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Sector Coupling - Energy-Sustainable Economy of the Future

Fundamentals, Model and Planning Example of a General Energy System (GES)

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for Aneta, Anke and Maria the authors

Foreword

More than 20 years ago, when I started my professional career after graduation, the standard wind turbine size was 250 kW and PV modules were unaffordable for ordinary people. Who would have thought that today, in the year 2022, several European countries manage to cover more than 40–50% of their electricity demand by variable renewable resources?

Electric energy has established itself as the energy source of the future because the conversion of natural resources into electricity is simple, the transmission is convenient and has low losses even over long distances. Electricity networks evolve to smart grids, no longer relying on large power plants but instead building on thousands of small and distributed generation units. Also, large renewable plants, especially offshore wind plants, are slowly shaping today's energy landscapes, delivering large amounts of energy to shore via submarine cables. At the demand side, electrification is seen in various sectors: in the transportation sector, electric vehicles are on the rise; industry is starting to use green hydrogen and its derivatives such as ammonia and synthetic fuels instead of fossil oil for their processes. These trends are here to stay, and even will need to accelerate to reach both decarbonization targets and European energy independency, which recently has turned into a question of energy security as well. This fast industrial revolution comes with a cost, and thus often meets resistance when it comes to implementation at local level. People ask if it is necessary at all or is it just the realization of a utopian vision.

The answer is provided by the daily alarming images that illustrate climate change. Not only the forecasts, which are known for at least 60 years, but the daily climate anomalies have made it clear to all of us that the use of fossil energy is destroying the climate and must be stopped as soon as possible and be replaced using renewable energy. It becomes increasingly clear that we have been acting much too slow and much too little, to reach both targets. War is financed by the export of fossil fuels, which immediately mixes military actions, supposed economic activities, and politics into a deadly cocktail. The pace towards 100% renewable energy and energy independence must be accelerated to put a stable end to that spiral.

The general energy system in all sectors such as electricity, transportation, industry, household, and agriculture must be rethought and reworked. This will also create new synergies that can lead to the mutual energy-exchange between the sectors and thereby stabilize the subsystems. New roles have been attributed to electricity but also to synthetic energy carriers, in particular green hydrogen. We look into exciting times with huge developments. These have demanded and still demand a lot of strength but also technical imagination, as there still are many obstacles on the way to a Net-Zero system.

Decisive on this path are the highly educated, young people who are not only convinced that climate is endangered but also, and above all, are able to do something against it – by acting. Therefore, higher education is in the focus of today's general interest, but also my personal attention. It is an essential building block for the success of the restructuring of the global power system transformation. Thus, this book, *Sector Coupling*, which has established itself on the market with its first German edition in 2021, is now published in English. It describes German experience towards sector integration on a European background. Coming from one of the strongest European economies, these experiences play an important role in shaping the European energy future. Projects and trends from this country will undoubtedly have a lasting influence on what happens in other places in this area.

I recommend the book, which is written by my colleagues from university, from Fraunhofer Institute, and from a German transmission system operator. It is based on their experience gained over the last 20 years in this field and is an excellent compendium and guide for students but also for everyone professionally interested in the subject. While reading, one senses that the authors have recognized the seriousness and complexity of the challenges and present it very nicely through systematic descriptions. Starting with a convincing motivation, modeling principles and approaches for the planning and operation of integrated systems, also considering energy market design, the topics are presented in a clear and well-founded manner. Books like this are needed more than ever.

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Preface

Sector coupling is a shorthand description of what needs to happen across the economy in the coming years to make it sustainable and **resilient**. Now that the **Energiewende has** established itself as a buzzword and also a trademark of the German way of producing energy from renewable sources at the beginning of this century, **sector coupling** can be understood as an **extension of** this idea to the entire energy industry.

As far as the **generation of electrical energy is concerned**, the **feasibility of** a **100% renewable** energy system is now **beyond doubt**. There are already numerous examples of how the 100% integration of renewable energy is possible through sophisticated management of electrical grids **without loss of grid stability** and supply reliability. In Germany, it is therefore timely, given the **phasing out** of **nuclear power** by 2022 and the recent decision to phase out **coal-fired** generation by 2035–2038, to consider how the other sectors, apart from electricity, will function when **100% of energy** is delivered **as renewable power. Is that even possible?** What other primary energy sources are needed, for example, to sustain sophisticated human mobility or the industrial landscape? These and other questions, such as **what energy mix** will be necessary for certain sectors in the **future**, must be answered on the basis of the results of systematic studies.

