Energy Transition for a sustainable society

Wilfried Winiwarter & Viktor J. Bruckman (Eds.)

KIOES Opinions 13 (2023)

ÖAW AUSTRIAN ACADEMY OF SCIENCES

Commission for Interdisciplinary Ecological Studies (KIOES)
KIOES Opinions 13 (2023): 1–64.
doi: 10.1553/KIOESOP_013

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Imprint:

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Cover photo credit: Fotofolia

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doi: 10.1553/KIOESOP_013

Dear Reader,

thank you for your interest in this important volume on opportunities of future energy provision. As the Chairperson of the Commission for Interdisciplinary Ecological Studies (KIÖS), it is my pleasure to introduce the background of this work. Commissions of the Austrian Academy of Sciences combine the excellence of Academy Members with excellent scholars invited by the general assembly into the co-operation for a particular theme. The interdisciplinary groups thus formed develop workshops, symposia and publications, often also working on the science-public interface. All commissions work on a pro bono basis and are independent, only led by scholarly values.

In matters of sustainable development, even the board range of knowledge within one commission can be somewhat limiting. Therefore, the Climate and Air Quality Commission (KKL) and KIÖS have formed several Joint Working Groups (GAGs) over the years, which, contrary to the commissions themselves, are formed only for one specific task. The "Energy Transition" group came together to discuss what can safely be seen as the central challenge to deal with the climate and biodiversity crises which are worsening as I write. The group, co-chaired by Viktor J. Bruckman and Wilfried Winiwarter, from February 1st, 2022 until March 2023 held a series of eight online workshop sessions and very quickly developed the contributions into a joint report, which was also presented to the wider public in a symposium.

It is my duty and pleasure to acknowledge the work done by the members of the group and the authors of this volume, Georg Brasseur, Viktor J. Bruckman, Karlheinz Erb, Simone Gingrich, Wolf Grossmann, Helmut Haberl, Robert Jandl, Hanns Moshammer, Ilona Otto, Peter Palensky, Lucy Y. Pao, Keywan Riahi, Celine L. Sauer, Karl Steininger and Wilfried Winiwarter. I would also like to acknowledge the unfailing administrative support by Karin Windsteig. It was a pleasure to co-operate with the chairpersons of KKL, Georg Kaser, Andrea Steiner and Wilfried Winiwarter; I would also like to acknowledge the support of the vice chairs of KIÖS, Martin Gerzabek and Christian Sturmbauer. The work of Commissions of the ÖAW is done pro bono, but administration and workshops are not for free. As this is our last joint work, because the Climate and Air Commission reached the end of their term of office by the end of March, 2023, I would like to end these acknowledgements with an expression of gratitude to Austrian tax-payers, who, via the budget allocation to the Austrian Academy of Sciences are not only the source of our funding, but also the addressees of our work, which is dedicated to contribute to the sustained well-being of humans and the ecosystems their life depends on.

Verena Winiwarter
Vienna, March 15th, 2023

Commission for Interdisciplinary Ecological Studies (KIOES)
KIOES Opinions 13 (2023): 1.
doi: 10.1553/KIOESOP_013

Introduction

Wilfried Winiwarter and Viktor J. Bruckman

Availability of energy is a key pillar of civilization. It allows any human individual to extend its reach via the power of draft animals or via the use of machinery. Societies in the past and present have strived to secure their growth via increasing their available energy. With the discovery of fossil fuels and the technology to utilize them efficiently, the age of industrialization was characterized.

Energy has a wide range of applications that are central for a functioning economy. Comfortable room temperatures via heating or cooling are essential for good living conditions and even more so for a productive working environment – just as artificial light is. Transport relies on energy, to enable interaction of people for productive exchange, or to extend markets and to allow cheap mass production of goods of all kinds. Energy is embedded in many materials, from bricks and concrete to steel or aluminum, essential for the buildings we live in and the vehicles that enable our mobility. Even modern telecommunication instruments, having the potential to reduce some of our travel burden, need reliable supply of energy.

The central position of energy in societies and economies also exposes their vulnerability. Limitations to energy availability led to price shocks and global economic crises in the past, the latest of which, as a consequence of the Russian war in the Ukraine, hit much of Europe in 2022. Such price shocks inevitably focus public attentions towards alternatives, alternatives of an energy system that requires less foreign and distant unreliable providers of energy, or that at least increases the choice among different providers. At the same time, challenges of climate change raise awareness of the global impacts of using fossil fuels. Increased temperatures have become evident in the 21st century, demonstrating the need of an energy transition also to reduce and avoid further release of greenhouse gases, first of all of carbon dioxide. In many contexts the term "decarbonization" is commonly used to comprehensively describe the pathway out of anthropogenic climate impacts, yet even a more precise "defossilization", i.e. moving out of fossil energy, still would not cover all relevant aspects (e.g. that of unsustainable use of biomass or that of non-CO_2 greenhouse gases).

Under the impression of the double challenge of climate change and energy security, a need for better understanding of energy provision in Europe arises that encompasses current conditions and expected or possible transitions into a system ready for future challenges. In such a view Austria cannot be seen separately, it merely can be highlighted. Members of two commissions of the Austrian Academy of Sciences, the Commission for Interdisciplinary Ecological Research, and the Climate and Air Quality Commission, joined forces for a common working group "energy transitions" to collect and present the important basics required for further informed discussions. The group invited twelve external experts for presentations in video sessions, engaged into internal discussions and structured the relevant questions and available knowledge to create this report. Members of the working group contributed to the writing of this report. They attempt to cover technological challenges of an energy transitions as much as its social requirements and consequences, they touch on concepts of energy needs and energy poverty as much as on the boundary conditions for technological achievement in a Europe that is part of a global society.

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KIOES Opinions 13 (2023): 3–6.
doi: 10.1553/KIOESOP_013

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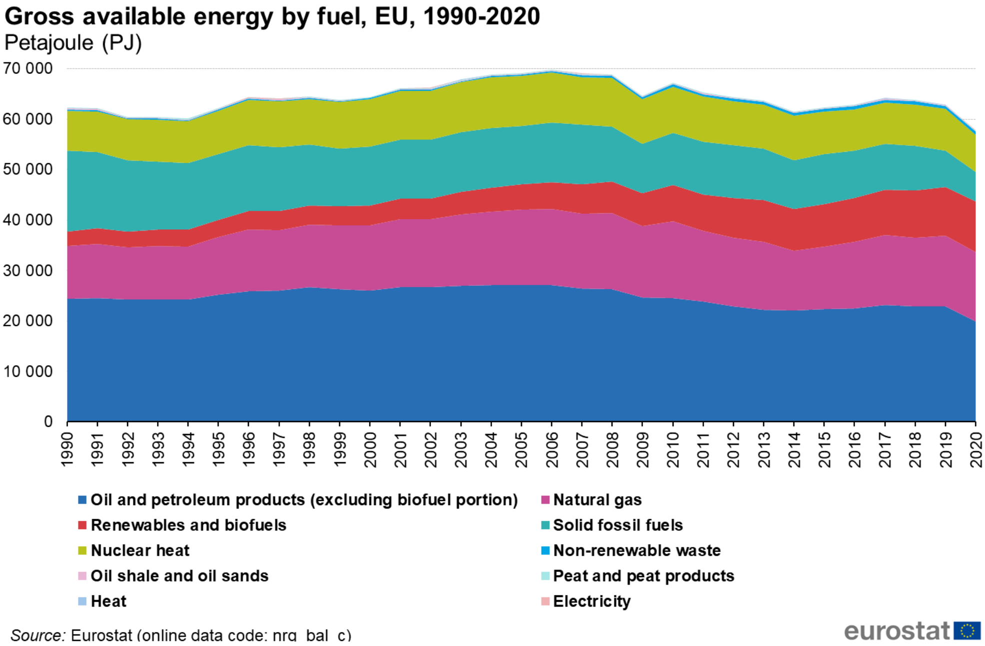
Present energy use, emissions, energy poverty[1]

Viktor J. Bruckman

Energy use in Europe

The amount of energy required within the European Union to satisfy all energy needs ranged between 60,000 and 70,000 PJ gross available energy (GAE)[2] per year in the last decade before the pandemic, with a steady decline from 2006. In comparison, the GAE of the federal state of Austria was 1,429 PJ in 2021 (Statistics Austria, 2022). The financial crisis in 2009 and the pandemic from 2020 led to stronger short-term but not lasting drops (Fig. 1). Crude oil and its products and natural gas were by far the most significant sources of energy. The European Union's primary energy production amounted to 24,027 PJ in 2020, resulting in necessary imports of 33,740 PJ in that year.


Gross available energy by fuel, EU, 1990-2020
Petajoule (PJ)

Source: Eurostat (online data code: nrg_bal_c)

Figure 1: Gross available energy by fuel, EU, 1990-2020.

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[1] Data in this chapter is derived from eurostat (https://ec.europa.eu/eurostat/databrowser/explore/all/all_themes), unless indicated otherwise

[2] Gross available energy (GAE): Primary production + Recovered & Recycled products + Imports – Export + Stock changes. It represents the quantity of energy required to satisfy all energy demands in a specific region. In contrast to final energy consumption, it includes energy needed by the energy sector (e.g. transmission, conversion).

The energy dependency (extent to which EU is dependent on imports) is highest for oil and petroleum products with 97 % (19,944 PJ in 2020) and Natural gas with 86.6 % (13,696 PJ in 2020). Overall, the energy dependency shows an increasing trend, from approx. 50 % in 1990 to 57.5 % in 2020, which is an important factor in considerations towards energy transition. The costs for imported energy amounted to € 331.4 billion in 2018 in the European Union (European Commission, 2020).

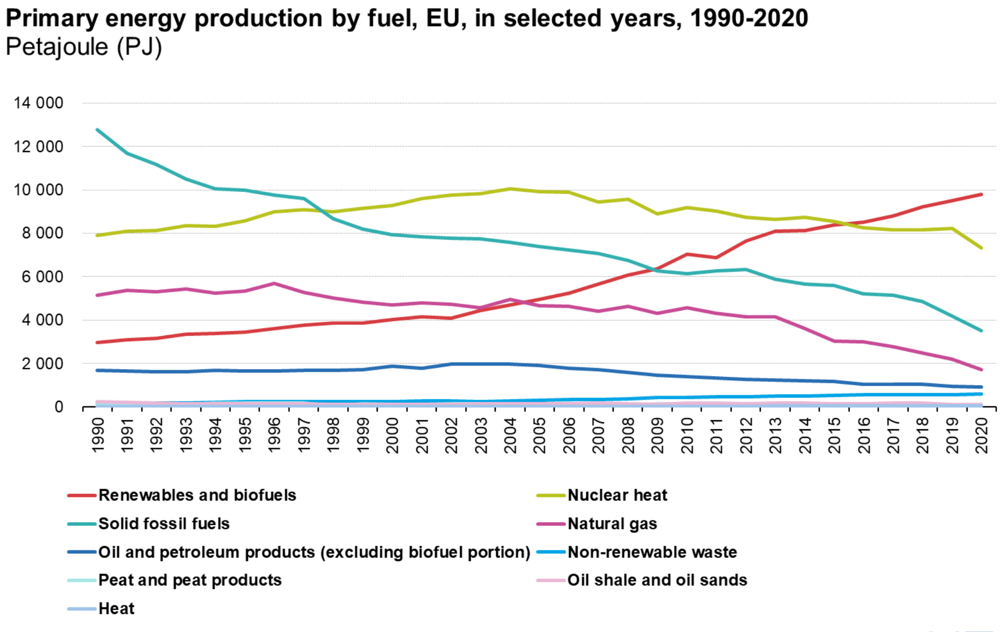
While remaining significant as imports, fossil fuels show a negative trend in primary energy production in the European Union (Fig. 2), and renewable energy accounts for the highest share since 2016 (40.8 % in 2020). Nevertheless, this corresponds to only 17.4 % of the GAE.

The total share of renewable energy sources on final energy consumption was 22 % in 2020 with the highest share in the electricity (37.4 %) and the lowest in the transport sector, respectively (10.3 %).

Emissions associated with the energy industry and energy transition

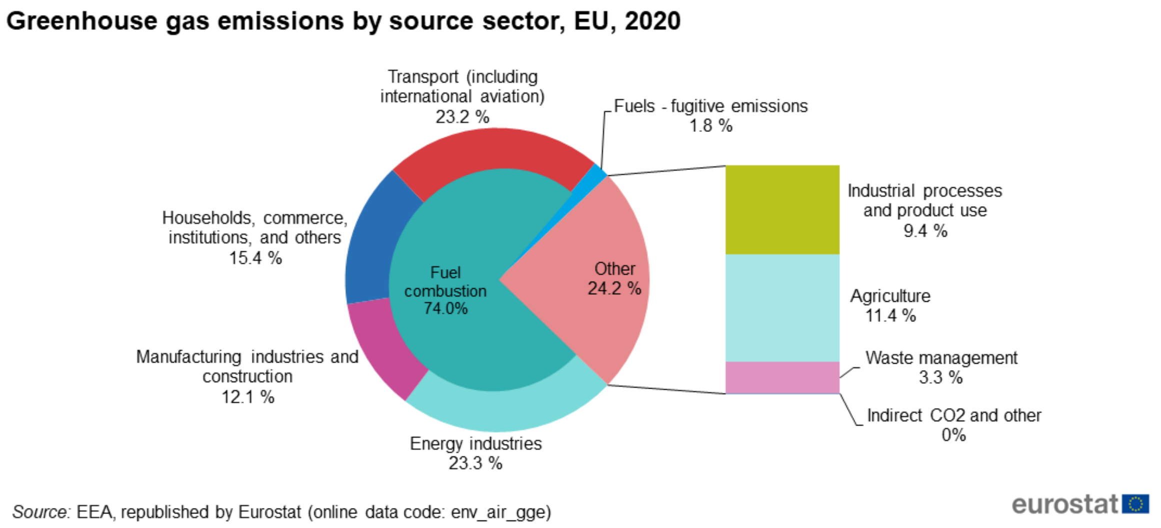
Greenhouse Gas emissions associated with energy industries (power plants, refineries) accounted for a total share of 23.3 % in 2020 (Fig. 3). At the same time, this sector showed the largest decline of -46 % over a period of three decades (1990–2020), equivalent to a drop of 657 million tons CO_2 (WEF, 2022). The transport sector is the only sector where emissions are still rising, and therefore needs increasing attention. Although some studies suggest that the ambitious EU emission reductions on road-based mobility is technically feasible by electrification (e.g. Krause et al. 2020), it remains doubtful if the necessary investments in electrical transmission and storage infrastructure can be realized (Brasseur, 2021).

