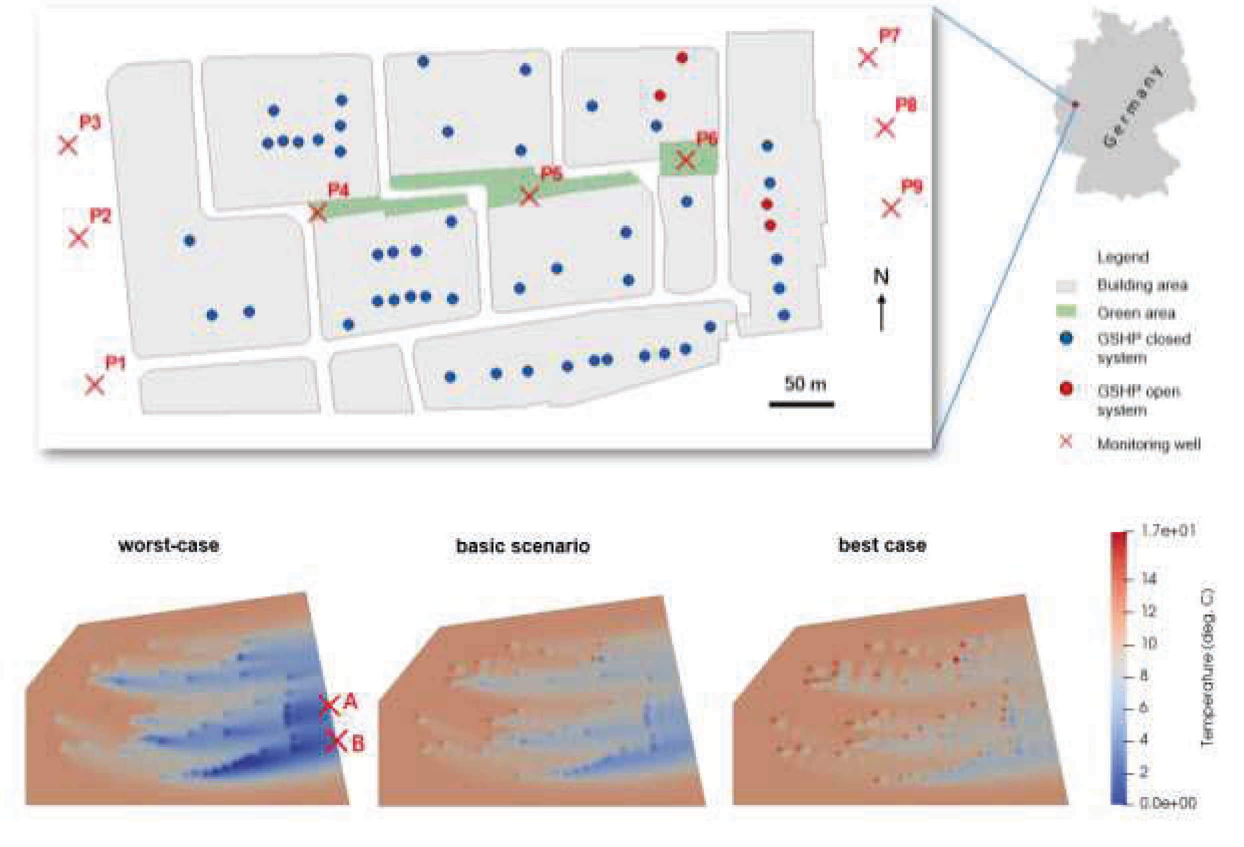

Figure 3: (a) The location of the study area and the location of GSHP systems in this neighborhood; (b) Modelled downstream groundwater temperature distribution.

As part of the monitoring activities, the groundwater level and temperature in the wells of this neighborhood have been continuously monitored from 2013 to 2017. As suggested by the groundwater level measurements, the groundwater flow direction of the study area is in general from west to east. From the documentation of drill cuttings acquired during BHE installation, it can be inferred that the aquifer is partially-saturated. The measured groundwater temperature in the downstream of GSHP installations exhibited a decrease of ~0.4 °C within 2013 to 2017 period. For the local water and environmental authorities, they wish to know whether the temperature drop will continue this trend or it will stabilize itself after a couple of years.

Based on the monitoring data and field-measured aquifer parameters, a 2D numerical model has been established to predict the long-term evolution of groundwater temperature. The simulation of 25 years showed that the downstream groundwater temperature is very heterogeneous. In locations where the GSHP systems are aligned with the groundwater flow direction, the temperature drop is much stronger, due to the superposition of cold groundwater plume. In other places where the GSHP systems are distributed, the temperature drop will be much smaller. A sensitivity analysis was also conducted by varying parameters such as subsurface thermal conductivity and groundwater flow velocity (see Figure 3b). In the basic scenario, the lowest downstream temperature will stabilize at around 8 °C, which is 3 °C temperature drop. In the worst-case scenario, the temperature drop will be around 6 °C, which is nearly compatible with the regulatory requirements. However, for locations in the downstream of a series of GSHPs in the east-west direction (the location marked with A and B in Figure 3b), groundwater temperature is likely to drop more than 6 °C, as the groundwater is continuously cooled along its way (see Meng et al. 2019). From this modelling study, two recommendations can be given. (1) For small neighborhood where the shallow geothermal energy is planned to be used intensively, an overall geological survey and planning is needed to avoid any interference between different GSHP systems, which is beneficiary for the long-term interest of individual owners. (2) In the current German climate conditions, house cooling load is much smaller than the heating demand which, however, may change in the future. In any case, it is recommended to use the GSHP system in both the cooling and heating modes. This will greatly reduce the risk of heat or cold accumulation in the subsurface.

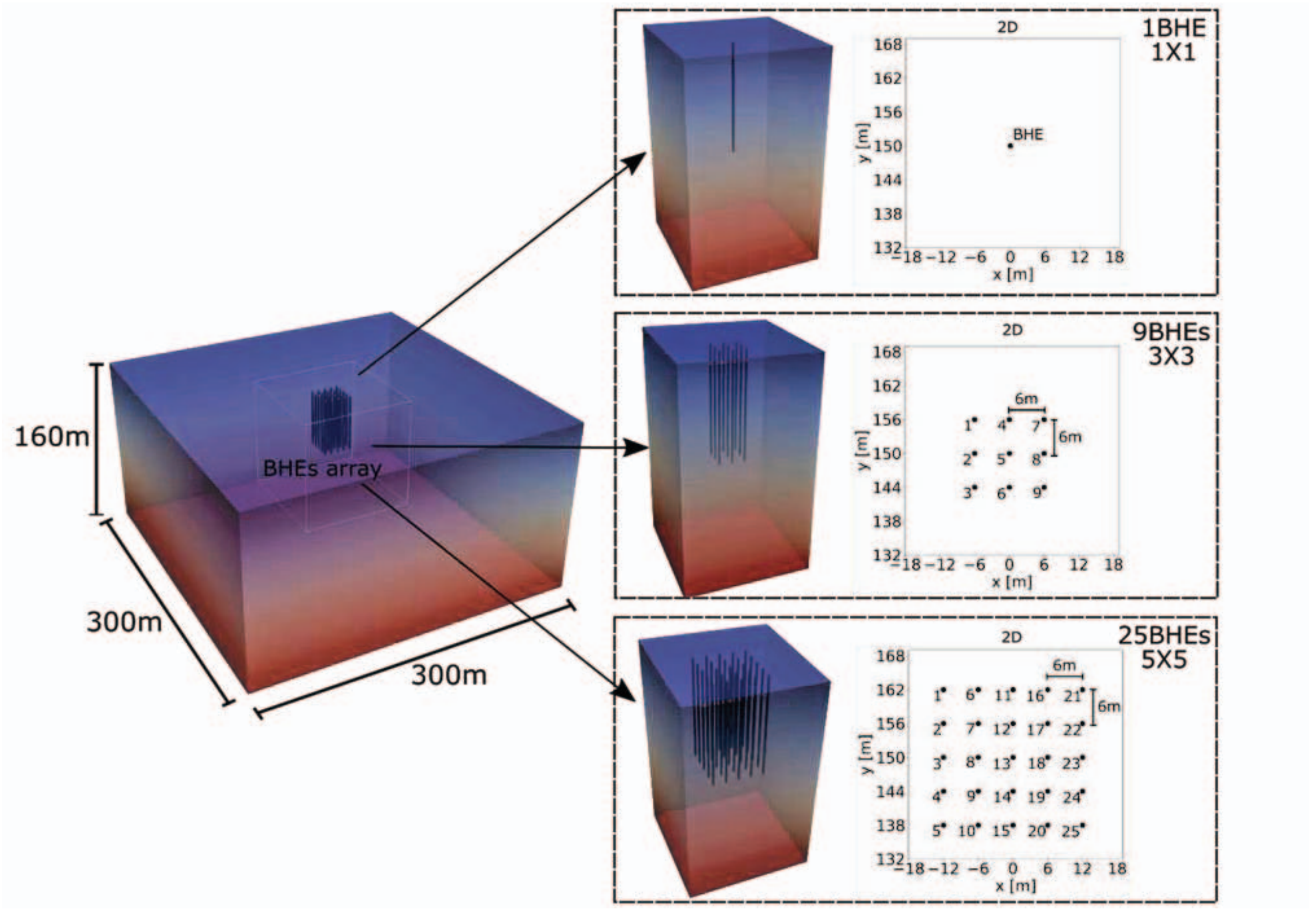

Figure 4: Numerical model setup representing large BHE arrays.

4. Thermal Load Shifting Behavior in Large BHE Arrays

A recent trend in the utilization of shallow geothermal energy is that larger and larger systems are increasingly being built, targeting commercial buildings and small neighborhood. Typically, a dozen or sometimes hundreds of Borehole Heat Exchangers (BHEs) are connected with a pipe network to form a BHE array in order to supply a higher thermal load from the building side. Especially in urban areas where the land is limited, such large BHE arrays are favorable. When designing such systems, the currently available analytical modelling approach imposes the same heat extraction rate on each BHE implying that the temperature distribution of the surrounding soil will remain in equilibrium. This assumption holds true for single up to a few BHEs, but it may deviate from the reality when the thermal plumes from neighboring BHEs are interfering with each other.

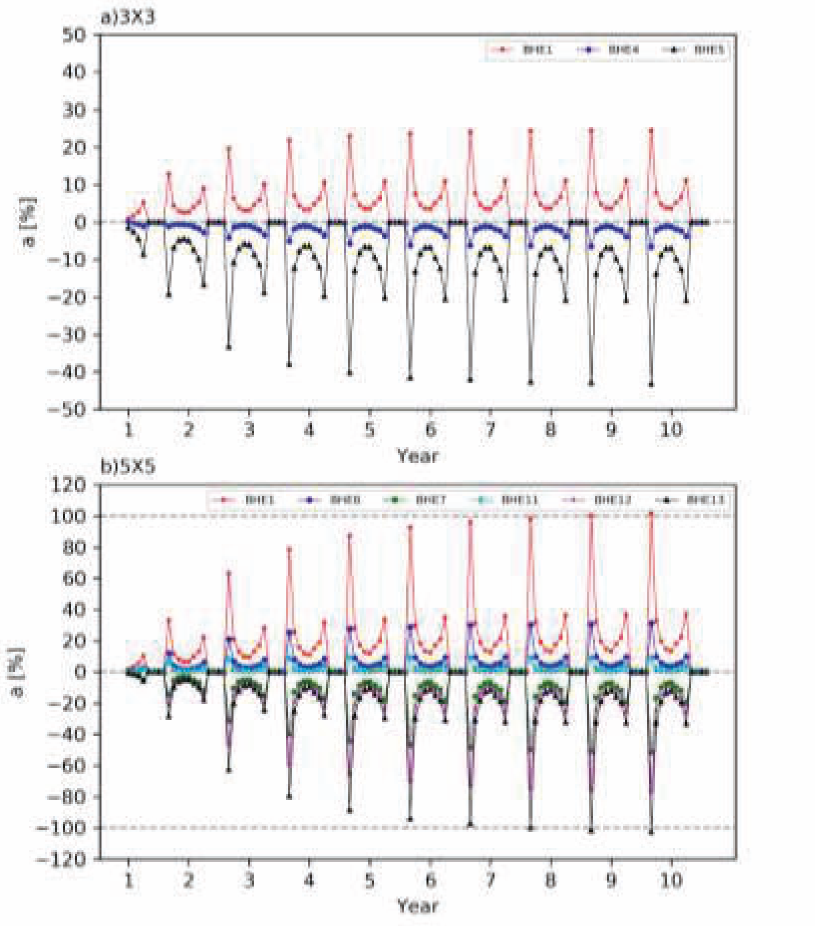

Figure 5: Percentage of Shifted Thermal Load in percentage of the average thermal extraction power of 87 W) in the 3x3 and 5x5 BHE Array Setup (black: center borehole, red outer borehole upstream)

In order to understand the dynamic heat transport process during the exploitation of shallow geothermal energy through BHEs and pipe networks, the numerical model OpenGeoSys has been coupled with the TESPy model. The former code was employed for the simulation of subsurface distribution, while the latter is used for reproducing the hydraulics and heat transport process in the pipe network. Numerical experiments have been conducted for a 3x3 and a 5x5 BHE array (see Figure 4). Groundwater was assumed stagnant in these models, and only thermal conduction was assumed to control the heat exchange process between the boreholes and subsurface. From the 3x3 and 5x5 cased, the specific heat extraction rates were kept the same at 12.5 W/m, with the total thermal load increasing linearly according to the total length of the BHEs. These systems were set up to run for a 10-year-long period.

The long-term simulation results reveal several interesting phenomenon.

1. In both array setups, the performance of the heat extraction rate is shifting. BHEs located at the outer part of the array are experiencing an increase of the heat extraction rate, while the BHEs located at the inner part of array are experiencing a reduction.
2. In the 3x3 array case, a maximum shift of 49 W was observed for the heat extraction rate for the BHE located at the center. In the 5x5 case the maximal shift was 87 W, again on BHEs located in the center, which means the shifting effect is enhanced in a larger array setup.
3. In the 3x3 setup, the change of heat extraction rate shift is for all BHEs strongest in the first 2 years, before a quasi-steady-state is reached whilst in the 5x5 case, reaching the quasi-steady-state will require 5 years. This indicates that a system with a larger array setup needs more time to reach a quasi-steady-state during operation.
4. When looking into the relative amount of shifted thermal load (Figure 5), it varies much more intensively over the seasons. In December and January when the average thermal load is high on each BHE (peak value at 625 W), the amount of shifted load accounts for 3% (3x3 case) to 10% (5x5 case) of the average value. However in April, when the average thermal load is relatively low but the subsurface temperature in the center is already low, the proportion of shifted load reaches 20% in the 3x3 case or even exceeds 100% in the 5x5 case.

5. Summary and Outlook

In order to achieve the target of cutting CO_2 emission, transition in the building heating technology is essential for Germany and other northern European countries. In this context, shallow geothermal energy, due to its low carbon footprint and large potential, can be further exploited through the Ground Source Heat Pump system. The study on an intensively utilized site in Germany shows that the environmental impact from the shallow geothermal installations is very limited. Policies and regulations should encourage more applications of GSHP system in newly built and renovated areas. Further research is needed to quantify the sustainable amount of thermal load that can be imposed on such large array system.

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Die Rolle der Fernwärme bei der Umsetzung der Energiewende

Marcel Krämer, swb Erzeugung AG & Co. KG Bremen

Während im Stromsektor bereits erhebliche Fortschritte hin zu einer nachhaltigen Erzeugung auf Basis erneuerbarer Energien zu konstatieren sind, steckt der Wärmesektor in dieser Hinsicht noch in den Kinderschuhen. Neben der Gebäudedämmung zur Verringerung des Energiebedarfs spielen die Technologien für die Bereitstellung von CO2-arm bzw. CO2-frei erzeugter Wärme eine wichtige Rolle. Fernwärme auf Basis von Kraft-Wärme-Kopplung kann hier einen wesentlichen Beitrag leisten und steht deshalb derzeit auch im Mittelpunkt verschiedener Förderprogramme der Bundesregierung. Anhand der Überlegungen, Planungen und Bauvorhaben eines städtischen Energieversorgers soll die Rolle der Fernwärme im Rahmen der Energiewende dargestellt werden.

Wer sich umfassend und aktuell über das Fernwärme-Thema informieren will, dem sei eine aktuelle Veröffentlichung von Panos Konstantin (s. Literaturverzeichnis) sehr empfohlen, in der auf alle relevanten Fragestellungen zu der Thematik eingegangen wird, die in diesem kurzen Text nur andeutungsweise behandelt werden können.

Was ist Fernwärme?

Der Begriff "Fernwärme" ist vermeintlich selbsterklärend - demnach handelt es sich um Wärme, die an einem anderen Ort als in der eigenen Wohnung hergestellt wird, und dann über Fernleitungen nach Hause gebracht wird. Die Arbeitsgemeinschaft Fernwärme (AGFW) gibt folgende Definition:

"Fernwärme ist Wärme beliebiger Herkunft, die mit Hilfe eines Trägermediums (meistens Heizwasser oder Dampf) gewerblich aufgrund eines Vertrages gegen Entgelt geliefert wird und mit deren Lieferung keine eigenen mietrechtlichen Nebenverpflichtungen erfüllt werden."[1]

Im Unterschied zu den regulierten Sparten Gas und Strom, bei den es einen wettbewerblichen Markt mehrerer Anbieter gibt, der von der Bundesnetzagentur überwacht wird, handelt es sich bei der Fernwärme ähnlich wie bei Trinkwasser und der Entsorgung von Abwasser um Versorgungsmonopole. Angeschlossene Kunden können üblicherweise nicht zwischen mehreren Anbietern auswählen.

Je nach Temperaturniveau der gelieferten Wärme kann Fernwärme als Prozesswärme (oder -dampf), zur Raumheizung und Trinkwassererwärmung, aber auch zur Kälteerzeugung genutzt werden. Im Sinne einer effizienten Energienutzung gehen die Bestrebungen dahin, möglichst niedrige Temperaturniveaus (ca. 90 °C Vorlauftemperaturen im Winter) in Fernwärmenetzen zu erreichen. Derzeit üblich sind Vorlauf-Temperatur-Niveaus von über 130 °C in den Wintermonaten und knapp unter 100 °C in den Übergangsmonaten (Frühjahr/Herbst). Im Sommer wird signifikant weniger Wärme von den Verbrauchern abgenommen, zumeist nur zur Trinkwassererwärmung, so dass hier nur eine erheblich schlechtere Effizienz auch der Wärmeerzeugung und -verteilung erreicht wird.