Such **studies have** been carried out for some time by many national research institutes such as **acatech** or **DENA. BDEW** and international organisations such as **CIGRE** or **ENTSO-E** clearly show the positive perspectives of a sustainable system of the future with different focal points. In these studies, **mathematical modelling methods** are used to verify the **plausibility analysis of** the results.

As active **contemporary witnesses**, the **authors have** accompanied the **energy transition** in Germany and Europe for more than 20 years. In development, applied research and industrial application, they have investigated a wide range of topics in this field as part of numerous collaborative projects. The authors would therefore like to thank a number of colleagues and discussion partners for the lively exchange of expertise that is a necessary part of processes such as the energy transition and sector coupling.

We would especially like to thank **Prof. Dr.-Ing. Torsten Birth (IFF)** for a purposeful **contribution**, especially for **Chaps.** 3 **and** 4, as well as his expertise and experience in the field of Power-2-X projects, which enriched the book.

The authors would like to thank **Dr.-Ing. Martin Stötzer** for his very valuable **contribution** to practical planning for the expansion of **H_2 infrastructures** in Germany.

In particular, we would like to make special mention of the following individuals whose contributions over the last few years to the topic of sector coupling should be acknowledged:

- **From CIGRE C6**: Dr. Bernd Michael Buchholz, Dr. Britta Buchholz, Prof. Dr. Nikos D. Hatziargyriou, Prof. Dr. Christine Schwaegerl
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- **By the project partner of the showcase project WINDNODE, funded by the Federal Ministry for Economic Affairs and Energy**: Dr. Frank Büchner (Siemens AG), Dr. Christoph Günter (InfraLeuna GmbH), Mr. Markus Graebig (50Hertz Transmission GmbH), Dr. Matthias Müller-Mienack (DNV-GL)

The book is divided into seven chapters.

Chapter 1 discusses the **motivation** for a sustainable energy system against the background of climate policy goals. Using a logical chain, it is shown that today's sustainable development has a long history. Milestones of this development, such as the **Club of Rome** report, the **Kyoto Protocol** or the **energy transition**, are discussed in this chapter. The term sector coupling is defined.

The basics for modelling sector coupling are presented in **Chap.** 2. The **energy hub model** and examples of optimisation methods are discussed in this chapter.

The energy consumption sectors and their specifics, in particular the **structure of energy consumption**, are shown in **Chap.** 3. Based on historical data, the possible perspectives for the sectoral energy mix design are discussed. Building on the results of selected studies, the paths to a **Net-Zero-Energy system** are outlined.

These find their systematic justification in the approach to hub modelling presented in **Chap.** 4. **Substitution possibilities** and the reversibility of energy conversions are also discussed.

The newly designed sustainable energy system, like today's, must ensure a high level of reliability, security and quality of energy supply. As it will be based on highly volatile generation, new **flexibility options** are needed to ensure this. These are discussed in **Chap.** 5.

A GES (General Energy System) is inconceivable without **digitization. Chapter** 6 therefore focuses on this important feature. Modern measurement technology, online balancing, and billing in the generation, transport and distribution of energy – these are the features of the future system discussed in this chapter.

Chapter 7 presents the perspectives of GES on an **international scale**. Since the book focuses on the German experience, the seventh chapter puts these efforts into a more general context.

The book was initiated by the increasing demand of the market. In particular, our esteemed supporters, **50Hertz Transmission GmbH Berlin**, the **Fraunhofer Institute for Factory Operation and Automation (IFF) Magdeburg** and **Steinbeis GmbH Stuttgart**, who are themselves significantly involved in shaping the energy transition and sector coupling, have encouraged us to continue this in 2020. **Springer Verlag**, in the person of **Dr. Daniel Fröhlich**, has also shown interest in this topic and provided us with very good support during the process, for which we would like to express our special thanks to all those involved.