It should be noted that energy required, and emissions generated for the transition of the energy system needs to be taken into consideration. Slameršak et al. (2022) have estimated that most of that energy needed for transition will be provided by fossil fuels, accounting for additional global emissions in the range of 70 to 395 Gt CO_2.



Source: Eurostat (online data code: nrg_bal_c)

Figure 2: Primary energy production by fuel.



Source: EEA, republished by Eurostat (online data code: env_air_gge)

Figure 3: Greenhouse gas emission by sector, EU, 2020 (shares of the emission total of 3.49 Gt CO_2-eq).

Energy Poverty

Along with climate change and security of supply, the energy system will have to face energy poverty as one of three major transformations in the coming decades (González-Eguino, 2015). It describes the inequality in access to energy and energy infrastructure and is thus associated with impacts on health, the economy, and the environment. Energy transition should therefore be approached as systemic since it may reduce some energy poverty (e.g. by creating green jobs) but also contribute to losses in some areas (e.g. in the automotive industry, or traditional fossil energy industries). In this context, the network analysis of the Agenda 2030 can help to identify co-benefits of measures originally aimed at individual goals, i.e. reducing energy poverty, enhancing environmental quality and mitigate climate change. Research is needed to find ways to increase accessibility of renewable energy and efficiency technology, in particular to communities with lower income (Carley and Konisky, 2020).

On the EU level, energy poverty is measured and addressed in several ways. One of the possible measures is achieved by the composite domestic energy poverty index (EDEPI), where wealthier countries, such as Sweden score higher, and Bulgaria, Hungary and Slovakia score the lowest (Witudo, 2022). The author presents a range of legislative and non-legislative approaches to decrease energy poverty in the EU. In view of energy transition highly relevant is the Renewable Energy Directive. While it does not directly contain any provisions on energy poverty, it promotes accessibility of renewables to low-income households, which is also stipulated as main research question by Carley and Konisly (2020). An integrative assessment of all consequences of energy transition has the potential of greatly reducing energy poverty. In turn, if not considered an important factor, it may leave us behind with more severe impacts on low-income households.

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KIOES Opinions 13 (2023): 7–10.
doi: 10.1553/KIOESOP_013

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Energy Transition Pathways

Keywan Riahi

Overview

Energy is underpinning all economic activities and has historically been a key factor for productivity growth, increasing convenience of services and higher quality of life. The current energy system, however, relies heavily on fossil fuels and is unsustainable with regards to its environmental impacts (e.g., climate change and air pollution) and social implications (e.g., vulnerability due to price volatility and supply disruptions) (Grubler et al., 2012; Riahi et al., 2012).

In particular limiting climate change to 1.5°C warming (with a low overshoot) consistent with the Paris Agreement will require a pronounced acceleration of the near-term transformation to reach net zero CO_2 emissions globally by around 2050 (IPCC, 2022; Riahi et al., 2022). Limiting warming to 1.5°C with high likelihood requires further emissions reductions to reach also net zero *greenhouse gas emissions* around 10–30 years after net zero CO_2 emissions is achieved. Climate neutrality means that net negative CO2 emissions are needed in order to compensate residual emissions of non-CO2 emissions across a range of "hard-to-abate" sectors (e.g., agriculture and industry).

Within this context, the EU has adopted a target to reach climate neutrality by 2050. Many alternative pathways are possible (Riahi et al., 2021; Keramidas et al., 2022; Tsiropoulos et al., 2020). Below, we focus on some shared characteristics and robust insights that emerge from the transformation pathways literature.

Balance between GHG emissions sources and sinks

Achieving the goal of climate neutrality requires fundamental transformation of particularly the energy system to achieve a balance between sources and sinks of emissions. While not all activities need to become net zero, anthropogenic sinks (removal from the atmosphere) need to be scaled up, while deep and rapid emissions reductions are introduced throughout all economic sectors, including the energy system.

Decarbonization of electricity supply is key and needs to be achieved more rapidly than other sectors

EU transformation pathways show that the electricity sector can play a key role and is generally decarbonized more rapidly that the energy use in other sectors (e.g., mobility, buildings, industry). A central element in this transformation is the upscaling of wind and solar power generation which reaches in many pathways more than a 10-fold increase by 2050 (> 5000 TWh) (Riahi et al., 2021; Keramidas et al., 2022; Tsiropoulos et al., 2020). Electricity generation from second-generation biomass plays an important role in many pathways, contributing the removal of CO_2 from the atmosphere. The expansion of bioenergy needs to be managed carefully to avoid trade-offs with biodiversity (Nabuurs et al., 2022). Successful upscaling and integration of renewable electricity hinges upon expansion and investments into the European power grid and power storage options.

Limiting energy demand is key and can be achieved while improving the quality of the energy services

The potential of demand-side measures to reduce GHG emissions is substantial and around 40–70 % of total emissions. Focusing on the demand-side of the energy transitions brings several advantages:

- Demand-side solutions are driven by end-use innovation and behavioral changes which can be introduced rapidly as they rely on granular technology associated with higher diffusion pace and higher learning and innovation rates (Wilson et al., 2020; Grubler et al., 2018; IPCC, 2022).
- Limiting energy demand has multiple benefits and is thus perhaps the most important measure in transforming the energy system. Any unit of energy that is not consumed has not only zero GHG emissions but also avoids trade-offs for all other sustainability dimensions, including energy security, pressure on land and other impacts (e.g., water and air pollution). (Roy et al., 2018)
- Limiting energy demand increases the flexibility of supply-side systems and reduces the reliance on potentially controversial supply-side technologies associated with higher sustainability risks or capital intensity (such as nuclear power, carbon capture and storage or removal of CO2 from the atmosphere) (Riahi et al., 2022).
- Most effective demand-side measures take a systems perspective, enhancing the circularity of the economy and enable shared economy. For example, a large number of studies show how integrating Shared Mobility services into city design and planning can improve the quality of mobility services with only a small fraction of the current infrastructure (< 5 %) (International Transport Forum, 2018). Shared mobility reduces not only energy demand and emissions, it has also critical benefits for other objectives, including less congestion, more convenience, freeing up space for greening of cities and increasing social interactions, and finally enabling more democratic access to services.

Electrification, hydrogen and synthetic (e-)fuels

From a technology perspective, a central driver towards net zero GHG emissions from the demand sectors (mobility, buildings and industry) is electrification and the shift towards electric appliances and services fueled by low-cost renewable electricity. The electrification potential by 2050 (as indicated by EU transformation pathways) is particularly high in the building sector (> 60 %), followed by the industry sector (> 40 %), and the transport sector (> 30 %) (Riahi et al., 2021; NGFS Climate Scenarios Data Set). In the industry and transport sector, hydrogen and e-fuels may play an increasingly important role, permitting the rapid reduction of oil and natural gas use in these sectors.

Digitalization as a key factor supporting the energy transition

Digitalization is creating opportunities through new goods and services with strong consumer appeal and large potential for energy demand and GHG emissions reductions (Wilson et al, 2020). Examples include shared mobility, renewable grid integration, and the sharing of consumer goods and services. Digital consumer innovations are critical enablers of demand-side energy transitions by connecting traditionally separated appliances into new (shared) systems with massively reduced energy and material inputs. A key aspect to unleash the full potential of digitalization are data ownership regulations that permit the use of digital data for societal benefit while securing data privacy of individual users.

Carbon dioxide removal (CDR) is necessary to achieve net zero CO_2 emissions

There is a wide portfolio of CDR options, ranging from afforestation and soil carbon enhancements in order to strengthen the planetary sink as well as novel technological options to remove CO_2 from the atmosphere and to store it underground in geological formations. The deployment of CDR at scale needs to be managed to avoid trade-offs with other societal objectives such as the SDGs. Current CDR activities add up to about 2 $GtCO_2$ globally and are dominated by the CO_2 uptake from afforestation, reforestation and management of existing forests. Emissions pathways indicate a long-term need of between about 4-10 $GtCO_2$ of CDR in order to offset residual emissions within a net zero emissions economy (Smith et al., 2023). Many EU pathways include 100s of Mt CO_2 CDR by 2050 (Riahi et al., 2021; NGFS Climate Scenarios Data Set).

Investments into low- and zero-emissions technologies need to be scaled up rapidly

Mitigation investment flows in Europe need to double to quadruple in order to achieve decarbonization consistent with global objective of limiting warming to below 1.5 C (low or no overshoot) (Bertram et al., 2021; Kreibiehl et al., 2022). Such investments would bring substantial benefits for Europe, increasing the resilience of energy supply and reducing the vulnerability due to fossil fuel supply disruptions and related price volatility. The macroeconomic mitigation costs of Europe (< 2 % loss of GDP by 2050) are modest and significantly lower than the global average, due to cost savings from reduced fossil fuel imports (Riahi et al., 2022).

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Commission for Interdisciplinary Ecological Studies (KIOES)
KIOES Opinions 13 (2023): 11–16.
doi: 10.1553/KIOESOP_013

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Energy savings and rebounds

Helmut Haberl and Karlheinz Erb

Given the urgency of addressing climate heating, options for reducing energy use without loss of societal wellbeing are high on the agenda, as evidenced by a new chapter introduced in the 6th report of Working Group III to the IPCC (Creutzig et al., 2022b). Its underlying question is to assess if it is possible to reduce the amount of energy required without reduction of the services provided by energy use, such as mobility, comfortable room temperature, or lighting.

The notion of 'energy services' was coined by Amory Lovins decades ago to highlight that societies do not need energy per se, but rather services provided by energy, such as healthy, comfortable and well-lit space for working and living, sanitation and hygiene, food or social inclusion or mobility (Lovins, 1979). Meanwhile, a large literature has emerged showing that most energy services could be supplied with significantly, often drastically less energy than is used today for their provision. For example, a recent study showed that global final energy demand could be reduced to 245 EJ/yr until 2050 – i.e., 40 % less than today, in contrast to increases projected in most other scenarios – if energy-efficient structures and technologies would be used to supply the required energy services (Grubler et al., 2018). This was by and large confirmed by a follow-up study (Creutzig et al., 2022a) and widely discussed in the report of Working Group III in IPCC-AR6 (Creutzig et al., 2022b). Reducing global final energy demand by that order of magnitude would strongly support global climate and sustainability goals because it would (1) reduce the amount of fossil fuels that need to be replaced by climate-neutral energy supply technologies, (2) reduce the mass of materials (e.g., concrete, steel, copper, aluminum (Kalt et al., 2022) or other metals, including rare-earths (Liang et al., 2022) for building up renewable energy capacities and (3) reduce reliance on contested technologies such as Direct Air Capture (DAC) or Bioenergy with Carbon Capture and Sequestration (BECCS) that need to be implemented to achieve ambitious climate goals (Grubler et al., 2018).

Defining energy services

Even after more than forty years of research, the definition of the concept 'energy services' remains contested, and a generally accepted definition has proven to be elusive (Fell, 2017). From an energy engineering perspective, energy efficiency potentials exist, when the same energy service can be provided with less energy input (Cullen and Allwood, 2010). Savings can be achieved along the entire supply chain:

- The conversion of primary energy (e.g., crude oil) to final energy (e.g., electricity and heat) can be improved; e.g., if more efficient refineries or powerplants are installed or waste heat is recovered and used for heating (cogeneration plants);
- The efficiency of the conversion of final energy to useful energy can be improved; e.g., by using condensing boilers instead of traditional ones;
- The same level of service can be provided by reducing useful energy required per unit of service (see the exergy – energy definition later in this chapter); e.g., by improving the insulation of a building and thereby reducing heat supply required per m^2 of floor area and year for maintaining the same room temperature as before.

From an engineering perspective, reducing useful energy demand is attractive because it also reduces all upstream conversion losses. For some services – e.g., room temperature – these potentials can be very large, as in the case of 'zero energy buildings' or 'passive houses' that can maintain a comfortable room temperature even in the absence of an active heating system. Such designs exist for new buildings, and even retrofits of existing buildings can come close to such standards, although this usually requires active components (Belussi et al., 2019). Economically efficient designs of such buildings become increasingly available (Kapsalaki et al., 2012).

Different concepts of 'energy saving potential'

Usually, different energy saving potentials are discerned: (a) the 'Theoretical Potential' is the maximum amount of energy that could be saved (without loss of energy services) with technologies that are thought to be possible within physical (primarily thermodynamic) principles. (b) the 'Technical Potential' is the amount of energy that could be gained by replacing currently prevalent technologies by the best currently available technologies. (c) the 'Economic Potential' (sometimes 'Techno-Economic Potential') is the part of the technical potential that can be leveraged with technologies that supply the same amount of energy services at lower costs than those in place today (Brugger et al., 2021). With regard to the latter, one can distinguish energy saving potentials whose realization is cost-efficient even at current energy prices from those that are only economically beneficial if external costs of energy supply are considered (macroeconomic or social perspective). Recent work suggests that considerable potentials exist to reduce energy use at low or no costs without sacrificing energy services through more efficient technologies if barriers for energy efficiency are removed, in particular if supported by new societal trends such as digitalization or implementation of circular economy policies (Brugger et al., 2021).

The 'rebound' effect

From the perspective of energy economics, energy services can be understood as goods (products) supplied using factor inputs such as capital, energy and other resources and technology; energy savings can then by leveraged if the services can be supplied with a different mix of factor inputs that reduces energy per unit of service (Haas et al., 2008). In this literature, the 'rebound' or 'take-back' effect (sometimes also called 'Jevon's paradox') receives much attention (Herring, 2006; Schipper and Grubb, 2000). The basic tenet is that raising energy efficiency will simultaneously raise demand for energy services because it makes them more cost-effective, convenient or attractive. A host of mechanisms may contribute to this effect. At the level of singe energy services in a household, one might assume that better insulation or more efficient heating systems might motivate consumers to enjoy warmer room temperatures; however, empirical evidence for such effects was weak (Schwarz and Taylor, 1995). At least in richer, industrialized countries, and with respect to room temperatures, such effects were only significant when more convenient central heating systems replaced work-intensive stoves, and negligible in other cases (Haberl et al., 1998).