Fernwärme wurde bereits sehr früh eingesetzt. Der geschichtliche Bogen lässt sich bis hin zu Anwendungen in China im 3. Jahrhundert v. Chr. spannen.[2] In größerem Maßstab spielt die Fernwärme jedoch erst im 20. Jahrhundert eine Rolle; den größten Aufschwung hat die

[1] vgl. Lubinski, S. 13
[2] vgl. Munser, S. 19

Technologie in den 70er und 80er Jahren in Deutschland erfahren. Aber auch in den USA, Mittel- und Osteuropa sowie Russland liefert Fernwärme einen nennenswerten Beitrag zur Wärmeversorgung.

Voraussetzung für Fernwärme ist eine geeignete Methode zur Herstellung der Wärme für die Wärmenetze. Als effizient und umweltfreundlich hat sich die Nutzung der Kraft-Wärme-Kopplung (KWK), also die gleichzeitige Erzeugung von Strom und Wärme, oder auch die Abwärmenutzung von fossil oder atomar betriebenen Kraftwerken bewährt. Durch die parallele Verwendung von Strom und Wärme kann der Anteil an Nutzenergie bezogen auf den Primärenergieeinsatz auf Werte von zum Teil über 90% gehoben werden. Nur als Absicherung und zur Bedienung der Spitzenlast werden in Fernwärmenetzen auch reine Heizkessel eingesetzt, die keinen Strom liefern.

Die Rolle Der Fernwärme in der derzeitigen Wärmeversorgung in Deutschland

Wärmeversorgung ist – ähnlich wie die Wasserversorgung – eines der Grundbedürfnisse des Menschen. Mit zunehmend optimierter und effizienter Energiebereitstellung und -nutzung sind dafür heutzutage häufig dezentrale Wärmeerzeugungsanlagen im Einsatz, weitgehend unter Verwendung der fossilen Energieträger Öl und Gas. Wie zuvor bereits beschrieben, reicht die zentrale Wärmeversorgung in Form der Fernwärmelieferung geschichtlich weit zurück. Im Gegensatz zu dezentralen Heizsystemen, die häufig ausschließlich zur Wärmebereitstellung dienen, nutzt die Fernwärme bei Kraft-Wärme-Kopplung den Primärenergieträger deutlich effizienter aus. Deshalb ist die Fernwärme aus Sicht der Ressourcenschonung und des Klimaschutzes vorteilhaft gegenüber dezentralen Systemen, soweit diese ausschließlich für Heizzwecke genutzt werden.

Der Anteil der Fernwärme am heutigen Wärme“markt“ ist allerdings noch deutlich ausbaufähig. 2017 betrug der Anteil der Fernwärme zur Bereitstellung von Raumwärme und für Warmwasserbereitung 8% (siehe Abb. 1)[3].

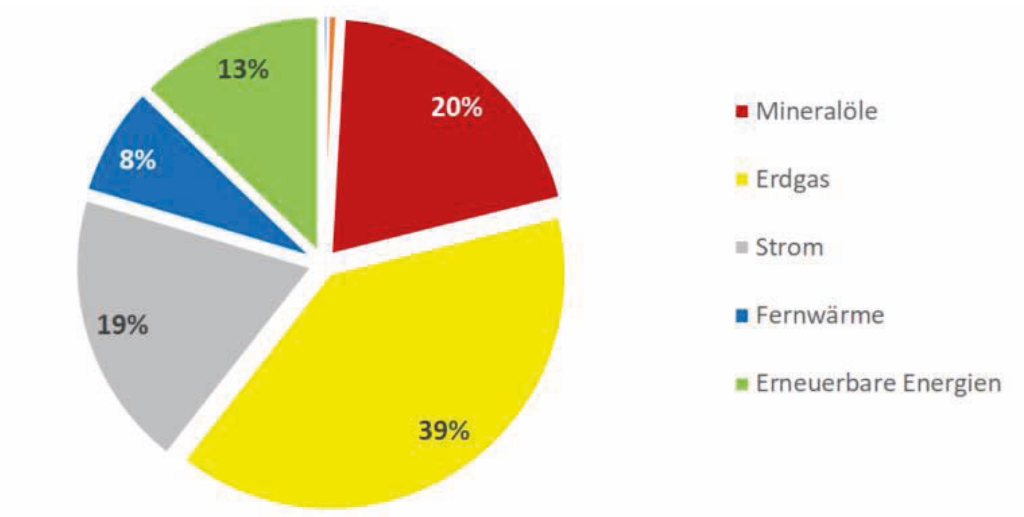

Abbildung 1: Aufteilung der für die Deckung des Wärmebedarfs von Endverbrauchern eingesetzten Energieträgern in Deutschland (2017)[3].

Gründe für den deutlich höheren Anteil an Erdgas-versorgten Wohneinheiten sind folgende: Als leitungsgebundene Energieform ist die Fernwärme vor allem zur Versorgung in Städten

[3] vgl. Arbeitsgemeinschaft Energiebilanzen; https://ag-energiebilanzen.de/10-0-Auswertungstabellen.html

und Ballungsgebieten geeignet. Das ebenfalls leitungsgebundene Erdgas hat im Vergleich zur Fernwärme den Vorteil, dass nur eine Leitung an den Endkunden verlegt wird, während bei der Fernwärme Vor- und Rücklauf verlegt werden müssen. Zudem hat das Erdgas ein deutlich höhere Energiedichte, so dass geringere Querschnitte bei gleicher Leistung ausreichen. Erdgas kann außerdem genutzt werden, um deutlich höhere Prozesstemperaturen zu erreichen, was z.B. für Gewerbe wichtig ist, das nahe an versorgten Wohngebieten liegt. Fernwärme hat üblicherweise Vorlauf-Temperaturen, die nicht höher als 140 °C sind.

Als kleines Gedankenspiel kann grob das Potenzial für Fernwärme abgeschätzt werden: Laut statistischem Bundesamt gibt es in Deutschland 80 Großstädte mit mehr als 100.000 Einwohnern.[4] Da Fernwärme sich insbesondere dort wirtschaftlich betreiben lässt, kann der Energiebedarf zur Raumheizung und Warmwasserbereitung dieser Städte als Potenzial benannt werden. Dieser Energiebedarf lässt sich vereinfachend über den Anteil der 80 Großstädte an der Gesamtbevölkerung in Deutschland abschätzen: dieser beträgt rund 30%. Der gesamte Energiebedarf für Raumwärme und Warmwasser betrug 2017 laut AG-Energiebilanzen rund 1800 PJ. Demnach kann ein Wärmebedarf in den Großstädten von 600 PJ abgeschätzt werden. Derzeit werden durch Fernwärme rund 180 PJ bereitgestellt. Selbst unter der Annahme, dass nur 50% des gesamten Potenzials wirtschaftlich erschlossen werden könnte, würde dies noch fast eine Verdopplung des heutigen Wertes auf 300 PJ bedeuten. Als effiziente und klimaschonende Wärmeversorgung hat also die Fernwärme noch erhebliches Potenzial.

Heute übliche Technologien

In früheren Zeiten war es üblich, die Fernwärme in Form von Dampf vom Erzeuger an die Abnehmer zu transportieren. Dies hatte insbesondere dann zusätzlichen Nutzen, wenn die Kunden das höhere Temperaturniveau des Dampfes für Anlagen oder technische Anwendungen nutzen konnten. Zudem wird mit Dampf auch die Kondensationsenthalpie genutzt; dadurch hat Dampf eine deutlich höhere Energiedichte als heißes Wasser und erfordert deutlich weniger Pumpenenergie. Heute wird bei weiterem Ausbau und der Erneuerung von Fernwärmesystemen üblicherweise auf Warmwasser-Systeme gesetzt. Dies auch vor allem deshalb, weil die Handhabbarkeit des Systems und die Sicherheit gegenüber einem Dampfsystem deutlich größer ist. Um die thermischen Leitungsverluste zu verringern, wird außerdem angestrebt, die Vorlauftemperatur weiter abzusenken, zumal moderne Bauten mit niedrigeren Vorlauftemperaturen beheizt werden können als schlechter isolierte konventionelle Gebäude. So wurde 2017 vom Bundeswirtschaftsministerium das Förder-programm „Wärmenetze 4.0“ ins Leben gerufen, das sich mit Wärmenetzen befasst, die eine maximale Vorlauftemperatur von 95°C haben.[5]

Tabelle 1: Vergleich der Betriebstemperatuten von Dampf- und Wassernetzen.

Temperaturen	Dampfsystem	Wassersystem	Zukunft
Vorlauf (Winter)	180..200 °C	Max. 140 °C	Max. 95°C
Rücklauf (Winter)	70 °C (Kondensat)	ca. 60..70 °C	ca. 45..50°C

[4] vgl. Statistisches Bundesamt, Mikrozensus 2011; https://www.destatis.de/DE/Themen/Laender-Regionen/Regionales/Gemeindeverzeichnis/Administrativ/zensus-grossstaedte.html
[5] vgl. BMWi, Wärmenetze 4.0; https://www.bmwi.de/Redaktion/DE/Downloads/B/bundesanzeiger-foerderbekanntmachung-waermenetz-40.pdf?__blob=publicationFile&v=14

Bei den verwendeten Rohren handelt es sich üblicherweise um Stahlrohre, die mit Polyurethan gedämmt sind. Der Aufbau des kompletten Verteilrohres ist: Stahlrohre (optional Edelstahl) - Polyurethan-Hartschaum-Dämmung - Mantelrohr aus Polyethylen-HD.

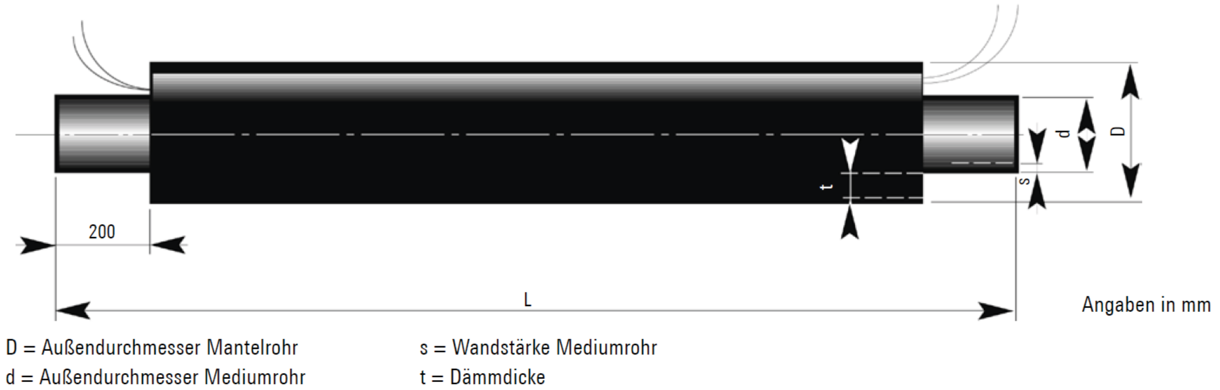

Abb. 2: Aufbau eines üblichen Fernwärme-Leitungsrohres.[6]

Diese werden im Zwei-Rohr-Verlege-Verfahren in offener Bauweise in die Erde gebracht. Dazu muss eine Baugrube geöffnet werden, die mind. 1 Meter tief ist. Die Breite hängt von dem Durchmesser der zu verlegenden Rohre ab; bei einer Transportleitung mit einem Nenndurchmesser von DN500, die mit einer wirtschaftlich angemessenen Dämmung von rd. 30 cm versehen ist, beträgt die Breite der Baugrube rund 2 Meter.

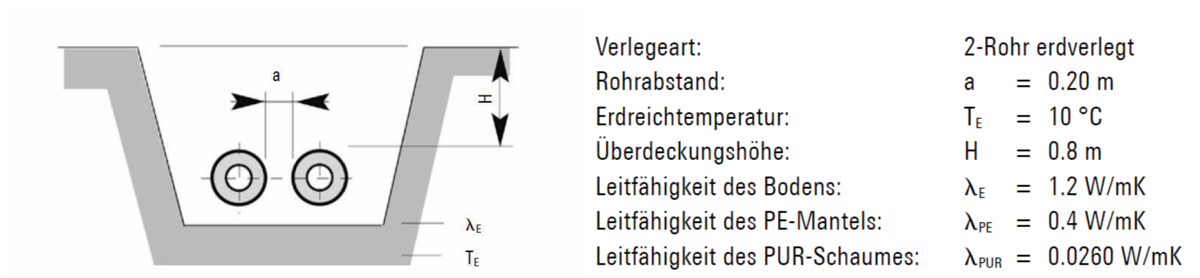

Abb. 3: Verlegeart und Kennzahlen der Rohrverlegung.[7]

Die aufwändige Erdverlegung wird in den Städten durch weitere konkurrierende Erdverlegungen erschwert: Neben der Abwasser-Infrastruktur sind dies Stromkabel und Gasleitungen, zudem Telefonleitungen und seit neustem auch Lichtwellenleiter/Glasfasern. Häufig ist die Ausführung der Erdarbeiten zwischen den einzelnen Gewerken nicht abgestimmt, so dass teilweise mehrfach die gleiche Straße geöffnet wird.

In Ostdeutschland ist bei der Fernwärme noch häufiger eine überirdische Verlegung der Transportleitungen anzutreffen und wird dort offensichtlich auch eher akzeptiert. In Bremen wird derzeit in einem aufwändigen Verfahren eine Trasse für eine Verbindungsleitung von rund 7 Kilometern festgelegt, die sich aufgrund von Bürgerprotesten (u.a. Baumerhalt) oder Stadtplanung (geplante Straßenbahntrasse) einen Weg des geringsten Widerstands suchen muss. Dieser ist hinsichtlich einer wirtschaftlichen Anschlussmöglichkeit von Kunden jedoch nicht optimal.

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[6] Quelle: German Pipe Industrie- und Fernwärmetechnik GmbH, Nordhausen; www.germanpipe.de
[7] Quelle: German Pipe, aaO.

Herausforderungen und Chancen der Nutzung der Fernwärme im Kontext der Energiewende

Die Energiewende ist bislang immer noch vornehmlich eine Stromwende. Während hier durch das Erneuerbare Energien Gesetz (EEG) in den letzten 20 Jahren ein erheblicher Zubau von Windenergie- und Photovoltaikanlagen stattfand, so dass der Anteil an der Stromerzeugung mittlerweile auf über 40% angewachsen ist[8], gibt es Vergleichbares im Wärmesektor erst seit 2009 mit dem Erneuerbare-Energien-Wärmegesetz. Dadurch wurde für Neubauten festgeschrieben, dass diese entweder besonders effizient zu sein haben, und/oder ihren (Rest-)Wärmebedarf anteilig mit Erneuerbaren Energien decken müssen. Dabei ist die Fernwärme aus Kraft-Wärme-Kopplung ebenfalls eine mögliche Option.

Die größte Herausforderung im Wärmesektor besteht darin, dass der überwiegende Bedarf an Raumwärme und Energie zur Warmwasserbereitung in Bestandsbauten existiert. Diese müssen jedoch bislang nicht systematisch bis zu einem Zieltermin auf erneuerbare Energien umgestellt werden. Und die Wirtschaftlichkeit einer energetischen Modernisierung mit/auf Erneuerbare Energien ist aufgrund der immer noch vergleichsweise niedrigen Preise der fossilen Energien nicht darstellbar.

Wie im Stromsektor konkurriert die Wärme-Erzeugung aus Erneuerbaren Energien mit Einsparung von Energiebedarf. Das Dilemma im Stromsektor besteht darin, dass der Zubau von WEA und PV zwar eine hohe Leistung zur Stromversorgung bereitstellen kann, diese aber abhängig vom fluktuierenden Wind- und Sonnendargebot ist. Zudem richtet sich die Stromnachfrage nicht nach dem Angebot. So kommt es nicht selten vor, dass Strom aus Erneuerbaren Energien verfügbar ist, dieser aufgrund von Nachfragemangel aber nicht genutzt werden kann. Die kapitalintensiven Anlagen sind aber erst dann nach den betriebswirtschaftlichen Kriterien „im Geld“, wenn sie im Jahr auch eine bestimmte Mindesterzeugung absetzen können (bzw. -vergütung erhalten). Derzeit ist dies noch durch Garantieabnahmen und Ersatzzahlungen bei Abregelung gewährleistet, das kann aber nicht dauerhaft so bleiben.

Der Wärmesektor ist zudem auch noch nicht entschieden darüber, ob er sich in eine Richtung des minimalen „Restwärmebedarfs“ entwickelt, also maximale Hausdämmung (Passivhaus) und Bereitstellung des restlichen Energie- (auch des Wärme-)Bedarfs durch Strom, oder in Richtung einer ausgewogenen Dämmung mit Nutzung klimaschonend bereitgestellter Wärme (wie z.B. Fernwärme) entwickeln wird. Dazu wird es noch gesetzlicher Rahmenbedingungen bedürfen, die derzeit aber noch nicht in Sicht sind.

Wirtschaftlichkeit der Fernwärmenutzung

Eine Wirtschaftlichkeitsbetrachtung hat üblicherweise mehrere Facetten, mindestens aus Sicht des Betreibers / Anbieters und aus Sicht des Kunden / Abnehmers. Der Betreiber des Fernwärmesystems erwartet eine angemessene Verzinsung seines eingesetzten Kapitals, während der Kunde den angebotenen Preis für die Wärmelieferung mit anderen Alternativen, wie der Versorgung mit Heizgas oder -öl, mittlerweile aber auch mit Wärmepumpen, vergleicht.

Die Fernwärmeversorgung ist ein vergleichsweise kapitalintensives Geschäftsfeld. KWK-Erzeugungsanlagen und Leitungsbau sind die Hauptkostentreiber beim Bau eines Fernwärmenetzes. Insbesondere wenn das Fernwärmesystem über eine Kohle-KWK-Anlage gespeist wird, liegen die variablen Kosten, inkl. der Absicherung durch Erdgas-betriebene Spitzenlastkessel nur bei geschätzten 15% der Gesamtkosten, die dem Endkunden in Rechnung gestellt werden (ca. 12 EUR/MWh von insgesamt rd. 80 EUR/MWh).[9]

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[8] vgl. Fraunhofer ISE; https://energy-charts.de/energy_pie_de.htm

[9] vgl. Konstantin, “Praxisbuch der Fernwärmeversorgung”, Kapitel 10

Die Wirtschaftlichkeit des Fernwärmesystems erhöht sich, wenn bei KWK-Anlagen durch hohe Strompreise auch nennenswerte Stromerlöse erzielt werden können. Für Abfall-Verbrennungsanlagen liegen die Gestehungskosten nochmals niedriger, da die Wärmeerzeugung hier im Wesentlichen mit der Stromerzeugung "konkurriert" und eine verstärkte Wärmeauskopplung zu Lasten von Stromerlösen geht, die in der ursprünglichen Wirtschaftlichkeitsbetrachtung der Abfall-Verbrennungsanlage angesetzt wurden.