Our **thanks** also go to Dr. **Tobias Hinrichs**, who carefully edited the German manuscript, and to **Polina Sokolnikova, MSc**, who did the graphic design of the two issues.

Thematically, the book is assigned to the **series Energy in Science, Technology, Economy and Society**, which the authors very much welcome. The **Corona crisis** in 2020 clearly demonstrated that the greatest challenges of our time, if addressed in a transparent and targeted manner, will meet with **broad societal support**. The same has been and will be the case with the **transformation of energy supply** to full sustainability and resilience. This is taking place on a slightly different time scale, is slower, but the approach is similar to the Corona Crisis: a broad spectrum of society needs to follow the same line, speak the same language, and each individual needs to make even a small contribution to its success. That's the case here, as the recent decisions to phase out coal have shown, for example, and that's why the book, which is mainly technically oriented, fits well into the series mentioned above.

The **book is aimed at** readers who are concerned with technical aspects of the energy transition and sector coupling. Primarily, these are **students** in the technical faculties of **universities and colleges**, but also **doctoral students** and **engineers working in practice** who are designing or will design the future system in the energy sector and at the municipal level.

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Contents

Abbreviations

AbLaV	Regulation on switchable loads
Acatech	German Academy of Science and Engineering
aFRR	Automatic frequency restoration reserve
ANB	Exit network operator
BDEW	Federal Association of Energy and Water Industries
CHP	Combined heat and power plant
BIKO	Balancing grid coordinator
GDP	Gross domestic product
BA	Balancing area
BG	Balancing group
BRP	Balancing responsible part
BNetzA	Federal Network Agency
BPO	Business process outsourcing
CBA	Cost-benefit-analyses
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CIGRE	Conseil International des Grands Réseaux Électriques (International Council for Large Electrical Networks)
DBA	Difference balance aggregate
DENA	German Energy Agency
DNV	International Accredited Register and classification Societies (Det Norske Veritas) Norway
DOD	Deep of discharge
DSM	Demand side management
DSI	Demant side integration
DSO	Distribution system operator
DSR	Demand side response
DTST	Delta time series transfer
EDP	Electronic data processing
EEG	Renewable Energy Akt

EEX	European Energy Exchange
EIC code	Energy identification code
EMS	Energy management system
EnWG	Energy Industry Act
ENB	Entry network operator
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSO-G	European Network of Transmission System Operators for Gas
EPEX	European Power Exchange
EqC	Equivalent circuit
EU	European Union
EUROSAT	Statistical Office of the European Union
FCR	Frequency containment reserve
gMSB	Responsible metering operator
GeLi Gas	Business processes change of supplier gas
GEODE	European Independent Distribution Companies of Gas and Electricity Association
GES	General Energy System
GFC	Grid forming converter
GPKE	Business processes in the field of metering
GWA	Gateway administration
HDI Index	Human development index
IEEE	Institute of Electrical and Electronics Engineers
ICT	Information and communication technology
iMS	Intelligent measuring system
MaBiS	Market rules for the execution of balancing group settlement for electricity
MaKo	Market communication
MDM	Meter data management
MES	Multimedia energy system
MAM	Market area manager
MILP	Mixed-integer linear programming
mFRR	Manual frequency restoration reserve
MsbG	Metering Point Operation Act
MSB	Metering point operator
NA	Not available
NABEG	Grid Expansion Acceleration Act
NDP	Network development plan
NRW	North Rhine-Westphalia
PEC	Energy consumption per capita and per year
POG	Cost limit
PST	Phase shifting transformer
PHES	Pumped hydroelectric energy storage

reBAP	Balancing energy price across control areas
rLM	Registered load flow measurement
SaaS	Software as a service
SCADA	Supervisory control and data acquisition
SGD Index	Sovereign risk score
SLP	Standard load profile
SMES	Superconducting magnetic energy storage devices
SNL	Fast disconnect load
SOC	State of charge
SOL	Instantaneous off-loads
STATCOM	Static synchronous compensator
Sup.	Supplier
SVC	Static VAR compensator
TSO	Transmission system operator
UPS	Uninterruptible power supply
UML	Unified modelling language
VKU	German Association of Municipal Enterprises e.V.
wMSB	Competitive metering operator
WAMS	Wide area monitoring system

Introduction: Climate Policy Goals of Sustainable Energy Supply

1

1.1 Why Do We Need a General Energy System (GES)?

1.1.1 World Population, Energy Resources and the "Full World"

In the development of mankind, several phases can be identified, which have always been characterized by significant progress in the conquest of the earth [1, p. 57]. As a result, the behavior of people changed, mostly radically. An example of this is the development of agricultural culture, which transformed people from gatherers and hunters into sedentary breeders and farmers.