In a broader (economy-wide) perspective, however, cost-efficient investments into energy efficiency imply that consumers save money, which they in turn can spend on other goods. Case studies in energy efficiency of automobiles and lighting systems found that rebound effects emerging from this mechanism may reduce the effect of energy efficiency investments by 10–40 %, depending on the energy intensity of the goods or services purchases with the money-savings resulting from the more efficient equipment (Borenstein, 2014). Moreover, if energy efficiency investments are coupled with other policies – e.g., regulations or carbon taxes – that raise the costs of energy-intensive goods or services, the effect can be mitigated (Haas et al., 2008).

Energy efficiency and growth theory

Still a different perspective emerges from the work of scholars who argue that energy, or more precisely: useful exergy, is a key driver of economic growth (Ayres and Warr, 2009a; Serrenho et al., 2014; Warr et al., 2010). Exergy is the mechanical-energy equivalent of energy (i.e., a measure of energy that considers the thermodynamic value of a specific energy source), and useful exergy is the physical work actually performed in an economy. Empirical studies suggest that useful exergy is highly correlated with GDP (Ayres et al., 2003; Serrenho et al., 2016), and Robert U. Ayres and Benjamin Warr have built an alternative economic growth theory on these observations (Ayres and Warr, 2009a). From that perspective, the rebound effect may be interpreted as the wealth gain achieved by raising energy efficiency instead of an unwanted side-effect of policies aimed at reducing energy use (Ayres and Warr, 2009b).

Such considerations motivate renewed interrogation of what energy services are, in what way they contribute to societal wellbeing (Brand-Correa et al., 2018; Brand-Correa and Steinberger, 2022; Fell, 2017; Kalt et al., 2019), as well as their role in ensuring decent living (Millward-Hopkins et al., 2020; Rao et al., 2019). The recently proposed 'energy service cascade concept' (Kalt et al., 2019) differentiates several steps between flows of useful energy and the delivery of wellbeing contributions. The authors argue that functions (i.e., physical action performed by energy) are provided by a combination of sociotechnical structures and natural resources (energy, materials). An example would be person-kilometers; i.e., the distances travelled per person and year. The service ('what is actually demanded') is often quite different. In the case of mobility, the service is often related to social inclusion (participation in the work process or engagement in social relations and activities) or supply with goods or other services (e.g., education, healthcare), while the actual movement across space, and even more so the distance, is often not an end in itself (Virág et al., 2022b, 2022a). In turn, what is regarded as a service or a benefit (wellbeing-contribution), depends on individual and societal valuation (Kalt et al., 2019) and is hence usually seen differently by different social groups, or even contested (Görg et al., 2017). Divergent perspectives on social wellbeing exist, ranging from the concept of 'hedonic' wellbeing (pleasure, enjoyment) to the 'eudaimonic' perspective focused on flourishing; i.e., the realization of potentials (Brand-Correa et al., 2018). The eudaimonic wellbeing concept builds upon work by Amartya Sen, Martha Nussbaum, Manfred Max-Neef and others (Brand-Correa and Steinberger, 2022). A broader range of resources required for service provision is considered in recently proposed concept of 'material services' (Carmona et al., 2017) or, formulated even more broadly, 'resource services' (Whiting et al., 2021). Such concepts appreciate that requirements for natural resources are usually systemically linked, an observation underlying the increasingly prominent concept of 'resource nexus' phenomena (Bleischwitz et al., 2018).

Raising eco-efficiency is good, but not sufficient

All these emergent perspectives have in common that they are skeptical of the ability of current socioeconomic structures to tackle current global sustainability problems (rapid and increasingly dangerous climate heating or the galloping loss of biodiversity (IPBES, 2019; IPCC, 2022)) while eradicating poverty, ending world hunger and ensuring a decent life for all within planetary boundaries (Fanning et al., 2022). This is also underscored by a recent systematic review revealing that, despite all environmental, climate or sustainability policies implemented thus far, decoupling of GDP from resource use and GHG emissions has so far never proceeded in a manner (i.e., sufficiently deeply and fast) that would be sufficient to reach ambitious climate goals (Haberl et al., 2020). Therefore, a growing number of scholars assumes that the systemic relationships between patterns in resource use (stocks and flows of materials and energy) and the delivery of services that are key for societal wellbeing, i.e. the stock-flow-service nexus (Carmona et al., 2022; Haberl et al., 2021; Pauliuk et al., 2021) needs to change fundamentally, if social wellbeing and ecological sustainability goals should be reconciled.

Conclusions

A range of options exist to reduce energy use without loss of social wellbeing and jeopardize decent living standards (see next chapter). Current research suggests that energy services – i.e., the contributions of energy to social wellbeing – enjoyed today in wealthy countries such as those of central Europe could be provided with substantially (30–50 %) less energy than today. Harnessing these energy saving potentials will require suitable policies, some of which may only require implementation of more efficient technologies, while others will require structural changes. The latter may include, for example, policies to reduce mobility functions (ton-km or person-km) required for provision of services such as social inclusion, access to health services and groceries, etc. through changes in settlement or infrastructure patterns, or changes in mode of transport from energy inefficient individual mobility to public or active mobility. Rebound effects can reduce energy savings from technological measures, but they can be counteracted through suitable design of policies and incentives. Ultimately, however, changes in biophysical (infrastructures), social (institutions) and economic (organization of production and consumption) structures will be needed to achieve a good life for all with less energy (and generally resource) demand, and achieve ambitious climate targets (APCC, 2023).

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Commission for Interdisciplinary Ecological Studies (KIOES)
KIOES Opinions 13 (2023): 17–18.
doi: 10.1553/KIOESOP_013

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Decent living standards

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Decent living standards (DLS) refer to the efforts defining a set of universal, irreducible and essential set of material conditions for achieving basic human wellbeing, along with indicators and quantitative thresholds, which can be operationalized for societies based on local customs and preferences. The approach proposes thresholds in physical and social wellbeing dimensions including housing, thermal comfort, nutrition, access to energy, water, sanitation, appliances, health care, education, and mobility infrastructure. Therefore, the approach goes beyond existing multidimensional poverty indicators by comprehensively addressing living conditions and the means of social participation. The DLS approach can offer a normative basis to develop minimum wage and reference budgets, and to assess the environmental impacts, such as climate change, of eradicating poverty. In the Global South context, the DLS discussion focuses on the energy needs for basic well-being. In the Global North, the approach focuses on the affluence of the wealthy and discusses the need for a demand-side transformation (Rao and Min 2018).

The IPCC AR6 WG3 SPM proposes that eradicating extreme poverty and providing decent living standards to all regions in the near-term can be achieved without significant global emission growth. However, Rammelt et al. (2022), who operationalize 'just access' to minimum energy, water, food and infrastructure, show that achieving just access in 2018 for the most underprivileged would have produced 2–26 % additional impacts on the Earth's natural systems of climate, water, land and nutrients, and further crossing planetary boundaries. This is equal to the impacts caused by the wealthiest 1–4 % of the population. Achieving just access to the natural resources and energy therefore calls for a radical redistribution of resources.

Bayliss et al. (2021) argue that satisfying human energy needs globally could be achieved using less than half of current energy consumption, however, this would require reducing inequalities and an improved provisioning system that could enable much higher satisfaction of human needs at lower energy needs. Energy inequality is large and driven by the most affluent.

Similar inequalities are observed in the lifestyle CO_2 emissions. Schuster and Otto (2022) who use representative population survey data from Germany show that the lifestyle greenhouse gas emissions in the lowest and highest emission groups can differ by a magnitude of ten. Income, education, age, gender and regional differences result in distinct emission profiles. The authors analyze lifestyle CO_2 emissions in sectors including housing, transportation, and consumption. In the housing sector, the most important sources of emissions are heating and electricity use. The per capita living space increases with income and most of the respondents like to live on their own or in two-person households. Excessive living space per person is ineffective from an energetic perspective, however, changing housing preferences through political means or incentives is difficult to achieve. Reduction of emissions in the housing sector are likely to emerge through access to fossil fuel free heating systems, switching to renewable energy sources in general, and improved house insulation and energy efficient home appliances.

In the transportation sector, it is noticeable that the majority of the population travels little. The remainder, however, have extremely mobile lifestyles. Income is correlated with carbon emissions also in the transportation sector. Travel and cars are still status symbols, not only for the wealthiest. The highest emissions in transportation arise in the 30–49 age group. The possible reasons could be that this age group has a fixed income, are cosmopolitan in outlook, but also are trying to establish themselves socially via status symbols. However, the debate on mobility-related emissions should clearly indicate that high income groups can buy their way out of mechanisms such as carbon pricing or afford to switch to e-mobility, and such policy implications clearly need to incorporate elements of social justice. In addition, men have a higher footprint in the transport sector than women. In the sector of consumption that includes food and non-food consumption, the CO_2 emissions from nutrition are not group specific. Dietary habits are not income specific and in the German sample the respondents across different regions and milieus had relatively similar eating habits. The reduction of meat consumption across different social groups could contribute the most in terms of reducing CO_2 emissions. Other variables including education and cultural background do not influence emissions in the food consumption. There are, however, important regional differences. In Germany the respondents living in the former GDR consume less energy than individuals in the former FRG who also have higher levels of consumption (Schuster and Otto, 2022).

Otto et al. (2019) furthermore concentrates on lifestyle greenhouse gas emissions of the most wealthy, that are not included in most of population surveys. The authors estimate that the emissions from 0.54 % of the wealthiest of the global population, are larger than lifestyle emissions of the world's poorest 50 %. The highest proportion of the emissions of the wealthiest was due to extreme mobility, including frequent flying with private jets and in business cabins as well as conspicuous consumption and the maintenance of multiple and large houses. The authors point out that policies are needed that target and curb emissions of the wealthy, since they can afford clean technologies as well as their lifestyle choices have an important downstream effect and influence aspirations and lifestyles of other social classes.

The DLS approach can help to address social justice issues in the transition to resilient and net-zero societies. Large inequalities in the resource and energy use exist between different countries as well as within countries. Multiple evidence shows the privileged consume disproportionately more resources and energy to maintain their lifestyles than the less privileged. In addition, the least privileged who are usually less mobile and often live in marginal areas and conditions are disproportionately more affected by environmental pollution and climate extremes. The poorest social groups also often perform work that makes them more exposed to the impacts of climate change and environmental pollution, including occupation in agriculture and construction. These inequalities must be taken into account. Defining a universal, irreducible and essential set of material conditions for achieving basic human wellbeing, along with indicators and quantitative thresholds, reflecting local customs and preferences, can help to go beyond poverty eradication and enable social participation of the least privileged. However, this discussion must also include redistributive policy instruments, setting standards and bans on most polluting and harmful activities and technologies.

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Commission for Interdisciplinary Ecological Studies (KIOES)
KIOES Opinions 13 (2023): 19–20.
doi: 10.1553/KIOESOP_013

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Civil society initiatives

Simone Gingrich

To achieve a rapid and strong reduction in greenhouse gas emissions while securing decent living for all, transformational change in resource use is required. Particularly affluent countries and income groups are challenged to decrease excessive energy use in production and consumption, while decarbonizing energy use required for meeting human needs (Pathak et al., 2022). Traditionally, public debates, policies and research have focused on increasing energy efficiency and reducing emissions intensity in production and consumption to achieve emissions reductions.

Recently, the focus of debates has broadened. The notion "demand-side solutions", applied e.g. in the recent IPCC report (IPCC, 2022), calls for not only efficiency improvements ("improve"), but also changes in energy services towards less emissions-intensive ones ("shift"), as well as avoidance of particular services while maintaining quality of life ("avoid") (Creutzig et al., 2022). This perspective has gone hand in hand with a shift in focus from techno-economic dimensions alone (following the rationale that technological advances will lead to emissions savings at reduced prices and thus ignite social change) towards incorporating human agency in a broad variety of roles beyond producers and consumers. The most recent IPCC report addresses collective action in multiple ways, with social actors in roles such as citizens, investors, consumers, role models and professionals (Pathak et al., 2022).

Sustainability sciences informed by systems science use the notion of "leverage points" to describe different types of intervention towards a socio-ecological transformation (Abson et al., 2017). The leverage points scale has been used to map political interventions, showing that a focus on shallower interventions alone results in incremental change only (e.g., a low carbon tax), while much deeper interventions changing the implicit system intent (e.g., the unquestioned political goal to achieve economic growth) would be required for fundamental change like the kind required for effectively reducing greenhouse gas emissions quickly (Dorninger et al., 2020).

To bring about transformative change, social movements have key roles to play: For example, since 2018 the climate strikes in 180 countries have brought the urgency of reducing emissions to the public agenda (Fisher and Nasrin, 2021). While global emissions continue to rise, some social movements in the context of energy and climate-change mitigation already demonstrate concrete impacts. For example, social movements directly influence political decision-making through campaigning against the expansion of fossil fuel extraction (Piggot, 2018). Others contribute to implementing low-energy mitigation strategies on the ground (Vita et al., 2020). Historical social movements (e.g., to end slavery to introduce women's reproductive rights) have taken decades to achieve their political goals (Sovacool, 2022). Continued political activism by social movements can be expected to contribute relevantly to leveraging emissions reductions in the future, and to contribute to a socially just energy supply (Sovacool and Brisbois, 2019).