Die Kosten für eine Verlegung von Fernwärmeleitungen sind neben der Größe der Leitungen auch abhängig davon, wo die Leitungen verlegt werden sollen: im innerstädtischen, bereits vielfach genutzten Bereich oder in vergleichsweisem baulastenfreiem Untergrund von z.B. Neubaugebieten. Nachfolgende Darstellung zeigt die Bandbreite nach [Kons], ergänzt um aktuelle Erfahrungen des Autors; von den Kosten fallen allein 40-50% für die Tiefbauarbeiten an. Diese Kostenposition ist derzeit eine der meistgefragten Bauleistungen, weshalb hier die Preise in der jüngsten Zeit erheblich gestiegen sind.

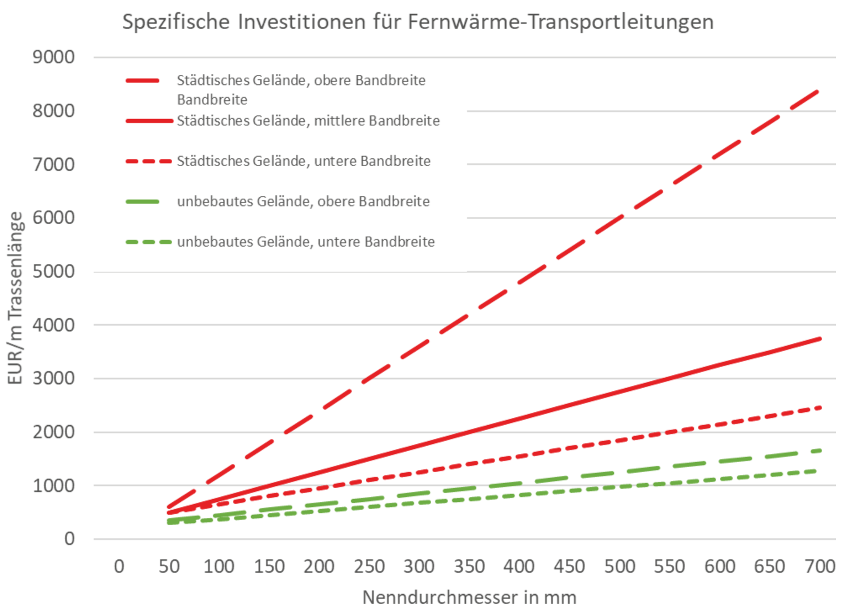

Abb. 4: Bandbreiten von Kosten für die Verlegung von Fernwärmeleitungen.[10]

Aufgrund der langen Abschreibungsdauern (bis zu 60 Jahre) kann eine solche Investition aber immer noch wirtschaftlich dargestellt werden.

Insgesamt lässt sich folgendes Schema für die Gesamtkostenbetrachtung zeigen:

Abb. 5: Kostenkomponenten für das Fernwärmesystem

Nach Konstantin setzen sich die Fernwärme-Gestehungskosten für ein beispielhaftes Versorgungsgebiet wie folgt zusammen:

[10] vgl. Konstantin, aaO.

Tabelle 2: Exemplarische Berechnung der Versorgungskosten in einem städtischen Fernwärmenetz.

Position	Einheit	Wert
Fernwärmeerzeugung	**€/MWhth**	**34 – 40**
(80% KWK-Erzeugung, 20% Spitzenkessel)		
Transport & Verteilung	**€/MWhth**	**25 - 28**
Hausanschluss	**€/MWhth**	**20 - 25**
(bezogen auf 15 Jahre Nutzung mit ca. 15 MWh/a)		
Gesamtkosten frei Haus (ca.)	**€/MWhth**	**79 – 93**

Der sich aus diesen hier dargestellten Kosten ergebende Preis für den Endkunden wird zwischen 80 und 90 EUR/MWhth liegen. Damit zeigt sich die Nutzung der Fernwärme für Endkunden im Vergleich zu alternativen Heizformen nicht auf den ersten Blick preiswerter. Doch unter der Berücksichtigung der entfallenden Kosten für Betrieb und Wartung der Heizanlage sowie u.a. entfallende Schornsteinfegerkosten kann das Angebot für den privaten Endkunden über einen längeren Betrachtungszeitraum wirtschaftlich vorteilhafter sein.

Für Großkunden wie Industrieunternehmen gelten üblicherweise andere Preise, die sich vor allem an den anlegbaren Preisen einer Eigenversorgung des jeweiligen Industriebetriebes orientieren. Aufgrund des hohen Anteils an der Abnahme von Leistung und Arbeit tragen solche Kunden aber erheblich zur Deckung der Strukturkosten des Systems bei.

Bei den Preisformeln für die Kunden wird üblicherweise versucht, eine den Kosten entsprechende Verteilung von fixen und variablen Kosten zu erreichen, mindestens je zu 50%. Kundenseitig ist der Wunsch jedoch ausgeprägt, einen mehrheitlich auf dem Arbeitspreis basierenden Wärmepreis zu bekommen, da durch entsprechendes Verbrauchsverhalten die Kosten dann direkt beeinflusst werden können.

Zukünftige Nutzung der Fernwärme

Die AGFW hat mit ihren Szenarien „40/40-Strategie“ und „70/70-Strategie“[11] mögliche Perspektiven für die zukünftige Fernwärmenutzung – auch zur Erreichung der Klimaschutzziele – formuliert. Darin zeigt die 40/40-Strategie, dass „der Ausbau der Fernwärme auf durchschnittlich 40% der Wärmebereitstellung in 40% der deutschen Kommunen mit einem hohen Anteil erneuerbarer Energien bis 2050 dazu fähig [ist], die Energiewende im Wärmebereich zu erreichen“. Dier 70/70-Strategie weist darüber hinaus Wege auf, um bis 2050 die 70 einwohnerstärksten Städte in Deutschland auf einen Anteil von 70% Wärmeversorgung aus Fernwärme zu entwickeln.

Die Erreichbarkeit – je nach politischem Willen – dieser Ziele hängt jedoch stark von der Gesamtstrategie der Energiepolitik ab. Gerade im Wärmebereich gibt es konkurrierende Systeme, so dass die Fernwärme nicht als einzige Option für eine klimaschonende Wärmeversorgung gesehen werden muss.

Besonders ist hier generell die staatlich geförderte umfängliche Gebäudedämmung zu nennen, die zu einem nur noch geringen Bedarf an Heizenergie und Energie zur Warmwasserbereitung führt. Hier finden sich insbesondere für Einfamilienhäuser Lösungen mit elektrisch

[11] vgl. AGFW, https://www.agfw.de/energiekonzepte/7070-4040-strategie/

betriebenen Wärmepumpen, z.T. in Kombination mit Photovoltaik-Anlagen zur Strombereitstellung oder thermischen Solaranlagen zur direkten Deckung des Wärmebedarfs.

Solange zudem die fossilen Energieträger Erdgas und Öl nicht wesentlich teurer werden, ist der preisliche Vorteil für Eigenheimbesitzer meist auf Seiten der Kalkulation mit den herkömmlichen Energieträgern.

Auch bei Wohngebieten gibt es Modelle, die eine Versorgung mit einer Heizzentrale vorsehen, die nicht an das städtische Fernwärmesystem angeschlossen werden, sondern eine „kleine“ BHKW-Lösung vorziehen. Hier kann es nur durch die strategische städtebauliche Entwicklung einen weiteren Ausbau der Fernwärmeversorgung geben.

Nicht zuletzt hat die Fernwärmeerzeugung in Kraft-Wärme-Kopplung das Problem, dass durch vermehrte Einspeisung von regenerativ erzeugtem Strom die Strompreise so stark sinken (z.T. sogar negativ sind), dass die Wirtschaftlichkeit, die in nennenswertem Maß von den Stromerlösen abhängt, gefährdet ist. Dies macht z.B. Investitionsentscheidungen für neue KWK-Anlagen stark davon abhängig, welches Energiepreisszenario erwartet wird.

Solange der Einsatz effizienter und klimaschonender Technologien im Wärmemarkt noch eine untergeordnete Rolle spielt, sind die umfangreichen Förderungen, u.a. durch das Kraft-Wärme-Kopplungs-Gesetz berechtigt und auch notwendig.

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Revision, fabrication and survey of a scaled rotor blade for tank tests of floating wind turbine systems

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Abstract

Floating Offshore Wind Turbines (FOWT) will play an important role for our energy industry in the near future. Consequently sites on the open ocean and therefore in deeper water further away from the shores need to be accessed for meeting future sustainable energy demands. For the realization of reliable floating offshore wind turbines, it is necessary to understand the dynamic behavior of floaters exposed to forces induced by wind and wave. Since it is very expensive to build a full-scale FOWT only for these investigations, scaled down FOWT are often preferred although upscaling may be problematic with the Froude and Reynolds scaling laws. This matter has been adressed so far with several approaches of scaling wind turbines for water-wind basin tests, see [1] & [2]. In this work a performance-scaled rotor of a DOWEC 6 MW wind turbine was designed with the goal of replicating at small scale its thrust force and, if possible, its power. The designed rotor and its computational simulation had to be validated by wind tunnel tests. Using a design algorithm developed by Schmitz [17] for calculating the blade dimensions it is found that the thrust coefficients almost match the prototypes' benchmark and also the power coefficient is in good proximity for low wind speeds. The designed blade was manufactured by 3D-printing and installed for testing in a Goettinger-type closed circuit wind tunnel. For the investigation of surface effects in these experiments two different blades were built, one with a rough surface resulting from the horizontal edges between the layers and another one with a smooth surface produced by sanding and applying a special foil. The results of the conducted wind tunnel test are compared with corresponding simulations whereby the performance-scaled rotor blade and the applied simulation code could be validated.

1. Introduction

In the energy sector there has been a big development over the last decade. Worldwide we saw increasing awareness regarding the ongoing climate change and its predicted serious consequences. Consequently a continuing strongly increasing demand for renewable energies is expected. From 2005 to 2015 the wind electricity production worldwide grew from 104 TWh to 838 TWh [4]. In 2016 for example the globally installed renewable power capacity increased by about 161 gigawatts, i.e. almost 9 percent more than in 2015 [5]. Also in Germany where the last nuclear power plant is planned to be shut down by 2022 the statistics show a strong rise in renewable energies while the electric power produced by nuclear and coal is declining [6]. Although Germany's GHG emissions reduction goal of 40 % for 2020 (compared to 1990) will not be achieved, it is hoped that the new plan for 2030 can still be accomplished. Currently also the reduction of coal power is discussed in this context. If these ambitions are to be met there will be a big need of renewable energy facilities like photovoltaic and wind power.

The onshore wind power sector in Germany is well developed; most available sites are already used or planned to be utilized. Therefore the annually installed onshore wind power stagnates while the implementation of offshore wind turbines is increasing [7]. Currently five wind parks are in the process of construction. Until 2020 the offshore wind power capacity of Germany could reach 7.700 MW [8]. A clear advantage of offshore sites is the much higher wind yield compared to sites deeper in the country. However the foundation of the pylons and the grid connection are problems to be solved in an economical fashion if we want to use this ample power supplied by sea wind. Near-shore regions with shallow water are currently exploited for large wind parks. However, these presently built and planned near-coastal wind parks cannot match the demand for renewable energy which is arising from shutting down nuclear and fossil power plants already in the near future. Therefore it will be necessary to develop technologies for wind parks in deeper water regions or even on the open ocean which requires floating wind turbines. Designing reliable floating deep water platforms for wind turbines requires realistic physical tests in order to validate the hitherto used coupled simulation codes in this new regime. The dynamic behavior of such systems is governed by strongly coupled aerodynamic, structural mechanic and hydrodynamic aspects. As building a 6 – 10 MW floating offshore wind turbine for the investigation of these effects is too expensive, scaled down models and corresponding upscaling simulations are inevitable.

2. State of the art

Proper scaling is absolutely necessary to achieve comparable and valid experiment results with scaled models. For the scaling of wind turbines the aerodynamic effects are needed to be perfectly represented by the small model. For tests of floating wind turbines the hydrodynamic effects must be regarded as well. To fully obtain the similarity between full-scale and model the non-dimensional numbers like the Reynolds number, the Froude number, the Euler number, the Chauchy number, the Keulegan-Carpenter number and the Strouhal number as described in [9] have to be considered. The most important numbers are the Reynolds and Froude number in order to properly scale a floating wind turbine and will be addressed in the next chapter. These and other non-dimensional numbers are discussed in [10, 1, 11] as well. However getting a similar Reynolds number and also a similar Froude number between prototype and model is not possible. This issue is familiar and also described in [11], There have been several approaches to mitigate this problem. One by adding a second scaling-factor for the wind velocity [12], or by calculating the best compromise between Reynolds number deviation and limiting the increased scaled time which leads also to a divergence for the Froude number [13]. Another approach was made by [14] which was apprehended in the main procedure as far as it concerns the scaling of floating wind turbines. There the Froude number is hold similar and the consequential effect of the divergence of the Reynolds number is counteracted by designing a new blade for the model wind turbine to gain the same thrust and power over the tip speed ratio (TSR). [14] was able to get a good match concerning the thrust coefficient (CT) with this way of scaling but the power coefficient could not be met quite so good, however this was not the main objective of the new designed blade.

a. Scaling Methodology

Hereby shall be described the scaling process for a performance scaled rotor blade. There are two main scaling laws for the downsizing of models for small scale tests. Both are carried out together with geometrical scaling of the objects size and are applied for the operational conditions of the model like hydrodynamic aerodynamic flow, time and forces. If a scaled model rotor blade is designed only for land based aerodynamic tests the Reynolds-number would be applied. Certainly for high scaling factors like 1:50 on wind turbines from these days the resulting Reynolds scaled wind speeds would be too high to reproduce them in a wind tunnel or wind-wave-basin. For example the wind velocity of 12 m/s in full scale would be for a 1 to 50 scaled wind turbine 600 m/s, which is in the supersonic area and therefore exceeds the speed of most wind tunnels. Also this blade will be later applied on a floating model wind turbine so the adherence of the Froude number is necessary if we want to have a floating offshore wind turbine model capable of reproducing both the aerodynamic and hydrodynamic effects of the full scale machine.

b. Tip Speed Ratio – TSR

The Tip-Speed-Ratio (TSR) similarity between model and full scale is very important for proper scaling. It is necessary for correct scaling of the rotational speed and accordingly the induced frequencies like the 3-P impulse on the rotor.

$$TSR = \frac{\omega \cdot R}{u} \tag{1}$$

The TSR scaling law is shown in the following equation.

$$TSR_m = TSR_f \tag{2}$$

c. Reynolds Number

The Reynolds number describes the viscosity effect on fluid flows and is defined by the ratio between the relative velocity of the fluid, u, multiplied by a characteristic length, L, and the kinematic viscosity of the fluid, v. In Order to maintain the ratio between viscous and inertial forces the Reynolds number must be the same for model and its reference. So the Reynolds number is of particular importance for determination of fluid flow speed in wind tunnel tests.

$$Re = \frac{u \cdot L}{v} \tag{3}$$

Scaling according to the Reynolds law means maintaining the Reynolds-number so that the Reynolds number in model-scale, Re_m, is equal to the Reynolds number in full-scale, Re_f. This leads to the definition of the Reynolds scaling law:

$$Re_m = Re_f \tag{4}$$

In most cases the same fluid is used for the model and the full-scale application. In this case the fluid is air and therefore the scaling law can be transformed to:

$$u_m \cdot L_m = u_f \cdot L_f \tag{5}$$

with um, Lm being the fluid velocity and characteristic length of the model test and u_f, L_f being the fluid velocity and characteristic length in full-scale.

d. Froude Number

For water basin tests of floating objects like ships or platforms for wind turbines the Froude number, Fr must be used for correct scaling. The Froude number is defined as

$$Fr = \frac{u_c}{\sqrt{g \cdot L}} \tag{6}$$

where u_c is the characteristic flow velocity, g is gravity and L is again the characteristic length scale. The Froude scaling law aims on preserving the balance of gravitational and inertia forces between full scale reference objects and the its scaled model, which is very important for testing small models of floating objects exposed to wave forces. The Froude scaling law can be defined by:

$$Fr_m = Fr_f \tag{7}$$

The subscripts m and f are denoting model-scale and full-scale, respectively.

e. Scaling Effects and issues

To design a most exact model of a floating offshore wind turbine it is necessary to scale the hydrodynamic and aerodynamic effects properly which are defined by different scaling laws. For water model tests like ships in wave tanks historically the Froude scaling law (Eqn. (7)) is conducted. It ensures that the hydrodynamic loads like wave forces are represented correctly in small scale. However for testing wind turbines the proper aerodynamic scaling is of same importance as the hydrodynamic. Especially for the nick torque on the floating platform due to a correct scaled thrust characteristic of the model rotor blade which is ensured by maintaining the Reynolds number (Eqn. (4)). The Problem with applying both scaling laws and using the same fluids is that the Froude number and the Reynolds number cannot simultaneously be maintained. When starting with Froude-scaling the Reynolds number in model scale will be significantly lower compared to the original rotor, which leads to different flow conditions. By applying a high scaling factor of $\lambda = 50$ to $\lambda = 100$ in model scale will be a laminar flow compared to a turbulent flow in full scale. This is today commonly named as the Reynolds scaling effect and makes the aerodynamic behavior of a Froude-scaled rotor blade incomparable to its original in full scale. As mentioned before when using the Reynolds scaling with scaling factors of $\lambda = 50$ to $\lambda = 100$ for big rotors another problem appears. The scaled flow velocity is too high for most available wind tunnels and especially for the wind speeds feasible in wind-wave-basins. Therefore the method of designing a scaled blade as recommended in the approach [10] will be conducted. The rotor blade and its operational conditions are scaled by maintaining the Froude-number and the tip speed ratio while simultaneously adapting the blade design to overcome the Reynolds scaling effect.