Each of these changes was also associated with social and health improvements in people's lives, as can be seen, for example, in the average life expectancy of people over time. Average life expectancy rose from about 20 years in the Stone, Bronze and Ice Ages to about 33 years in antiquity [2] and the Middle Ages [3] and about 40 years at the turn of the 1900s, reaching a value of 80 years today (see Fig. 1.1.).

People owe the last "leap" in life expectancy to the widespread use of energy, which revolutionised life and its quality. From 1850 onwards, it was thermal energy that facilitated movement and work with steam engines, and from around 1900 onwards, electrical energy that very quickly found its use everywhere as a refined form of energy. Even today, after the rapid development of energy production from renewable sources (e.g. PV, wind), which is certainly due to the progress of technology, the electrification of transport, for example, has become attractive again, as it was at the end of the nineteenth century.

Electricity, which began to be used more frequently around 1880, was initially generated from hydroelectric power (Niagara power station, commissioned in 1895). This energy could then be transported effectively and efficiently as alternating current.

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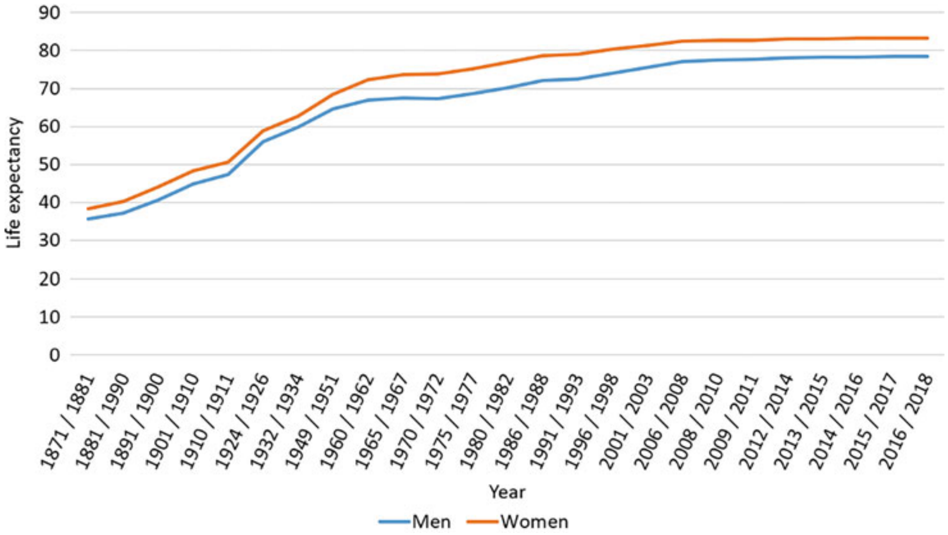

Fig. 1.1 Life expectancy at birth in Germany. (Data source: [3])

This was a crucial leap in the development of modern civilization. Since hydroelectric resources were limited, primary fossil fuels were quickly tapped for the production of electrical energy. Later, as the world's population grew rapidly (see Fig. 1.2), nuclear energy was added. However, both forms of energy have a downside. Emissions from fossil energies rose to such a high level that it became necessary to think about reducing them, while the call to phase out nuclear energy is based primarily on the now widely perceived risks of its use and the final storage of nuclear waste.

Since the first report of the Club of Rome (founded in 1968 as an independent initiative; see https://clubofrome.org/ or also in German at https://www.clubofrome.de/) with the famous title The *Limits to Growth* (1972), awareness of sustainable growth and a sustainable economy has increased considerably. In the latest publication entitled *Club of Rome. The Great Report* [5], published on the occasion of the 50th anniversary of the organization in 2018, the forecasts from 1968 are definitely confirmed.