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Commission for Interdisciplinary Ecological Studies (KIOES)
KIOES Opinions 13 (2023): 21–24.
doi: 10.1553/KIOESOP_013

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Energy needs, social potentials and barriers to change – with a focus also on possible input from health-related civil society initiatives

Hanns Moshammer

Every life form needs and consumes energy in order to sustain its structure and functioning. The daily energy need of the human body depends on age, sex, weight (and muscle mass) and the amount of physical activity but can be approximated by 2,000 kcal or about 2.3 kWh. Even at rest, the energy needed to sustain homeostasis, is about 100 kJ per kg body weight and day. But since the early days of humankind, since the beginning of the use of fire, energy was not only consumed in the form of food. Fire served at first to provide warmth and protection, but it also helped increasing the scope range of foodstuff digestible and eatable by human guts. External energy in the form of fire also helped preserving food. But throughout human development beginning in the Neolithic revolution, energy capture was much more than calories uptake through food and cooking foodstuff over a fire. Indeed, Ian Morris in his book "Why the West Rules for Now" [1] uses energy capture as his first and likely most prominent indicator of social development. As he points out, his aim is to measure social development, not to pass judgment on it. Higher social development is not "better", it only the describes the ability "to get more things done". But since in history societies that had less of this capacity than other societies often were overthrown and defeated, this inevitably accelerated the struggle for highest energy consumption. In the year 2000, the highest *per capita* energy consumption is found in the United States with 228,000 kcal (about 265 kWh) per day. Morris compares that to estimated 3,500 kcal (about 4 kWh) per day in present hunter-gatherer societies [1, 2].

As Roger Pielke points out in his blog [3] using 2010 World Bank data, average life expectancy per country increases with the energy use *per capita*. He concludes: "Energy poverty is not the only factor which contributes to below-average life expectancies, but it is clearly a very important factor." It is noteworthy that in his scatter-plot he draws a linear regression line. But when looking at the data points one does get the impression that the dose-response curve is not linear but clearly shows signs of saturation at the higher levels of energy consumption. But certainly, being able "to get more things done", at least up to a certain point, is beneficial for human life expectancy. This is confirmed by Lloyd [4] who sets the saturation point of this effect at about 2,000 kg oil equivalent *per capita* per year (about 65 kWh per day). The detrimental effect of energy poverty is therefore most clearly demonstrated in developing countries like Kenya [5]. But even there, clean energy in the form of access to electricity is to be preferred over energy from dirty biomass burning [6].

Steinberger et al. [7] warn against this simplified approach. They conclude: "Increases in primary energy and carbon emissions can account for only a quarter of improvements in life expectancy, but are closely tied to growth in income. Facing this carbon-development paradox requires prioritizing human well-being over economic growth." Indeed, energy consumption and wealth are strongly correlated. Salehnia et al [8] point out that energy consumption has only a small effect on life expectancy that even depends on the starting point. Renewable energy fares better in that regard than fossil fuels. But the strongest effect on life expectancy was found for the GINI coefficient. Thus, a more equal distribution of wealth in a society is better than a higher wealth (measured as GDP) on average. The beneficial effect of renewable energy on life expectancy and the adverse effect of fossil fuel consumption is further elaborated using the example of China by Wang and Luo [9] and Wang et al. [10]. Especially the use of solid fuel like coal as source of heating is detrimental to health.

In summary, at low energy use an increase is beneficial to health, standards of living, calorific intake, life expectancy, and literacy levels [5]. At higher levels of energy use, a runaway social selection process [11] seems to take hold: competition both between and within groups favors those who are able to harness the most of the energy, even if this development is detrimental to the group or humankind as a whole.

Under current conditions higher energy use effects on life expectancy reaches a saturation level at around 2,000 kg oil equivalent per capita per year (Fig. 1). But according to the studies described above, even below this level a more egalitarian and cooperative society structure would provide better and larger gains than a further increase in energy consumption.

As a medical doctor, I am concerned about the individual physiological energy need and how it relates to the actual need of a civilized person. The human physiology was shaped in an evolutionary process mainly in the early (Paleolithic) phases of humanity. For survival, humans needed to store energy in their bodies (mostly in form of fat) and to live on these resources repeatedly for more or less prolonged times. Consuming calories for storage was delightful and the sweetness of sugar became a joyful signal. These mechanisms triggered behaviors that remained health promoting as long as they were interrupted by phases of shortage and repeated short bouts of massive physical exercise. Living in an environment with plenty and continuous food sources and a lack of physical demands is not health-promoting for a physiology that was shaped under these very different circumstances. So, even if the Paleolithic diet would really be reflected by the concept of this name developed in the 1970ies [12], following such a diet now would not be beneficial to health.

During the Neolithic revolution, humans started shaping the environment to their needs (with settledness and with breeding of plants and animals) also with the intention of protecting themselves against extreme (meteorological) events: They built storage

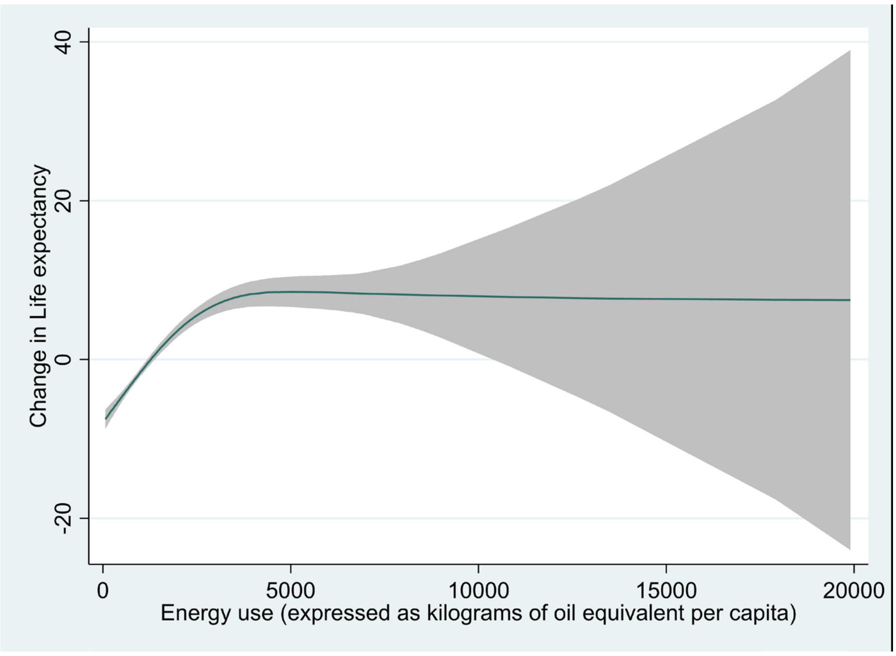

Figure 1: Association between annual energy use per capita and life expectancy at birth, data from the World Bank Development indicators database (http://data.worldbank.org/?display=default). 1000 kg oil equivalent per year equate to about 32 kWh per day. The latest fairly complete data on energy use were from 2014. Non-linear regression (general additive model, spline with 3 degrees of freedom for energy use, weighted by population number), local effect estimates and 95 % confidence interval, produced with STATA Vers. 17. Note the limitations at high energy use due to few datapoints leads to large uncertainty.

facilities to prepare for droughts, they built shelters to protect from storms and heavy rain, etc.). But, in the longer run, it turned out that these new facilities were not only used against emergencies but became amenities for the whole life. With settledness came the possibility of amassing property. And with more property at stake, extreme events caused increasingly larger losses. What was started as a means to support life during extreme events, became the most vulnerable asset during such extremes. Or, to give a more modern example: Our society compliments itself for its inclusiveness. To allow handicapped persons or parents with baby buggies access to the platform of the metro station, elevators were built. But mostly these necessary aids for the disadvantaged are used by everybody, not only by those in need, thus increasing our unhealthy and sedentary life-style.

All these are but small examples demonstrating how our current energy need by far exceeds the actual physiological need. Amenities that offer more than just bare survival, are nevertheless often necessary for a civil life. It is practically impossible to define how much is too much or at which point the side-effects outweigh the intended benefits. But it is quite obvious that that point of optimal energy consumption has long been exceeded by most individuals in our society and by most societies on earth. Therefore, as health professionals, we can contribute to the debate by informing individuals and the society as a whole about the "benefits of less". "Burning fat, not fossil fuel" as a slogan is good for the individual health, the local environment (because of less noise and air pollution produced), and for the global environment due to the reduced carbon foot-print.

The world is locked in a stand-still, where "everybody" (and this description applies both to individuals and to nations!) knows what has to be done to mitigate climate change, but everybody also waits for the first move by someone else, nobody trusts others enough to take the first step, and nobody feels that his personal action alone can make a difference. In this situation, pointing out the individual and local benefits of local action for the global good might make the difference. Therefore, in this debate, medical input regarding win-win measures could be an important game changer [13]. Unfortunately, many medical doctors are rather conservative and feel responsibility only for individual patients, not for society as a whole, and do not feel prepared to engage in political debates. But hopefully this is changing and a new generation of medical doctors (and students) does take an increasingly active part in civil society initiatives like scientists4future [14], doctors4future [15], students4future [16].

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Commission for Interdisciplinary Ecological Studies (KIOES)
KIOES Opinions 13 (2023): 25–27.
doi: 10.1553/KIOESOP_013

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Potentials and limitations of regenerative power: Hydro, wind, and solar

L. Y. Pao

Wind and solar energy are undergoing a revolution in growth and advancement in response to a combination of technological, social, political, and economic factors. It is especially fueled by goals of many countries to defossilize their power grids as well as their entire economies (Heal 2017, Cardenas et al. 2021). The result has been an unprecedented increase in wind and solar energy. In particular, the world added over 90 GW of wind capacity in both 2020 and 2021 (EIA 2022, Wiser et al. 2022) and added over 125 GW of solar photovoltaic (PV) capacity in both 2020 and 2021 (EIA 2022, IRENA 2022). The world added approximately 24 GW of hydropower in each of 2020 and 2021. With a capacity factor of 40 % for wind, each of the 2020 and 2021 added wind power capacities amounts to an added 315 TWh of wind energy generation per year; with a 20 % capacity factor for solar PV, the newly installed solar PV capacity in each of 2020 and 2021 yields 219 TWh of added solar energy generation annually; and with a 45 % capacity factor for hydropower, the added hydropower in each of 2020 and 2021 provides 24 TWh of hydroelectric energy annually. While the growth rates of solar PV and wind power are expected to increase significantly over the next decade, the growth of hydropower is expected to remain at approximately the same level. Because hydropower has a longer history of development, its requirements of the geographical terrain, and that many of the best sites for hydropower have already been developed, installed hydropower is growing more slowly.

Although it is difficult to predict future growth rates, it is worthwhile to consider published forecasts to gain a sense of the potential magnitude of installed capacity increases in the coming decades. Installed renewable power generation capacity will need to grow from the approximately 2,500 GW currently to at least 27,700 GW by 2050 if the world is to achieve the goal of limiting global warming to no more than 1.5° C increase in average temperature relative to pre-industrial levels (IRENA, 2021). The installed capacity of solar PV would need to grow from 849 GW in 2021 (IRENA 2022) to over 14,000 GW, and wind power (onshore and offshore) would need to grow from 839 GW in 2021 (Wiser et al. 2022) to 8,100 GW by 2050 (IRENA 2021).

The Austrian government set a goal increasing from its current 80 % renewable electricity level (IRENA 2022) to achieving 100 % renewable electricity by 2030 (IEA Wind TCP 2020). At the end of 2021, Austria had 22 GW of installed renewable power generation, with 14.7 GW of hydro power, 3.5 GW of wind power, 2.7 GW of solar PV, and 1.3 GW of bioenergy (IRENA 2022); and goals of additional 10 TWh of wind power, 11 TWh of solar PV, and 5 TWh of hydropower over the 2020-2030 period have been set (IEA Wind TCP 2020).

However, multiple challenges exist for the wide-scale deployment of wind and solar energy. First, addressing the impacts of wind and solar energy's inherent intermittency (variability that is often unpredictable for more than a few days) on regional power grids is a growing challenge. Wind and solar energies are non-dispatchable. When available energy from a wind or solar farm is high and exceeds grid demand, any energy that cannot be stored must be curtailed. This idling of equipment is not entirely different from the operation of thermal power plants that sit idle as energy demands fall periodically throughout the day. However, curtailed solar and wind energy represents a lost opportunity for revenue generation and for decarbonization. Further, intermittency can pose a risk to the reliability of systems. When the available solar and/or wind energy drops and/or there is an increase in grid demand, options must be available to avoid a "solar or wind energy mismatch." Such options include using power from other sources, some of which may emit greenhouse gasses, or relying on shifting flexible demand in time, although that potential is currently limited. Overall, significantly decarbonizing the grid with substantial amounts of variable renewable energy at low cost requires new approaches to ensure the resilience of a power grid whose physics of operation requires supply-demand balance. Various options are being developed to address this objective, which can be used together or individually, but each one presents challenges.

Currently, the fluctuations in the availability of wind and solar energy resources are typically addressed via capacity from dispatchable power sources that are often carbon-based and can be expensive if their existence is required specifically for this purpose. Another option is demand-response strategies to encourage power usage when renewable energy is plentiful, but their impact has historically been modest. Another strategy is to expand transmission infrastructure connections to other grids; however, these options also require investment in physical infrastructure and, often, a significant land area. Further, they can face regulatory issues as transmission lines cross borders causing delays and increasing costs.

A further option is energy storage. Energy storage is already widely used at short timescales (from a few seconds to many minutes), but there is increasing interest in using long-duration storage (operating following daily, seasonal, or more sporadic cycles) to solve the growing solar and wind energy mismatch issue (Ziegler et al. 2019, Trancik 2020). However, long-duration GW-scale storage is relatively expensive because of the large energy capacities required and the high costs of current storage technologies (Zhang 2021). The issue is not just the installed storage capacity (GW-scale), but also the energy content needed to be stored (TWh-scale). Energy storage costs are projected to be a strong function of regional grids and their resources and demands but are relatively high across many different contexts (Cardenas et al. 2021). Thus, for long-duration, grid-scale energy storage to be a viable solution, new advances are needed in solar and wind energy harvesting and energy storage technology, as well as in economic evaluation and community integration (Aziz et al. 2022). It is anticipated that storage would be used in conjunction with other options (including demand-response, increased capacities of solar and wind energy systems, supplemental generation, and transmission line expansion) to provide the most cost-effective and performance-effective solution for a particular grid.

In addition to developing low-cost and scalable technical solutions for addressing solar and wind intermittency, the ultimate goal of decarbonizing the grid is to benefit society. Therefore, regardless of which technological solution addresses the question of intermittency, implementing these systems at specific sites requires careful consideration of the interplay between communities and engineered systems, otherwise projects may not achieve their promised benefits. As such, social acceptance is a general challenge that should be addressed by any renewable energy development project, including those with integrated storage (Aziz et al. 2022).