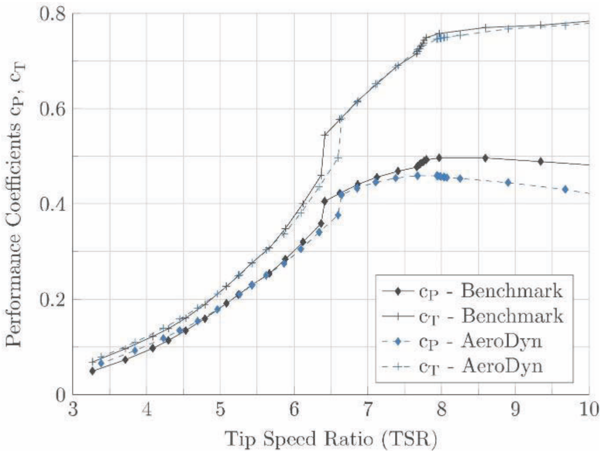

Figure 1: Power coefficient c_P and thrust coefficient c_T of the benchmark and their recalculatoin with AERODYN

3. Calculation Methods

Here are the calculation tools and methods presented which were also described in [3] and used to calculate thrust and power characteristics of a wind turbine rotor. For the simulations the open source code *AeroDyn*, which is developed by NREL and part of FAST code, is used. To get the stationary operational conditions of the model rotor, a number of simulations cycles with a row of different wind velocities and rotational speeds are computed with *AeroDy*n. These operating points are the same at which the performance parameters of the reference turbine are known (see Fig. 1), but also modified for non-pitching Operation conditions and special calculation points for the comparison of the wind tunnel tests in which one rotor blade Stands vertically without rotating and only variations in the angle of attack and wind speed.

As other aero-elastic codes, *AeroDyn* is based on the Blade-Element-Momentum- Theory (BEM). According to this theory the total thrust force acting on the rotor is calculated by integrating the thrust forces acting on small blade elements over the whole rotor. Considering such a small blade element, the thrust force F_T acting on that blade element could be computed with the formula

$$F_T = F_L \cdot \cos(\phi) + F_D \cdot \sin(\phi) \tag{8}$$

were F_L is the lift force, F_D is the drag force and a is the aerodynamic angle of attack.

The lift and drag forces in turn are defined as

$$F_L = 0.5 \cdot c_L(Re, \alpha) \cdot \rho \cdot c \cdot v_{rel}^2 \tag{9}$$

and

$$F_D = 0.5 \cdot c_D(Re, \alpha) \cdot \rho \cdot c \cdot v_{rel}^2 \tag{10}$$

with the air density ρ, the blade element chord length c and the relative wind speed as seen by the blade element v_{rel}. Furthermore $c_L(Re, \alpha)$ and $c_D(Re, \alpha)$in equations (9) and (10) are denoting the lift coefficient and the drag coefficient, respectively. These coefficients are specific to the airfoil profile used at the blade element under consideration and are highly depending on the actual aerodynamic angle of attack α as well as on the Reynolds number Re. Therefore, in order to get the thrust force on the rotor, both the lift coefficient and the drag coefficient have to be determined as functions of the angle of attack for each of the airfoils used in the blade before the *AeroDyn* simulations can be undertaken.

Generally this could be done through measurements in wind tunnel tests or by the use of Computational Fluid Dynamics (CFD) Software. Moreover, for a couple of airfoils these polar data can be also found in literature. For this paper the open source CFD code *XFoil* by Mark Drela [15] was used, which computes polar data based on a 2D panel method and a 2D integral boundary layer solver. From comparison with experiments it is known, that *XFoil* overestimates the lift in the stall region and underestimates the minimum drag. However, as presented in [16] these differences are fairly small. Additionally *XFoil* is characterized by lower computation times compared to full CFD simulations. Thus, *XFoil* was chosen to determine the aerodynamic coefficients. Verifying these results with full CFD simulations will be part of future work. Furthermore, AirfoilPrep (by NREL) was used to modify the polar data gained by *XFoil* to consider the 3-D delayed stall and to prepare the polar data for use in *AeroDyn*. Therefore, the polar data were expanded to the α = ± 180 ° range needed by *AeroDyn* and corrected according to Selig's and Eggers' method. After these preparations, finally the thrust and power characteristics of a rotor can be determined with *AeroDyn*. *XFoil* was also used for the modification of an airfoil shape accordingly to the needs of manufacturing and assembling.

a. Modification of the Low-Reynolds Airfoil

For the blade the maximum airfoil thickness at 2/3 of the rotor radius was defined not to be smaller than 10 mm in order to have enough space for a studding with 4 mm diameter inside the blade. Consequently a new airfoil design was needed for the performance-scaled model blade. A modification of the SD2030b shape as presented in Fig. 2 could be accomplished that met both the required aerodynamic performance and the maximal thickness needed for manufacturing requirements.

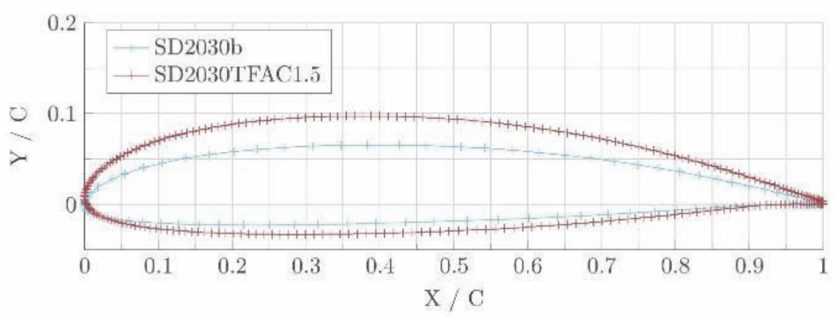

Figure 2: Low Reynolds airfoil SD2030b and the modified SD2030-TFAC1.5

The adjustment of max-blade-thickness was made with *XFoil* and led to a new airfoil shape based on the SD2030b named as SD2030TFAC1.5 accordingly to the adjustments performed. This airfoil was designed step by step adjusting the thickness and chamber ratio and calculating the lift and drag coefficients for a list of angles of attack a. The Reynolds-number was as before set to 30.000 which matches the Operation conditions for the most blade sections. Afterwards the new lift to drag ratio from the new airfoil was calculated and checked whether it is high enough like from the SD2030b. Further if the lift coefficient had to reach above the value of 1.0 which is necessary to gain the needed aerodynamic performance according to the benchmark of SD2030b. After several iterations a good aerodynamic performing airfoil shape was designed with a maximum thickness t/c of 0.13 which is presented in Fig. 2. Here shall be mentioned that first other low Reynolds airfoils (SG6042, FX63-137, E387, A25, Goe602, ClarkY, SD7003) were tested as well, but none of them showed the required lift and lift to drag ratio at these low velocity conditions. In Fig. 3 the lift and drag coefficients determined by *XFoil* for Re = 30.000 and *Ncrit* = 7 of the original SD2030b and the modified SD2030TFAC1.5 are compared over a from ±60 °. This shows that the modified airfoil almost matches its thinner original and should be the perfect replacement for the new rotor blade. According to [18] the 3D stall correction for drag is not necessary and, applied for model conditions, the resulting drag coefficients with 3D correction showed very high deviation from the uncorrected values. Therefore the *XFoil* determined polars were only expanded to ± 180 degree AoA (= Angle of Attack))using *AirfoilPrep* from NREL and 3D correction was neglected.

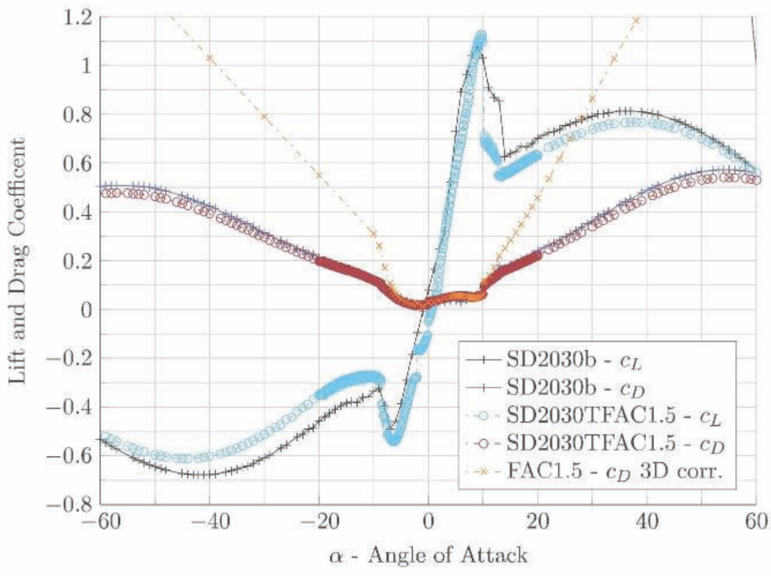

Figure 3: c_L and c_D coefficients of the original SD2030b airfoil, its modified version and the too high 3D corrected Cd values

b. Performance Scaled Blade

First a Simulation was carried out to test the new airfoil with the old chord and twist design of the study project. The results show potential but the thrust is quite poorer then with the unmodified SD2030b airfoil. The adjustment of chord and twist distribution was conducted by trying the designing according to Betz [19] and Schmitz [17]. Both theories enable to dimension wind turbines and deliver the chord length and twist angle for a rotor blade conditional to its radius. The input needed are the design TSR, the airfoil and its lift coefficient for the chosen optimal angle of attack α_D Both theories include axial discharge losses.

Betz chord length and twist angle is defined by the following equations:

$$c_{Betz}(r) = 2 \cdot \pi \cdot R \cdot \frac{1}{z} \cdot \frac{8}{9 \cdot c_L} \cdot \frac{1}{TSR_D \cdot \sqrt{TSR_D^2 \cdot \left(\frac{r}{R}\right)^2 + \frac{4}{9}}} \quad (11)$$

$$\alpha_{i,Betz}(r) = \arctan\left(\frac{2}{3} \cdot \frac{R}{r \cdot TSR_D}\right) - \alpha_D(r) \quad (12)$$

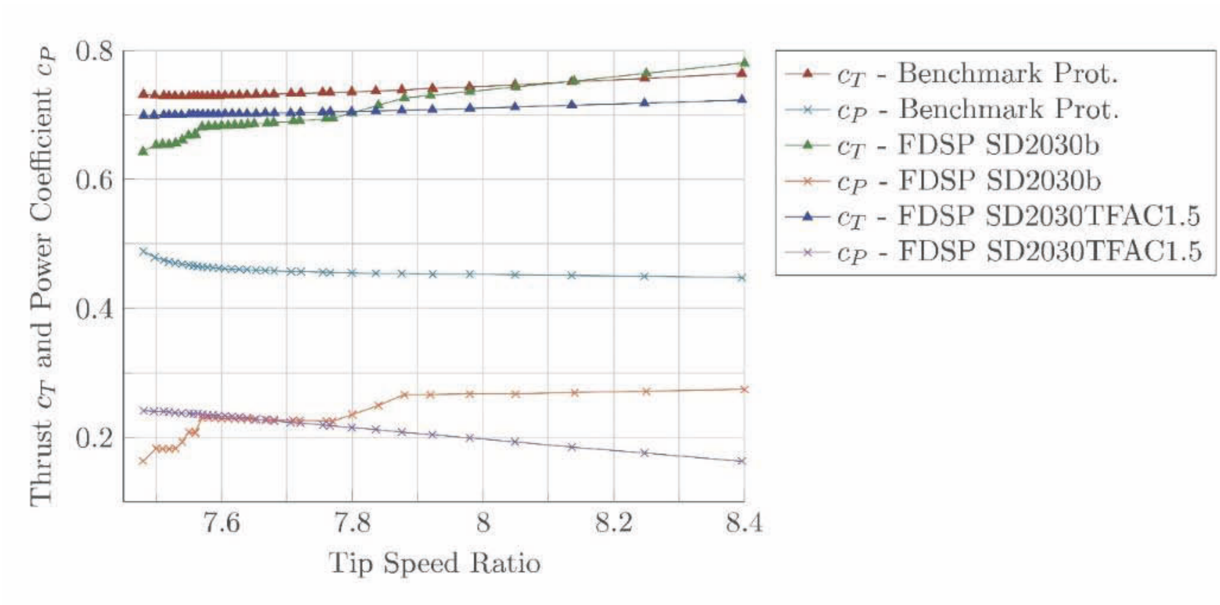

Figure 4: c_P and c_T prototype and final design SP with new and old airfoil SD2030b and SD2030TFAC1.5 (at modified operation conditions without pitching)

With TSR_D higher than 3 the 11 can be simplified according to [20]:

$$c_{Betz}(r) = 2 \cdot \pi \cdot R \cdot \frac{1}{z} \cdot \frac{8}{9 \cdot c_L} \cdot \frac{1}{TSR_D^2 \cdot \left(\frac{r}{R}\right)} \quad (13)$$

Schmitz blade design theory additionally contains swirl losses in the turbine outflow [20] and are defined by:

$$c_{Schmitz}(r) = \frac{1}{z} \cdot \frac{16 \cdot \pi}{c_L} \cdot r \cdot sin^2\left(\frac{1}{3} \cdot \frac{R}{TSR_D \cdot r}\right) \quad (14)$$

$$\alpha_{i,Schmitz}(r) = \frac{2}{3} \cdot \arctan\left(\frac{R}{TSR_D \cdot r}\right) - \alpha_D(r) \quad (15)$$

Both calculations show relatively good results while the designing after Schmitz matches the aimed benchmark of the prototype a little better and also considers the tip flow deprivation. The thrust force graphics of the simulated model rotor are just a bit lower than the prototypes. For an almost exact match the chord-length was increased with 5 mm for all blade sections and thereafter the thrust coefficients matched the benchmark very good as presented in fig. 7.

With this design the intended aerodynamic resemblance between the prototype in full scale and the scaled rotor was achieved. The power coefficient differs clearly from the benchmark. However this was not the main goal of the blade design as the thrust is most important for replicating the dynamic behavior of a floating offshore wind turbines.

Later the new performance scaled rotor blade was simulated with the original operation conditions with applied pitching. The comparison with the prototype benchmark is shown in fig. 8 to 9. The deviation between the c_P benchmark and the c_P performance scaled blade is very low as expected from the results with the modified Operation conditions. The power coefficient of the Schmitz adjusted blade design does not reach the prototype benchmark. For low TSR up to 6.5 they match quite good but with further raising TSR the deviation becomes bigger. Comparing the thrust forces in Fig. 10 for both operation conditions shows clearly that for the modified Operation points the match is perfect while on original conditions the force curves separate when pitching Starts.

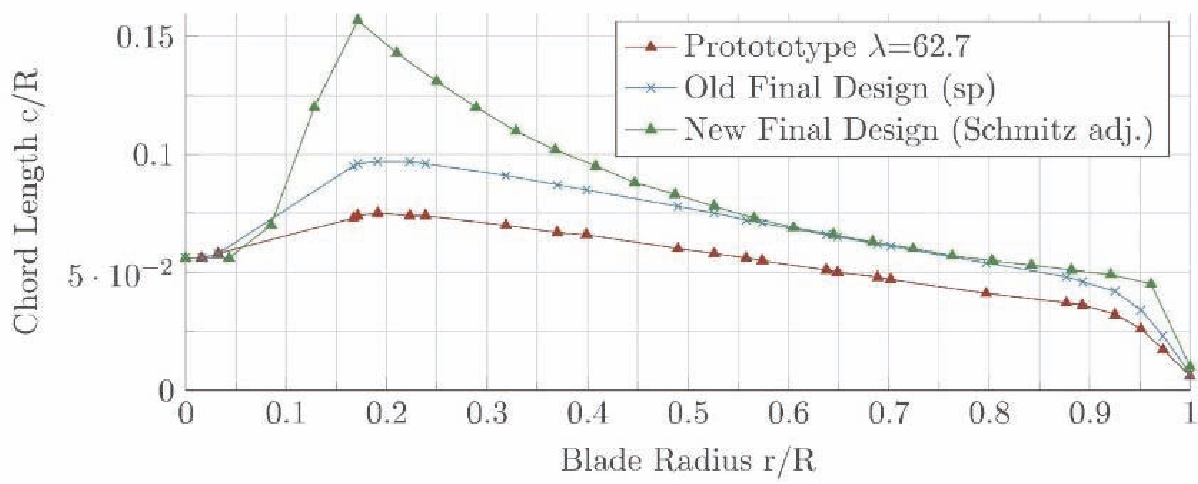

Figure 5: Chord distribution of the prototype blade, the old final design from the previous study project and the new blade with Schmitz adj. design

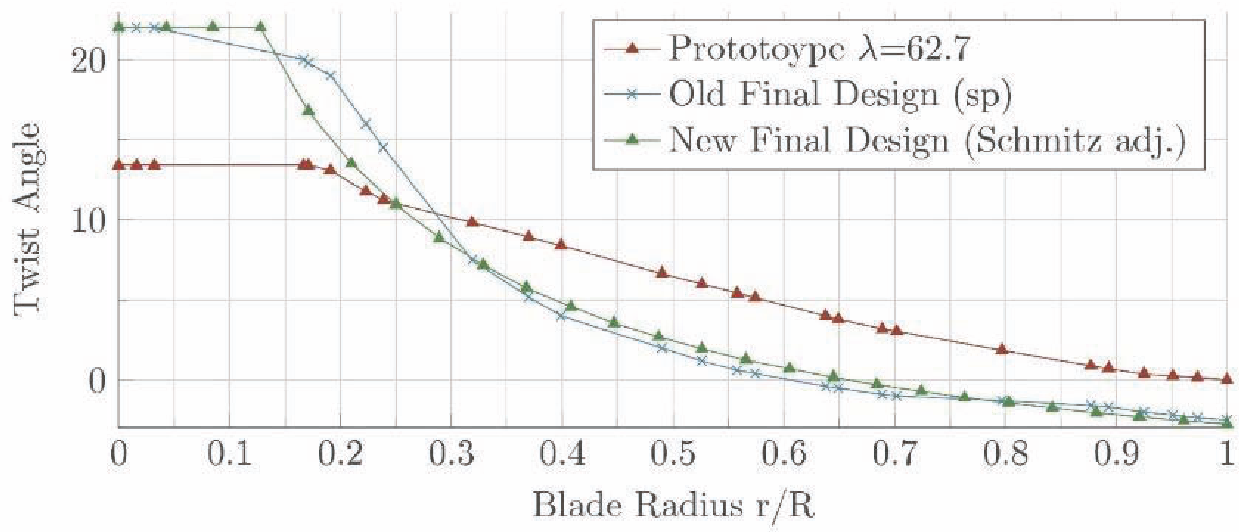

Figure 6: Twist distribution of the prototype blade, the old final design from the previous study project and the new blade with Schmitz adj. design