Especially the last few years have shown that mankind no longer lives in an *empty world*. The term *empty world* was created by the Club of Rome and assumes that

> the economy is relatively small compared to the ecosphere, where our technology of extraction and harvesting is still weak and our goals low. Fish reproduce faster than we can catch them, trees grow faster than we would cut them down, minerals in the earth's crust are abundant, and natural resources are not really scarce. In the empty world, the undesirable side effects of our production systems were widely distributed and were often absorbed with less effort [5, p. 394].

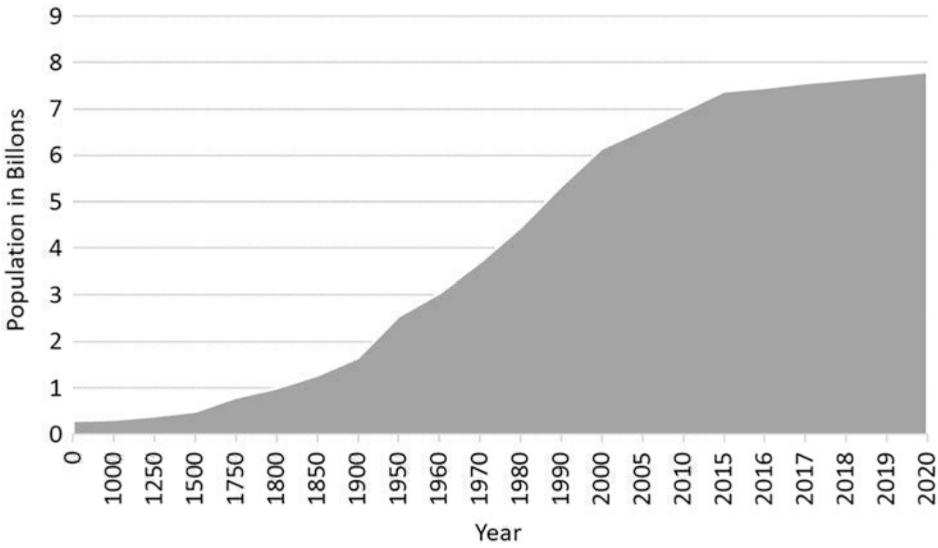

Fig. 1.2 World population. (Data source: [4])

Even if this thesis sounded utopian 50 years ago, today we are more than convinced, e.g. because of the climate change that has become visible due to the rise in temperature, that our world can no longer be used indefinitely and is therefore a *full world.* A tangible sign of this is the measurable exhaust pollution in the atmosphere, which can no longer regenerate and thus cements the above-mentioned global warming effect.

Over the years, the idea of a *New Economy* has emerged, aiming at the sustainable development of humanity in a full world. This presupposes, first of all, the use of complex and not simple growth assessment methods. In place of GDP (Gross Domestic Product), which practically does not take into account any restrictions and is oriented towards the maximum profit, other evaluation factors were proposed and introduced. The United Nations 2030 Agenda includes seventeen Sustainable Development Goals (SDGs) [6]. These can be applied to development plans down to local authorities to address the high complexity of sustainable growth at the planning stage. Various tools are available for this purpose, which are described in detail on the Internet, e.g. at www.sdg-portal.de.

SDGs 1–11 characterize socio-economic goals. SDG 12 is dedicated to sustainable consumption and production, SDGs 13–15 formulate the environmental goal, and SDGs 17 and 18 address equity and partnership. Even this simple list shows that this system cannot be expressed with the one-dimensional logic of GDP.

Using this system, not only municipalities but also countries can be assessed according to the SDG principles. Starting from 100 as the maximum achievable number of this multi-criteria assessment, three Scandinavian countries (Sweden, Denmark and Finland) were rated highest in 2020 with a score between 84.7 and 83.8 [7]. These were followed by

France (81.1) and Germany (80.8). The USA with a score of 76.4 was then ranked 31st, China with a score of 73.9 was ranked 48th, the Russian Federation (71.9) was ranked 57th and India (61.9) was ranked 117th, with the Central African Republic bringing up the rear with a score of 38.5.

It has become clear from the discussion of the 2030 Agenda that all seventeen goals must be pursued simultaneously. A coherent policy is needed to achieve these socio-economic and environmental goals simultaneously. However, this means revising the current technological, economic and political goals.