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Commission for Interdisciplinary Ecological Studies (KIOES)
KIOES Opinions 13 (2023): 29–35.
doi: 10.1553/KIOESOP_013

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Renewable energy potentials: Biomass/bioenergy

Karlheinz Erb, Simone Gingrich and Helmut Haberl

Biomass production in ecosystems

Biomass is produced by green plants in the process of photosynthesis; i.e., through conversion of radiant energy from the sun into chemically stored energy. Biomass production of ecosystems is usually measured as 'net primary production' or NPP, defined as the amount of chemically stored energy produced by the plant, net of its own energy requirements. In other words, NPP is gross primary production (GPP; the entirety of carbon fixed in photosynthesis) minus plant respiration; i.e., the CO^2 released as a result of the plant's catabolism (Lieth and Whittaker 1975).

NPP is either used by the plants to build up their standing crop (biomass stock) or serves as input of trophic energy on which all heterotrophic food webs (and hence the diversity of animals, fungi and heterotrophic micro-organisms) depend (Vitousek et al 1986). Humans use biomass for provision of food and feed as well as a raw material for various purposes, but also for the provision of technical energy derived from combustion of solid, liquid or gaseous biomass (Coelho et al 2012, Creutzig et al 2015, Rogner et al 2012). The effects of land use and biomass harvest on ecological energy flows and carbon stocks in ecosystems is assessed using the 'human appropriation of net primary production' (HANPP) indicator framework (Haberl et al 2014).

Biomass in the energy system

Currently, biomass provides approximately 10 % of global technical primary energy supply (Turkenburg et al 2012). In the year 2020, renewable energy contributed 17 % to primary energy supply of the European Union; the share of biomass of the EU's renewable primary energy supply is approximately 60 % (https://ec.europa.eu/eurostat/de/web/energy).

From an energy system perspective, bioenergy has several advantages over other renewable resources. Biomass is flexible because it can be stored and used whenever energy is needed, in contrast to intermittent sources such as solar or wind energy. It can replace other combustible energy carriers in many applications. For example, solid biomass can be used in power plants or other stationary installations, and liquid biomass can be used for vehicle motors (Turkenburg et al 2012). On the other hand, an important disadvantage is that the efficiency of producing mechanical energy (and electricity) through combustion is limited by the Second Law of Thermodynamics, in contrast to the direct conversion of mechanical forms of renewable primary energy sources such as wind or hydropower into electricity.

Moreover, it cannot be taken for granted that one additional energy unit supplied to the energy system replaces fossil fuels. Just as well, rebound effects (see chapter 'Energy savings and rebounds', p. 11) can occur; that is, additional energy supplied to the energy system can support rising energy demand rather than reducing use of other fuels (Bird et al 2012). Empirical analyses suggest that such effects can be substantial, and adding one additional energy unit of biomass or hydropower may in some instances only replace as little as ~10 % of fossil-supplied energy units (York 2012). Such effects can be counteracted through carefully designed policies, but it is important to judge success of renewable energy policies not by the amount of additional energy supplied, but by the reduction of fossil energy achieved.

Bioenergy and Net Primary Production

In principle, increases in bioenergy provision can be achieved by (1) expanding the extent of land use allocated to energy crops, (2) raising harvest rates in forests or by increasing yields (biomass harvest per unit of area and year) of energy crop plantations, or (3) increasing the efficiency of biomass use, i.e. the increase of cascadic uses. However, all these strategies have limited potential (Erb and Gingrich 2022).

Ecosystems are already under massive land-use pressures. This sets boundaries to significant increases of biomass harvest for energy through expansion of land use for this purpose. The current (2010) total NPP of land ecosystems amounts to approximately 59 PgC/yr. This is ~4 % less is than the NPP of potential natural vegetation, i.e. the hypothetical NPP of ecosystems that would exist in the absence of land use (Kastner et al 2022). Main reasons are land degradation, agro-ecosystems whose NPP falls short of potential NPP, and land use for biologically unproductive purposes such as built-up land (settlements, infrastructures). In addition, 15 % of current NPP is harvested or destroyed during harvest, for food, feed, fuel or fibres. The energy content of all harvested biomass is about 343 EJ/yr, of which 57 EJ/yr are biomass used for bioenergy (including biogenic wastes; Tab. 1).

For comparison, the global primary energy supply was 585 EJ/yr in 2021, 493 EJ/yr of which originated from fossil fuels (Clarke et al 2022). Global fossil fuel use exceeds total current socioeconomic biomass harvest by ~40 %. A ratio in a similar order of magnitude can be found for Austria (Table 1). In other words, substituting biomass for fossil fuels at larger scales would entail a doubling of current harvest levels – a considerable challenge, given that already today many ecological implications relate to land use (Arneth et al 2019).

Table 1. Comparison of Net Primary Production (2010) and energy use (2019), globally and for Austria. Sources: (Kastner et al 2022, Clarke et al 2022, BMK 2020).

	Global [EJ/yr]	Austria [EJ/yr]
Actual NPP	2 159	2.111
Total harvest	343	0.696
- of which: bioenergy	57	0.225
Total fossil energy supply	493	0.979
Factor [energy supply / total harvest]	1.44	1.41

Challenges of raising biomass supply for energy

Generating large amounts of additional biomass harvest by expanding land areas used for energy crops would require massive land-use changes. These would in turn result in substantial releases of carbon to the atmosphere and put high pressures on biodiversity (Creutzig et al 2021). Currently, more than three quarters of the earth's ice-free land are under use. Large expansion of land used for bioenergy will likely result in competition between bioenergy production and other land uses such as food production or biodiversity conservation (Haberl 2015, Smith et al 2010). It may also lead to rising competition for other scarce resources such as water (Coelho et al 2012) and trigger further land degradation (Arneth et al 2021).

Raising the productivity on currently used agricultural areas, i.e. pushing biomass yields on this land, is also intricate. Such an intensification of production is likely to rely on higher inputs of mineral fertilizers, pesticides and energy inputs in agriculture, at least if it is based on currently available technology (IAASTD 2009). Thus, and also because potentials for cascadic use of biomass for energy are limited (Haberl et al 2010, Haberl and Geissler 2000), mobilization of large bioenergy potentials requires raising harvests on forested land to make more biomass available for energetic purposes (Smith et al 2014). These interdependencies result in complex systemic feedbacks between many components of the land system, among others demand for other land-based resources, most notably food, which in turn depend of future diets (Erb et al 2016), future levels of agricultural yields and hence agricultural technology (Theurl et al 2020), desired levels of biodiversity protection (Erb et al 2012), and many others (Arneth et al 2019).

The opportunity carbon costs of bioenergy

Besides issues of land-competition and degradation, several other critical elements relate to bioenergy utilization for climate change mitigation (Fig. 1). A key element that only recently gained attention in the scientific literature are the opportunity carbon costs of bioenergy (Erb et al 2022, Marques et al 2019, Ter-Mikaelian et al 2015, Norton et al 2019). This concept acknowledges that many managed ecosystems, when left undisturbed, can absorb often very substantial amounts of carbon over long (decadal to centennial) time periods. The reason behind this mechanism is that carbon pools in used ecosystems, including forests, are smaller than they would be in the absence of land use (Erb et al 2018, Matuszkiewicz et al 2021, Gingrich et al 2007). This is a result of current and past uses that create a disequilibrium between inflows (NPP) and outflows (mortality). When taken out of use, many ecosystems enter a phase of natural succession, or recovery, and draw substantial amounts of carbon from the atmosphere. This mechanism is one reason why land ecosystems offer substantial potentials for "natural climate solutions" (Griscom et al 2017).

This implies that biomass harvests are associated with 'opportunity carbon costs': If left unharvested (or harvested less intensively), ecosystems would absorb carbon from the atmosphere. Maintaining or even raising biomass harvest levels results in ecosystems absorbing less carbon than they would otherwise, i.e. reduces the strength of the C sink (Searchinger 2010). This foregone C-sink needs to be considered when gauging the full GHG implications of bioenergy. It is correct that this C-sink (i.e. the yearly flow of C from the atmosphere into biota and soils) would saturate after a defined time period, usually decades or centuries. But then the ecosystem would represent a larger pool of carbon (stock of biomass and C in biota and soils) that had previously been in the atmosphere (Haberl 2013).

Conceptualizations of the opportunity carbon costs of harvest therefore highlight the fact that biomass utilization for the substitution for fossil fuels is time-dependent. This is reflected in concept of "carbon parity time", which represents an extension of the "carbon debt" approach (Fargione et al 2008, Mitchell et al 2012). The carbon debt expresses the initial carbon losses due to land clearings, e.g. from forests to cropland dedicated to bioenergy production. These carbon losses are consequently "repaid" through sub-

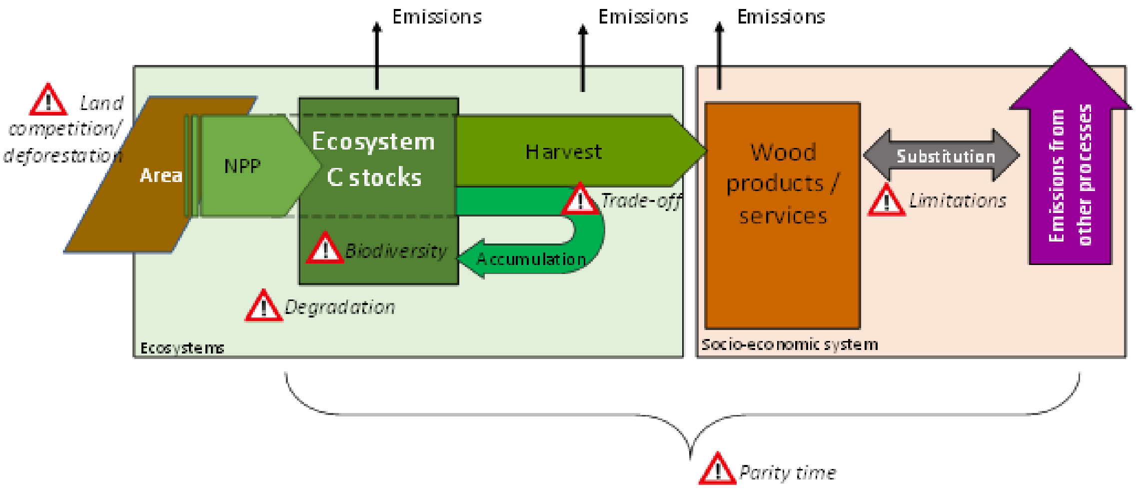

Figure 1: Carbon dynamics in ecosystems and their connection to socio-economic activities. Pictograms indicate critical elements requiring attention if bioenergy production is to be raised.

stitution of bioenergy for fossil energy. The carbon parity time expresses the time required for the sum of substitution of emissions and forest recovery to equal the opportunity carbon cost of the initial harvest. In temperate and boreal zones, this time is in the range of few to several decades, sometimes centuries (Nabuurs et al 2017), although large uncertainties relate to such assessments and system boundary selection additionally hampers comparability of results (Bentsen 2017, Cowie et al 2021).

Another perspective focuses on stocks and flows of carbon in forest ecosystem and management intensity (i.e. wood harvests). This research deals with C stock-flows at different levels of wood harvest, thereby considering that the C stock of a forest depends strongly on harvest intensity (frequency of harvest events, i.e. rotation period). Above the optimal ('maximum sustainable yield') length of the rotation period, there is an inverse relation between C-stocks in the forest and yearly wood output. Under equilibrium conditions, C stocks approach a maximum as harvest levels are reduced (rotation period extended), and conversely, C stocks decline as harvest levels are raised (rotation period approaches maximum sustainable yield). This implies existence of a time-dependent trade-off between maximization of C stocks (achieved by reducing harvests) and maximization of harvests (which reduces the C-sink compared to its potential). Consideration of the fact that the C-sink will saturate allows calculation of C payback times of various intensity levels of forest management (Holtsmark 2012, 2015, Haberl et al 2013, Luyssaert et al 2008, 2018, Cherubini et al 2011, Lin and Ge 2020).

The importance of substitution coefficients

Besides ecosystem carbon dynamics, the quantity of emissions avoided by substituting existing fuels with biomass is a vital element of these considerations. The decisive factor for the climate effect of substitution is the actual substitution coefficient (Kalt et al 2019), i.e. the quantity of emission reductions achieved per unit of biomass use. The substitution coefficient depends on the emission intensity of the substituted products. It declines when bioenergy systems are less energy-efficient (because bioenergy then replaces less fuels), and when the fuel replaced has lower GHG emissions per unit (e.g., if natural gas is replaced instead of coal). With the ongoing decarbonization of the energy system resulting from the increasing spread of nearly GHG-neutral technologies such as photovoltaics or wind power, the substitution coefficient is falling, and may fall even further in the future as such renewable sources spread.

Conclusions

How much biomass can be sourced sustainably for bioenergy at regional and global levels has become a controversial topic, and consensus remains elusive despite a surge of academic publications, even in assessment reports (Coelho et al 2012, IPCC 2022, 2019, 2018, Smith et al 2014). Agreement is emerging that sustainable bioenergy potentials are limited, owing to the many ecological and social trade-offs and the repercussions of bioenergy production on the ecological carbon dynamics that can only be revealed in non-use counterfactual analysis and are thus often neglected. But exactly where that limit should be set, and how to design optimal systems and pathways remains an important research question, and subject matter of controversial debates, owing to the complex and multifaceted interactions in land and biomass-use systems.

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Renewable energy potentials: Woody biomass

Robert Jandl

Several European policies and directives advocate both the increased utilization of forests for the provision of biomass for the bioeconomy, and decreased forest harvesting rates in order to promote the sequestration of atmospheric CO_2 in the biomass and soils of forests. It is challenging to reconcile these two objectives on the same tract of land (Köhl et al., 2021). Particularly, a dim view is taken on the use of wood for energy production in Europe and the topic remains controversial. Many examples worldwide, both in developing and highly developed countries exist where forests are degraded, unsustainably managed and even destroyed for the sake of energy extraction (Searchinger et al. 2022). However, when sustainable forms of forest management are implemented, forests are multifunctional and can deliver ecosystem services, long-lasting wood products and bioenergy (Forest Europe 2020). The limitations of the quantitative contribution of European forests both for reaching the climate objectives and the energy demand need to be recognized and only a small climate change mitigation effect can be expected from European forests (Grassi et al., 2019).