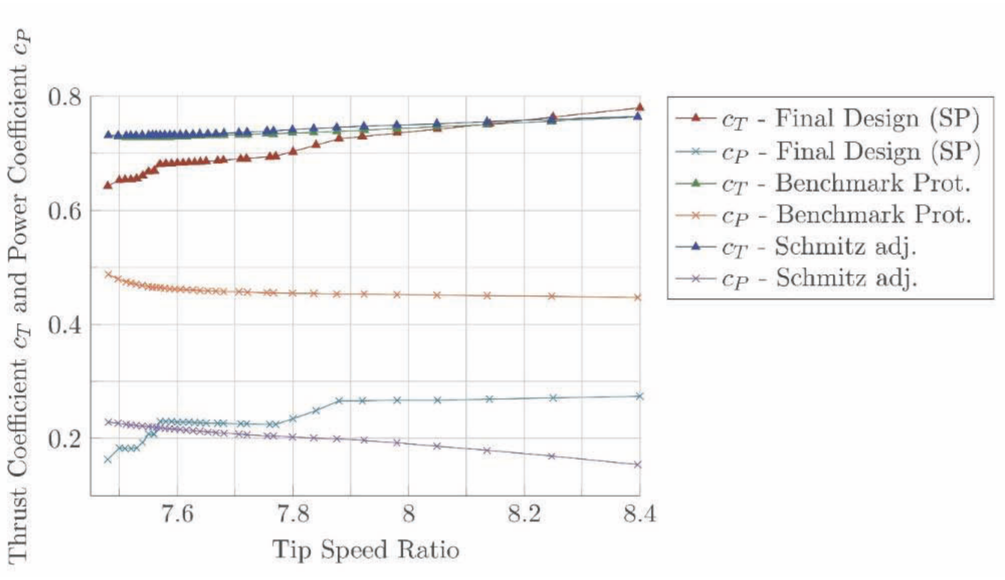

Figure 7: c_P and c_T full scale prototype and final performanc- scaled rotor blade (MOC = modified operation conditions without pitching)

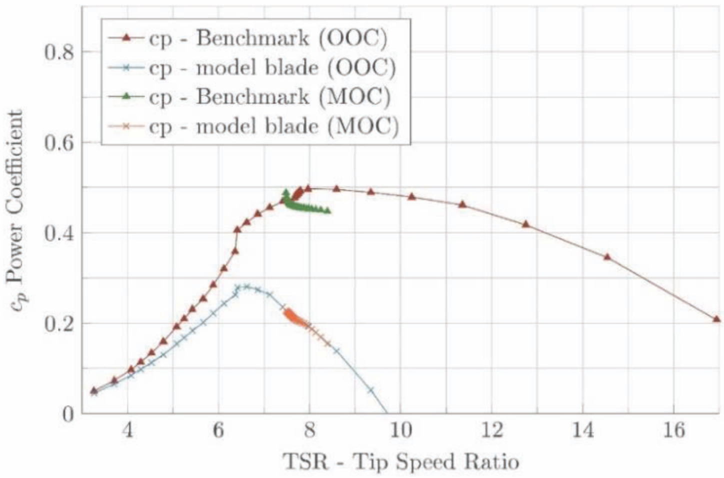

Figure 8: Thrust coefficient full scale prototype and final performance-scaled rotor blade

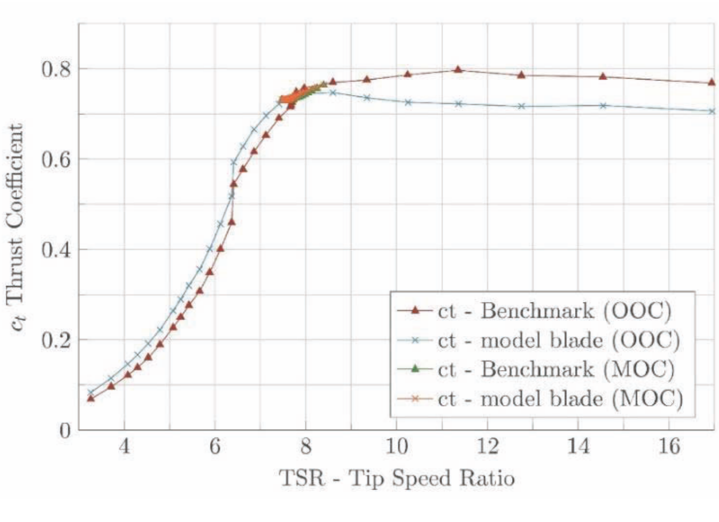

Figure 9: c_P power coefficient full scale prototype and final performance-scaled rotor blade

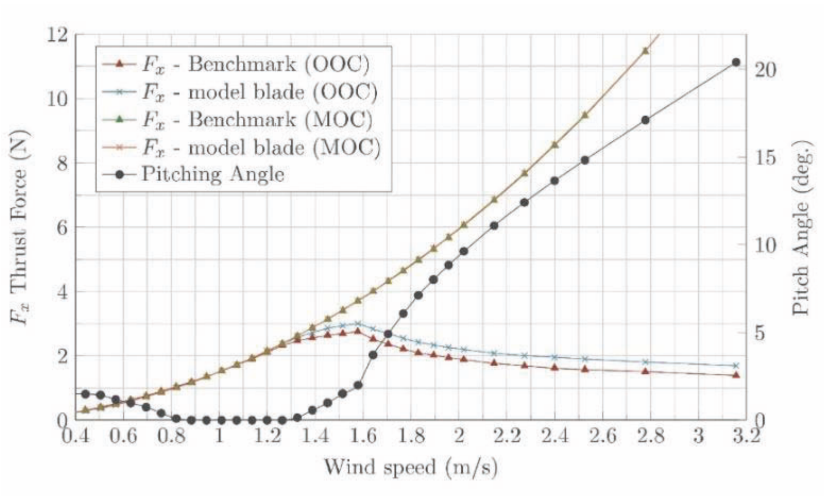

Figure 10: Thrust force F_X full scale prototype and final performance scaled rotor blade (OOC = original operation conditions with pitching; MOC = modified operation conditions without pitching)

4. Wind Tunnel Experiments

For a validation of the simulated rotor blade physical tests are necessary. The best Option would have been to build the complete rotor with three of the performance scaled rotor blades and put it into a wind tunnel. Unfortunately most available wind tunnels are too small for a 2 m diameter rotor. Using a bigger scaling factor to reach the needed dimensions for a full rotor test in a wind tunnel would lead to very small wind flow velocities which are not achievable without low turbulence and height quality flow.

The physical tests shall be executed at the low velocity wind tunnel of the chair of ocean engineering (LMT) at the University of Rostock. Its jet square measures 1.4 by 1.4 meter while the area of low turbulence and good flow quality is about 50 cm in each direction from the square center.

A model of the 1 to 62.7 scaled down rotor blade shall be put to the physical aerodynamic test in a wind tunnel. First the experiments had to be planned in Order to build a model that meets all the needs for the tests. The idea was to place the model in upright position in the center of the tunnel jet. With the blade rotatable about its span axis likewise as to pitching. Accordingly the model blade can be examined in different inflow angles and wind speeds. For a good coherence between this test and the Simulation of the spinning model rotor the wind velocities for the physical test are set in the same area as they are under the Froude-scaled operational conditions. A rotating rotor blade is exposed to different wind speeds over the rotor radius. The relative wind speed is increasing from the root to the blade tip. In the wind tunnel test this flow condition can’t be replicated for the fix upright mounted model blade. Consequently the wind tunnel test was simulated in *AeroDyn* with one fix upright standing blade. If the physical test in the wind tunnel meets the results of the Simulation under equal conditions this would present the indirect validation of the designed rotor blade and its Simulation results under scaled down operational conditions.

The scaled wind speeds are from 0.378 to 3.16 m/s while the relative wind speed over the blade radius, set together from the wind inflow speed and the flow component of the rotation, are from 0.42 to 10.8 m/s. A good coherent wind flow with acceptable turbulences can be achieved for minimum 5 m/s wind speed. Accordingly the tests were conducted with 6 different inflow speeds from 5 to 10 m/s in 1 m/s steps.

The other test variable is the pitching or inflow angle for the whole blade. They were set up to high values ±60 above the normal used inflow angles to have a good range of Operation conditions for comparison with the corresponding *AeroDyn* Simulation. Due to the fact that every blade section has another twist angle and the rotational flow component was missing most of the blade will not be operating in its aerodynamic flow condition that it was designed for. Never the less if the model blade was designed right the results to the physical test should be identical or near on the values to the computed one.

According to the main goal, of designing a Froude-scaled rotor blade model that matches the thrust and if possible the power coefficient of the full scale, the wind tunnel test is carried out to measure the normal forces on the blade model induced from the wind inflow. These are then compared to the likewise *AeroDyn* Simulation. The forces are measured by a 6 axis force balance. On this force balance an electric rotation device is mounted for the automatic adjustment of the model blade pitching angle. In order to get usable wind tunnel measurement results some basic points need to be reviewed and fulfilled. When it comes to wind tunnel testing the blockage ratio of the wind tunnel jet needs to be examined. The blockage ratio is calculated as the projected model area divided by the wind tunnels jet area:

$$BR = \frac{A_{model}}{A_{WT_{Jet}}} \tag{16}$$

The solid blockage effect is described as the flow speed increase due to the model surface area blockage in the tunnel area. This also causes an increase in dynamic pressure that again increases all forces and moments as described in [21]. Moreover the wake blockage effect also increases the dynamic pressure on the model due to lower wake pressure by which the wake size increases. These effects are especially to consider in wind tunnels with a closed experimental area. The tests in this work were conducted in a wind tunnel with an open experimental area, as in fig 17 shown. The blockage ratio caused by a 90 ° pitched model rotor blade is only 4.1 percent high and therefore its effect can be neglected.

Also important is the wind tunnels' flow quality represented by its degree of turbulence and the velocity distribution. The model blades are placed about 1.5 m behind the jet opening in the middle of its square area. As the according wind tunnel investigations show the turbulence grade increases the further away it gets from the middle of the tunnel square fig. 11. With a model of 1 m length the blade is just within range of acceptable turbulence. Above 500 mm from the tunnel square middle the grade becomes higher than 2 % and is therefore unsuitable for good experimental results. Small velocities with 10 m/s and under are not different over the tunnel square which is good for the planned test with the scaled rotor blade.

Furthermore sampling rate must be high enough to avoid data interpretation mistakes. For force measurement on airfoils and rotor blades the vortex shedding frequency is the number to consult. The vortex induces a feedback force with its detachment frequency back on the model. According to *Nyquist* the double height of this frequency is needed for recording its effects on the blade. The vortex shedding frequency is defined by the Strouhal-number Sr:

$$Sr = \frac{f \cdot L}{v} \tag{17}$$

with f = vortex shedding frequency, L the dimension of the overflowed object like the diameter of an cylinder and v the flow velocity. For Reynolds numbers from Re = 100 to 2x10E5 the Sr-number lies in a stable area and is about Sr = 0.2 [22]. The Reynolds numbers of the wind tunnel tests are within these boundaries so the vortex shedding frequency can be determined with equation 17. The maximal frequency f = 400 Hz is given at the blade tip where L = 0.005 m for a wind velocity of 10 m/s. The minimal is f = 18 Hz at 5 m/s on circular profile at the blade root with L = 0.0558 m. Accordingly a sampling rate of 1.200 Hz, which is the Standard sampling rate used in experiments at the LMT wind tunnel, is high enough to fulfil the *Nyquist* criteria for the wind tunnel tests at given parameters.

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Figure 11: Wind tunnel with model blade 1

For the wind tunnel tests the Reynolds-numbers were checked if they lie in the area for which the lift and drag coefficients of the airfoil were determined. With wind speeds and chord distribution given the Reynolds-numbers were calculated with 3 for all 6 velocities over 22 blade sections with different chord length. The highest and lowest are 104.211 and 3.698 for 10 m/s at the longest blade chord and at 5 m/s at near the blade tip. At two third rotor span the average Reynolds-number is 33.314 and therefore quite on spot for the calculated airfoil polars with Re = 30.000.

The wind tunnel of the chair of ocean engineering is a subsonic closed circuit Goettinger design. Its technical parameters are presented in table 3. The measurement area of the tunnel is open and with a 1.4 m square jet and a 2.8 m long measurement section relative big.

The forces induced on the model blades by the wind flow were measured with a 6 axis force balance presented in fig. 12 on the left. In y direction vertical to the wind inflow are two load cells mounted within the force balance. In wind direction one load cell is placed and in z direction three. They can be exchanged to meet required measurement sensitivities.

For data acquisition the *HBM* AB22A *MGCplus* measurement amplifier was used in Connection with the *CatmanEasy* v5.2.1 Software. Besides forces and moments on the balance, wind speed, air pressure, temperatures and other environmental and experimental data is recorded with in total 26 sensors.

Figure 12: Force balance and electric rotation device

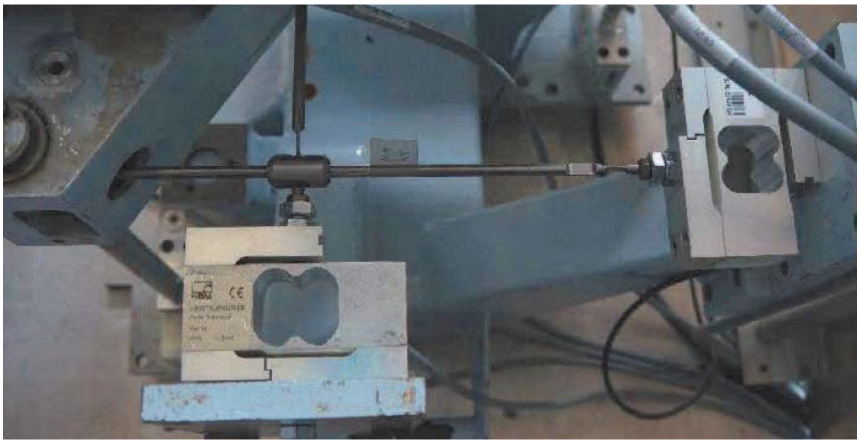

Figure 13: Load cells build-in the force balance

In order to have the force and moment values at the root of the model blade the measured data at the 6 axis force balance have to be calculated. Fortunately this was already implemented in the *CatmanEasy* Software. But the hub high of the rotor is missing in this calculation so it had to be revised. The normal forces F_x, F_y and F_z are not affected by that but the torque values are. In fig. 14 the static structure of the force balance is presented. The following equations are for the calculation of the forces and moments in the middle of the blade rood:

$$F_x = F_{xm} \tag{18}$$

$$F_y = -F_{y1m} - F_{y2m} \tag{19}$$

$$F_z = F_{z1m} + F_{z2m} + F_{z3m} \tag{20}$$

$$M_x = (F_{z1m} + F_{z2m}) * 0.1 - F_{z3m} * 0.2 + (F_{y1m} + F_{y2m}) * a \tag{21}$$

$$M_y = -F_{xm} * a + (F_{z1m} - F_{z2m}) * 0.2 \tag{22}$$

$$M_z = \left(F_{y1m} - F_{y2m}\right) * 0.2 \tag{23}$$

The quality of measured data can be rated with the Standard deviation from the single measurement and from the arithmetic average. Measurements with only statistic errors have a frequency distribution in shape of the bell curve around the actual value. Normally the average values are presented with their Standard deviation like F_y — 11 ± 0,04 N for example.

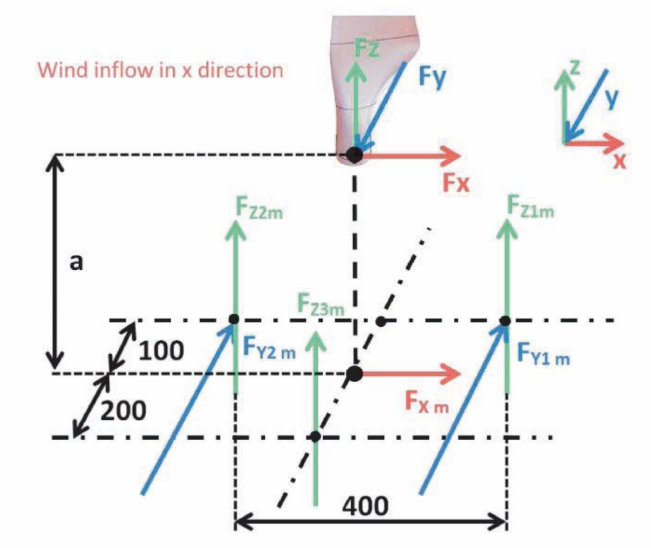

Figure 14: Sketch of the 6 axis force balance with axis to the blade root for calculation of forces and torques at the blade root or rotor hub center

5. Results of Wind Tunnel Tests

All tests conducted in the wind tunnel were also simulated in *AeroDyn* with according Operation conditions. Therefore the number of blades was reduced to one and the Operation conditions were adjusted equal to the planned experiments. On the day of the tests the average air temperature in the tunnel was about 25 °C. Consequently the environmental conditions 4 in *AeroDyn* were examined. A direct comparison between 25 °C and 0 °C, at which all previous simulations were computed, is presented in fig 15. The forces from the run at 25 °C are lower compared to the Simulation at 0°C. Due to the lower air density at higher temperatures there are less air particles per second that flow around the blade. Therefore the forces induced from the airflow on the rotor blade decline as showed. So far the simulated physics met the real. The average error for a 25 °C difference in F_x is 0.073 N and in F_y 0.103 N. This is not high but had to be included. Therefore all simulations of the wind tunnel tests were performed at environmental conditions of 25 °C.