In order to achieve comparability of previous economic indices with sustainability assessment, the *New Economic Foundation* has developed a GPI (Genuine Progress Indicator) index that includes both private consumption expenditure (i.e. components of GDP) and 25 other components expressing sustainability and living comfort [8]. The initial research showed that the GPI factor decoupled from GDP in the 1970s.

GDP continued to rise in the *full world*, while the GPI or SDG remained constant. This makes it clear that the welfare of people in a *full world* must be measured differently than with GDP. Only in this way can action be aligned with an increase in welfare.

In summary, it can be stated that not only the technical limitations, such as the scarcity of resources or increasing emissions, but also socio-economic objectives, which have gained in importance in recent years, will place even greater emphasis on the goals of the conversion (e.g. the energy turnaround). After renewable power generation from photovoltaics or wind turbines has been able to establish itself after more than 20 years technological development and can now compete with fossil technologies without subsidies, it is quite conceivable that in the future complex assessments, e.g. with GPI factor, will also be successfully used to shape technical developments, such as in electromobility. It is therefore not particularly surprising that electromobility is currently experiencing the most rapid development in the Scandinavian countries. Therefore, there is a correspondingly high level of acceptance for society’s welfare goals, which are not only oriented towards GDP.

A widely used index that characterizes human development, the HDI (Human Development Index), combines three groups of indicators, with 1.0 being the highest achievable value. These indicators are: Life Expectancy, Education, and GDP (Gross Domestic Product). Specifically, they cover: Life expectancy at birth, adult literacy, primary, secondary and tertiary enrolment rates, GDP per capita. It is published in annual reports of the United Nations Development Programme, with a variety of additional economic, social and political data [9].

Figure 1.3 presents the values of HDI indices compared to energy consumption per capita for different countries.

The direct relationship between these two values is visible: high energy consumption is associated with a high HDI index value up to about 50 MWh PEC (~100 GJ PEC). The further increase in PEC energy consumption does not necessarily lead to an increase in the HDI index value. For example, the HDI index for Germany is 0.94, which is obviously

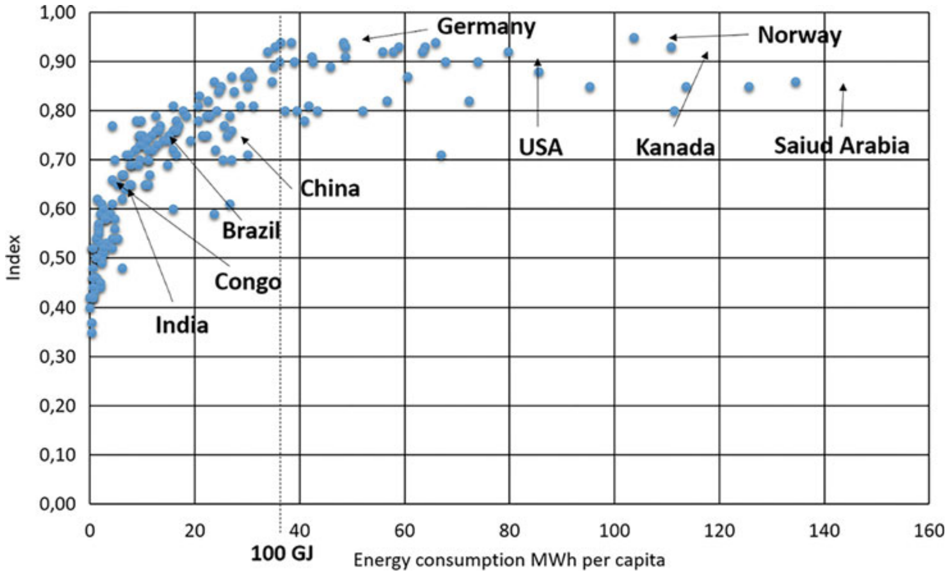

Fig. 1.3 Prosperity index versus energy consumption per capita and year (PEC). (Data source: [10])

better than the HDI index for Saudi Arabia (0.83). Nevertheless, Saudi Arabia has more than twice the PEC energy consumption compared to Germany.