Ideally, harvested wood (primary wood) is turned into valuable and long-living products, and is utilized in a cascade with energy production as final step. Realistically, some primary wood that could be used for valuable products is directly turned into fuel wood (Fig. 1).

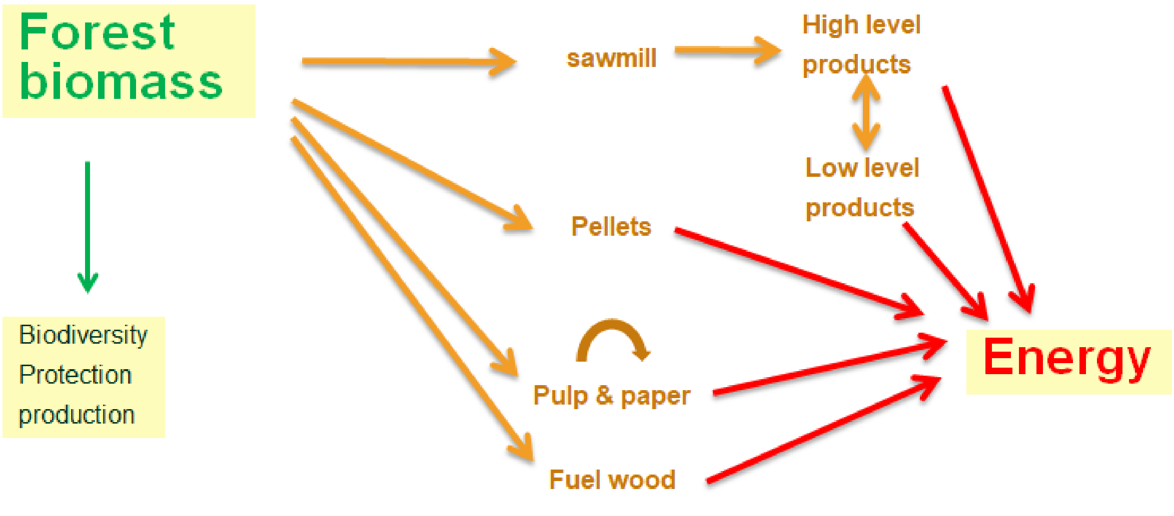

Figure 1: Energy production from wood biomass in a cascade from wood to energy and fuel wood production. Adapted from Schulze et al. (2021)

In Europe, approx. 17 % of the energy supply comes from renewable sources, e.g. hydropower, wind energy and solar energy. Primary biomass and wood processing residues, respectively, contribute 23 and 19 % of the renewable energy. The contribution of primary biomass to the total European energy demand is 4 %, and woody residues add another 3 % (EC 2019, Forest Europe 2020). The origin of the wood resources for bioenergy varies widely within Europe. In Mediterranean countries primary wood from coppices is a major source of bioenergy (Camia et al., 2021). Coppicing is a traditional form of forest management where forest owners collect woody biomass for subsistence. Overall, the relevance of coppices decreases in Eastern and South-Eastern Europe because more advanced forms of forest management are implemented (Wolfslehner et al., 2009). The per-capita energy consumption as share of the total energy consumption varies within Europe. It is between 15 and 20 % in Northern Europe, almost 10 % in South-East Europe, and around 5 % in Central Europe (Forest Europe 2020). In view of the growing demand for solid wood products and wood fibre, the cost of using wood for energy increases. Wood fibre based industries (pulp, particle and fibre board) draw on the same raw material as modern fuelwood (wood residues, small diameter logs) (FAO 2022).

In temperate and boreal regions, the major sources of primary biomass for energy are (i) harvesting residues such as a part of the small-sized tree tops and branches that are unsuitable for wood processing; (ii) trees that are damaged by storms or insects or pathogens and that are not accepted by the wood industry, (iii) primary wood in rural areas where small-holder foresters choose between the use of fossil fuels or locally available woody biomass, mostly for domestic heating (Westin et al. 2023). The major source of energy from wood in the temperate and boreal region comes from residues of wood processing. This applies particularly for countries with economically strong wood industries.

In Austria, 30 % of the total energy demand (1454 PJ) originates from renewable sources. Within renewable energy wood is the single largest energy source (BV 2021). In the year 2020 a total of 44.4 Mio m^3 were used. Processing timber included several wood product cycles and generated an equivalent of 15.4 Mio m^3 wood that was converted to bioenergy. In addition 10.1 Mio m^3 of primary biomass was used as energy source (Tab. 1, data from Strimitzer et al., 2021).

Table 1: Wood flow in Austria in the year 2020; Source: Strimitzer et al. (2021). Note: the detailed wood flow diagram is annually updated by the Energy Agency; https://www.klimaaktiv.at/erneuerbare/energieholz/holzstr_oesterr.html).

	Mio m³
timber import	14.8
domestic production	22.4
other wood	7.2
Total timber use	44.4
bioenergy from wood processing	15.4
from primary biomass	10.1
Total bioenergy from wood	25.5

Technically, the supply of energy from forest biomass can be increased. Figure 2 shows that the forest area, the harvesting rates and the standing stock of biomass have increased since at least 1961. An active and determined forest administration, skillful forest management, and a framework for forest policy and governance guarantee the implementation of sustainable forest management (Forest Europe 2020). Raising the harvesting rate will increase the amount of harvesting residues, primary biomass, and bioenergy generated as side stream of wood processing. The effect diminishes once forest technology can process so far unsuitable timber assortments.

Regionally, particularly in rural areas, recent increases in prices for fossil fuels and insecurities in their supply have strengthened the interest in wood-derived energy sources, mainly for heating purposes. Households in rural areas often have the technical infrastructure, storage capacities, and local fuel wood suppliers enabling them to switch between forms of energy. The demand for fuel wood was high and the price for fuel from hardwoods showed – for the first time in many years - a sharp increase in 2022 (Statistik Austria, 2022). It can be expected that producers respond to emerging opportunities and at least temporarily increase the harvesting level. Even a new interest in coppice forests has been observed, where fuel wood production is described as a synergistic effect with erosion control and increases in biodiversity, respectively (Johann, 2021).

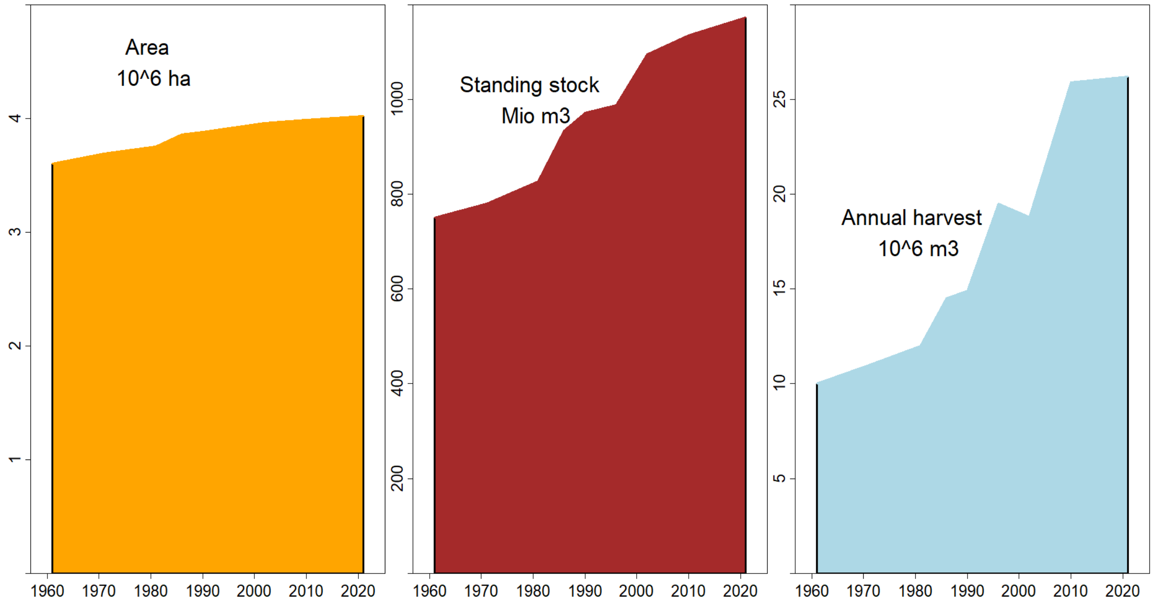

Figure 2: Temporal development of the forest area, the standing stock of stem wood, and the harvest rate in Austrian forests; Source: www.waldinventur.at.

On the national level, the impact of increasing the bioenergy production from wood will be rather small. Presently, 186 PJ (13 % of the total Austrian energy demand) are derived from wood-based bioenergy. An increase of wood bioenergy production by 15 % would have an almost negligible effect for the Austrian energy supply. Larger increases in fuel wood production are unsustainable and would exhaust the forest resources within a few decades (Braun et al., 2016).

Generally, wood will be part of the renewable energy mix in industrialized countries. Advantages of energy from biomass are that it - other than solar or wind energy - can be released on-demand, that the required technology is already installed, and the resource is domestic. Trade-offs are the low energy content of wood as compared to fossil fuels, the emission of fine particles upon incineration, and ecological concerns of unsustainable nutrient export from forest sites. A large-scale and long-term reliance on forest biomass for the energy supply in Austria and in all Europe is unrealistic, but the regional relevance for the energy supply, primarily heating, is a valuable and stable contribution to the national energy budgets.

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Commission for Interdisciplinary Ecological Studies (KIOES)
KIOES Opinions 13 (2023): 41–44.
doi: 10.1553/KIOESOP_013

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Energy storage, energy carriers, and means to store and to carry energy

Georg Brasseur

Environmental conditions that are hostile to life, such as UV light, X-rays and gamma radiation, as well as high-energy particles from the sun and the universe, permanently cause mutations in living organisms. Only those life forms that are better able to adapt to the environmental conditions through random mutations reproduce and are more likely to survive than less adapted life forms that die out. This process of natural selection (survival of the fittest), which has been going on for about 3.5 billion years [1], has also enabled organisms to optimize ATP (adenosine triphosphate), an energy carrier that is important for their own metabolism. ATP decomposes reversibly in the cell into ADP (adenosine diphosphate), releasing energy, and can be converted back into ATP by supplying energy. In aerobic cellular respiration, energy is supplied by glucose ($C_6H_{12}O_6$) ingested with food or obtained via photosynthesis. Glucose is a carbohydrate that has the energy-giving hydrogen atomically bonded to carbon. In order to keep living beings alive longer when food is scarce, the energy density of the body's energy carrier must increase, and in a further optimization step in evolution, vegetable oils and animal fats emerged. These are still hydrocarbon molecules, but with little oxygen content, since this is freely available in the ambient air.

In anaerobic cellular respiration, such as in cyanobacteria, ATP is provided via a less efficient fermentation process in which ammonia (NH_3) plays a crucial role. Again, hydrogen is present as an energy carrier in atomically bound form, but this time bound to nitrogen rather than carbon.

What can we learn for the energy transition from evolution, which has optimized energy carriers over a very long time and billions of experiments according to the principle of natural selection? Hydrogen is an excellent energy carrier only if it is atomically bound to nitrogen or carbon. Since carbohydrates contain a lot of oxygen in the energy carrier, but oxygen is freely available in the ambient air, energy carriers that can be easily transported and stored should contain as little oxygen as possible, following the pattern of vegetable oils and animal fats. Two examples: When burning one cubic meter of methane stoichiometrically (about 9.9 kWh/m^3 @ 1 bar), one simultaneously burns about 9.5 cubic meters of air[1]. And for gasoline and diesel (about 12 kWh/kg), the stoichiometric mass ratio of air to fuel is about 14.7 [2].

Hydrogen (H_2) is the lightest and smallest molecule and a very reactive gas. It therefore hardly occurs in the atmosphere. The high gravimetric energy density of 33 kWh/kg [3] is not very helpful in terms of an easily transportable and storable energy carrier, since gas and liquids require a transport container. The volumetric energy density of H_2 is low at only 3 kWh/m^3 @ 1 bar [3] and thus lower by a factor of 3.3 than that of methane (CH_4) [4], although there is one additional carbon atom (atomic mass 12) in the molecule. This shows the effectiveness of the atomic bonding of H_2 to carbon. In the liquid state, the energy

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[1] Methane is assumed here to be an ideal gas. For complete combustion, each gas molecule of methane (CH_4) - assumed here to be an ideal gas - requires two oxygen molecules ($2*O_2$). Thus, one cubic meter of CH_4 requires two cubic meters of oxygen for complete combustion. Therefore, at 21 % oxygen content in the air, the volume of air required is 9.52 cubic meters. Since methane is a much more effective greenhouse gas than CO_2, either a catalytic exhaust gas aftertreatment ensures that no unburned methane is released into the atmosphere (internal combustion engine) or combustion takes place with a strong excess of air (gas boiler).

density ratio of methane @ -162 °C [4] to hydrogen @ -253 °C [3] is 2.6.

Ammonia (NH_3), another energy carrier for hydrogen, is a corrosive gas that becomes liquid -33 °C @ 1 bar [5] and offers a higher energy density than H_2 despite the additional nitrogen atom (atomic mass 14).

- Gaseous: $NH_3/H_2 = 1.27$ @ 1 bar and (NH_3 @ 9 bar) / (H_2 @ 700 bar) = 2.65
- Liquid: (NH_3 @ -33 °C) / (H_2 @ -253 °C) = 1.5

This demonstrates that today's fossil hydrocarbons and ammonia, as well as their synthesized counterparts – so-called "drop-in fuels" – are significantly superior to molecular hydrogen as an energy carrier and storage. Furthermore, without significant conversion, drop-in fuels can use existing transport routes, transportation means and storage facilities, as well as be available to consumers such as power plants, industrial processes and households. However, the hydrogen for synthetic hydrocarbons (methane, diesel, gasoline, methanol, kerosene, ...) must be provided from renewable sources, such as mainly solar and wind power plants, via electrolysis of fresh water, and the carbon must come from a closed loop. In a nutshell: Mankind does not have the time that evolution could take to find better storable energy sources.