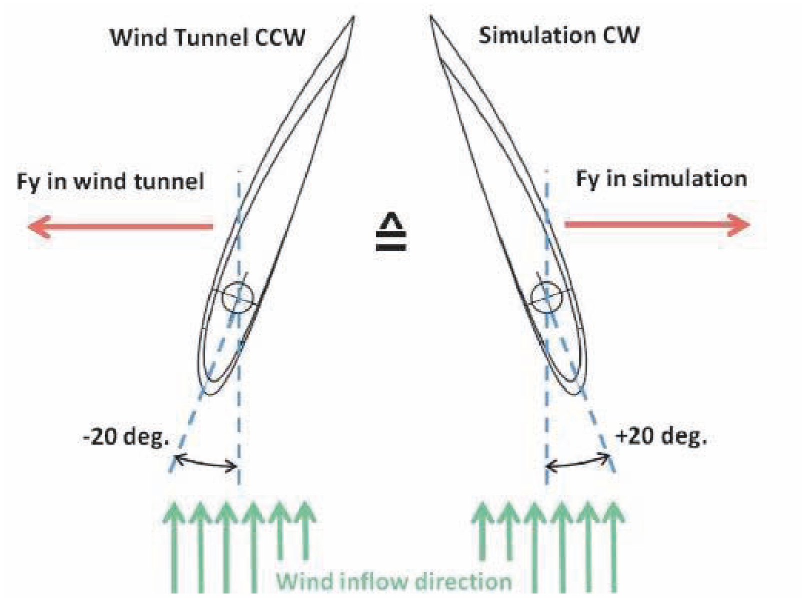

Figure 15: Wind inflow conditions in wind tunnel and Simulation

In the CAD design process a mistake was made concerning the building direction of the airfoils what accordingly lead to a wrong counter clock wise rotation direction. Unfortunately this was discovered late in the manufacturing process when blade two was already laminated. Certainly this inconsistency to the original blade and the computed Simulation has been overcome by mirroring the regarding parameters in the evaluation of the wind tunnel test results. Conversion equation for F_y from the wind tunnel results with AoA = Angle of Attack for the whole blade:

$$-F_{YWT}(-A_oA) = F_{YSim}(+A_oA) \tag{24}$$

6. Results and Conclusion

The purpose of this work is to present an applicable scaling and modification technique for wind turbine rotor blades with relatively high applied scaling factors of about 1:50 and 1:100. For the wind tunnel test a scaling of 1:62.7 was chosen allowing to use the maximal available airflow area and to work within the expected range.

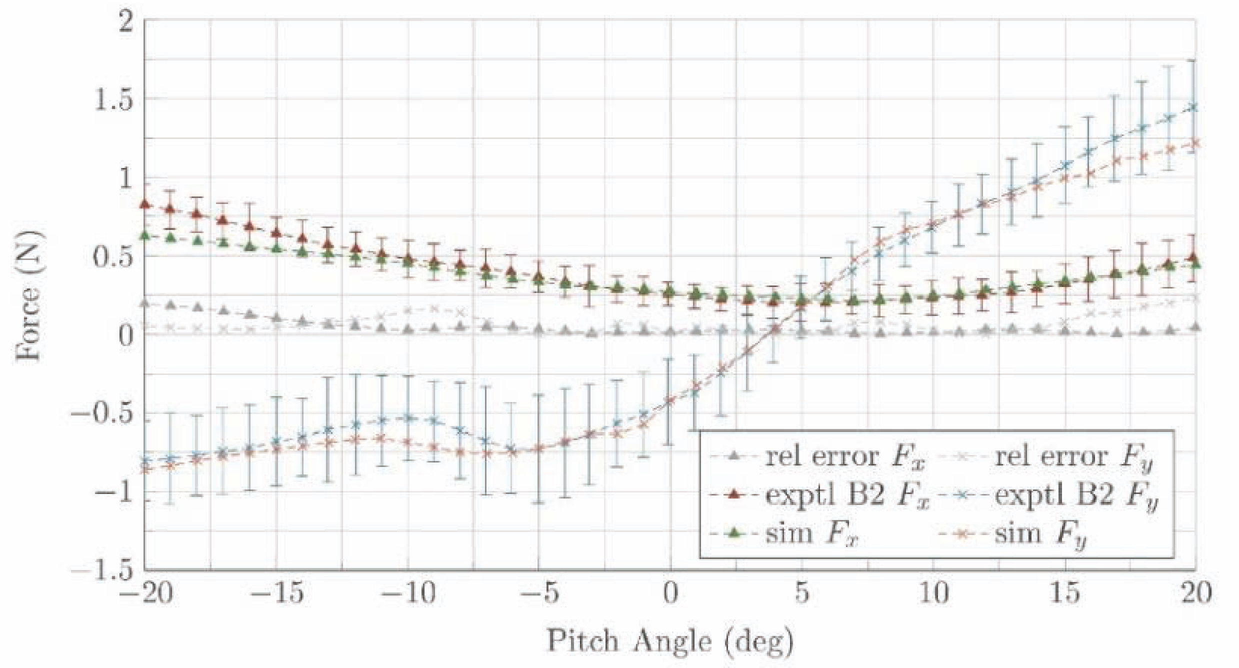

Figure 16: Simulation and wind tunnel test model blade 2 AT 7 mps, thrust force Fx , lift or downforce Fy , (UAcutoff 10 deg,, 25 °C)

Moreover in the interesting area of pitching angles between about ± 20 degree the forces are in good accordance between calculations and measurements. Figure 16 shows the applied pitch angles in the original operation conditions. For the presented range the forces of the conducted tests are in good agreement with the model. Therefore the Schmitz adjusted performance-scaled rotor blade and its *AeroDyn* Simulation can be considered as being validated within the interesting pitching range by the physical test .

A cause for the differences in thrust could be that the polar data were determined with *XFoil*. It is well known that this code is not perfectly accurate, especially for low Reynolds number conditions, as described in Section 1.4. However, as the test results for low pitch angles and therefore low angles of attack and furthermore the F_y results support well the simulations and are in good accordance even for higher angles the possible errors in the polar data cannot be significant. Rather, the missing 3D stall correction (after Selig's and Eggers) for these *XFoil* polars might be the cause of deviations in F_x. It is well known according to the research from [18] that more refined corrections are very complex and CFD computations may be required. Such work will be carried out in the future and should allow to check the applied lift and drag coefficients. It may also be worthwile to note, that the thrust deviation occurs for all tested wind speeds on both blades. This could indicate a systematic error in the wind tunnel measurements. The calibration measurements before and after the test run with each blade showed a light deviation in F_x of about 0.15 N. We conclude that this cannot be the cause for the deviations at high thrust forces with large pitching angles. Here also one has to await future CFD results for determining whether the cause lies in measurement errors in the wind tunnel experiments. A possible improvement of the *AeroDyn* simulation might be possible if the lift and drag coefficients calculated with *XFoil* for the modified airfoil SD2030TFAC1.5 could be validated with CFD. Furthermore, it should be noted that the Reynolds-numbers from blade root to blade tip increase from about 5k to 100k. Therefore it would be advantageous to use specific polar data for the different blade sections along the blade radius which are calculated for the main operation point of the rotor. In future, as mentioned, the polar data which are currently determined with *XFoil* are planned to be calculated with CFD and moreover the *AeroDyn* simulation of the scaled original operation conditions and the wind tunnel tests should be recalculated with CFD as well.

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DECOMMISSIONING OF NUCLEAR FACILITIES

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Abstract

KIT[1] researchers are strongly involved in German decommissioning working groups (e.g. within German Nuclear Society (KTG), Association of German Engineers (VDI)), in the international decommissioning network (IDN) of the IAEA, and are actively engaged i.e. in the organization of international workshops. Additionally, KIT coordinates the newly founded Decommissioning Competence Cluster, strongly supported by the state of Baden-Württemberg, in which various partners from the region are actively involved.

The KIT research aims are to standardize decommissioning procedures, to increase efficiency, to further minimize radioactive waste amounts, to reduce radiation exposure rates to staff, and to design autonomous and/or remote-operated decontamination techniques, which can be used in highly contaminated areas.

The standardization of the entire decommissioning process allows for an automation which reduces staff deployment and thus occupational radiation exposure. In the management field, the research aims to improve and optimize the whole process from procurement, awarding the tender, execution of decommissioning until the final disposal of radioactive material. One example in this respect is the implementation of the lean management principles to the decommissioning of nuclear facilities.

In the technology field, the research team develops new practical technologies and improves and automates the existing tools, machines and technologies for the decommissioning of nuclear facilities. The main objectives in this area are to minimize the nuclear radiation which endangers the staff working at nuclear facilities and to achieve an environmentally friendly and effective decommissioning process. Current research projects from different disciplines like the measurement, ablation and decontamination techniques and the treatment and reduction of radioactive waste will be described to give an overview on the activities of TMRK. In the measurement technique the project “MAFRO” aims to develop a comprehensive system for the remote-controlled measurement of radioactive contaminated surfaces while the project “MerEN” aims to develop a monitoring system with integrated measuring sensors for radioactive ferrous and non-ferrous scrap metal. In the ablation technique, the goal of both Projects “AMANDA” and later “MANOLA” was to develop an autonomously climbing manipulator for the ablation of contaminated surfaces like walls and ceilings. The two projects “DePRoV” and “SimViDekont” will be presented within the paper as examples of decontamination techniques introducing a new technology for decontamination of tubings with the aim of avoiding secondary waste. Furthermore, the project “NENAWAS” deals with the treatment and reduction of secondary waste produced during decommissioning of the reactor pressure vessel and its build-in components. All those activities take place in close cooperation with industry and with research and education partners.

[1] The Karlsruhe Institute of Technology (KIT) was founded within the German excellence initiative program in 2009 by a merger between the large-scale research institution of the Helmholtz Association and the University of the State of Baden-Wuerttemberg. The world’s first professorship for Technology and Management for the Decommissioning of Nuclear Facilities (TMRK) was established in June 2008 at the KIT. This professorship is part of the Institute of Technology and Management in Construction (TMB) and is headed by Prof. Dr.-Ing. Sascha Gentes.

1. Introduction

Over 115 commercial power reactors, 48 experimental or prototype reactors, over 250 research reactors and several fuel cycle facilities have been retired from operation worldwide. Some of these have already been fully dismantled [1]. Most parts of a nuclear power plant do not become radioactive during their operational lifetime, or are contaminated at only very low levels. Most of the metal can be recycled. Already today, proven techniques and equipment are available for dismantling nuclear facilities safely and these have been well demonstrated in several parts of the world. On the other hand, decommissioning costs for nuclear power plants, including disposal of associated wastes, are high relative to other industrial plants but can be reduced, and contribute only a small fraction of the total cost of electricity generation.

Generally speaking, early nuclear plants were designed for a life of about 30 years, though with refurbishment, some have proved capable of continuing well beyond this. Newer plants are designed for a 40 to 60 year operating life. At the end of its life of any power plant needs to be decommissioned, cleaned up and demolished so that the site is made available for other uses.

For nuclear plants, the term decommissioning includes all clean-up of radioactivity and progressive dismantling of the plant. This may start with the owner's decision to write it off or declare that it is permanently removed from operation.

1.1. Decommissioning options for nuclear plants

The International Atomic Energy Agency (IAEA) has defined three options [2] for decommissioning, the definitions of which have been internationally adopted:

- Immediate Dismantling (or Early Site Release/'Decon' in the USA[2]): This option allows for the facility to be removed from regulatory control relatively soon after shutdown or termination of regulated activities. Final dismantling or decontamination activities can begin within a few months or years, depending on the facility. Following removal from regulatory control, the site is then available for re-use.
- Safe Enclosure ('Safstor') or deferred dismantling: This option postpones the final removal of controls for a longer period, usually in the order of 40 to 60 years. The facility is placed into a safe storage configuration until the eventual dismantling and decontamination activities occur after residual radioactivity has decayed. There is a risk in this case of regulatory change which could increase costs unpredictably.
- Entombment (or 'Entomb'): This option entails placing the facility into a condition that will allow the remaining on-site radioactive material to remain on-site without ever removing it totally. This option usually involves reducing the size of the area where the radioactive material is located and then encasing the facility in a long-lived structure such as concrete, that will last for a period of time to ensure the remaining radioactivity is no longer of concern.

Each approach has its benefits and disadvantages. National policy determines which approach or combination of approaches is adopted or allowed. In the case of immediate dismantling (or early site release), responsibility for completion of decommissioning is not transferred to future generations. The experience and skills of operating staff can also be utilised during the decommissioning programme, which may be undertaken by the utility or handed over to a specialist company, with transfer of licence and accumulated funds. Alternatively, Safe

[2] DECON: a method of decommissioning, in which structures, systems, and components that contain radioactive contamination are removed from a site and safely disposed at a commercially operated low-level waste disposal facility, or decontaminated to a level that permits the site to be released for unrestricted use shortly after it ceases operation.

Enclosure (or Safstor) allows significant reduction in residual radioactivity, thus reducing radiation hazard during the eventual dismantling. The expected improvements in mechanical techniques should also lead to a reduction in the hazard and also costs.

In the case of nuclear reactors, about 99% of the radioactivity is associated with the fuel which is removed following permanent shutdown. Apart from some surface contamination of the plant, the remaining radioactivity comes from "activation products" in steel which has long been exposed to neutron irradiation, notably the reactor pressure vessel. Stable atoms are changed into different isotopes such as iron-55, iron-59 and zinc-65. Several are highly radioactive, emitting gamma rays. However, their half-life is such (2.7 years, 45 days, 5.3 years, 245 days respectively) that after 50 years from closedown their radioactivity is much diminished and the occupational risk to workers largely gone.

1.2 Decommissioning experience in Germany

Eleven of Germany's 19 shutdown units are subject to immediate dismantling. At the Lubmin (Greifswald) nuclear power station in the former East Germany, where five reactors had been operating, immediate dismantling was chosen. Similarly, the site of the 100 MWe Niederaichbach nuclear power plant in Bavaria was declared fit for unrestricted agricultural use in mid-1995. The 15 MWe Kahl experimental BWR (Boiling Water Reactor) was shut down in 1985 following 25 years of operation. After decontamination, the plant was completely dismantled and the site was cleared for unrestricted use. The 250 MWe Gundremmingen A unit was Germany's first commercial nuclear reactor, operating 1966-77. Decommissioning work started in 1983, and progressed to the more contaminated parts in 1990 using underwater cutting techniques. This project demonstrated that decommissioning could be undertaken safely and economically without long delays, allowing for recycling of most of the metal. Most of the eight German units shut down in March 2011 after the Fukushima accident will be dismantled within about 15 years.

1.3 Legal aspects of decommissioning in Germany [3]

The relevant German legal system is embedded in the comprehensive context of legislation of the European Union. It is also in accordance with the safety standards of the International Atomic Energy Agency (IAEA) and the recommendations of the International Commission on Radiological Protection (ICRP). All aspects of the peaceful use of nuclear energy are regulated in the Atomic Energy Act (AtG), which also includes the basic legal conditions for the decommissioning of nuclear facilities. The Atomic Energy Act (§ 7 AtG) stipulates that a licence is required for the decommissioning of nuclear facilities. The licence is granted by the federal state authority.

Ordinances based on the Atomic Energy Act, such as the Radiation Protection Ordinance (StrlSchV) and the Nuclear Licensing Procedure Ordinance (AtVfV), contain essential regulations for the decommissioning of nuclear facilities. The Radiation Protection Ordinance (StrlSchV), among others, provides limitations for occupational exposure. Furthermore, the release of radioactive materials from nuclear regulatory control arising in the process of facility decommissioning is regulated in the Radiation Protection Ordinance (StrlSchV).

The Nuclear Licensing Procedure Ordinance (AtVfV) adresses the course of the licensing process. This includes, among others, provisions on application documents to be submitted, the involvement of third parties, and the public hearing.

The German law, enforcing IAEA's 1997 Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management came into force in Germany on 18th June 2000. The decommissioning of nuclear facilities, however, is only part of this convention.

Also applicable to the decommissioning of nuclear facilities is the Environmental Impact Assessment Act (UVPG). It stipulates requirements relevant to the procedures, the contents, and the public involvement in connection with the environmental impact assessment. The legal framework is substantiated by sublegal rules and regulations. The latter are relevant for the decommissioning of nuclear facilities and includes rules of the Nuclear Safety Standards Commission (KTA), regulation of authorities, and technical specifications.

In particular the Decommissioning Guide is relevant to the decommissioning of nuclear facilities licensed in accordance with § 7 of the Atomic Energy Act. It is also part of the sublegal framework which was elaborated by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) within the Federal State Committee for Nuclear Energy with the Decommissioning Working Committee of the Reactor Safety Technical Committee. This decommissioning guideline identifies the provisions relevant to decommissioning which are scattered across various sublegal documents and describes their application. It also includes proposals for a practical approach to the decommissioning of nuclear facilities and it serves to harmonise the licensing procedures.

Storage of nuclear fuels is subject to strict safety requirements. Nuclear fuels may only be stored once a storage licence pursuant to § 6 Atomic Energy Act (AtG) has been granted or when they are used in an installation licensed pursuant to § 7 AtG, e.g. a nuclear power plant. To protect the population, the state takes care for the safekeeping of these materials if such a licence has not been granted. This could occur, if, for example, nuclear fuels were to be found or secured at border controls.

The responsible authority for the federal custody pursuant to § 5 Atomic Energy Act is the Federal Office for the Safety of Nuclear Waste Management (BfE). It has taken up this task on 30. July 2016 from the Federal Office for Radiation Protection (BfS) that had been responsible until then. In order to be prepared for responding in the event of an emergency, storage located are rented in the intermediate storage faciltiy (Zwischenlager) Nord near Lubmin where it would be possible to store smaller volumes of nuclear fuels. This is a precautionary measure for protecting the population.

As an exception, federal custody could also become necessary if an existing licence expired and there was no other option for legal storage, e.g. a supervisory order pursuant to § 19 para. 3 sentence 2 AtG. In this case, larger volumes of nuclear fuels would be taken over initially at their previously licensed storage place. The Federal Office for the Safety of Nuclear Waste Management would then have to take all measures for guaranteeing safety in compliance with the state of the art of science and technology.

1.4 Decommissioning strategies

Two decommissioning strategies have been and are being applied in Germany [4]:

- Direct dismantling: With this strategy, a nuclear power plant is dismantled directly after it is permanently shut down, for example all parts of the facility are removed and the natural state is restored in the form of a so-called greenfield site, or the facility is still used once it is no longer subject to monitoring under nuclear legislation (subsequent industrial use). Experience shows that this process lasts several years; in the case of dismantling a nuclear power plant at least a decade. Once dismantling has been completed, a storage site for radioactive waste or spent fuel elements can be retained until these are transported to a disposal site.

- Safe enclosure: With this strategy, a nuclear power plant is put in a secure, low maintenance state after it has been completely shut down. It is then only dismantled after a period of safe enclosure, for example 30 years. The safe enclosure strategy has rarely been used in Germany so far, and at present there are no plans to use it for any of the plants to be decommissioned.

1.5 Dismantling a nuclear power plant

Nuclear power plants are dismantled in several stages, which generally require also several decommissioning and dismantling licences under nuclear legislation. Before dismantling begins, the plant is still in almost the same technical state as during operation. During this phase between final shutdown and issuing the first licence for decommissioning, measures are taken in preparation of dismantling, for example drawing up a detailed overview of the plant's radioactive inventory using measurements and samples, removing fire loads and operational waste and drawing up the application documentation for the first decommissioning licence.