Energy consumption per capita per year is expressed in MWh in Fig. 1.3 (whereas many sources express it in gigajoules – GJ: 1 MWh = 3.6 GJ) to ensure a direct comparison with commonly used figures in electrical energy technology. This can be illustrated by the following example. In Germany, an annual consumption of about 50 MWh can be converted to a 25-h full load work of a 2 MW wind turbine. Thus, assuming 2000 full load hours per year, a 2 MW wind turbine can cover the energy consumption of about 100 statistical (in this per capita calculation the total gross energy consumption, household, industry, etc., is meant) German citizens. Here, full load hours are a mathematical measure for the degree of utilization of a technical system. The value of the full load hours of a power plant (generation unit) is calculated by dividing the energy generated annually by the nominal output of the plants (see also Table 1.5).

Figure 1.3 shows that per capita energy consumption in the USA, for example, is still about 2.5 times higher than in China. Saudi Arabia leads with an energy consumption of 134 MWh PEC. African countries use comparatively the least energy with a consumption of 2.7 MWh PK. India also has a lot of catching up to do in PEC energy use, with a consumption of 6.7 MWh PEC and an index of 0.61.

In order to relate prosperity to GDP and thus to energy security, one of the most complex indices is suitable, the Global Energy Security Index, which consists of 15 individual parameters that take several factors into account [11]. The normalized value [0, . . .,1] of

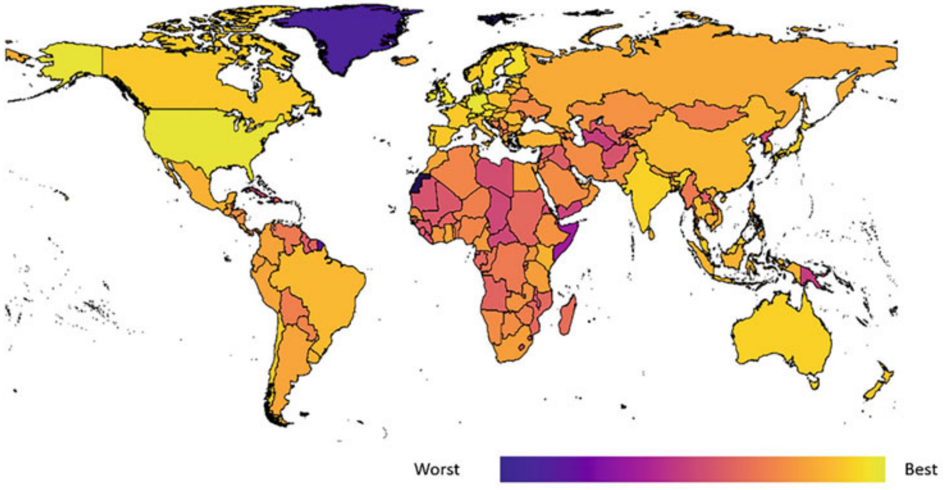

Fig. 1.4 Global Energy Security Index [11]

this index is calculated by the weighted addition of the individual parameters (as shown in Eq. 1.1.),

$$GESI = \sum_{i=1}^{15} (w_i \cdot P_i), \tag{1.1}$$

where w_i is the weighting and P_i *is* the value of the i-th parameter. The sum of the weighting factors is equal to 1 ($\sum_{i=1}^{15} w_i = 1$).

The index itself was last recalculated in 2020 and is shown graphically in Fig. 1.4.

The Global Energy Security Index (Fig. 1.4) provides a comparative assessment of individual countries, as does the HDI (Fig. 1.3). The countries marked in yellow in Fig. 1.4 (USA, EU, Australia, etc.) are also among the countries that report the highest energy consumption per capita (cf. Fig. 1.3).

Of course, other indices that assess wealth and energy consumption have been and continue to be developed. To describe them all, however, would go beyond the scope of this book.

1.1.2 Energy Consumption and CO_2 Emissions: From Kyoto Protocol to Paris Agreement to Green Deal

As already described in Sect. 1.1.1, the targeted use of external energy sources has led to an increase in human prosperity since the nineteenth century. Since energy was mainly produced by burning fossil fuels, carbon emissions can be used as a consumption indicator.

Thus, Fig. 1.5 illustrates the history of industrialization using this ratio.