The energy transition must start with saving energy. This means increasing the efficiency of processes and using existing infrastructure. The establishment of a new intercontinental energy vector hydrogen would require enormous amounts of raw materials [6] and primary energy for plant construction (ships, pipelines and storage) as well as skilled labor, which cannot be provided in the time available and additionally release many gigatons of greenhouse gases; keyword annual production quantities of steel, concrete, aluminum, copper, fiber-reinforced plastics, etc. Hydrogen can therefore not be a new intercontinental energy vector.

If Europe were to produce the amount of fossil energy required in 2019 (17 100 TWh) [7] via electricity, 488 power lines of 4 GW capacity each (= 1 952 GW) would have to be operated around the clock, and the failure of a single line would inevitably lead to a blackout in Europe, since the Frequency Containment Reserve (FCR) in Europe is limited to 3 GW [8]. That the "488 power lines" approach is unrealistic needs no further explanation. It is equally unrealistic to try to generate the fossil energy needed by Europe with wind turbines or photovoltaics: In the case of wind turbines, the number of wind turbines available in Europe in 2019 (82,000 with an average installed capacity of 2.5 MW and an annual utilization rate of 26 % [7]) would have to be increased to 3 million wind turbines; that is, 36 times more wind turbines. For photovoltaics, the area of solar cells installed in Europe in 2019 (2 072 km^2 with an annual capacity utilization of 12 % [7]) would have to be increased to 228 000 km^2. This area is 111 times the existing one and is approximately the size of Romania.

In 2019, Europe imported 58 % of the energy products needed by the huge sum of € 320 billion [9]. Thus, even in the future, Europe will not be energy self-sufficient. Even if a lot of primary energy can be saved by increasing the efficiency of processes, the potential is limited because volatile energy has to be partly transformed and temporarily stored until it is in a form required by consumers. Europe must therefore continue to import readily transportable and storable fuels. However, these green drop-in fuels must come from regions where the yield of volatile energy is much higher than in Europe, so that the huge amounts of raw materials and primary energy required to build plants can be made available in a foreseeable period of time.

Nevertheless, Europe needs green hydrogen in large quantities for defossilization of industries such as steel, cement, and chemicals, as well as for refineries and for high-temperature processes in basic industries [10]. Since hydrogen cannot be imported to Europe, it must be produced in Europe via electrolysis from water with European electricity.

Europe must at least generate electricity for those consumers who *have no other option*. Because, as already shown, neither hydrogen nor electricity can be imported to Europe intercontinentally in the quantities required. These consumers, which rely exclusively on electricity, include the ICT sector, e-motors, railroads, lighting, households, heat pumps, and industrial sectors for electrolyzers to generate the green hydrogen to defossilize the processes. Road transport is not included, as it also has other options.

For the population and for industry, it is unrealistic and unreasonable to have to live in a supply-driven energy system in the future instead of a consumer-driven one as has been the case up to now. The consequence is the construction of green energy storage facilities to be able to exchange large amounts of energy between seasons (Fig. 1, [11]). Neither pumped hydro storage plants nor batteries have the necessary storage capacity for this purpose.

Hydrogen is also only suitable to a limited extent, since underground caverns made of stable rock are needed for this purpose and presumably no classic natural gas storage facilities can be used because the hydrogen molecules, which are very reactive to methane and tiny, could perforate their sealing layers and thus also make them unusable for methane storage.

To bridge cold doldrums without endangering Europe's grid stability, as many calorific power plants must be operated in parallel to the volatile power plants until the entire consumer load is covered. Even after a successful energy transition, grid operation will therefore continue to generate high costs, as personnel and maintenance must be maintained for the standby operation of the calorific power plants.

Through the use of Carbon Capture and Storage (CCS) [6], [14], [15] and/or Carbon Capture and Utilization (CCU), it might be possible to use existing fossil-fueled power plants to bridge cold and dark doldrums without emitting greenhouse gases, since CCS technology could inject the fossil CO_2 emissions into basalt rock or old natural gas fields. The "Schwarze Pumpe" project in Germany [12] and Norway's offer to inject all CO_2 emissions from German coal-fired power plants into its own natural gas fields can serve as an example [13]. With CCU, the captured fossil CO_2 emissions from the fossil power plants could be used in a pyrolysis process to convert them into recyclable carbon for, for example, plastics production or to carburize the soil.

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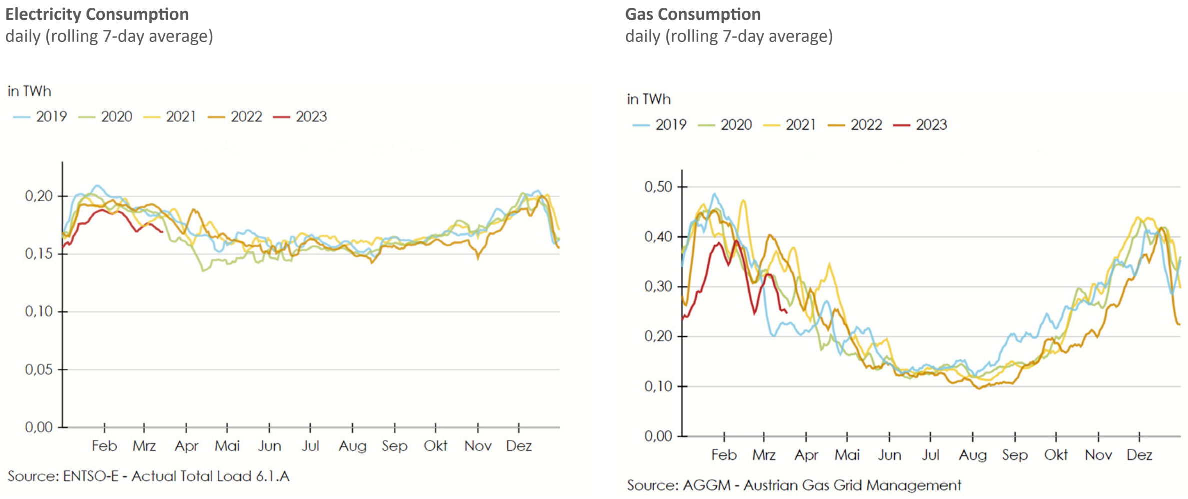

Figure 1: Annual trend of electricity and gas consumption in Austria. Note the fairly constant level of electricity consumption, at about half the value of the winter maximum, or two thirds of the summer-winter difference, of gas consumption. Data from [11] based on original CC-BY license.

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Commission for Interdisciplinary Ecological Studies (KIOES)
KIOES Opinions 13 (2023): 45–47.
doi: 10.1553/KIOESOP_013

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Opportunities of digitalization

Wilfried Winiwarter and Peter Palensky

Background situation

Energy transport is limited by physical constraints. Whether there is material transfer (in pipelines, by ships, trains or trucks) or merely transfer of electrical current in power lines, adequate infrastructure (that is defined by its capacity) is needed. Moreover, while any fuel can be stored, electricity merely can be converted, and storage (such as in hydroelectric storage plants) typically comes with extra losses of 20 % or more and potentially with high capital expenses.

Energy consumption often follows distinct temporal patterns. Households need energy for lighting and heating in winter, and potentially for cooling in summer. With easy storage options, fuel transport nevertheless can be performed on a constant (low-cost) level. Fuels will be released from storage when needed, and peak transport only is required for the "last mile", the distance between a storage place and the user. It will depend on the situation to define what the "last mile" in practice means.

The way to provide electricity is more complex. In a balanced grid, electric generation and consumption must match at any given moment (otherwise the power system will collapse). In practice, this happens by pooling basic power supply (such as nuclear plants or coal fired power plants, also run-of-the-river hydro plants) for the base load with power plants that can be started when needed, such as hydroelectric storage or gas fired power plants. Storage (such as pumped hydro, flywheels, solid state batteries, flow batteries that store the energy in liquids outside the device, compressed air, or thermal storage) can also provide fast generation (or consumption) capacity if needed.

Challenges to the grid have become higher with renewable energy sources such as wind or solar. As such electricity sources provide sizeable shares of total power production (e.g., Germany or Denmark, on an annual average, about 37 % (Burger, 2021) and 61 % (DEA, 2021), respectively, from wind and photovoltaic) and as production from these sources depends on weather conditions, demand/supply matching problems get more pronounced. Distribution grids, designed for housing loads, also face serious congestion problems either due to "demand side" solar production or due to EV charging situations. High shares of fluctuating renewables also put fast production facilities that can counter-balance these fluctuations, e.g., expensive gas and hydro-storage plants, into the spotlight. To some extent the irregularity of renewable electricity production can be compensated by accurate weather prediction, such that forecast electricity production figures allow to more precisely dispatch electricity from other sources.

Smart grid preconceptions

While classically, production follows consumption, a renewable power system contains large shares of non-dispatchable generation. Ideally, consumption would follow generation whenever possible in this case. Here digitalization may take a key role.

Developing an electrical grid into a smart grid needs more than just a bundle of individual measures. It requires developing the grid into a digital platform. There are initial starting points, but the overall developments are not yet fully predictable. Initiators of such developments are

- Observability: real-time metering of electricity consumption to allow price signals with respect to peak or base consumption, PMU (phasor measurement units), power quality meters.
- Transactions: short-term contracts of power delivery on an automated marketplace. Booking / purchasing to be done via the internet. Both energy providers and consumers exchange "packages" of energy, taking advantage of the respective opportunity infrastructure offers for a given space and time.
- Flexibility and Storage: batteries, electric vehicles (with compensation of owners possible), demand response, smart cities, flexible industrial loads.
- Integration: smartly connecting energy systems across sectors (e.g., heat, gas, electricity, built environment), with dynamic markets (e.g., on neighborhood level or congestion markets), between TSO and DSOs, and between countries contributes to resilience and flexibility.

Such an infrastructure needs operating policies, and it needs to be protected against misuse as well as criminal acts scaling from vandalism up to electronic warfare. A smart grid needs to have a defined and secure way of payment, needs to be safe against interruptions (both the data transfer and the power lines themselves) and it needs to come with some redundancy (resilience), in order to buffer eventually appearing problems.

There are considerable issues to be sorted out with regard to data safety, data ownership, digital identity, and possible data transfer, comparable to the issues with data on mobile phone use. As a smart grid benefits immensely from the co-existence of the individual parts, ownership structures will be quite complex. A mechanism of identifying responsibilities regarding extension, service and repair of hardware compounds to be used by all partners needs to be elaborated.

Research focus

A complete electrical grid is a huge, expensive, and complex infrastructure. Out of the three possible scientific methods, analytical, experimental, and numerical investigation, it is often only the latter that is possible. Each element of a smart grid, a grid using information and communication technology to improve its operations, can be described in a numerical model, simulated in scenarios, and the result validated independently. The considerable challenge of model coupling to arrive at cosimulation of all relevant compounds has been described in detail by Palensky et al. (2017). Optimizing smart grids requires addressing the reliability of grid components, especially of sub-grids (micro-grids) near the consumer to maintain angular (phase in), frequency, and voltage stability in alternate current. Such systems and their structural design, also for future power systems, are shown by Peyghami et al. (2020).

Based on an understanding of the general operations of such a power system, further details may be derived. This includes the challenges of integrating battery energy storage systems, where components of such a storage system are analyzed, their applications compared, and size and locations in networks are discussed (Stecca et al., 2020). Advanced trading systems have been developed, based on communication technologies, taking advantage of blockchain technologies and thus allowing peer-to-peer energy trading directly between consumer and producer (Esmat et al., 2021). Decentralization is a key concept of such developments.

Also new challenges to energy systems are a subject of extensive studies. Misuse of communication systems may bring extra challenges. Cyber attacks may attempt to exploit system vulnerabilities (Pan et al., 2020). Understanding modes of attack and system vulnerabilities potentially leading to blackouts allows to design simulation frameworks to analyze impacts and to protect against such attacks (Rajkumar et al., 2020).

Expectations and limitations

While optimizing the use of physical devices that constitute a grid will not allow it to exceed any of the capacity limitations, its logistics can be substantially extended. Given the fact that capacity now is defined by peak capacity, and peak consumption may achieve up to 2-4 times average consumption, substantial transport and distribution improvements are possible. Optimization may even extend towards using buffer storage devices (from pumped hydroelectric to e-vehicle batteries) selected close to expected future users, such that transmission capacity is relieved.

The overall concept follows and actually is strongly determined by a market approach. There is considerable risk that such market approaches can be best used by market participants that possess financial flexibility – or in other words, that consumers that lack necessary financial backing would be at a disadvantage, having to bear the times/situation of high costs and being pushed more heavily into energy poverty. Also here, appropriate compensation and policy guidance will be needed.

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Commission for Interdisciplinary Ecological Studies (KIOES)
KIOES Opinions 13 (2023): 49–52.
doi: 10.1553/KIOESOP_013

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Co-benefits and trade-offs of building intercontinental energy trade networks

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The challenge of intermittency

For the expansion of renewable energy supply wind and solar are the most promising technologies, both in terms of quantitative potential and low economic cost (IEA, 2021). It is their inherent intermittency (variability that is unpredictable for more than a few days for solar and wind) that poses a challenge (Gowrisankaran et al., 2016). This can be addressed by adding storage, by demand-side management (including shifting demand across time), by expanding the geographical area where generation is located and linking generation and demand sites with (medium- and long-distance) energy trade, or any combination thereof (Grossmann et al., 2013, 2015). Which particular combination of these components and which technology for each of them can contribute to the highest societal benefit is governed by various factors, including cost, security and flexibility. This section looks at the last of the elements mentioned, spatial enlargement of the generation grid and respective contributions to societal benefits.

Wind and photovoltaic electricity in large trade networks

Wind patterns differ within continents. Linking respective generation sites at within continental scale by energy trade or combining with other renewables could thus deliver substantial economic benefits by balancing periods of low wind (Veers et al., 2019). While the basic pattern of solar insulation is absolutely predictable, there is weather influence as well, thus generation of solar energy is foreseeable within weather forecast reliability (i.e. usually for a period of about two weeks). As low-pressure areas with resulting low PV production can extend across larger areas, in Europe up to 1000 to 2000 kilometers, a regional expansion of integrating PV generation sites at or beyond that scale of distance can ensure robust supply in a system that can then accommodate for short-term (up to days) intermittency, with ahead management based on weather forecasts (Malvoni et al., 2017).