The dismantling of plant components generally starts with the areas of low contamination, then moves on to areas with higher contamination ("from the outside to the inside"). Broadly speaking, the dismantling of a nuclear power plant proceeds as follows:

- Stage 1: Dismantling of components of the plant no longer required for remaining operation and removal of the spent fuel elements as soon as possible
- Stage 2: Dismantling of components with higher radioactivity, for example the reactor pressure vessel and the biological shield
- Stage 3: Decontamination of buildings and removal of the entire facility (buildings and site) from supervision under the scope of application of nuclear and radiation legislation
- Stage 4: Conventional demolition or re-use of the building.

1.6 Technologies for dismantling and compliance with regulations

For proper execution of decommissioning, it is important to use mature, reliable technologies that satisfy the requirements of safety, radiation protection and swift project implementation. Technologies are required for various processes: decontamination, dismantling and disassembling, activity measurements and waste conditioning.

The following criteria apply when selecting individual technologies:

- radiation protection aspects, with the goal of keeping the radiation exposure of staff to a minimum
- suitability and effectiveness of the process
- the most comprehensive possible clearance of residual substances and plant parts
- reducing the volume of radioactive waste and space-related aspects.

The selection and application of technologies is licensed and supervised by the competent Land authority. Technical experts support the authorities in this process.

The Atomic Energy Act and its related ordinances primarily provide the legal framework for decommissioning nuclear power plants. In order for a plant to be decommissioned and dismantled, the operator must apply for a licence. The licensing procedure for the first decommissioning is subject to an environmental impact assessment. For this reason, the application for issuance of the first licence has to outline the overall decommissioning concept and its potential impacts on man and the environment. Subsequent stages of licensing cover the technical implementation of the dismantling measures. In the federal system of Germany the competent licensing authority of the Land where the site is located carries out the licensing procedure.

The competent supervisory authority of the Land monitors the compliance with the decommissioning licence. It reviews whether the decommissioning activities satisfy the conditions and obligations specified in the licence. Independent authorised experts carry out supplementary checks on behalf of the Land supervisory authority.

In the framework of the distribution of responsibilities between the German Federation and the Länder laid down in the Basic Law, the Federation is responsible for structuring the framework applicable to decommissioning (Atomic Energy Act, Radiation Protection Ordinance, notifications by the Federal Environment Ministry such as the decommissioning guide, and recommendations and guidelines from the Nuclear Waste Management Commission, et cetera). The Federation is also in charge of supervising the administrative actions of the Länder authorities, and of supervision relating to the legality and expediency of implementation. It works in close relationship with the Länder, both in bodies that include representatives of all Länder and bilaterally with individual Länder.

During the process of decommissioning the hazard potential of a nuclear power plant lies in the kind and the amount of radioactive inventory which could be partially released during an incident. Removing the fuel elements of a nuclear power plant reduces the activity inventory to around one ten-thousandth of the original level, thus significantly lowering the hazard potential.

A range of technical and administrative measures ensure protection for operating staff, the population and the environment against inadmissibly high radiation levels both during normal operation and in case of anomalies and incidents. These measures include:

- confinement of the radioactive inventory in systems and rooms in order to prevent release and spread
- shielding measures to reduce radiation exposure at the workplace
- individual protection measures for personnel, for example the requirement to wear special protective suits, gloves, overshoes and where necessary breathing masks
- training for plant personnel and external staff
- targeted ventilation at the plant and filtering waste air and treating waste water to minimise the volume of radioactive substances that are permitted to be released into the environment in a controlled way in accordance with the official licence.

There is also close monitoring of the technically unavoidable discharge of radionuclides via waste air and waste water. Limits for these discharges are laid down in the licences. In practice, levels fall far short of these limit values during both operation and decommissioning. Further safety aspects cover conventional occupational safety when dealing with chemicals, accident prevention, et cetera, which are relevant at every industrial installation.

2. KIT decommissioning activities

As mentioned before, techniques for decontaminating and dismantling of nuclear facilities are already available to a certain degree, however, much is still to be done [5]. In this sense, the professorship of technology and management for the decommissioning of nuclear facilities (TMRK) describes itself as an education and research institute with the aim of establishing a major study course focusing on the decommissioning of nuclear facilities. Furthermore, the focus is on creating a competence team in this field, improving current technologies and developing new ones, carrying out pilot projects, and retaining the competence within the field of technology and management of the decommissioning of nuclear facilities.

The scope of work of TMRK therefore includes several disciplines and the implemented research projects described in the following are only some examples of its activities in the field of dismantling and decontamination technology.

2.1 Examples from shaving and ablation technology

Decontamination is defined as the removal of contamination from surfaces of structures or equipment by washing, heating, chemical or electrochemical treatment, mechanical cleaning, or other techniques. When decontaminating concrete surfaces, mainly mechanical scarifying techniques such as needle scaling, scrabbling or shaving/milling are used [6]. The milling process has many advantages like high performance, high-precision treatment depths, low to middle noise emission and, in particular, the minimization of waste production. The main disadvantage of the milling process until now is that its use can only be applied within a big arrangement like a portal scaffolding system. All systems require a short-term stay of staff within the contaminated areas.

2.1.1 Project-AMANDA: Autonomous Manipulator for Decontamination Assignments

The innovative research project AMANDA was awarded the innovation prize in 2008 from the state of Rhineland-Palatinate for the development of a solution for the decontamination of large concrete wall or ceiling surfaces. The remote-controlled system is a climbing manipulator carrying a milling unit. The suction plates (vacuum system) hold the manipulator safely to the surface to be treated. The performance of AMANDA is between 6 to 8 m^2/h with controlled milling depths of 3 to 4 mm [7]. The system only needs one remote-operator.

2.1.2 Project-MANOLA: Manipulator Operated Laser Ablation

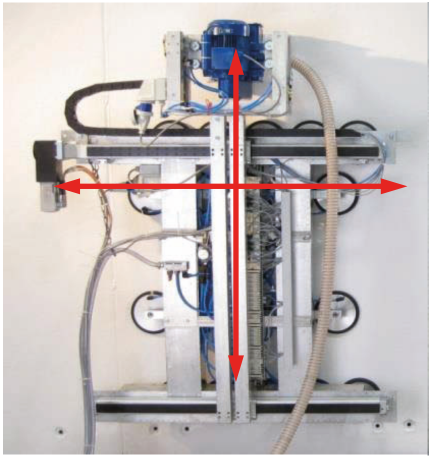
TMRK does not only aim at improving or developing new processes but also at continuously improving the newly developed systems. The research project MANOLA is a further development step of AMANDA, the latter having already shown the operability of integration between a decontamination process and the stand-alone support system. This new support system, however, has an even further enlarged degree of freedom, due to the capability of rotating about its own axis and the newly developed trolley system allowing a remote deployment. Furthermore the integrated unit for decontamination of concrete surfaces is carried out with a special developed laser unit for wall ablation instead of milling.

2.2 Examples from Measurement Technology

An efficient surface decontamination process requires knowledge about the degree of contamination resulting from the type of nuclear radiation and its energy spectrum received by the element to be treated. Being capable of measuring these values, the decontamination process can be gradually adapted to the on-site conditions. TMRK researchers therefore aim at integrating the measurement component directly into the decontamination system in order to achieve a high degree of autonomy within one system.

2.2.1 Project-MAFRO: Manipulator Operated release Measurement of Surfaces

The research project MAFRO is based on the results of MANOLA. It is jointly undertaken by the KIT-Institute for Process Control and Robotics (IPR) and the TMRK. MAFRO has already started with the end of 2011 and aims at creating an integrated system for the three main steps required for surface decontamination; i.e. radioactivity measurements of the components (Pre-Measurement Process), the decontamination process itself, and the release measurement (Post-Measurement Process). Since a complete system for measurement, decontamination, and final release does currently not exist, the target system will address this requirement. It contains three components, the manipulator as a support system with an additional transport system (trolley system), the laser device as a decontamination tool, and a detector head which is under development. The detector head will be implemented into the manipulator as a radioactivity measurement tool. Additionally, an integrated scanner will generate a model of the surroundings. This allows the manipulator to navigate autonomously and collision-free whereby, the documentation of the release measurement process should be comprehensive and accurate. Moreover, the whole process will be remote-controlled from a safe distance.



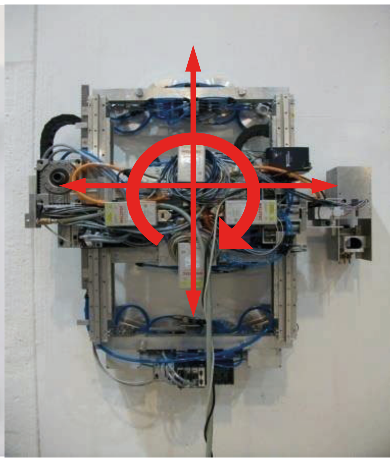


Fig 1: AMANDA *Fig. 2: MANOLA* *Fig. 3: Trolley System*

2.2.2 Project-MerEN: Monitoring System with integrated Measuring Sensors for Radioactive ferrous and non-ferrous Scrap Metal

The research project MerEN deals with radiation sources passed on without permission, abandoned, lost, misplaced or stolen and which are therefore called "orphan sources". Orphan sources may be encountered by an individual who is unaware of their risks. Such radioactive sources are frequently found in scrap yards and metal processing facilities and represent a threat to the people and to the environment. Thus a radiological monitoring of materials in these locations is becoming increasingly important.

As part of the research project MerEN a monitoring system with integrated measuring sensors for radioactive ferrous and non-ferrous scrap metal is to be developed. With such an equipment the operator of the scrap-metal sites would have the opportunity to detect radioactively contaminated material at an early stage, i.e. before a possible radioactive source has been crushed and mixed with non-radioactive material. Once a potential radioactive source is detected, the user would receive instructions on how to proceed. This can avoid contamination with regard to product purity and can significantly help to avoid occupational health and safety risks for the staff and the environment.

2.3 Examples of Decontamination and Waste Treatment

The TMRK doesn’t limit its research to the decommissioning of nuclear reactor facilities; the encompasses all sites where radioactive contamination exists. Examples are the treatment of inevitable secondary waste in the decommissioning of nuclear facilities, but also the decontamination of tubings from the petrol and gas industry.

2.3.1 Project- NENAWAS: Development of a New Treatment and Disposal Technique for the Elimination of Secondary Waste

During the decommissioning of a nuclear facility, the reactor pressure vessel and its build-in components have to be cut into small pieces to allow the final disposal in a nuclear repository. Due to the high radiation levels of these components, the applied cutting technique has to be performed submerged under water and to be controlled remotely. One of the cutting techniques which best suits these conditions is water abrasive suspension cutting, since it can be applied in very complicated and narrow geometries. Furthermore there is no direct contact to the cutting material which avoids reset forces and makes it impartial to material tension. The only major drawback of this technology is the generation of large amounts of secondary waste, due to the usage of the added abrasive.

With the NENAWAS project, new treatment and disposal techniques are being developed in order to eliminate the inevitable secondary waste. For this purpose, the resulting mixture of used abrasive and radioactive metal is in a first step separated by a newly developed separation system significantly reducing the amounts of contaminated waste. The remaining radioactive waste is in a second step subsequently disposed as part of the concrete used for stabilizing and shielding the cut parts in the so called KONRAD containers. The specific concrete mixture which allows the admixing of the remaining secondary waste is also being developed at KIT in cooperation with the Institute of Concrete Structures and Building Materials (IMB).

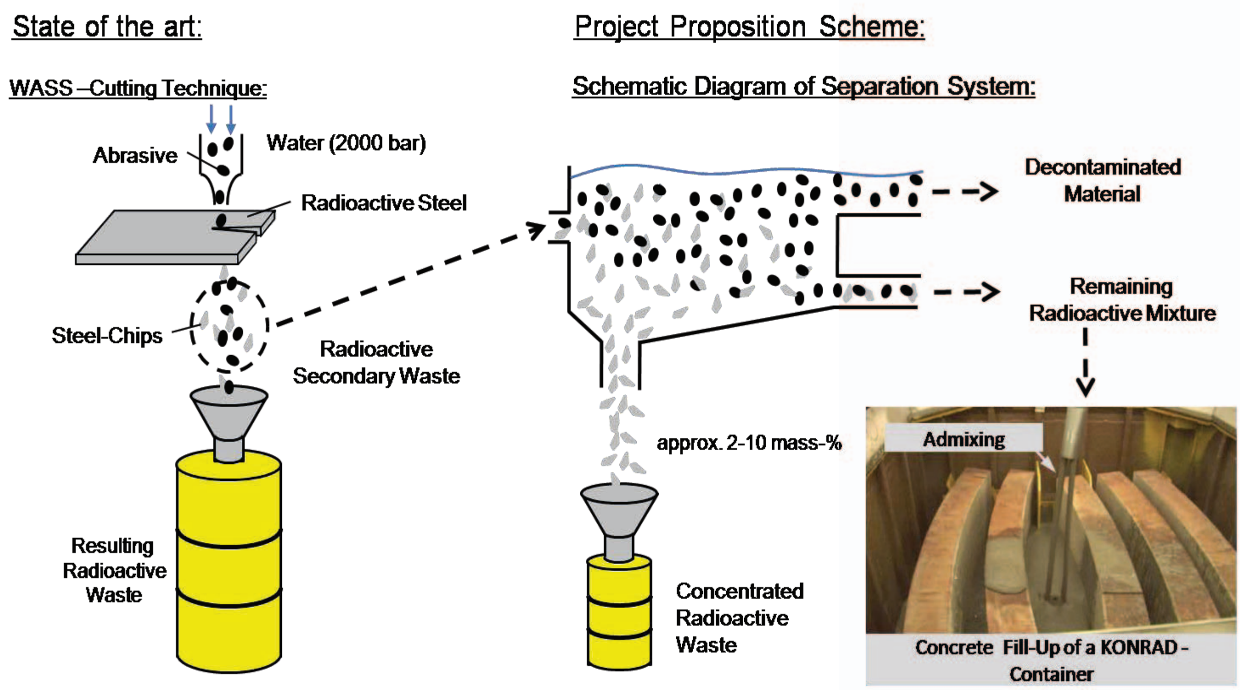


Fig 4. Sketch showing principle of NENAWAS [8]

2.3.2 Project-DePRoV: New Process for Decontamination of Tubings by means of Vibration Technology

In oil and gas production facilities technologically enhanced naturally occurring radioactive material (TENORM) is found in scales within tubings and must be removed. Currently used decontamination methods in this field are based on water-jet and abrasive blasting technology which produces a high amount of secondary waste [9]. The main goal of DePRoV was to develop a novel decontamination technology avoiding secondary waste. The characterization of the scales has shown that they are hard and brittle and can be removed only by applying a defined mechanical force to spall it. The chosen decontamination method is based on vibration resulting from a mechanical tool. A test stand has been built to investigate the decontamination process; meanwhile in order to enable experiments in comparable conditions, different types of deposits were formed inside the pipes. The next step was to evaluate the process describing relevant factors of influence, namely the hardness and thickness of the deposits, the tool's geometry, distance between the tool and the inner wall of the pipe, the rotation parameters (frequency and the imbalance mass of the vibrator), as well as feed rate.

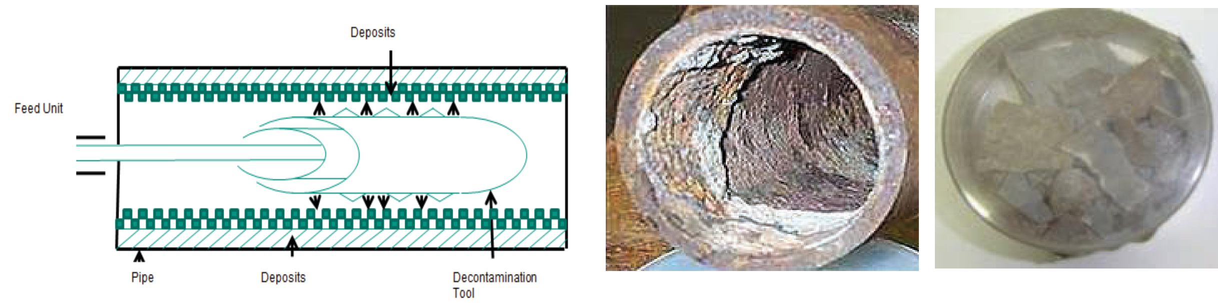


Fig 5. Sketch showing DePRoV principle (left), tubing (center),removed scales (right)

2.3.3 Project-SimViDekont: Create a Simulation Model to qualify the new Vibration Technology for the Decontamination of Tubings

The SimViDeKont research project is a cooperation between the Institute for Information management in Engineering (IMI) and the TMRK. It is a further development of the DePRoV project and aims at creating a simulation model to examine and to qualify the new vibration method for the decontamination of tubings. This model shall be validated through comparisons of test results in physical prototypes.

As mentioned above, the results of the DePRoV research project confirm the functioning principle of the vibration process for the decontamination of tubings, however, the finalization of an exact investigation was not yet possible. In order to carry out this validation within a suitable time frame and without any radiation hazard, new attempts have been investigated making use of modern simulation technologies which enable researchers to investigate complicated processes and procedures virtually as well as to examine its efficiently, adaptability and repeatability in an ecologically and environmentally safe manner.

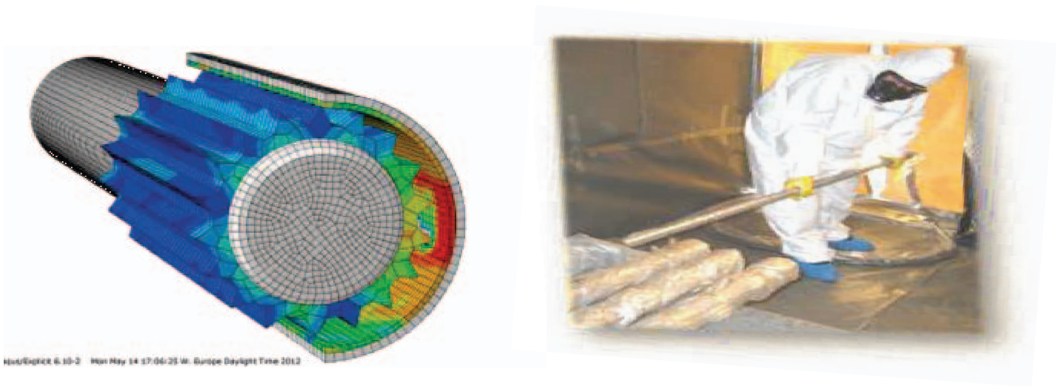


Fig5: Simulation of Vibration Process "SimViDekont Project"

3. Conclusion

This report gives a short survey of the current situation of nuclear decommissioning in Germany which demonstrates that the end of the use of nuclear power in Germany does not mean the end of research in this field. Besides being mandatory for further improving economic efficiency, speed and above all safety and environmental quality of the required conversion to green-field conditions, this research also provides the opportunity of developing a new field of technology and acquiring a cutting edge participation in a market with global proportions. The TMRK is well positioned in this regard and also engages in the transfer of the acquired knowhow to other fields of application such as the oil and gas industry.

With its two main policies, “Continual Improvement” and “Sharing Knowledge”, the TMRK invites all interested parties in education and research institutions, in industries and authorities to cooperate in this field aiming at achieving sustainability in terms of technology and management for the decommissioning of nuclear facilities.

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Towards an effective climate protection approach after Paris: A revised concept of economic environmental policy instruments

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1. Problem

According to the data of the Intergovernmental Panel on Climate Change, the limitation of global warming to 1.5 to 1.8 degrees (Art. 2 para. 1 Paris Agreement), which is binding under international law, can only be achieved if all emissions worldwide are reduced to zero within 10 to 20 years (see in detail Ekardt et al. 2018a). At the same time, the Convention on Biological Diversity (CBD) requires us to stop and reverse the loss of species. Germany and the EU are miles away from this. Economic instruments such as cap-and-trade systems, levies or changes to the subsidy system would be a particularly interesting means of making progress here, especially in the form of a reform of EU emissions trading (EU ETS).

Friends and opponents combine economic environmental policy instruments with certain basic views of neoclassical economics. This article wants to show that economic instruments are and remain the most effective - i.e. most goal-oriented - policy approach of transformation to sustainability, because they can successfully avoid threatening control problems and at the same time address many environmental problems in parallel even if key assumptions of (especially neoclassical) economics are not considered convincing. At the same time, a reform thrust for the EU ETS becomes clear, which should and could free itself from the mainstream of current discourses and which should also aim at (drastically) more ambitious reform approaches. In all of this, economic instruments or pricing always functions as a generic term for the types of instruments such as cap-and-trade schemes, levies, or subsidies, even if they differ in part in whether a price comes about directly as in the case of levies or indirectly as in the case of a cap and trade.[1]

2. Economic Instruments, Technology and Frugality

The common idea of economic instruments such as emissions trading is that they stimulate technical innovations and thus reconcile environmental protection with economic growth. However, it is doubtful whether environmental protection can be based on purely technological strategies. From the point of view of critics, this might seem to speak against relying on economic policy instruments in environmental protection. But economic instruments can also stimulate frugality, as will be shown below. These instruments are not as limited as friends and opponents seem to suggest.

Indeed, it is very doubtful whether purely technical options such as renewable energies and energy efficiency can achieve as far-reaching goals as described above in such a short time and whether options such as carbon capture and storage (CCS), secure use of nuclear energy or geoengineering will be available within the very short time frame established by Art. 2 para. 1 Paris Agreement – and what costs and possibly dramatic risks those “wonder

[1] Extensive references on all the questions dealt with in this article - and a much more detailed treatment of all points overall - can be found in Ekardt 2018; Ekardt 2019; Ekardt et al. 2018a, 2018b; those other references are not included here for space reasons.

technologies" would trigger is still subject to special doubts. Ultimately, the challenge (= zero emissions in only a couple of years; not by 2050 or 2100) for the purely technical route is probably too great. It should also be borne in mind that the problem of relocating emissions, land use, etc. to other countries is hardly sustainable and could also be questionable from a normative point of view. Another important factor is the expected lack of technical solutions to certain problems, for example in the area of nutrition.

Furthermore, renewable energy and efficiency options also cause collateral damage. And besides climate change, other environmental problems must also be solved in the longer term, both existentially (and economically and in order to maintain world peace). However, technical solutions are often far worse off with regard to environmental problems other than climate change. Key examples of this are the damaged ecosystems with biodiversity loss, the disturbed nitrogen cycles and soil degradation. Solutions here mean that humanity will also have to withdraw in parts from the land and curb agricultural production. This implies an end to ever larger living areas and steadily rising animal food consumption; likewise, lower specific yields due to the elimination of mineral fertilizer cannot be offset by ever greater land use, and much more. Furthermore, it will hardly be possible to completely convert the material basis of all wealthy goods to renewable resources - also competing with food production and suffering from further problems - or virtually inexhaustible resources.

Even if all the points mentioned were not true and it were indeed possible to get both climate and other environmental problems under control by purely technical means (and therefore with sustained growth on domestic and global level), the probably unsolvable problem would remain at last that with ever further growth the technical options would still (!) have to become better. Not only today's energy consumption has to be covered. At the latest this endless spiral may collide with the physical finiteness of the world at some point - not so much the "if" as the "when" seems questionable in this respect.

Many economists may not like the need for frugality, but it is not against economic instruments. For example, if the necessary reduction targets were translated into a cap-and-trade system that would gradually phase out fossil fuels completely from the market in a couple of years (according to Art. 2 para. 1 Paris Agreement), greenhouse gas emissions would be strictly limited, creating an incentive for more renewable energies, efficiency and, if necessary, frugality. Because if technology alone is simply not enough to achieve the cap, such an approach also triggers frugality, since the cap as such is strictly binding. In principle, however, something similar can also be said about pricing, e.g. by means of levies, even if not with the same reliability, because the price and thus only indirectly a cap is determined there.

3. Economic instruments, cost efficiency and (post) growth

This leads to the question of whether the need for frugality in environmental protection undermines growth society. Thus, economic instruments seem not to be able to fulfil their concern for cost efficiency, which economists usually postulate as a most important goal. But even if this assumption was correct, it could be made plausible that the path via environmental economic instruments remains "more economical" than alternative strategies. That economic instruments can thus be a central part of post-growth strategies and the criticism of the economic focus on cost efficiency cannot speak against economic instruments is, of course, not yet apparent to friends or critics.

In fact, frugality as one (!) sustainability strategy constitutes a contrast to the idea of eternal economic growth which is extremely influential on a worldwide scale and also in the occident. Growth and its promotion is seen by many as the key political and social goal. Greater well-being, stable welfare states, increased human happiness, increased freedom, job creation and much more are expected from it. Furthermore, in the coming decades, the developing and emerging countries will probably try to fight the often dramatic poverty that implies economic growth. At the same time, however, economic growth is a key driver of the climate and resource problems, as growth also increases the consumption of fossil fuels, despite all the opportunities for green growth. These are the lessons that can be learned from the history of industrialized countries, and this is exactly what the emerging countries are imitating.

If - as shown - frugality has to be an essential part of the sustainability turnaround, then less will be sold (e.g. fewer holiday flights). This could take us to an unplanned transition to a post-growth society, i.e. a society that is permanently without growth or even has to adapt to processes of shrinking (firstly in the industrialized countries). Certainly one can also develop individual business ideas from the idea of frugality that have to do with starting points such as "sharing", ”regional”, "slow", service orientation or especially educational measures and courses. This could enable individual companies to grow. All in all, however, if genuine frugality achieves its environmental objectives and is not cancelled out by rebound effects or shifting problems to other countries, other sectors or other environmental realms, it is highly likely that we would all, to put it bluntly, buy less. And from an economic point of view, this will most likely not allow the growth society of the past to continue in the habitual ways. Consequently, there are already companies today that deliberately opt against growth - and even more companies that manage to exist without growth without an explicit intention to do so. This is not about deliberately avoiding growth. The transition to a post-growth society could simply be the side effect of a problem-adequate energy and climate policy if it includes considerable amounts of frugality.

The hope that "new ideas" will simply grow permanently in the future and thus enable eternal ("qualitative") growth without any consumption of natural resources and simply replace the gross domestic product with "new criteria" does not really eliminate the problem situation described, because in this way either no growth or a high consumption of resources is generated again. If, despite all this, one imagines further growth permanently (!) and in all parts of the world (!), explicitly or implicitly by avoiding the questions raised, this is based on purely technical measures of sustainability, which are only insufficient if one considers the aforementioned frictions. The possible course of damage to environmental problems is not adequately taken into account here. If the world is driven into wars and civil wars on shrinking natural resources, for example, this is likely to end the growth age relatively obviously, despite all the difficulties in quantifying in detail.

It is obvious that overcoming growth would result in considerable need for reform and open research questions regarding the labor market, the state budget, the tax system, the pension insurance system or the banking system, including the question of the arduous transition phase. This cannot be analyzed in detail here. I just want to mention one aspect. If frugality could actually lead to the end of the growth society, some may now assume that the turnaround in energy and climate change will hardly make economic sense, as is so often claimed. But there may be a misunderstanding here: A structured economic rethinking will always remain economically more sensible or more cost-efficient than a world of climate wars. Furthermore, frugality can just help to avoid certain social costs and conflicts that may come along with technical options (including wind energy).

Nevertheless, the antagonism of economic instruments and post-growth approaches that seems obvious from the point of view of friends and critics does not exist. Post-growth is neither per se expensive nor do economic instruments (as we already saw in the last section) only promote technology change and thus also growth. Whether economic instruments are really always more cost-efficient than, for example, regulatory solutions lies beyond the focus of this contribution. We will see in sections 5 and 7 that the real argument for economic instruments is precisely not cost efficiency.

By the way, the widespread objection that resource and climate protection, for example, costs money and yet also needs growth, would miss the point. Behind this assumption is the unspoken idea that environmental protection is simply a question of expensive pollutant filters. However, this fails to recognize that effective protection of livelihoods is today a problem of resource-intensive lifestyles and economies. And that the "expensive pollutant filters" have essentially shifted environmental problems to other countries.

4. Economic instruments and cost-benefit analysis

Common headings such as "economizing" or "monetization" often lead friends and critics to assume that economic evaluation (here specifically cost-benefit analysis - CBA) and economic instrumentation must be welcomed or rejected together. The connection is supported by the fact that many economists combine both by "calculating" the optimal environmental status by means of a CBA and then suggesting the amount of tax or the cap in such a way that exactly this optimal environmental status is achieved in the medium term. Economic instruments are thus justified from an economic point of view as a means of internalizing external costs, with social damage such as environmental problems representing the external costs. The talk of internalizing external costs then actually presupposes the validity of economic assessment as a method, for otherwise we do not know exactly what costs we should internalize.

As described elsewhere (Ekardt 2018, 2019), the CBA is indeed exposed to sweeping criticism, although some crucial points of criticism by no means - as assumed by economists - concern only the level of application (which raises already unsolvable problems). The most important objections against CBA are about the empiricist epistemology behind it and its compatibility with liberal-democratic constitutional law. However, economic instruments remain very important governance instruments, since they do not have a necessary connection with CBA. Rather, the definition of the objective to be pursued can be seen as a political decision (possibly forced by a human rights requirement such as preventing climate change) - and economic policy instruments such as levies or cap and trade can then be used to implement this objective. This is because financial pressure, as it emanates from such instruments, has the potential to influence human behavior (by means of prices) in such a way that the politically set goal is achieved. The fact that economic instruments do not have to be linked to target setting by means of a CBA, but can also be the instrument of a policy goal set elsewhere, has long been known at least to some, if not most economists under the heading "standard price approach".

5. Economic instruments primarily as a broad-based means against rebound and relocation effects, both factually and geographically

After all, environmental economic policy instruments do not receive their key justification from an exact internalization of external costs, and it would also be helpful not to let the debate about them generally revolve as much around the concept of cost efficiency (as would correspond to the typical economic textbook). Economic instruments simply do not need this. Above all, they promise to effectively solve certain governance problems such as rebound effects, spatial and sectoral shifting effects, enforcement problems and depicting problems, which could hardly be effectively solved without them. This escapes the typical perspective of friends and critics on cost efficiency alike. This is again explained by the example of climate change and the pricing of fossil fuels with the aim of removing them completely from the market.

Both a cap in certificate trading and sufficiently high tax rates avoid the rebound effect that is always threatening when regulatory measures are taken against individual products or investments. This is because the mechanism of quantity control - directly or indirectly via prices - and its immanent focus on absolute consumption reductions prevent increased actions or generally greater prosperity as a result to ecologically improved actions. Likewise, cap and trade schemes and levies can prevent shifting effects if they are used across a wide geographical area and in all sectors. Shifting effects will no longer exist: after all, all areas and sectors are covered (at least by means of border adjustments).

The problem of depicting many environmental issues (e.g. biodiversity loss) can also be solved - in parts - by cap-and-trade schemes or levies that addresses easy-to-grasp governance units such as fossil fuels (or livestock). They generally require less detailed knowledge on the part of the controlling public sector, since the quantity control instruments only establish a framework. Under which conditions all this really succeeds, however, always depends on whether ambitious quantity targets or tax rates are chosen, whether broad sectoral and geographical regulation actually succeeds, whether an easy-to-grasp control parameter is chosen (e.g. fossil fuels in contrast to biodiversity) and which areas are to be considered in parallel.

In any case, the usefulness of economic instruments is determined by their ecological effectiveness; it does not need (or at least not primarily) a reference to possible cost efficiency, and conversely, a rejection of the idea of cost efficiency of economic instruments would not remove the basis of those instruments either (whether economic instruments are always the most cost-efficient way of achieving objectives, even if there is a basic tendency to do so, can therefore be left open here). If one formulates the idea of avoiding governance problems positively, one can also say: Only economic instruments - assuming a strict cap or a high price as well as a broad sectoral and geographical application - have the potential to solve the core of environmental problems as a problem of excessive use of resources and sinks. This is because those problems are quantity problems; and only economic instruments can reliably take us to absolute quantity reductions (under the conditions just mentioned in the parenthesis in the last sentence) through caps or prices.

For an EU ETS reform, this then implies that the cap would have to be adjusted to the above-mentioned Paris temperature limit, i.e. to a cap zero within 10 to 20 years. Furthermore, all old certificates would have to become void, all fossil fuels integrated, loopholes such as the Clean Development Mechanism (CDM) eliminated and additional pricing instruments for livestock and land use in general established (see Section 7).

6. Economic instruments without homo oeconomicus

Proposals for instruments, whether economic, regulatory or other, require sound assumptions about how the norm addressees behave and react to governance incentives. Economist proponents of economic policy instruments widely rely on homo oeconomicus as a behavioral model that critics regard as disproved. The idea that economic instruments only have an effect on people who behave like a homo oeconomicus is, however, mistaken. Rather, a more complex behavioral theory brings about the expected effectiveness of such instruments.

Indeed, economic instruments motivationally appeal first to the self-interest of citizens and companies by setting a price incentive (directly or indirectly via quantity restrictions). They also eliminate the problem of public goods, which is typical for environmental problems, by urging everyone to act, not just individuals, on a broad sectoral and geographical scale. However, other factors are also addressed which the narrow homo-oeconomicus model does not expect in this way. For example, new conceptions of normality are triggered (as well as new values); the image of free consumption of nature will gradually be replaced by a more careful use of scarce environmental resources. And this is strictly necessary to achieve social change. Thus economic instruments are not automatically based on homo oeconomicus, so that its affirmation or criticism does not automatically affect the use of economic instruments. All this does not rule out the need for additional instruments, e.g. informational and planning measures (such as a move towards the city of short distances).

Therefore, the idea that economic instruments do not influence the given situation of companies, consumers and so on does not apply. It is also inappropriate to hear again and again worries about price elasticity. Firstly, practical experience with environmental economic instruments so far refers solely to very moderate price effects, but not to many times higher prices, as would be necessary to achieve the objectives of the Paris Agreement or of the CBD, for example. Secondly, the notion of a cap-and-trade approach (unlike levies) is overseen by the debate on price elasticity. This is because a cap as such is inevitably achieved if it is properly executed.

The idea that economic instruments destroy the intrinsic moral motivation to act has not been proven either. Rather, this is merely an assumption that could apply, but does not have to apply under any circumstances. Furthermore, the question of whether pricing can eliminate an altruistic motivation to act does not seem particularly relevant to environmental problems, because this motivation is rather weak when it comes to sustainability.

7. Economic instruments without monothematic orientation - for an integrated solution of various environmental problems

So far, economic instruments have been discussed by economists and their opponents mostly in response to single environmental problems, whereby climate change has largely dominated the debates for some time. A particular argument for instruments could be, however, that they can effectively address several different environmental problems at the same time. Again, friends and critics alike seem to take little notice of this.

In particular, the pricing of fossil fuels has potentially very positive effects not only on energy sources and climate change but also on other resource and sink problems, since fossil energy plays a key role in particular in land use and fertilization as well as in air pollutants and thus indirectly for soil degradation, public health, biodiversity losses, disturbed nitrogen cycles, water pollution and other environmental problems. After all, if pricing as a whole pushes back conventional agriculture, this has a positive effect on those other areas. Pricing here promotes more efficient solutions such as reduced food waste, but also, for example, more organic farming, which is composed of consistency, efficiency and frugality aspects. Transport and processing would also become more expensive.

Pricing of fossil fuels in the EU ETS reform proposed above would of course have to integrate - comparatively easy to grasp - livestock and also be combined with another (probably not ETS-based) pricing instrument for land use. This combination would make the production of animal food less attractive and would imply animal food production primarily in pasture farming with the consequence of lower production volumes. Until now, the production of animal food wastes many times more vegetable calories to produce an animal calorie. The proposed combination of capping fossil fuels, livestock and maybe land use in general avoids the run e.g. from fossils to bioenergy and indirectly addresses non-fossil-based greenhouse gas emissions - and various other environmental problems. If pricing land use in itself is done e.g. by means of a progressive tax, small-scale farming and - in conjunction with fuel taxation - organic farming will be promoted at the same time. As with the pricing of fossil fuels, the broad spatial and factual application, i.e. EU-wide plus a supplementary border adjustment, is important as additional tool to avoid shifting effects. It is also beneficial for enforcement that fossil fuels are an easily graspable control variable, unlike, for example, non-fossil-based land use emissions per se.

This does not rule out the need for complementary climate and environmental policy instruments (see Ekardt 2018; Ekardt et al. 2018b). An example could be regulatory protection regulations for wetlands and forests for reasons of climate and biodiversity protection, among others, since depicting the relevant emissions for integration into emissions trading may create problems.

To sum up: It is a misleading discussion whether economic instruments are adequate for solving the existentially threatening environmental problems of our time or whether they are precisely a danger. The potential of economic instruments just goes further. This is why they are being addressed here as the main instruments for an evolution towards greater sustainability.

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