While solar has become the cheapest electricity source in mankind history (if reasonable low-cost financing is available, IEA (2020)), and storage options such as battery and pump hydro are reasonably available to overcome the diurnal fluctuation (López Prol and Schill, 2021), the seasonal variability is more challenging. Seasonal fluctuation grows with geographical latitude (and respective distance to the equator). At the northern latitude of Austria, for example, winter insolation (and thus PV generation of any panel) is only about one fifth of the summer production. For any Northern location the other – Southern – hemisphere has an exactly complementary pattern with respect to the seasons. Therefore, intercontinental (more precisely interhemispheric) energy trade can accommodate seasonal intermittency. This trade is possible through electricity transmission or in shipping energy carriers, such as hydrogen or ammonia.

Relative to autarkic constellations within each hemisphere the transhemispheric transmission interlinkage of just two PV generation sites can already reduce required aggregate storage capacity by about two thirds, and aggregate PV capacity by about a quarter, with the resulting system still delivering robust supply at any point in time, rendering substantial economic benefits. Interlinking more than two locations can further decrease demand for PV and in particular for storage. Such quantifications arise when considering long-term insolation data (20 years, hourly, globally disaggregated) and economic optimization at reasonable cost factors for transmission, PV generation and storage. Relative to intra-hemispheric designs such transhemispheric interlinkages can reduce electricity cost by up to 50 %, with further progress in interhemispheric connectors by even more (Grossmann et al., 2015).

Co-benefits and trade-offs

At the continental scale a widely distributed and high number of generation sites ranks higher in energy security and stability than a centralized system of only a few (fossil) generators (Blaker et al, 2017). For example, the NordNed project between Norway and the Netherlands, operating since 2008, presents qualitative improvements of supply security and additional opportunities to overcome potential electricity shortages, as well as good access to flexibility (Nooij, 2011). Especially in Europe international grid connections have proven to contribute to overall energy security (Renewable Energy Institute, 2019). For intercontinental configurations time zone diversity and latitudinal integration lead to additional demand and supply smoothing as indicated above (Brinkerink, et al., 2019). Advanced forms of such distributed generation also provide the ability of remote control, which therefore can ensure a safer and reliable operation in emergency situations (Hoang, et al., 2021).

While fossil fuels are often concentrated in politically unstable regions, which raises geopolitical conflict potential as importers are highly vulnerable for export restrictions and price fluctuations (Renewable Energy Institute, 2019), as experienced with the oil crisis with Saudi Arabia and more recently with Russia, renewables are found much more evenly spread around the globe, additionally to their nature of rich supply (especially of solar), they do not face the same diplomatic and political tensions. This can likely contribute to reduce geopolitical risks (Renewable Energy Institute, 2019).

Any future global deployments of renewable energy systems bear potential for developing economies, international cooperation, and sustainable development (Chilán, et al., 2018). Emerging economies can be stimulated by the investments connected to the renewable energy deployment and international cooperation, accelerating local economies and local energy coverage (Chatzivasileiadis, et al., 2013), but with comprehensive societal benefits crucially dependent on how local, and in particular indigenous communities are transparently and fully integrated into the project planning and development (O'Neill, et al., 2021; Maher, et al., 2022; Chandrashekeran, 2021; Van de Graaf & Sovacool, 2014). Electricity transmission with the perspective of a global or intercontinental grid drives the creation of green jobs and welfare improvement (Brinkerink, et al., 2019). Socio-economic impacts of renewables are strongly driven by employment and job creation, with the renewable sector connected to higher employment potential and job creation than the fossil fuel sector (Ram, et al., 2022). Employment opportunities seem to emerge especially for the young and in developing countries, the most so for countries with low growth rates (Chilán, et al., 2018).

On the other hand, there clearly are trade-offs and barriers. Not only is the renewable generation capacity generation itself connected to large up-front investment and highly capital intensive, so is the installation of transmission lines. Getting integrated in a grid of direct transmission requires some degree of trust among trading partner countries. It may thus arise first among countries cooperating in other fields already (e.g. within the Commonwealth). It may, however, also increase geopolitical dependencies (Brinkerink, et al., 2019). While local production might still benefit the major producing nations, others will be dependent on their supply. As it is renewable electricity produced locally that is directly transmitted, both, the supplier and the demander are interested in a smooth and constant exchange - to ensure electricity supply (for the receiving nation) and revenue flow and avoiding the need of storage facilities (for the generating side), with roles switching across seasons (Chatzivasileiadis, et al., 2013).

Energy security

How safe is such a power supply? If evaluated from the end situation, a complete European energy supply from European PV generation and by PV import would require about 150 cables of a capacity of 6.2 GW connecting Europe with many countries around the world. This amount of cables would be able to cover the maximum current total energy consumption and does include a security buffer of excess capacity.[1] European electricity consumption varies considerably throughout the year (by a factor of almost 3), and in winter demand is also about 40 % higher than in summer. Many different solutions are possible in the power supply system. For example, batteries could be installed to cover peak consumption, which causes a significant proportion of the fluctuations in electricity consumption. This would reduce the need for cables. PV, batteries and cables thus do not only complement each other, they can also substitute for each other. Also considering the buffer, the destruction of up to 20 cables would hardly affect the European power supply, in the worst case energy demand management is possible to avoid peak demands. It is very unlikely, except in the case of a major war, that so many cables would fail at the same time. Scenarios that can realistically be envisaged here can be carefully evaluated as a prerequisite for entering this form of power supply. Time is pressing, and it is advantageous that an additional component is now becoming available for energy supply. Politicians are increasingly pushing for solutions and this new component increases the flexibility for decisions. This frees from the pressure to commit all stakeholders to one solution; rather, many components can contribute to the solution in many ways.

If real-time dependency on electricity from abroad transmitted in an intercontinental electricity grid is considered a risk too large to bear, the alternative is to trade energy in other carrier media. Electrolysers can transform renewable electricity into hydrogen, and chemical transformation to process to ammonia, characterized by different advantages for transport. Such transformation to media that are well storable (and thus avoid real-time supply risk) come at the economic cost of substantial transformation losses: the production of hydrogen to date is connected to losses of 40 % (with potential to reduce losses to at best 30 %), for compression for transport and decompression thereafter to losses of 8 % each, and when used in e.g. a fuel cell of another 40 %. In total, for such energy trade, with current best available technologies only about 35 % of the initial electricity arrive for final demand use. Other co-benefits and trade-offs are the same as covered above for direct transmission, yet due to these transformation losses at a respectively lower economic scale. Real-time dependency, however, is avoided, therefore such a system also comes with lower direct incentives for continuously sustained cooperation (Brenneman, 2009).

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[1] Present cables have capacity of about 2 GW at voltage of 600 kV. Voltage has been increased by about 10 % per year for several years; a first high voltage direct current (HVDC) landline with 1.1 MV already exists. This voltage may become common for high-capacity cables, increasing the capacity by a factor of 4. While cables are being laid, newer cables have higher capacity, beginning with 2 GW ending with let´s say 10 GW, would result in an average of 6.2 GW, as in the beginning the number of new cables added per year will be lower so that many cables will have high capacity.

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Conclusions: Perspectives and challenges of energy transition

Wilfried Winiwarter

With this volume we do not claim to comprehensively treat the value and the need of energy provision to our society. Instead, picking up from individual opinions expressed during the internal presentations and discussions within the working group this volume provides a collection of individual facets, of isolated aspects that in combination allow useful and sometimes surprising insights.

Which technology, what investment will be needed to safeguard human wellbeing for the future, specifically for the situation in Europe? The need to move away from the combustion of fossil fuels has become apparent with the gradually developing climate change, exacerbated by the necessity to avoid dependence from politically unreliable trade partners. Fossil fuels, however, have contributed so much to this world becoming home of 8 billion people, and Europe largely one of the wealthiest regions on earth.

Abandoning fossil fuels requires a transformation that is not modest. Such a transformation will not work as the adoption of one single, plug-in measure that immediately solves issues once and for all. Hence, any serious suggestion to an energy transition meeting the needs of the Paris accord (limiting climate change to a temperature increase of well below 2°C, globally) looks into bundles of measures – and it needs to strive into adopting all reasonable measures quickly and effectively. This is well reflected in the individual contributions presented here. Several sections of this volume refer to demand-side measures – measures that would allow to decrease energy consumption in order to also limit production as much as possible. Other important contributions demonstrate the technological progress: measures exist or are being developed that are essential for the supply-side of a clean energy provision. Authors of this volume do not necessarily agree on the priority of measures, but it becomes clear from the above that any debate on priorities (even regarding measures that eventually may turn out to be wasted) is pointless in the view of the overall urgency.

Considerations on the demand side start out from the biophysical requirements of humans, and extend into the needs (on a society level) for a healthy life. It turns out that, under European conditions, lifestyle emissions, i.e. those emissions that only occur due to activities enjoyed by a rather small fraction of the overall population, can make up considerable parts of the total carbon footprint. At the same time, the issue of energy poverty is raised, where citizens are not able to fully participate in society due to their personal lack of having energy available. This exemplifies that a uniform cut of energy provision will not allow for a sustainable future, while there clearly is huge potential in saving when provision is limited to the needs and not to the excessive use by some.

Remarkable are the new technologies available already now or in development to be deployed in the near future. Physical limitations exist, especially regarding the transmission of the most versatile form of energy, electricity, for which moreover its storage is challenging. But its generation from renewable sources has become affordable or even profitable and hence also production increased largely over just a few decades. Also, storage and transport as energy rich chemicals (hydrogen and derived fuels, such as ammonia, alcohols or hydrocarbons) has made considerable progress. Even electric transmission capacity can be greatly increased without hugely extending the infrastructure by extending peak loads to much longer time periods, using smart grids that also regulate consumption patterns. Simply switching over to electricity as the single energy provider for all consumers will not work, however.

Hence, also the existing energy pathways that guide us into the scenarios also used by IPCC to take us into a sustainable future (1.5° and 2° scenarios based on SSP1 storylines) combine strategies that massively limit energy demand while considering the most advanced technologies to allow for sustainable supply. These strategies exist and their effects have been quantified successfully. Their implementation, however, remains to raise considerable challenges towards a fair and just distribution of the efforts required –at least as considered by a majority of people within countries, and a majority of countries worldwide. Accomplishing such political agreement remains the key challenge of this century.

Schedule of working group sessions & presentations by external experts

Session 1 – Overview, Global Energy Production and Markets – February 1, 2022

Alessia de Vita, E3-Modelling: The EU on the pathway to carbon neutrality: challenges and opportunities
Wolf Grossmann, Wegener Center of University of Graz: Contributions to a new energy system

Session 2 – Energy storage – March 1, 2022

Eric Loth, University of Virginia: How do we design the Future of Wind Energy and Storage?
Dennice Gayme, Johns Hopkins University: The promise and challenges of energy storage

Session 3 – Energy distribution and grids – April 5, 2022

Peter Palensky, TU Delft: The digital transformation of our energy system
Sonja Wogrin, TU Graz: Modeling Austria's power system on its path towards climate neutrality

Session 4 (internal meeting) – May 3, 2022

Session 5 – Energy for decent living and wellbeing – June 7, 2022

Julia Steinberger, University of Lausanne: 10 stylized facts about "Living Well Within Limits"
Narasimha D. Rao, Yale University. Demand-focused Perspective on Energy Transitions

Session 6 – Energy justice – June 28, 2022

Marie Claire Brisbois, University of Sussex: Creating effective, fast, and fair energy transitions
Vlad Coroamă, Technical University Berlin: Digitalisation, Energy and Sustainability (The Good, the Evil, and the Complex)

Session 7 – Energy poverty, social innovation – July 12, 2022

Shonali Pachauri, IIASA: Energy poverty considerations in energy transitions to a low carbon future
Richard Hewitt, University of Madrid: Social innovation and the energy transition: Looking at the problem the other way round

Session 8 (internal meeting and report planning) – August 25, 2022

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Simone Gingrich studied ecology at the University of Vienna and obtained her doctorate degree in social ecology at the Alpen-Adria-Universität Klagenfurt. She habilitated for social ecology and serves as assistant professor, researcher and lecturer at the Institute of Social Ecology, Department of Economics and Social Sciences, University of Natural Resources & Life Sciences, Vienna (BOKU). Simone Gingrich was elected as member of the Young Academy in 2018. Her research interests are long-term socio-ecological research (LTSER) at local to global scales, land and resource use, socioecological metabolism, application of socio-metabolic accounting to various spatio-temporal contexts and inter- and transdisciplinary sustainability research.

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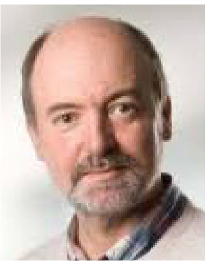

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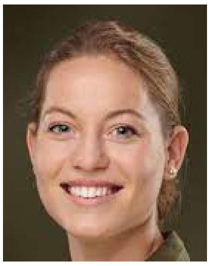

Celine Sauer is obtained her B.Sc. degree ("Renewable Ressources") at the Technical University of Munich in 2019. During her bachelor studies, she worked as a research assistant and supported the BMBF project Trans-SEC in Tanzania especially with the field work on site, coordination of and support of data collection, -cleaning and -analysis. In her Master studies in "Global Studies – economy and environment", of which Celine obtained her degree in 2023, her thesis focused on "Socioeconomic implications of and constraints for transhemispheric renewable energy supply: a European macroeconomic case study analysis". During her master studies, Celine has worked in the fields of European Affairs, regional and rural development, as well as for the H2020 AURORAL project for developing rural investment opportunities for sustainable development. Moreover, she lead the "Transforming Education Squad"-initiative of oikos International for several months, to encourage, empower and co-develop a transformation of higher education towards more sustainability. Since February 2023 she works as a sustainability consultant in the company denkstatt, with focus on decarbonization.

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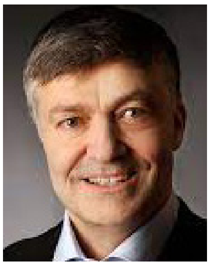

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